IEA
SOLAR R&D

INTERNATIONAL ENERGY AGENCY

solar heating and
cooling program
task VII

central solar heating plants with seasonal storage

[illegible]
and operation of [illegible]
[illegible] for [illegible]
plants with seasonal
storage

may 1983

INTERNATIONAL ENERGY AGENCY

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Program was formulated among a number of industrialized countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organization for Economic Cooperation and Development (OECD) to administer that agreement. Twenty countries are currently members of the IEA, with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Program, the participants undertake cooperative activities in energy research, development, and demonstration. A number of new and improved energy technologies that have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA Committee on Research and Development (CRD), assisted by a small Secretariat, coordinates the energy research, development, and demonstration program.

Solar heating and cooling program

Solar Heating and Cooling was one of the technologies selected by the IEA for a collaborative effort. The objective was to undertake cooperative research, development, demonstrations, and exchanges of information in order to advance the activities of all Participants in the field of solar heating and cooling. Several tasks were developed in key areas of solar heating and cooling. A formal Implementing Agreement for this Program, covering the contributions, obligations, and rights of the Participants, as well as the scope of each task, was prepared and signed by 15 (now 20) countries and the Commission of the European Communities. The overall program is managed by an Executive Committee, while the management of the tasks is the responsibility of Operating Agents who act on behalf of the other Participants.

The tasks of the IEA Solar Heating and Cooling Program and their respective Operating Agents are:

- I Investigation of the Performance of Solar Heating and Cooling Systems — Technical University of Denmark
- II Coordination of R&D on Solar Heating and Cooling Components — Agency of Industrial Science and Technology, Japan
- III Performance Testing of Solar Collectors — Kernforschungsanlage Jülich, Federal Republic of Germany
- IV Development of an Insolation Handbook and Instrumentation Package — United States Department of Energy
- V Use of Existing Meteorological Information for Solar Energy Application — Swedish Meteorological and Hydrological Institute
- VI Performance of Solar Heating, Cooling, and Hot-Water Systems Using Evacuated Collectors — United States Department of Energy
- VII Central Solar Heating Plants with Seasonal Storage — Swedish Council for Building Research
- VIII Passive and Hybrid Solar Low-Energy Buildings — United States Department of Energy
- IX Solar Radiation and Pyrometry Studies — National Research Council, Canada

Collaboration in additional areas is likely to be considered as projects are completed or fruitful topics for cooperation identified.

Task VII — Central Solar Heating Plants with Seasonal Storage

In colder climates, solar energy for heating of buildings is least abundant when it is needed most — during the winter. Seasonal storage is needed for making solar heat gained during warmer months available for later use. From investigations of various storage methods, two observations can be made: the choice of storage method will greatly influence the working conditions for and the optimal choice of the solar collectors and the heat-distribution system; and, based on the technology that is available today, the most economical solutions will be found in large applications. The objective of Task VII is to determine the technical feasibility and cost-effectiveness of such seasonal solar-energy storage for large-scale district heating systems. The Participants will evaluate the merits of various components and system configurations for collecting, storing, and distributing the energy and will prepare site-specific designs for specific systems.

The work is divided into two phases, preliminary design and parametric study of design alternatives. The work during the first phase is undertaken in five Subtasks:

Subtask I a)	System Studies and Optimization (Lead Country: Canada)
Subtask I b)	Solar-Collector Subsystems (Lead Country: USA)
Subtask I c)	Heat Storage (Lead Country: Switzerland)
Subtask I d)	Heat-Distribution System (Lead Country: Sweden)
Subtask I e)	Inventory and Preliminary Site-Specific System Design (Lead Country: Sweden)

The Participants in this Task are Austria, Canada, the Commission of European Communities, Denmark, Germany, the Netherlands, Sweden, Switzerland, the United Kingdom, and the United States.

This report documents work carried out under Subtask I b) of this Task. The cooperative work and resulting report is described in the following section.

central solar heating plants with seasonal storage

Charles A. Bankston
Consultant to Argonne National Laboratory
United States

May 1983

This report is part of the work within the IEA Solar Heating and Cooling Program,
Task VII: Central Solar Heating Plants with Seasonal Storage
Subtask I b): Solar-Collector Subsystems

Unrestricted Distribution.

Document ANL/ES-139
Energy and Environmental Systems Division, Argonne National Laboratory
Argonne, Illinois 60439, USA

PARTICIPANTS IN IEA TASK VII, SUBTASK 1(B)

Manfred Bruck
Austrian Solar and Space Agency
Vienna, Austria

Tom LeFeuvre
National Research Council
Ottawa, Canada

Dolf van Hattem
Commission of the European Communities
Joint Research Center
Ispra Establishment, Italy

Kurt K. Hansen
Technical University of Denmark
Lyngby, Denmark

Heinz Riemer
Kernforschungsanlage Julich G.m.b.H.
Julich, West Germany

Bernd Steinmueller
Philips G.m.b.H.
Aachen, West Germany

Cees den Ouden
Aad Wijsman
Institute of Applied Physics - TNO/TH
Delft, The Netherlands

Heimo Zinko
Studsvik Energiteknik AB
Nykoping, Sweden

John van Gilst
Sorane, S.A.
Lausanne, Switzerland

Brian Rogers
University College
Cardiff, United Kingdom

Charles A. Bankston
Washington, D.C., United States

CONTENTS

CONTENTS (Cont'd)

CONTENTS (Cont'd)

TABLES

TABLES (Cont'd)

TABLES (Cont'd)

FIGURES

FIGURES (Cont'd)

FIGURES (Cont'd)

CENTRAL SOLAR HEATING PLANTS
WITH SEASONAL STORAGE:

BASIC PERFORMANCE, COST, AND OPERATION OF SOLAR COLLECTORS FOR HEATING PLANTS WITH SEASONAL STORAGE

by

Charles A. Bankston

ABSTRACT

This report -- prepared as a part of the International Energy Agency's Solar Heating and Cooling Program, Task VII (Central Solar Heating Plants with Seasonal Storage [CSHPSS]), Subtask 1(b) (Solar-Collector Subsystems) -- reviews the performance and cost of, as well as operating experience with, collector subsystems suitable for CSHPSS application. The types of collectors considered include horizontal collectors (solar ponds), stationary nonconcentrating collectors, distributed line-focus tracking collectors, and central-receiver tracking collectors. Design, installation, and operational considerations are discussed, and performance and cost models are recommended for use in the preliminary design phase of Task VII. Comparing the collector subsystems in terms of idealized CSHPSS use, the subtask participants find the tracking collectors to be most attractive for many locations.

1 INTRODUCTION

1.1 Objective

The objective of Subtask 1(b) of the International Energy Agency's (IEA's) Solar Heating and Cooling Program, Task VII, was to provide the participating countries with technical and economic data on solar-collector arrays, for use in preliminary design and cost optimization of site-specific solar-heating plants. We (the subtask participants) have identified the types of collectors that are suitable for central-heating-plant applications, developed analytical models that reliably predict collector performance, developed adequate cost information for preliminary decisions, assessed the reliability of analytical techniques used to predict the performance of large arrays of collectors, and provided a guide to the literature dealing with the design, operation, maintenance, and reliability of collectors.

We have not identified or rated specific products and have not attempted to provide the detailed information on dimensions, mounting practice, plumbing connections, valve specifications, etc. that would be necessary for final design and the preparation of engineering drawings.

The results given in this report should not be used to judge the economics of solar-heating plants vs. conventional alternatives, because these results do not provide a complete picture.

1.2 Study Guidelines

Solar collectors are part of a rapidly evolving technology. Even the most mature collector types are still in their infancy in terms of production experience. Some of the collectors considered in this report have not progressed beyond the prototype stage, and there are many types for which one good-sized central solar-heating plant (CSHP) would require more collectors than have been produced to date. In order to make meaningful comparisons in such a rapidly changing field, we adopted several guidelines for our study at our second working meeting, held in Villars, Switzerland:

- The collector efficiency should be based on what could reasonably be expected to be specified by a designer in 1982-83 for delivery in 1984-85. This guideline requires the use of judgment on the part of the subtask participants. The practical consequence is to permit the inclusion of collector concepts that are still in the development stage, provided there is experimental or compelling theoretical evidence that the collectors will achieve their promised potential by the mid 1980s.

- The costs should be indicative of a substantial production level (i.e., the first CSHP should not represent a large fraction of the collector production history). For this report, a "substantial" production level is taken as 200,000 m^2/yr by a single manufacturer. (In addition to this guideline, the entire task group has agreed to work with July 1980 U.S. dollars ($) as the currency base and with an agreed-upon inflation schedule and rate of exchange, which was distributed by Subtask 1[a]. The applicable currency-conversion and inflation rates are cited in Table 1.1.)

- The selection of the collector subsystem and its method of deployment is quite sensitive to the total size of the system (load). For the present study, it was agreed that the size of the collector arrays for a single CSHP should be within the range of 2,000-20,000 m^2, with an annual production of 200,000 m^2 by a single manufacturer.

- The maximum collector temperature in a CSHP, which has a major effect on the efficiency and cost-effectiveness of the system, is determined by the allowable storage temperature. Most of the effort of Task VII will be in preliminary design studies, so it was agreed that the collector temperature (storage temperature) would be allowed to range from 30 to 150°C.

Table 1.1 Currency Exchange Rates and National Inflation Rates for Participating Countries

Country	National Currency (symbol)	Rate of Conversion as of June 30, 1980 (national currency/U.S. $)	Inflation (%)		
			1980	1981	1982
Austria	Schilling (Sch)	12.40	6.3	6.8	4.3
Canada	Dollar (Can.$)	1.15	10.1	12.5	11.2
Denmark	Krone (Kr)	5.41	12.3	11.7	10.5
Germany	Deutsche mark (DM)	9.75	5.5	5.9	5.4
Italy	Lira (L)	840.00	21.2	17.8	16.4
Sweden	Krona (SEK)	4.13	13.7	12.1	8.5
Switzerland	Franc (Fr)	1.61	4.1	6.5	5.6
The Netherlands	Florin (fl)	1.91	6.5	6.7	6.4
United States	Dollar ($)	1.00	13.5	10.4	6.7
United Kingdom	Pound (£)	0.42	18.0	11.9	9.5

Source: Personal communication (author's phone conversation with spokesperson for U.S. Department of Commerce), Dec. 1982.

1.3 Sources of Information

During the course of this investigation, we have received information on collectors from all participating countries. Most of the information regarding thermal performance and costs has been taken from U.S. sources, but many of the facts about collector-array performance, operation, installation, and reliability have come from other participants. The principal sources of information within participating nations and the type of material available are cited below:

- Austria conducts a national program for solar and heat-pump technology that includes research at universities and institutes; technology development; monitoring of hot-water heating of swimming pools; space heating and industrial solar systems;

development of codes and standards; and technology transfer. Austria is one of the founding members of IEA and participates in several Solar Heating and Cooling Tasks.

- The Canada Mortgage and Housing Corporation (CMHC) has sponsored a number of studies related to CSHPs. A report prepared for CMHC by Spectral Engineering contains the most useful information on collector costs, performance, and engineering.[1] However, most of the Canadian information was drawn from U.S. sources, so it does not constitute an independent resource.

- The Commission of the European Communities (CEC) is conducting a large solar-energy program involving all the primary forms of application (thermal conversion, photovoltaics, biomass, etc.). It is also participating in, or has participated in, various Tasks of the IEA Solar Heating and Cooling Program. (The CEC presently is a participant in Tasks VI and VII.) The CEC's Joint Research Center in Ispra, Italy, is among the best-equipped laboratories in Europe in the solar field.

- Denmark is the lead country for IEA Task I and is an active participant in Task III. The Technical University of Denmark's Insulation Laboratory has been active in developing procedures for collector reliability and durability testing.

- Germany is the lead country for IEA Task III, Solar Collector Testing, and for the IEA solar-power plant at Almeria, Spain. Germany has strong industrial programs for collector development and is a leading producer of high-quality materials for solar components.

- The Netherlands is also an active participant in IEA Task III. The Institute of Applied Physics (TNO/TH) in Delft has been active in developing procedures for collector testing and has started developing procedures for collector reliability and durability testing.

- Sweden was the first country in the world with operational CSHPs. Installations at Studsvik, Lambohov, and Ingelstad are already in operation, and larger installations are being designed and built. The research center at Studsvik conducts research on solar collectors, and the Building Research Council supports a substantial amount of solar-energy research and development (R&D). Also, there is a very promising industrial effort for developing large-size solar collectors.

- Switzerland has an active testing program for solar collectors. There are test benches in Wurenlingen, for collectors working at temperatures below 100°C; in Lausanne, for collectors working in the temperature range from 100 to 300°C; and in Rapperswil and Davos, for testing the durability of all types of collectors. Collector development is done exclusively by industry.

- The United Kingdom is an active participant in the IEA Task III work on solar-collector durability and reliability. The Solar Energy Unit of University College, Cardiff, is at the forefront of this work.

- Although the United States does not have a program for the development of central solar heating, it is probably the leader in the development and production of solar collectors. Much of the development work is now in the private sector; this is particularly true of flat-plate and evacuated solar collectors. The federal government, through the U.S. Department of Energy (DOE), has played a leading role in the development of advanced collector technologies. Much of the work has been accomplished through the major DOE laboratories, as follows:

Argonne National Laboratory (ANL)	- Compound parabolic concentrators
Brookhaven National Laboratory (BNL)	- Plastic-film collectors
Jet Propulsion Laboratory (JPL)	- Parabolic-dish technology
Lawrence Livermore National Laboratory (LLNL)	- Shallow solar ponds
Los Alamos National Laboratory (LANL)	- Collector R&D, materials R&D
Sandia National Laboratory, Albuquerque (SNLA)	- Line-focus collectors, materials R&D
Sandia National Laboratory, Livermore (SNLL)	- Central-receiver technology
Solar Energy Research Institute (SERI)	- Tracking-collector technology for industry, materials R&D

(A bibliography of English-language solar-collector material, arranged according to national origin, is included in this report. The bibliography supplements the cited references, providing additional material of possible interest to system designers.)

1.4 Previous Studies

Central solar-heating plants employing long-term storage have been designed and built in Sweden (see Refs. 2-5). These plants are all relatively small, and all use different collector types. The plant at Studsvik has stationary concentrating collectors mounted on a rotating turntable.[6] The Lambohov project used flat-plate collectors (FPCs) distributed on the roofs of apartments.[2,4,5] The Ingelstad project used polar-mounted parabolic troughs.[3] A much larger project is in progress in Sweden at Lyckebo, where a plant will be built to supply the needs of 550 residences.[7]

A study commissioned by the CMHC to evaluate the potential of central solar heating in the Canadian continental climate examined flat-plate and evacuated collectors.[8] This study concluded that thermal and parasitic losses were too large to make these collector types viable for use in central plants. More recent work has drawn attention to the use of the central receiver, either for heating plants directly or in a cogeneration mode.[1,9-14] The most recent of these studies (see Ref. 14) compares various solar collectors in terms of cost-effectiveness for central solar heating. The results of that study are directly applicable to the present work and are used extensively throughout this report.

The subtask participants are not aware of studies of CSHPs in the U.S. other than those undertaken as a part of this project (IEA Task VII); however, large collector arrays have been designed for industrial application,[15] and there have been studies of the use of large arrays for low-temperature applications.[16,17] The latter studies have both confirmed that the transport system may determine the cost-effectiveness of large arrays. Both studies show that, in the U.S., central-receiver systems tend to have lower costs because of the optical energy transport, but that the line-focus, distributed-receiver systems (troughs) are competitive at low temperatures.

1.5 Preliminary Selection of Collector Technologies

The depth of information required for this task demanded that the scope of the project be narrowed early in the process to include only those generic categories of collectors that are viable candidates for application in CSHPs in at least one of the participating countries. The initial list of collectors for consideration included single- and double-glazed (SG and DG) FPCs; low-cost or innovative FPCs; shallow and salt-gradient solar ponds; evacuated collectors; stationary concentrating collectors; north-south (N-S), east-west (E-W), and polar-axis parabolic troughs; parabolic dishes; and point-focus central receivers. Preliminary cost-effectiveness estimates were made for these collectors on the basis of U.S. experience. These estimates, together with discussion at the first and second working meetings and reference to the literature cited earlier, eventually narrowed the list to five collector types: FPCs, shallow solar ponds, evacuated (concentrating or nonconcentrating) collectors, E-W parabolic troughs, and central receivers. The basis for these selections was primarily the technical and economic maturity of the technologies and the interest of the participating countries. Reference 1 describes generic collector types and their relative advantages in more detail.

2 THERMAL PERFORMANCE

2.1 Thermal Efficiency of Collector Modules

2.1.1 Stationary Nonconcentrating Collectors

Flat-plate collectors represent the most mature technology in all countries. In the U.S. alone, more than 300 manufacturers of FPCs currently sell about 2×10^6 m^2 annually for space heating, hot water, and swimming-pool heating. In the U.K., more than 60,000 m^2 were manufactured in 1981. Most other Task VII countries also have substantial production.

A wide spectrum of FPCs is available, ranging from low-cost, unglazed swimming-pool heaters to sophisticated, selective-coated, double- or triple-glazed metal and glass collectors. The typical high-performance, long-life FPC on today's market is a tube-and-plate absorber with either a selective coating and single glazing or a black absorber coating and double glazing. It is capable of delivering useful energy at temperatures of 40 to 100°C, weighs 25 to 40 kg/m^2, and costs \$100-150 (U.S.)/m^2 at the manufacturer's plant. Installation, including support structure, piping, valves, pump, insulation, controls and electrical equipment, and all direct and indirect field labor and indirect charges, can bring the cost of the installed collector array to \$350-450 (U.S.)/m^2. The performance of FPCs has reached maturity; manufacturers are now more concerned with reducing costs than improving efficiency, and no significant gains in efficiency are expected in the next five years.

Efficiencies are measured and reported according to standard test procedures developed in the U.S. (see Ref. 18) and in Europe. The U.S. standard bases the collector efficiency on the gross area of the collector, while European practice is to use the net operative area. Researchers at the U.S. National Bureau of Standards (NBS) have shown that under properly controlled conditions, these test methods yield the same results when corrected for the area differences.[19] In this report, we use gross area unless otherwise noted.

The peak instantaneous collector efficiency is usually represented by an equation of the form:

$$\eta = F_R \alpha \tau - F_R U_L (T_i - T_a)/I_g \tag{1}$$

where:

α = Receiver absorptance

τ = Glazing transmittance

U_L = Receiver heat-loss coefficient

T_i = Fluid inlet temperature

T_a = Ambient temperature

F_R = Heat-removal efficiency factor, and

I_g = Global irradiance incident on the collector surface.

The parameters α, τ, U_L, and F_R can be measured or calculated independently, but they are more commonly determined from standard test results as the coefficients of the linear equation relating the efficiency η and $(T_i - T_a)/I_g$ [i.e., $\eta = a + b\,(T_i - T_a)/I_g$].

At angles other than those near normal incidence, the efficiency is reduced (for FPCs) by an incident-angle modifying factor, $K_{\alpha\tau}$, applied to the first term of Eq. 1:

$$\eta = K_{\alpha\tau}\ F_R\alpha\tau - F_R U_L (T_i - T_a)/I_g \tag{2}$$

For most FPCs, this factor can be adequately approximated by (for $\theta < 80°$):

$$K_{\alpha\tau} = 1 - b_o[(1/\cos\theta) - 1] \tag{3}$$

where:

θ = Angle between the incident radiation and the collector normal, and

b_o = Incident-angle modifier coefficient.

As was already stated, FPC performance is unlikely to improve in the next few years. Therefore, we have selected performance curves that represent the best available collectors in 1979, when the results above were obtained, as indicative of what may be typical by 1985. These parameters do not necessarily represent the most cost-effective FPC for a particular application. The recommended equations are:

$$\eta = 0.807\ K_{\alpha\tau} - 4.43\ (T_i - T_a)/I_g \tag{4}$$

where:

$$K_{\alpha\tau} = 1.0 - 0.10[(1.0/\cos\theta) - 1.0] \tag{5}$$

and

$$\eta = 0.717\ K_{\alpha\tau} - 3.32(T_i - T_a)/I_g \tag{6}$$

where:

$$K_{\alpha\tau} = 1.0 - 0.12[(1.0/\cos\theta) - 1.0] \quad (7)$$

for selective SG and DG collectors, respectively.

2.1.1.1 Evacuated Collectors. Nonconcentrating evacuated collectors have been under development for some time in the U.S., The Netherlands, West Germany, Switzerland, Italy, and Japan. In recent years, heat pipes have replaced serpentine tubes for transporting the absorbed solar energy by the optical and selective absorber strips to the fluid manifold.

Heat-pipe (HP) collectors offer simplified manifolding, which reduces both thermal and hydraulic losses; simplified freeze protection; greatly reduced fluid inventories, which reduce night losses; and unidirectional heat transfer, which improves dynamic performance under intermittent sun conditions. When properly matched with the correct fluid and manifold design, the HP can also limit the temperature attained by the absorber under stagnation conditions, thereby increasing the collectors' reliability and durability.

In preparing efficiency curves for evacuated collectors that use HPs to transport solar energy to the fluid manifolds, one must consider the thermal resistance between the condenser of the HP and the collector-loop fluid. This resistance produces two effects not normally considered with liquid-cooled FPCs:

- η_O is dependent on the insolation level, and
- At constant $\Delta T/I_g$, the efficiency η strongly depends on I_g.

Efficiency curves for different insolation levels are shown for Philips Laboratory (Einhoven, The Netherlands) evacuated-collector arrays in Fig. 2.1.* (These curves are based on net aperture area, which may be as much as 20% less than the gross area.)

The two effects produced by thermal resistance can be seen clearly from this figure. In the opinion of research people at the Philips Laboratory,* it is absolutely necessary to measure the collector efficiency, for evacuated collectors and for HP-assisted collectors, at a minimum of two different insolation levels.

Proper simulation of the performance of this type of collector requires consideration of the nonlinear behaviors indicated in Fig. 2.1. A yearly

---

*Source: Private communication from a contribution offered at a subtask working meeting (undated).

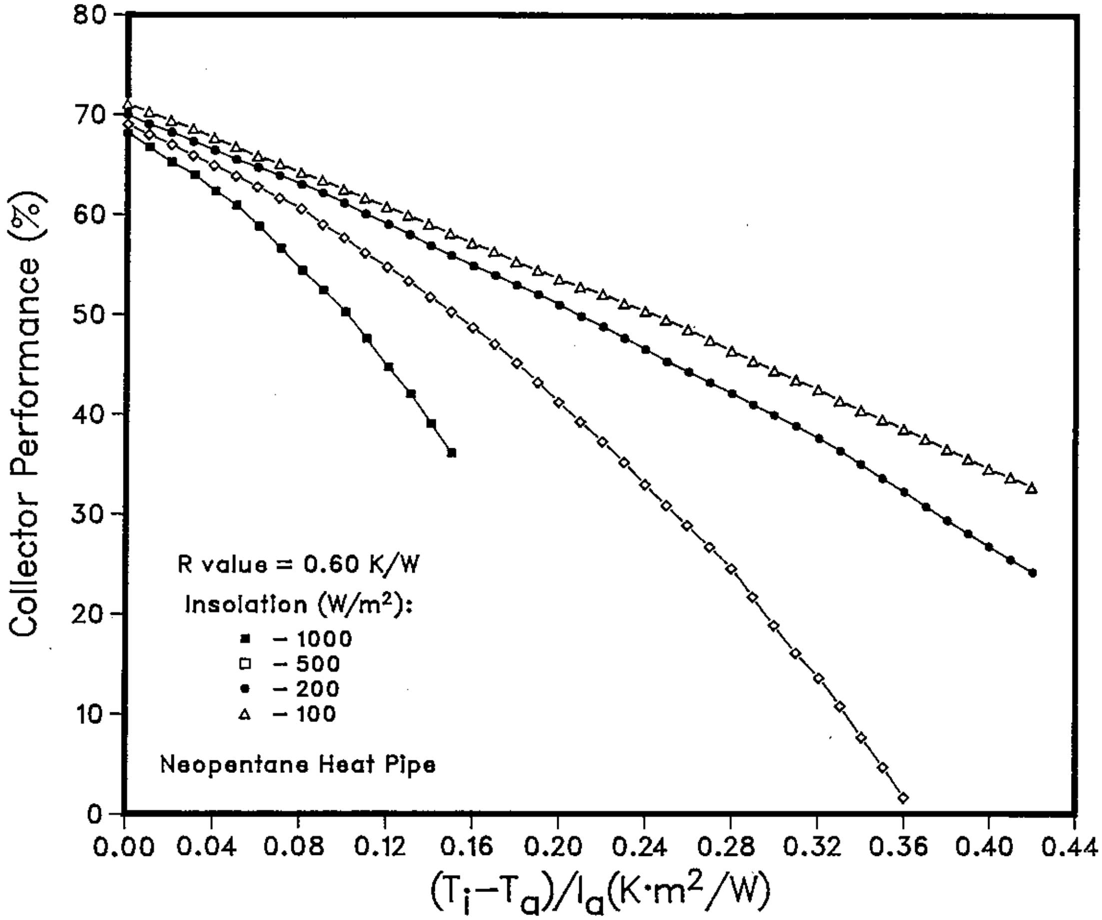


Fig. 2.1 Instantaneous Performance Curves for Phillips Laboratory Ripple Heat-Pipe (HP) Collector (Source: based on private communication)

performance calculation based on a single, linear efficiency curve can lead to underestimation of the yearly performance by more than 10%. Figure 2.2, obtained using equations presented in this section, compares the efficiency of evacuated FPCs with that of conventionally glazed collectors.

2.1.1.2 Solar Ponds. Solar ponds may be considered to be FPCs that are restricted to horizontal deployment, but ponds have quite different performance characteristics than do conventional FPCs and are treated separately here. Two types of ponds are currently under investigation for solar application:

- Shallow ponds, in which the absorber is usually a plastic envelope blackened on the bottom to absorb the radiation, insulated from the earth and covered with an additional plastic or glass glazing; the plastic envelope is filled with a few centimeters of water, which is heated in a batch mode and drained back to the load or storage when it reaches the desired temperature.

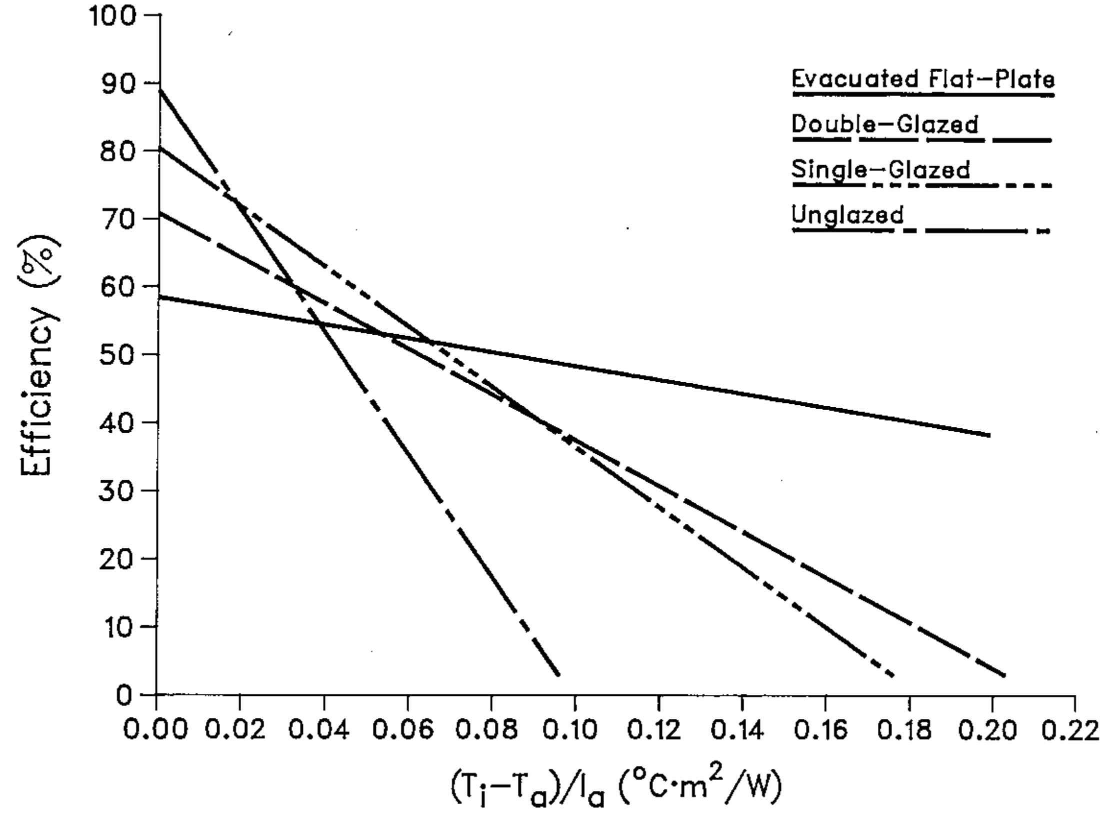


Fig. 2.2 Instantaneous Efficiency Curves for Typical Flat-Plate Solar Collectors, Based on Gross Area

- Salt-gradient ponds, in which an optically thick layer of water is stabilized against natural convection by adjusting the concentration of saline solution so that it just counterbalances the destabilizing buoyancy forces.

Salt-gradient ponds provide substantial energy storage as well as collection and are, therefore, attractive for central-plant applications. The preliminary screening calculation included salt-gradient ponds (Fig. 2.2), but these were later dropped from consideration because of their lack of development and their inapplicability at extreme latitudes.

The performance model for shallow ponds is based on the work of the LLNL Solar Group.[20] The pond model is basically the same as Eq. 2, with a modified incident-angle factor. Specifically, the efficiency for shallow ponds is given by the following:

$$\eta = 0.64\ K_{\alpha\tau} - 4.4(T_i - T_a)/I_g \qquad (8)$$

where:

$$K_{\alpha\tau} = \cos\left[\frac{\pi}{2}\left(\frac{2\theta_z}{\pi}\right)^{1.24}\right] \tag{9}$$

and

θ_z = Zenith angle

2.1.2 Stationary Concentrating Collectors

Stationary concentrating collectors provide a modest amount of concentration without the necessity for tracking the sun. Examples of concentrating collectors are those employing some variation of the compound-parabolic-concentrator (CPC) reflector system invented by R. Winston at The University of Chicago and developed by ANL and The University of Chicago. Other nonimaging optical systems are also included in this category. Most frequently, these collectors use an evacuated tube as the receiver, so they are often referred to as "evacuated-tube" collectors (ETCs). It is really the optical response of the stationary concentrators that distinguishes them from flat-plate evacuated collectors, described in the preceding section.

In their present state of development, concentrating ETCs are capable of delivering energy at temperatures of up to about 150°C with reasonable efficiency. Today's collectors normally weigh 30 to 40 kg/m^2 and cost about \$200-250 (U.S.)/m^2 at the manufacturer's site. The cost of the installed collector array may be \$400-550 (U.S.)/m^2. The current generation of concentrating ETCs uses aluminum or aluminized plastic reflectors, uncoated glass tubes, and multilayer selective coatings that have rather low emissivities (≈ 0.05) but also exhibit rather poor absorption (<0.80). Recent advances in the optical design of nonimaging concentrators[21] have not yet been exploited in commercial designs. For these reasons, it was the consensus of a special workshop on evacuated-collector technology sponsored by the DOE in 1979 that the optical efficiency of concentrating evacuated collectors could probably be improved by 50%. Present evacuated collectors are also known to have high manifold heat losses -- frequently the manifold losses equal the combined radiation and conduction losses from the tubes. The workshop participants estimated that the overall loss coefficient U_L could be reduced by 25%. Thus, the technology of concentrating evacuated collectors, unlike that of FPCs, is immature and has considerable potential for performance improvement.

In our initial attempts to model the thermal performance of evacuated collectors, the potential for improvement was taken into account by considering two models, one representing a state-of-the-art commercial collector and the other representing an advanced collector (defined as a collector with a 50% greater efficiency and a 25% lower U_L). Since the proposal of this hypothetical collector, experimental results from an advanced prototype collector under development by R. Winston's group at The University of Chicago have confirmed that the assumed level of performance is possible and perhaps even conservative.[22-24] The new collector employs a shaped vacuum tube in which the reflective surface is deposited on the inside. (This means that silver can be used to enhance the reflectivity.) A metallic receiver is used so that the higher-performance selective coatings can be applied, and the geometry of the tube employs the most advanced optical design. The net result is a collector that matches or exceeds the performance of a high-quality parabolic trough at temperatures up to about 300°C and requires no tracking or seasonal adjustment. Although the integrated CPC collector is still far from being a marketable product, its development (coupled with other advances reported in the private sector) justifies inclusion of an advanced evacuated collector in our study.

Thermal-efficiency curves for typical conventional and advanced stationary concentrating collectors, determined using equations in this section, are shown in Fig. 2.3; a curve for a typical commercial parabolic trough is included for comparison. The expected characteristics of the advanced collector are based on laboratory measurements.

The modeling equations for a stationary concentrator with an evacuated receiver are similar to those for FPCs, except for the optical efficiency. The

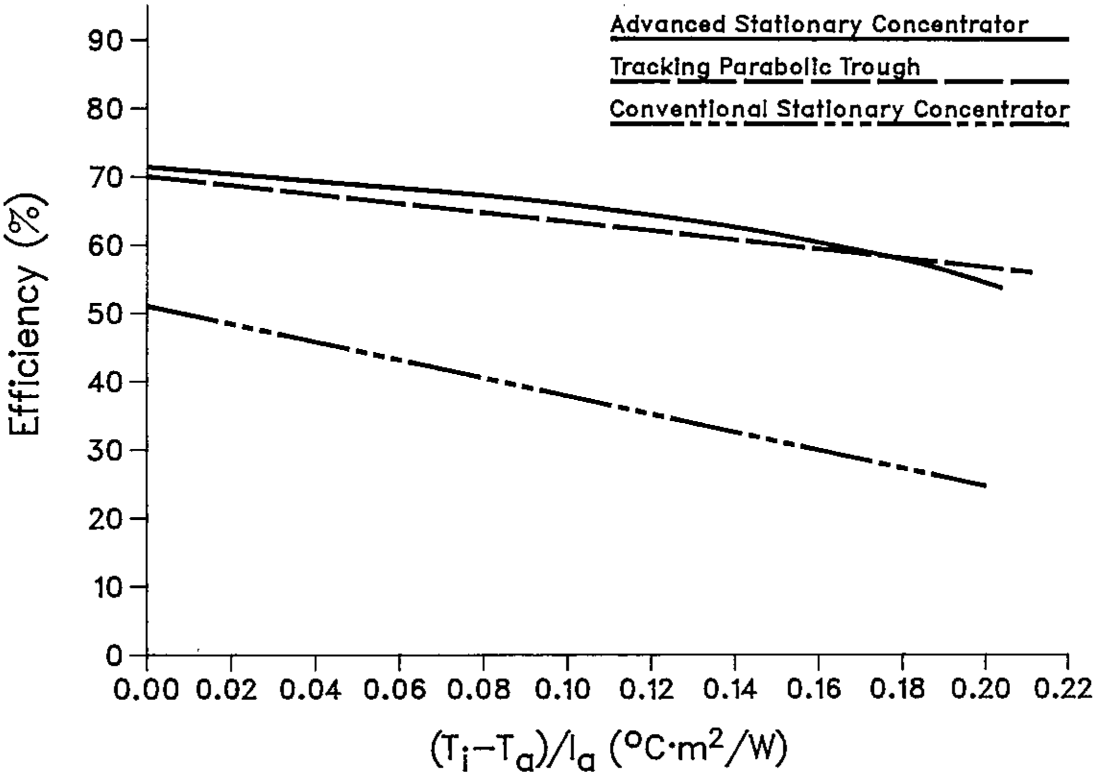


Fig. 2.3 Instantaneous Efficiency Curves for Typical Stationary and Tracking Solar Collectors

concentrating optics exhibit a complex response to the orientation of the sun and generally use only a fraction of the diffuse radiation. Details concerning a description of the angular response of CPCs and other optical systems are available in the literature.[25-28] The response to the beam radiation can generally be approximated by the product of two incident-angle modifying factors: one ($K_{\alpha\tau}$,NS) related to the projection of the angle of incidence onto a plane normal to the collector and passing through the sun -- i.e., the N-S plane; and one ($K_{\alpha\tau}$,EW) related to the projection of the angle of incidence onto a plane orthogonal to the plane of the collector and the N-S plane. If the axis of the tube and reflector system lies in the N-S plane, the usual configuration for drainable Owens-Illinois* (OI) and SUNMASTER** collectors, the angular response to changes in projection of the incident angle on the N-S plane is adequately described by Eq. 3. The angular response to changes in the transverse direction, E-W, is much more complex and depends upon the design of the reflector. Examples of measured incident-angle modifiers for the transverse-plane angle for several collectors are shown in Fig. 2.4. The measured response of the SUNMASTER collector has been verified by detailed ray-trace calculations by McIntire,[25] whereas the measurements on the various reflector systems of the OI and General Electric‡ (GE) collectors do not match the calculations as well. Partly for this reason, we have chosen a model based on the SUNMASTER reflector system. The angular-response curve increases substantially for the first 35 degrees; this is important in calculating the total energy collected in a day.

The specific equations used for the study are:

$$\eta = \eta_o K_{\alpha\tau},\mathrm{NS}(\theta_{NS}) \cdot K_{\alpha\tau},\mathrm{EW}(\theta_{EW}) - F_R U_L (T_i - T_a)/I_a \qquad (10)$$

where:

$$I_a = I_b \cos\theta + I_d(\theta_c/2\pi) \qquad (11)$$

and

$$\eta_d \simeq \eta_o \iint (K_{\alpha\tau},\mathrm{NS} \cdot K_{\alpha\tau},\mathrm{EW})(\cos\theta_{NS} \cdot \cos\theta_{EW}) d\theta_{NS} d\theta_{EW} \qquad (12)$$

where the integrals are carried out over the acceptance angle of this collector, θ_c. For the SUNMASTER collector, Eq. 12 reduces to the following:

---

*Owens-Illinois, Inc., Toledo, Ohio.

**Sunmaster Corp., Corning, N.Y.

‡General Electric Co., Schenectady, N.Y.

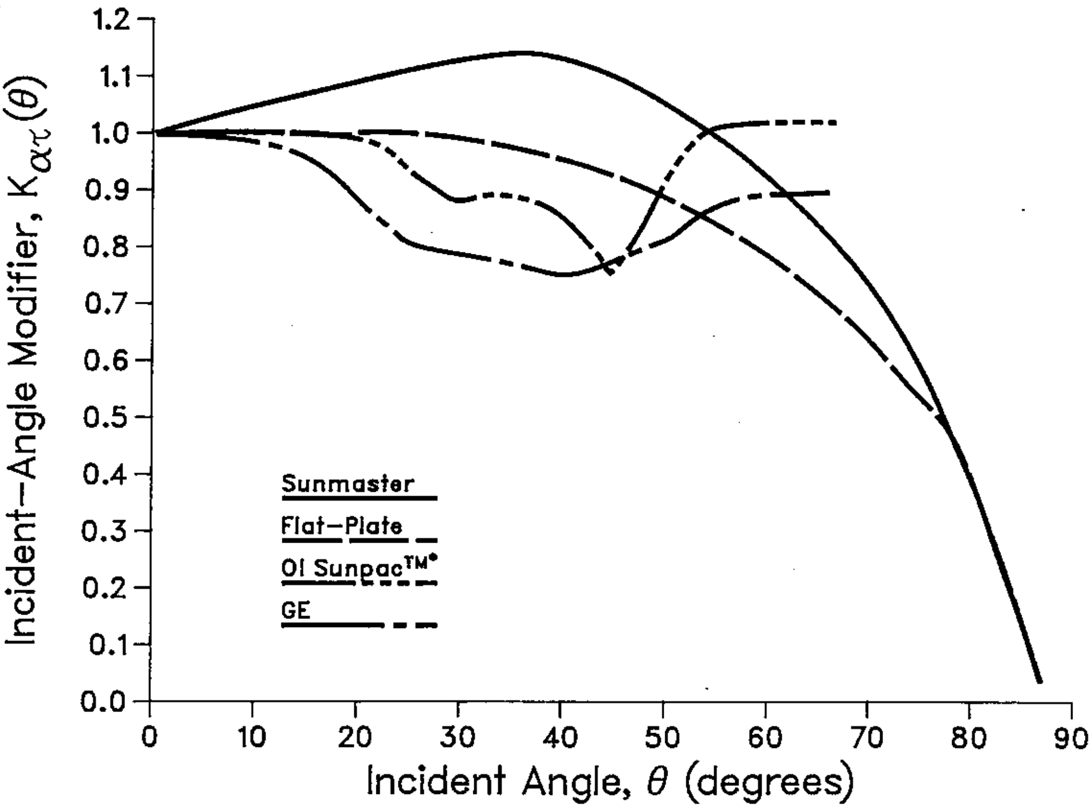


Fig. 2.4 Incident-Angle Modifiers for Several Commercial Stationary Concentrating Collectors

$$\eta_d \approx 0.71\ \eta_o \tag{13}$$

The parameters (based on gross area) used for the commercial and advanced collectors are given in Table 2.1.

2.1.3 Parabolic Troughs

Only tracking parabolic-trough collectors (PTCs) will be considered in this study. They are generally considered to be superior to the fixed-aperture, tracking-receiver troughs, which suffer a cosine loss associated with the fixed aperture (this disadvantage is especially important at high latitudes, where sun angles are always low). The original screening calculations included N-S, E-W, and polar-axis tracking PTCs. Polar-axis trackers are considered impractical for large arrays, and although the N-S-axis collector collects more energy annually than the E-W-axis collector, most of the advantage occurs in the summer when the energy is least valuable (unless one has an infinite,

---

*"SUNPAC™" is a registered trade name of Owens-Illinois Inc., Toledo, Ohio.

Table 2.1 Values of Parameters Used for Commercial and Advanced Collectors

Parameter	Value Used Commercial Collector	 Advanced Collector
η_o	0.51	0.70
$F_R U_L$	1.31	1.00
$K_{\alpha\tau}$,NS	1.0-0.17[(1/cosθ)-1]	1.0-0.05[(1/cosθ)-1]
$K_{\alpha\tau}$,EW		
0°	1.0	1.0
15°	1.08	1.08
30°	1.14	1.14
45°	1.11	1.11
60°	0.94	0.94
75°	0.65	0.65
90°	0	0

ideal storage with no losses). We have, therefore, carried out the more detailed calculations only for the E-W-axis PTCs. Nothing in the model presented below, however, restricts its use to the E-W orientation.

Sandia National Laboratory in Albuquerque, N.M., has been the lead laboratory in the U.S. for the development of line-focus technology for many years. The SNLA approach has been to develop collectors that will set the standards for commercial-product development, often supported by government, to match. This approach has been so successful that the DOE recently declared line-focus technology ready for the private sector and suspended further government support. Indeed, a series of tests run by SNLA and the Desert Solar Exposure Test Laboratory (DSET) in Phoenix, Ariz., indicates that some very-high-performance collectors are on the market (see Ref. 29 for test methodology and Refs. 30-38 for results with specific collectors). Results for the three top collectors tested under this program are shown in Fig. 2.5 and compared with the 1985 goal set by SNLA. The optical efficiency of one of the commercial collectors already exceeds the 1985 goal. Although none of the collectors has attained the heat-loss goal, one of the commercial collectors comes very close. We have, therefore, selected another hypothetical collector for our performance model -- one with an optical efficiency of 0.807, equal to the highest measured efficiency, and with heat-loss coefficients equal to the 1985 SNLA goal. In equation form, the IEA model collector is described by:

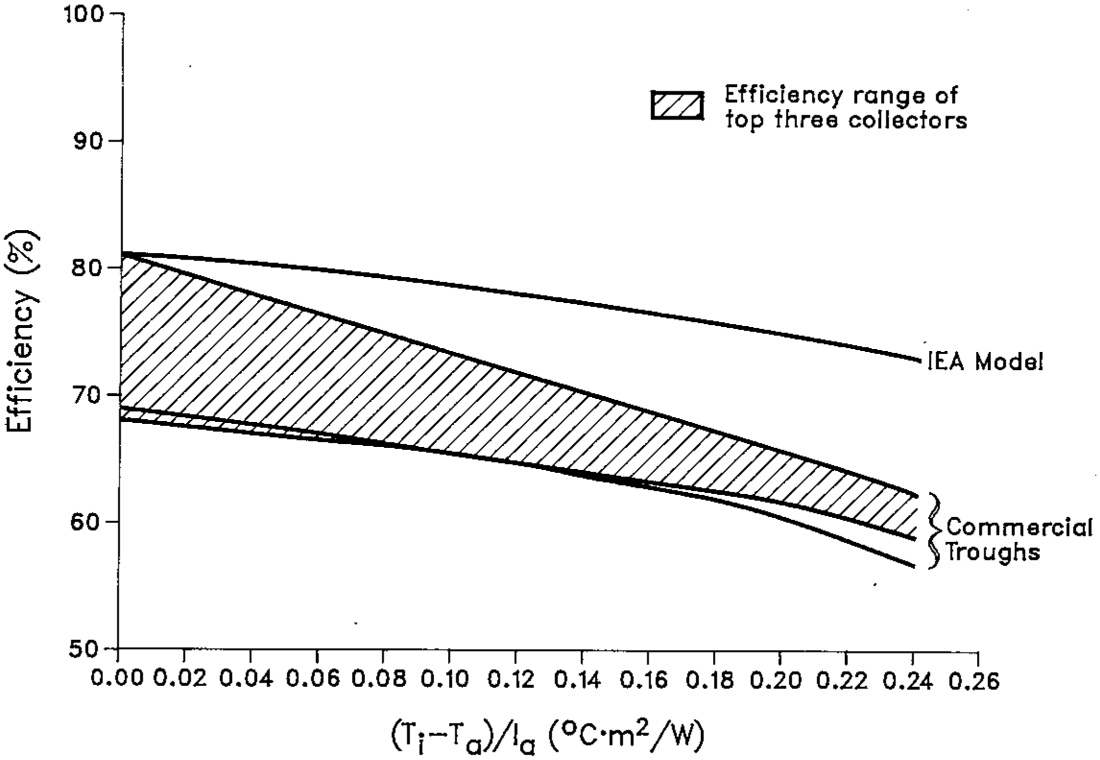


Fig. 2.5 Instantaneous Efficiency Curves for Several Commercial and Advanced Parabolic-Trough Collectors (Source: based on information from Refs. 30-38)

$$\eta = 0.807\ K_{\alpha\tau} - 0.0887\ (T_i - T_a)/I_b - 0.8693[(T_i - T_a)/I_b]^2 \qquad (14)$$

where:

$$K_{\alpha\tau} = \{\ 0°,1.0;\ 10°,1.0;\ 20°,1.0;\ 30°,0.99;\ 40°,\ 0.95;\ 50°,0.88;\ 60°,0.82;\ 70°,0.68;\ 90°,0.0\} \qquad (15)$$

The incident-angle modifying factors (Eq. 15) were actually measured on a turntable mount at SNLA and should be quite reliable. The $(\Delta T/I)^2$ term in the efficiency correlation is a controversial matter. It cannot be justified on theoretical grounds, but it has become rather prevalent practice. A recent publication quantifies the potential for error in using ($\Delta T/I$) correlations based on measurements obtained for very limited ranges of I.[39] The errors can be quite large at high values of $\Delta T/I$, but in our applications ΔT is relatively small, so the errors do not become excessive except when I is very small and little energy is available. Using the $\Delta T/I$ correlations in areas where I is lower than the measurement range will generally yield too low a prediction for the collected energy. The SNLA investigators are working on a two-parameter correlation equation that separates ΔT and I. Because IEA Task VII calculations will frequently involve conditions quite different from the measurement conditions, a well-validated two-parameter correlation could be quite valuable. Corrections for end losses are available in the article by Gaul and Rabl.[40] Generally, end losses will be negligible in large arrays.

2.1.4 Central Receivers

Although there are now seven operating central-receiver installations in the world, we know of no experimental data upon which to base or validate a thermal model. We must, therefore, rely upon analytical studies to guide the modeling. The usual procedure is to design each central-receiver installation using an optical-analysis computer code that optimizes the cost-effectiveness of each heliostat. Codes such as MIRVAL and DESOL have been developed by the University of Houston and SNLL for this purpose. These codes are available and should be used for detailed design of CSHPs after the plant site has been specified and the central-receiver concept selected.

For preliminary design studies and system-performance predictions, however, a simple thermal-optical model is needed. Equation 2 serves as the basis for such a model, but it requires some reinterpretation. For the central receiver, the modifying factor can be redefined as the "field efficiency factor" (i.e., the fraction of sunlight falling on the total area of the heliostat mirrors that strikes the receiver). The field efficiency includes (and is limited to) the effects of losses due to cosine effect, blockage, shading, tower shading, atmospheric absorption, and mirror absorptivity. Mirror absorptivity is a constant of the field efficiency (as reflectivity "r") if desired. The atmospheric attenuation, which does not vary with sun position, was calculated on the basis of 10% attenuation per kilometer. The high concentration ratios of central receivers, coupled with the low operating temperatures of CSHPs, combine to produce a situation where the thermal losses from the receiver are only a small fraction of the plant power and can be neglected. These assumptions and reinterpretations result in the simple representation:

$$\eta = \alpha \eta_o(\lambda, \gamma) \tag{16}$$

where:

α = Absorptance of receiver
η_o = Heliostat field efficiency as a function of the altitude angle, λ, and the azimuthal angle, γ.

Field efficiency factors have been tabulated by Eicker for two specific central-receiver configurations based on calculations made at SNLL using the MIRVAL code.* The small system consists of 85 heliostats and was designed

---

*Source: Eicker, P.J., private communication to A. Rabl (1979).

by McDonnell Douglas Corp. for the Small Solar Power Program. The large field consists of 7505 heliostats and was designed by Martin Marietta for central power. Field layouts and characteristics are shown in Figs. 2.6 and 2.7, and the field efficiencies are presented in Tables 2.2 and 2.3.

In the small central-receiver system (Fig. 2.6), each heliostat consists of 12 spherically figured panels arranged in a 2 x 6 pattern; panels are canted, with the degree of cant determined by position in the field. The aim point for all heliostats is the center of the aperture, 35 m above ground level. Heliostat reflectivity is 0.9. The receiving tower is 33 m in height and supports a square aperture with 3.5-m sides, facing north and tilted 30° downward. System latitude is 34.9° north.

The large central-receiver system (Fig. 2.7) has four rectangular apertures facing north, south, east, and west. The center of the receiver is 166.4 m above ground level, and the tower has a height of 182.9 m.

2.1.5 Summary of Module Efficiencies

The collector-module efficiencies described in this section form the basis for subsequent calculations and comparisons presented in this report. They are also the basis for the collector-subsystem models supplied to Subtask 1(a) for

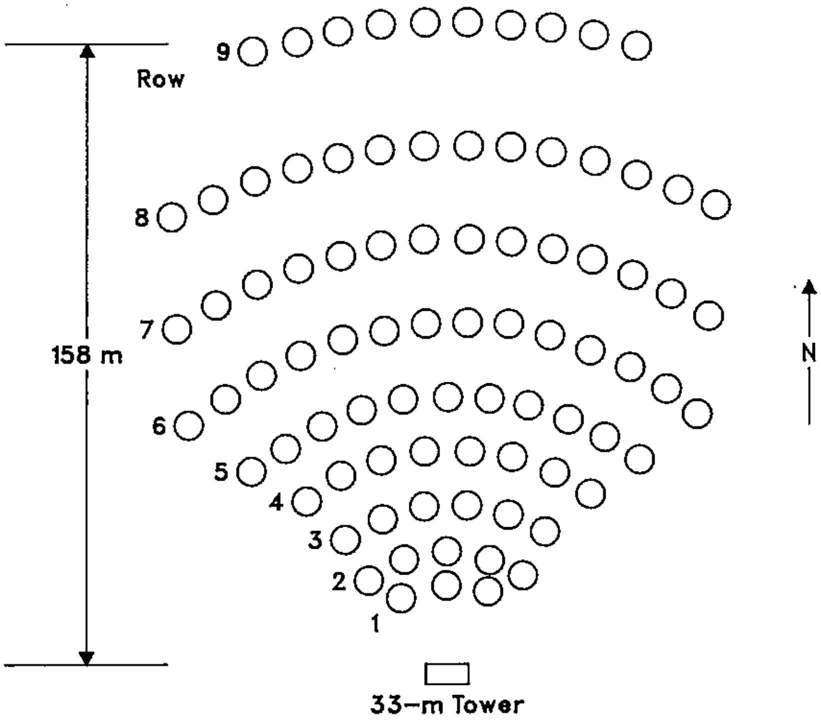


Fig. 2.6 Heliostat Deployment for Small Central Receiver (Source: P.J. Eicker, private communication, 1979)

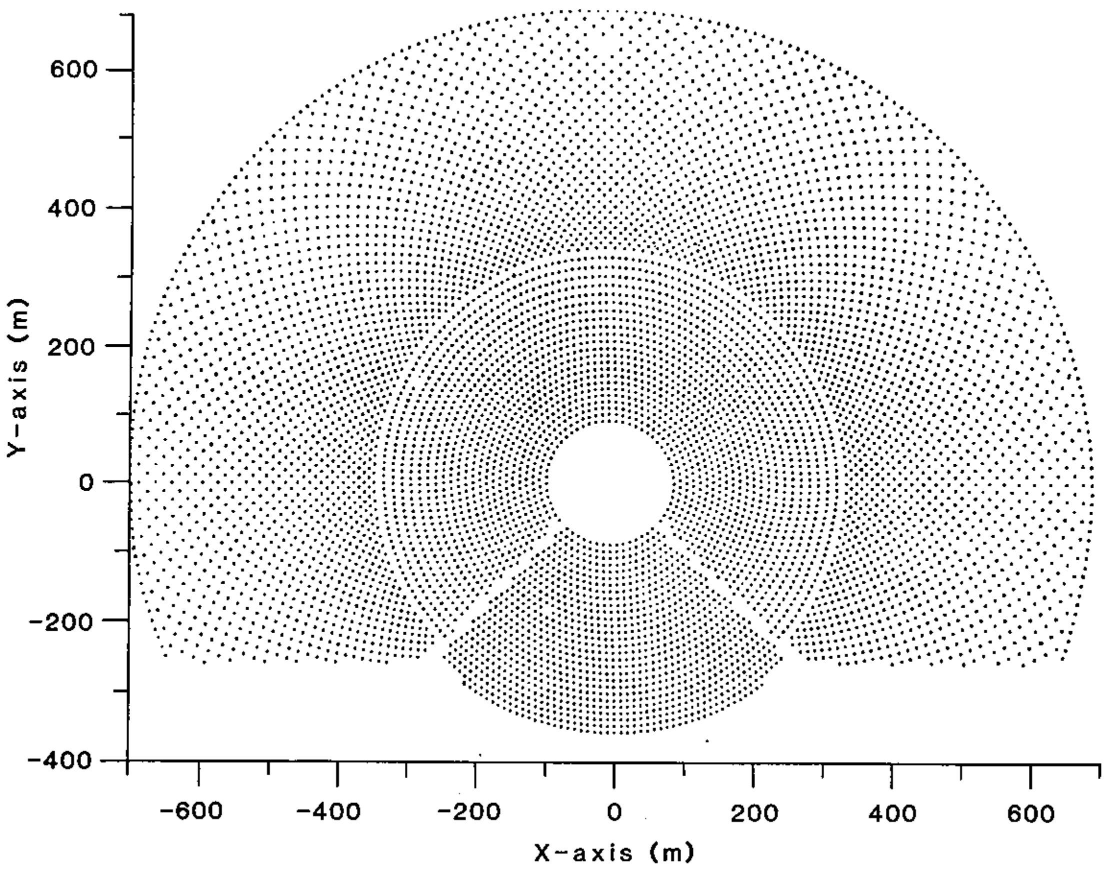


Fig. 2.7 Heliostat Deployment for Large Central Receiver
(Source: P.J. Eicker, private communication, 1979)

use in MINSUN optimization calculations. For reference, these models are summarized in the first column, "Boston, Mass., U.S. (Base Case)," of Tables 2.4-2.6 and are displayed graphically in the accompanying figures (Figs. 2.8-2.10).* The angle effects are significant, so it is not adequate to compare the collectors on the basis of peak efficiency. In subsequent sections of this report, we calculate the energy collected annually by each type of collector for several locations and two load profiles of interest and compare the collectors on the basis of cost per unit of energy delivered. These comparisons are more meaningful than the peak efficiencies.

In addition to the module-efficiency models recommended for the 1(a) studies, Tables 2.4-2.6 contain data based on collector-efficiency models provided by some of the participating countries from their national experience. The tables also show the productivity of the collector modules at various temperatures. In most cases these entries are simply calculated values based on the collector models listed in each column and on a national meteorological data base. However, some of the figures represent actual field experience or estimates based on other data.

---

*In Figs. 2.8 and 2.9, "DG SS" means double-glazed selective surface, and "SG SS" means single-glazed selective surface.

Table 2.2 Field Efficiencies for Small Central Receiver[a,b]

	Field Efficiency, by Azimuthal Angle[d]						
Evaluation[c]	0°	30°	60°	75°	90°	110°	130°
5°	0.384	0.404	0.366	0.330	0.300	0.240	0.212
15°	0.701	0.687	0.576	0.495	0.429	0.367	0.315
25°	0.789	0.771	0.662	0.584	0.521	0.445	0.391
45°	0.814	0.814	0.757	0.708	0.661	0.603	0.544
65°	0.811	0.806	0.754	0.753	0.724	0.689	0.642
89.5°	0.723	0.729	0.748	0.726	0.730	0.736	0.736

[a] Source: P.J. Eicker, private communication (1979).

[b] Includes losses due to cosine effect, tower shadowing, blocking and shading, reflectivity, atmospheric attenuation, and spillage.

[c] Horizon = 0°.

[d] South = 0°.

2.2 Efficiencies of Collector Arrays

When collector modules are combined to form large arrays and operated as part of a system, a number of new considerations arise. These considerations include the effects of the surroundings and of nearby collector modules on the optical performance; the effect of heat losses from the plumbing on the thermal performance; the effect of variability of flow rate and fluid inlet temperature at different collectors as a result of hydraulic effects; the effect of operating and control strategies used during start-up, shutdown, and cloudy periods on the dynamic thermal performance; the effect of the pumping power required to supply the fluid to the array under steady and dynamic conditions on the net efficiency of the array; the effects of soiling or optical degradation of materials on the optical or thermal performance of the collector field; and the effect of necessary (required) maintenance and repair on the availability of the system.

All of these considerations are highly site-, system-, and design-specific; therefore, we will not attempt to deal comprehensively with array losses. We merely provide the designer or analyst a guide to some of the relevant literature and some rough quantitative estimates of the magnitude of the losses that may occur in properly designed systems.

Table 2.3 Field Efficiencies for Large Central Receiver[a,b]

	Field Efficiency, by Azimuthal Angle[d]						
Elevation[c]	0°	30°	60°	75°	90°	110°	130°
5°	0.216	0.215	0.206	0.204	0.199	0.194	0.192
15°	0.446	0.448	0.425	0.423	0.405	0.392	0.385
25°	0.560	0.558	0.537	0.522	0.516	0.498	0.491
45°	0.719	0.640	0.626	0.618	0.605	0.594	0.599
65°	0.684	0.670	0.671	0.668	0.660	0.655	0.641
89.5°	0.683	0.683	0.686	0.672	0.682	0.687	0.681

[a] Source: P.J. Eicker, private communication (1979).

[b] Includes losses due to cosine effect, tower shadowing, blocking and shading, reflectivity, atmospheric attenuation, and spillage.

[c] Horizon = 0°.

[d] South = 0°.

The sources of information we have identified are summarized in Table 2.7. Each heading of the table is discussed quantitatively in the subsequent paragraphs of this section. The minimum credible magnitudes of these effects for use in preliminary design are quantified in Sec. 2.2.6.

2.2.1 Optical Losses

Optical influences inherent in the design and siting of the array include losses due to shading of the collectors by the surroundings or by other collectors, optical gain due to reflections from the surroundings or other collectors, orientation of the collectors, blockage of a central receiver by collector mirrors, and atmospheric attenuation of radiation between mirrors and a central receiver.

Stationary solar collectors are generally oriented so that the normal to the collector aperture lies in the N-S plane to achieve maximum energy collection. This is a fairly flat (cosine) maximum, however, so that small

Table 2.4 Collector-Module Efficiency Models for Stationary Nonconcentrating Collectors

Collector Type	Boston, Mass., U.S. (Base Case)	Vienna, Austria	Corona-tion, Canada	Ispra, Italy (CEC)	Copenhagen, Denmark	Hamburg, W. Germany
Single-Glazed Flat Plate with Selective Absorber, Latitude Tilt						
Optical Efficiency, $F_R\eta_o$	0.808	0.84		0.79	0.808	0.82
Loss Coef., F_RU_L (W/m^2·°C)	4.4	4.1		5.25	4.4	4.5
Incident Angle Mod. (parabolic trough), b_o	—	—		—	—	—
A(η)/Gross Area	1.00	<1.0		1.0	1.0	<1.0
Energy at 30°C (kWh/yr)	800	600		735	660	500
Energy at 50°C (kWh/yr)	—	400		485	—	—
Energy at 90°C (kWh/yr)	290	100		157	220	260
Contributor/Source[a]	NBS	Bruck		van Hattem		Stein-mueller
Double-Glazed Flat Plate with Selective (or Block) Absorber, Latitude Tilt						
Optical Efficiency, $F_R\eta_o$	0.717	0.79	0.70	0.77	—	0.72
Loss Coef., F_RU_L (W/m^2·°C)	3.22	3.1	5.0	—	3.22	3.20
Incident Angle Mod. (parabolic trough), b_o	0.12	—	—	—	0.12	—
A(η)/Gross Area	1.00	<1.0	1.0	—	1.00	<1
Energy at 30°C (kWh/yr)	—	550	740	—	610	—
Energy at 50°C (kWh/yr)	—	430	—	—	—	—
Energy at 90°C (kWh/yr)	—	150	170	—	—	—
Contributor/Source	DSET	Bruck				
Evacuated Tube with Selective Flat-Plate Receiver, Latitude Tilt						
Optical Efficiency, $F_R\eta_o$		0.72		0.68		0.72
Loss Coef., F_RU_L (W/m^2·°C)		1.3		1.7		1.2
Incident Angle Mod. (parabolic trough), b_o		—		—		—
A(η)/Gross Area		<1.0		<1.0		0.81?
Energy at 30°C (kWh/yr)		—		767		—
Energy at 50°C (kWh/yr)		620		659		620
Energy at 90°C (kWh/yr)		890		480		500
Contributor/Source		Bruck				Stein-mueller
Double-Glazed Shallow Solar Pond, Horizontal						
Optical Efficiency, $F_R\eta_o$	0.64				0.64	
Loss Coef., F_RU_L (W/m^2·°C)	0.44				4.4	
Incident Angle Mod. (parabolic trough), b_o	—				—	
A(η)/Gross Area	1.00				1.00	
Energy at 30°C (kWh/yr)	640				480	
Energy at 90°C (kWh/yr)	170				90	
Contributor/Source	LLNL					

Table 2.4 (Cont'd)

Collector Type	De Bilt, The Netherlands	Stockholm, Sweden	Switzerland	Albuquerque, N.M., U.S.	Kew, U.K.
Single-Glazed Flat Plate with Selective Absorber, Latitude Tilt					
Optical Efficiency, $F_R\eta_o$	0.79	0.75	0.80	0.808	0.808
Loss Coef., F_RU_L (W/m^2·°C)	4.6	4.0	3.0	4.4	4.4
Incident Angle Mod. (parabolic trough), b_o		0.1	—	—	0.1
A(η)/Gross Area	<1.0	1.0	—	1.0	1.0
Energy at 30°C (kWh/yr)	550	666	—	—	497
Energy at 50°C (kWh/yr)	375	474	—	—	323
Energy at 90°C (kWh/yr)	160	235	—	1580	118
Contributor/Source[a]	Wijsman	Zinko	Atlantis Energie, A.G.	NBS	Rogers
Double-Glazed Flat Plate with Selective (or Block) Absorber, Latitude Tilt					
Optical Efficiency, $F_R\eta_o$	0.77	0.70		0.717	0.717
Loss Coef., F_RU_L (W/m^2·°C)	2.70	3.2		3.22	3.22
Incident Angle Mod. (parabolic trough), b_o	—	0.12		0.12	0.12
A(η)/Gross Area	<1.0	1.0		1.00	1.0
Energy at 30°C (kWh/yr)	620	648		1840	461
Energy at 50°C (kWh/yr)	480	487		—	322
Energy at 90°C (kWh/yr)	290	282		440	147
Contributor/Source		Zinko		DSET	Rogers
Evacuated Tube with Selective Flat-Plate Receiver, Latitude Tilt					
Optical Efficiency, $F_R\eta_o$	0.65	0.62	0.70		
Loss Coef., F_RU_L (W/m^2·°C)	1.5	1.62	1.8		
Incident Angle Mod. (parabolic trough), b_o	—	—	—		
A(η)/Gross Area	0.81	0.8	—		
Energy at 30°C (kWh/yr)	570	646	—		
Energy at 50°C (kWh/yr)	480	543	—		
Energy at 90°C (kWh/yr)	345	385			
Contributor/Source	Wijsman		Atlantis Energie, A.G.		
Double-Glazed Shallow Solar Pond, Horizontal					
Optical Efficiency, $F_R\eta_o$		0.64		—	
Loss Coef., F_RU_L (W/m^2·°C)		4.4		4.4	4.4
Incident Angle Mod. (parabolic trough), b_o		—		—	—
A(η)/Gross Area		1.00		1.00	1.00
Energy at 30°C (kWh/yr)		331		1250	190
Energy at 90°C (kWh/yr)		51		550	10
Contributor/Source		Zinko		LLNL	Rogers

---

[a] This table presents new results contributed by subtask participants. Where possible, subtask participants or their sources have been specified.

Table 2.5 Collector-Module Efficiency Models for Stationary Concentrating Collectors

Collector Type	Boston, Mass., U.S. (Base Case)	Coronation, Canada	Copenhagen, Denmark	Stockholm, Sweden	Albuquerque, N.M., U.S.	Kew, U.K.
Contemporary CPC with Evacuated Receiver						
Concentration Ratio, C	1.1		1.1	1.1	1.1	1.1
Optical Efficiency, $F_R\eta_o$	0.51		0.51	0.51	0.51	0.51
Loss Coefficient, F_RU_L	1.3		1.3	1.3	1.3	1.3
$A(\eta_o)$/Gross Area	1.0		1.0	1.0	1.0	1.0
Incident Angle Mod. (long.), b_o	0.05		0.05	0.05	0.05	0.05
Incident Angle Mod. (trans.)	—		—	—	—	—
Orientation of Axis	N-S		N-S	N-S	N-S	N-S
Energy at 30°C (kWh/yr)	560		490	514	1110	289
Energy at 50°C (kWh/yr)	—		—	370	—	234
Energy at 90°C (kWh/yr)	380		320	315	860	156
Contributor/Source[a]						Rogers
Advanced CPC with Evacuated Receiver						
Concentration Ratio, C	1.1	1.5	1.1	1.1	1.1	1.1
Optical Efficiency, $F_R\eta_o$	0.70	0.77	0.70	0.70	0.70	0.70
Loss Coefficient, F_RU_L	1.0	—[b]	1.0	1.0	1.0	1.0
2nd-Order Loss Coefficient	—	—	—	—	—	—
$A(\eta_o)$/Gross Area	1.0	—	1.0	1.0	1.0	1.0
Incident Angle Mod. (long.), b_o	0.05	—	0.05	0.05	0.05	0.05
Incident Angle Mod. (trans.)	—	—	—	—	—	—
Orientation of Axis	N-S	E-W	N-S	N-S	N-S	N-S
Energy at 30°C (kWh/yr)	810	1070	712	761	1580	458
Energy at 50°C (kWh/yr)	—	—	—	692	—	391
Energy at 90°C (kWh/yr)	650	1000	570	575	1370	292
Contributor/Source						Rogers

[a] This table presents new results contributed by subtask participants. Where possible, subtask participants or their sources have been specified.

[b] Radiation losses based on an emittance of 0.07.

deviations are tolerable. Simulation codes such as TRNSYS provide for deviation from the N-S plane. Single-axis tracking collectors are also oriented so that the normal or the axis always lies in this plane. Two-axis aperture tracking collectors follow the sun, so the normal for the aperture always coincides with the incident beam radiation. Heliostats are always adjusted so that the reflected beam strikes the receiver. In properly designed and sited fields, the corrections needed because of orientation should be negligible.

The tilt angle for fixed collectors is generally derived from an optimization analysis using site-specific variables. In this report we consider fixed collectors tilted at the latitude angle for purposes of comparison, because this has been found to be a useful rule of thumb for diurnal-storage heating systems. Optimal tilt angles for systems with seasonal storage will be lower than the latitude angle.

Table 2.6 Collector-Module Efficiency Models for Tracking Concentrating Collectors

Collector Type	Boston, Mass., U.S. (Base Case)	Corona-tion, Canada	Copenhagen, Denmark	Stockholm, Sweden	Switzer-land	Kew, U.K.
Parabolic Trough						
Concentration Ratio, C	20	20	20			20
Optical Efficiency, $F_R\eta_o$	0.807	0.70	0.807	0.79	0.75	0.807
Loss Coefficient, F_RU_L	0.089	0.27	0.089	0.51	1.5	0.089
2nd-Order Loss Coefficient	0.87	—	0.87	—	—	0.87
$A(\eta_o)$/Gross Area	1.0	1.0	1.0	1.0	—	1.0
Incident Angle Mod. (long.)	—	—	—	—	—	—
Incident Angle Mod. (trans.)	1.0	1.0	1.0	1.0	—	1.0
Orientation of Axis	E-W	E-W	E-W	E-W	—	E-W
Energy at 30°C (kWh/yr)	690	760	710	705	—	412
Energy at 90°C (kWh/yr)	650	680	660	624	—	354
Contributor/Source[a]	Sandia			Zinko and Hakansson	—	Rogers
Central Receiver - Small North Heliostat Field						
Concentration Ratio, C	1000	—	—	—		1000
Receiver Absorptivity	0.98	0.85	0.98	0.98		0.98
Loss Coefficient, F_RU_L	0.0	0.16	0.0	0.0		0.0
$A(\eta_o)$/Gross Area	1.0	—	1.0	1.0		1.0
Optical Effic., η_o	—	—	—	—		—
Energy at 90°C (kWh/yr)	850	1120	820	820		383
Contributor/Source						Rogers
Central Receiver - Large Surrounding Heliostat Field						
Concentration Ratio, C	2000					
Receiver Absorptivity	0.96					
Loss Coefficient, F_RU_L	0.0					
$A(\eta_o)$/Gross Area	1.0					
Optical Effic., η_o	—					
Energy at 90°C (kWh/yr)	NA					
Contributor/Source						

[a] This table presents new results contributed by subtask participants. Where possible, subtask participants or their sources have been specified.

Intercollector shading losses can be serious in collector arrays of all kinds, but shading of the array by the surroundings is generally not very serious in a properly sited field. Shading by terrain, buildings, or landscaping occurs only when the sun is at very low angles and little energy is available to most collectors. Intercollector, or inter-row, shading is inevitable in any practical installation, because the cost of additional piping (and thermal and hydraulic losses) and the cost of land generally dictate that some shading be accepted. In the northern latitudes the shading losses can be large, so it is especially important to optimize the intercollector spacing. Figure 2.11 shows the annual reduction in incident radiation due to shading for a flat-plate (infinite-row) collector field in Copenhagen (56°N) as a function of the inter-row spacing and the collector tilt. For collectors with a latitude tilt, the annual reduction for practical arrays would generally be in the 5-10% range.

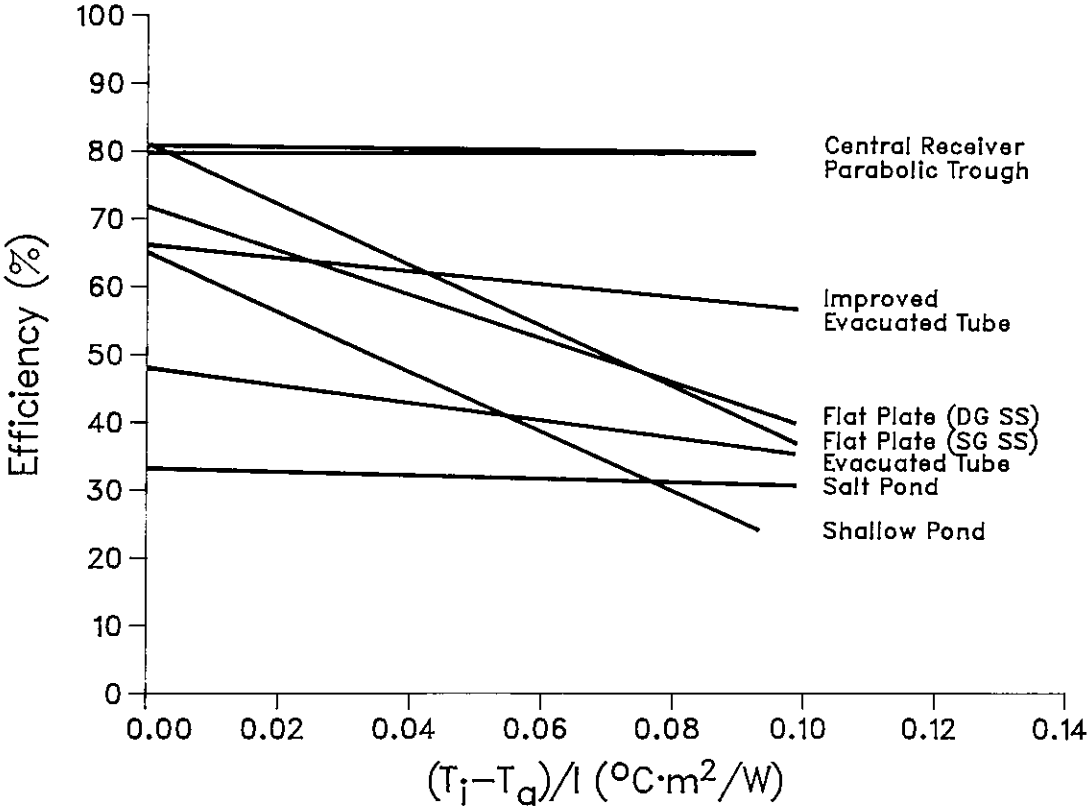


Fig. 2.8 Recommended Instantaneous Collector Efficiencies

The shading of beam radiation is fairly straightforward to calculate. The average beam irradiance available to a fixed- or single-axis tracking collector is given by:

$$I_a = I_b \min \left\{\cos\theta, \frac{\cos\theta_g}{\psi}\right\} \tag{17}$$

where θ is the incident angle between the beam radiation and the collector normal, θ_g is the incident angle between the beam and the normal to the ground, and ψ is the aperture divided by the ground area occupied by the collector field.

Equation 17 does not apply to the first row, which receives full beam radiation. The handbook by Harrigan contains design curves of row shading factors for E-W-axis and N-S-axis parabolic troughs for 26 cities in terms of the typical meteorological year (TMY).[46] Figure 2.12 is an example for Boston. The shading losses are much greater for N-S fields than for E-W fields. This is one of the reasons the E-W field is frequently specified. Figure 2.12 applies only to the interior rows. Since the first row is unshaded, the shading factor for a field of N rows may be calculated from the relation:

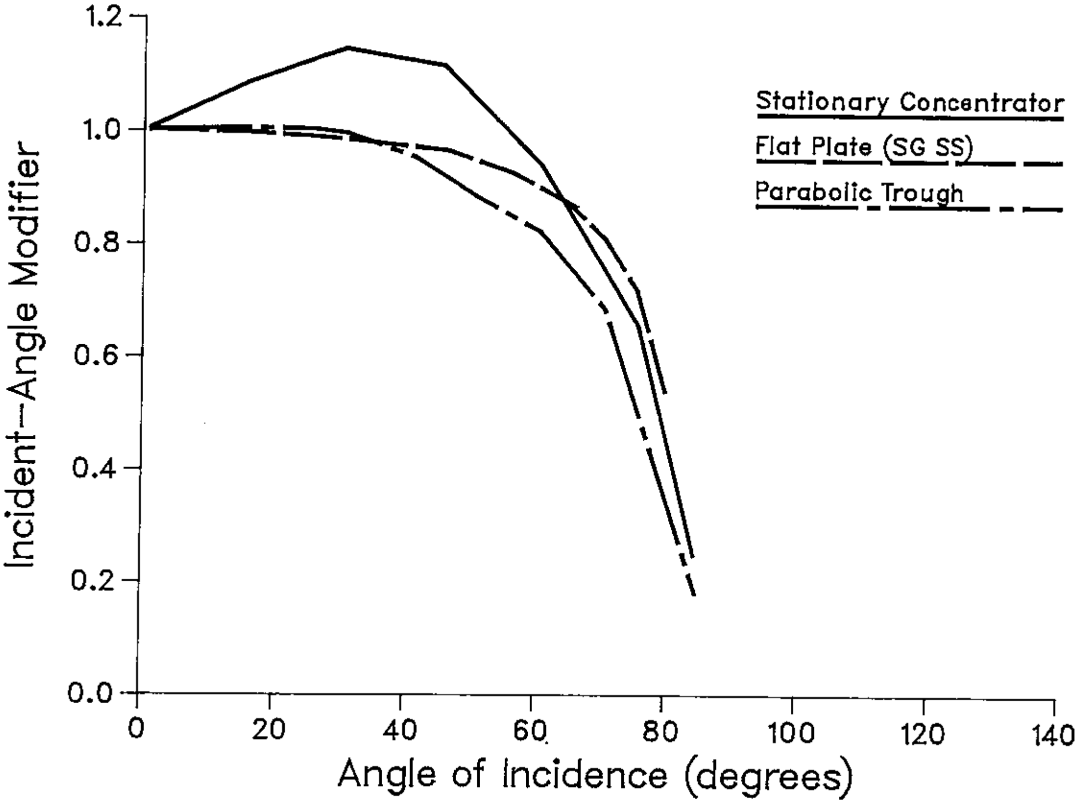


Fig. 2.9 Recommended Incident-Angle Modifying Factors for Flat-Plate, Stationary Concentrating (N-S), and Parabolic-Trough Collectors

$$f_{field} = 1 + (N - 1)f/N \tag{18}$$

where "f" is the row shading factor from Fig. 2.12.

Shading calculations for nonconcentrating or low-concentrating-ratio collectors that use all or part of the diffuse light are more complicated. Analytical expressions for the daily shading effects have been published by Jones and Burkhart.[41] We are not aware of any comparable expressions for the shading of low-concentrating-ratio collectors that accept diffuse radiation over a limited angular window. The approximate consequences of Jones and Burkhart's analysis for fixed and E-W tracking collectors are given by Kutscher.[15] Figure 2.13 shows the results for FPCs and stationary concentrating collectors as a function of the latitude.

2.2.2 Thermal Losses

The collector-module efficiency takes account of the steady-state thermal losses from the collector itself. The collector array is subject to additional steady-state losses from the manifolding and to dynamic losses associated with the intermittent operation of the system. In addition to these direct losses of thermal energy, the average efficiency of the array may be less than the

Table 2.7 Sources of Information on Array Effects[a]

Collector	Loss Type				
	Optical	Thermal (Steady)	Thermal (Dynamic)	Hydraulic	Soiling and Degradation
Flat Plate	Jones and Burkhart [41] Inter-row shading	CMHC [1] Transport heat loss	CMHC [1] Transport night loss	CMHC [1] Pumping power	Rogers[b] Soiling
	Hansen[c] Inter-row shading	Lior[d] Transport heat loss, flow distribution, inlet temperature	Wijsman[e] Collector night loss	van Hattem [42] Pumping power	
	Zinko and Hakansson [43] Horizon and inter-row shading	Wijsman[e] Transport heat loss	Steinmueller [44] Collector night loss	Lior[d] Pumping power	
	Steinmueller [44] Inter-row shading, ground reflectance	Kutscher [15] Transport heat loss	Zinko and Hakansson [43] Collector night loss		

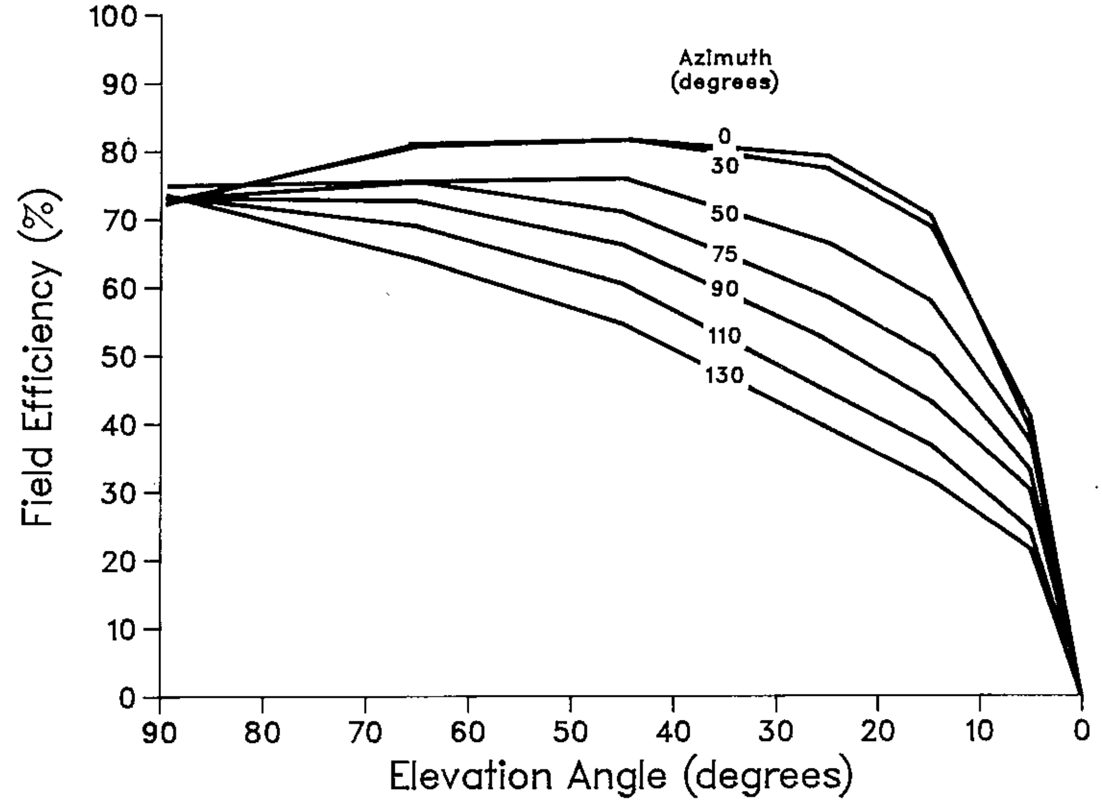


Fig. 2.10 Field Efficiency Factors for Small Central Receiver

efficiency of a single module operating at the same inlet temperature because of nonuniform distribution of flow and fluid temperature among the individual modules. All of these effects are under the control of the subsystem designer rather than the component supplier. We cannot, therefore, provide specific data or make recommendations for the subsystems under consideration, but rather must confine our discussion to general remarks; the references listed in Table 2.7 provide more detailed information. In general, however, it will be necessary for the designer of the collector subsystem to analyze the thermal losses from the array and to select configurations, components, and materials that give the most cost-effective performance.

The following sections cite approximate figures based on the assumption that the subsystem is configured to optimize its overall cost-effectiveness rather than to minimize thermal losses. These figures may be useful for conceptual design, but the designer should define all thermal losses for each site and system considered to be beyond the conceptual stage.

2.2.2.1 Steady-State Losses. The components that contribute to the steady-state thermal losses from the array include the interconnecting piping; the valves,

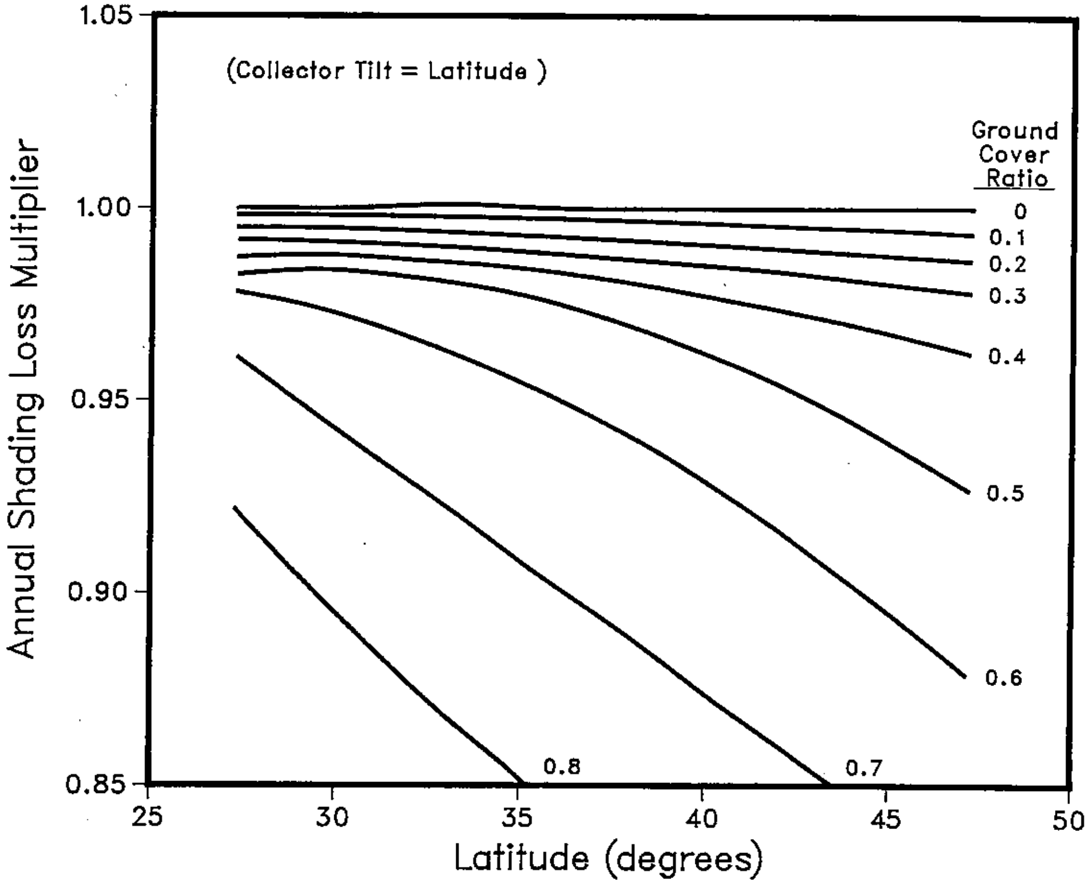


Fig. 2.13 Annual-Insolation-Reduction Factors for Shaded Arrays of Flat-Plate and Stationary Concentrating Collectors (Source: Ref. 15)

may have heat losses equivalent to more than a hundred diameters of insulated pipe.

Manifold losses for stationary collectors have been analyzed by several of the project participants (Wijsman, Steinmueller, and van Hattem) and by Spectral Engineering.[14] Calculated steady-state heat losses range from 5 to 30%, depending upon the temperature, collector site, and array configuration. In the U.S., a number of analyses and experiments can be cited that include steady-state thermal losses from the array piping, along with other effects. Menuchin et al., for example, combine manifold losses and flow-maldistribution effects in their analysis for optimal arrays.[51] Their results for modest array sizes (<288 collectors) indicate combined losses of the order of 5-10%. Experimental results from field installation on building systems have been analyzed and reported by McCumber and Weston,[52] who found that of 52 arrays analyzed, only four produced the predicted energy within 5%. Twelve collected more energy than expected and 36 collected less. (The instrumentation did not allow the separation of losses.) Similarly, the performance of the six industrial process-heat (IPH) systems reported by Kutscher and Davenport fell short of predictions (by factors of 2-4), but it was not possible to identify specific losses from the available data.[53]

At the third working meeting of Task VII in October 1981, Subtask 1(b) participants reviewed the calculations available for steady-state thermal losses and agreed that well-designed systems could achieve losses as low as those indicated in Sec. 2.2.6.

2.2.2.2 Dynamic Losses. The largest of the dynamic losses are associated with the cooling of the collector, heat-transfer fluid, and array components at night. Minor dynamic losses may also result from intermittent cloudiness or other transient phenomena. The magnitude of the losses depends upon the mass of the various components and the fluid inventory, the operating and ambient temperatures, the insulation of components, and the operation and control strategy. Kutscher[15] expresses the night losses in the form:

$$Q_\ell = [1 - \exp(-\Delta t/\kappa)]\ Mc_p(T_i - T_a) \tag{21}$$

where:

Δt = Duration of shutdown,

κ = Time constant for the piping (i.e., $Mc_p/U \cdot A$), and

Mc_p = Heat capacity of the piping system and residual fluid.

In Eq. 21, $U \cdot A$ is meant to include the effect of valves, fittings, and pumps, in addition to straight insulated piping. Again, the data of Meyer should prove useful to the designer.[50]

In calculating the loss from the collector, it is appropriate to include only the mass of the absorber structure and the internal tubing, headers, and fluid inventory. The glazing, insulation, and containment usually are much less significant.

Kutscher recommends that, for a rough preliminary estimate, the designer assume that the collector will cool to the temperature of the environment each night and that the insulated manifolding and associated components will lose only one-half the energy stored above the environmental temperature.[15]

Night losses have been calculated by Mikkelson,[54] Wijsman, Steinmueller, and Spectral Engineering and have been measured by Zinko.[45] Most of the calculations indicate that stationary collector arrays with combined heat capacities in the range of 10 to 40 $kJ/m^2 \cdot K$ will experience dynamic losses of the order of 10 to 20%. An approximation, based on the experience of the Subtask 1(b) participants and developed at the third working meeting, stated the following for FPCs with typical heat capacities:

$$Q_\ell = 1.15\ (\bar{T}_i - \bar{T}_a)\ \ kWh/m^2 \cdot yr \tag{22}$$

The experiments of Zinko et al. at Knivsta confirm the general form of the relationship for evacuated collectors.[45] The magnitude of the losses at 60°C operating temperature ranged from 16 to 31%, depending upon the type of collector. Zinko's results show that the evacuated collectors have low loss coefficients, U_L, and do not cool to ambient temperatures at night. However, because such collectors generally have high fluid inventories, the losses are still substantial.

Parabolic-trough collectors have lower fluid inventories and less area of manifolding than stationary collectors and, therefore, may be expected to exhibit lower steady-state and dynamic losses. Calculations by Sharp and by Morton indicate dynamic thermal losses of about 5% for an optimal E-W array of 5000 m^2 operating at a delivery temperature of 315°C.[55] This is consistent with the calculations reported in Ref. 1, in which the dynamic losses for large trough arrays operating below 100°C were less than 1%.

2.2.3 Hydraulic Losses

The determination of hydraulic losses, or the pumping power required to overcome the resistance to fluid flow through the collector array, is the most difficult subject to generalize. The array's pumping power depends strongly upon the fluid, the characteristics of the collector, and the arrangement of series- and parallel-flow connections, but it can also be greatly affected by the size, number, and characteristics of pipes, fittings, valves, and pumps and by the operation and control strategy. Where the hydraulic losses are large, they can become the most important consideration in the selection of a collector or even the general type of collector to be employed. Most stationary collectors on the market today have been designed for deployment in small systems (e.g., in domestic water-heating systems), where pumping power is not an important consideration. It is likely that the advent of large CSHPs will lead to the development of flat-plate and evacuated collectors that will be better suited for large arrays.

Several computer codes are available especially for the analysis (or optimization) of collector-array piping.[16,55] In addition, there are many network codes, such as those used for district-heating distribution systems, that can be used to compute pressure drop, flow rates, and pumping power for specified combinations of fluid elements. To the writer's knowledge, there are no codes available that will perform cost optimization of a collector array, taking into account all the cost and performance (optical, thermal, and hydraulic) factors. Therefore, all quantitative results we have used to estimate the probable impact of hydraulic losses on array performance are based on calculations that are specialized in some (often unstated) way.

Stationary concentrating systems, line-focus (parabolic-trough) systems, and central-receiver systems were included in a study of generic collectors for large process-heat applications conducted by Bird et al., Battelle Pacific

Northwest Laboratory (PNL).[16] This study used common economic parameters and performance demands to compare the cost-effectiveness of six collector types for applications requiring 50, 150, 300, and 600 MW (thermal) at temperatures from 65 to 800°C. Bird found that parabolic troughs provided the lowest-cost energy for temperatures below 175°C and that central receivers excelled at temperatures greater than 175°C. The PNL results indicate that pumping-power costs are excessive for the stationary concentrator. This conclusion is disputed by Winston, however, who contends that the characteristics of the stationary concentrating collector chosen for the study were unsuitable for large arrays (Ref. 24 and unpublished information, June 1982).

The studies by Spectral Engineering for CMHC[1,14] also showed very high parasitic losses for the stationary concentrator -- presumably for the same reasons that produced the PNL results. The optimization studies of Sharp and Morton[55] result in very low (≈1%) parasitic powers. This low value is confirmed by the calculations done by Spectral Engineering.

Pumping-power requirements for FPC arrays have been calculated by van Hattem and Spectral Engineering and by Menuchin et al.[51] in the U.S. There is little consistency in assumptions, sizes, or sites. Menuchin treats optimization for flow distribution and thermal and hydraulic losses; the calculations exclude shading and are limited to small arrays and relatively low-impedance collectors. The Spectral Engineering study[1] treats large arrays, but it fails to optimize the configuration. Both of these studies indicate pumping losses of less than 5%.

2.2.4 Soiling and Degradation

The permanent loss of performance due to changes in the optical properties of the collectors is so specific to the material of construction and the site that it is virtually useless to discuss the subject quantitatively.

The factors in Table 2.8 represent an optimistic view of how well the optics will retain their original properties, assuming that they are made from relatively nondegradable materials (glass) and are well maintained. The nonconcentrating collectors could conceivably suffer little change in performance, because they are insensitive to scattering and diffuse reflection. Highly concentrating optical systems, on the other hand, must have mirrors of high specularity in order to retain their design levels of concentration.

Preliminary results of material-exposure tests in industrial environments indicate that both soiling and corrosion may be serious problems in some environments.[56] Small amounts of moisture, combined with airborne clays, combine to form an extremely tenacious film that may reduce the reflectivity of mirrors by 90% within a year in bad locations. These films are often immune to noncontact cleaning methods and sometimes to contact methods as well. Stromberg* reports that films on the mirrors of collectors at the IEA Small Solar Power Project in Almeria, Spain, reduced mirror spectral reflectivity by as much as 0.5-1% per day. Most of the degradation noted at Almeria is reversible by washing, but the long-term effects of soiling and repeated washing are unknown.

2.2.5 Availability

Availability is the complement of the fraction of time the system is out of service for maintenance or repair. Experience with building systems and with first-of-a-kind industrial systems has been mixed, but some systems have operated with availabilities near unity. In many cases the operator can choose among performance degradation, operating costs, and availability; for example, one can choose the frequency of cleaning, the time for cleaning (night cleaning would be more expensive), and weather conditions. The operator does not have the same sort of discretionary control over other maintenance items (e.g., the repair of a broken pump impeller).

We have assumed that flat-plate and evacuated collectors can be maintained with an average downtime of one day per month, while the more complex tracking collectors may require three days per month.

2.2.6 Summary of Array Efficiencies

Many factors combine to reduce the collector-array efficiency below the value measured for a single module (in fact, some factors tend to increase the efficiency). Table 2.8 presents some estimates that the subtask members consider reasonable for preliminary designs and that may also serve as goals for the system designer. The combined effects, quantified by the product of the array efficiency-reduction factors, indicate substantial reductions for all collector systems and significant variations among systems. Central receivers fare the best, because they do not suffer the thermal and hydraulic losses in the energy-transport system suffered by distributed collector systems. Central receivers appear to be vulnerable to degraded operating performance because of soiling and maintenance and repair needs.

All the array losses are interrelated, and it is seldom possible to reduce the magnitude of one loss without increasing that of one or more others. Therefore, it is essential to reoptimize the array configuration, components, and parameters over again whenever the site, application, or major components change significantly. This process should be a part of the Phase II design effort.

---

*R. Stromberg, SNLA, personal communication (1981).

Table 2.8 Energy-Reduction Factors Affecting Output of Collector Arrays[a]

	Collector Type			
Loss Type	Flat-Plate	Evacuated	Trough	Central-Receiver
Optical Losses[b] (shading, blocking, etc.)	0.90	0.90	0.95	Included In Eff.
Thermal				
Steady State (manifold losses, flow-distribution effects)	0.90	0.90	0.98	1.0
Dynamic (night losses, intermittency)	0.88[c]	0.93[d]	1.0	1.0
Hydraulic (parasitic power)	0.95	0.95	0.98	0.99
Soiling and Degradation[b] (loss of reflectance or transmittance of optics)	1.0	1.0	0.95	0.95
Availability (loss due to downtime for maintenance and repairs)	0.97	0.97	0.90[e]	0.90[e]
Net Reduction Factor (product)	0.66	0.69	0.78	0.85

[a] These factors were developed by the Subtask 1(b) participants at the third working meeting of IEA Task VII in October 1981. The factors are based on a combination of analysis, experience, and engineering judgment and are intended for use in conceptual design of systems.

[b] Although these effects reduce the input available to the receiver, the factors are applied to the net collector output.

[c] Based on the empirical formula $Q_\ell = 1.15\ (T_s - T_a)/Q_c$, derived at third working meeting.

[d] Based on modification of formula in footnote c.

[e] Assumptions -- no data available.

The efficiency-reduction factors for hydraulic losses displayed in Table 2.8 show at least the right general relationships between collector types. With good design of both the module and the field, it should be possible to hold losses within the indicated bounds.

Clearly, the present understanding of large-system performance and design is incomplete. Steps to alleviate this deficiency are recommended.

3 DESIGN AND INSTALLATION

Information required for design and installation of large solar-collector arrays has been fragmentary and generally inadequate, as is evidenced by the disappointing performance of many of the early space-heating and IPH systems. Through recognition of mistakes, compilation of more complete data bases for design, and development of stronger infrastructures for construction and installation, the situation is improving. Good collections of design data and guidance documents have been published recently in the U.S. and have become available in other countries as well. Collector manufacturers are also a good source of both general and specific design data and should be consulted early in the design process. It is beyond the scope of the subtask participants' work to attempt to review the available information on this subject and provide recommendations for appropriate practice. This chapter, therefore, merely lists some of the important considerations (other than performance and cost) and provides the reader with some guides to the English-language literature.

3.1 Siting and Environmental Considerations

In selecting a site for the collector subsystem, the fundamental considerations are the intensity and availability of solar radiation, the proximity to the load, and the presence of airborne contaminants that could reduce the radiation intensity or degrade the performance of the collectors. The importance of good siting cannot be overstated. Prospective sites for a major plant should be thoroughly investigated; radiation-monitoring and material-sampling instrumentation should be deployed as early as possible. More detailed information may be found in Refs. 1, 3, 5, 14, 15, 46, 49, 57, and 58.

3.2 Solar-Collector Design

The general types of solar collectors to be used in CSHPs were described in Chapter 2. Tracking solar collectors, such as central receivers or PTCs, traditionally have been regarded as designed for large-array applications, whereas FPCs and ETCs have been used chiefly in smaller-scale, domestic applications. The dimensions of the latter are usually limited by the need for easy installation on buildings. Experience in Sweden showed that ETC systems based on modules of only some 2-3 m^2 each usually involved a large, costly effort for installation, plumbing, support, etc.[59] Recently, large-area (12-m^2) collector modules have been developed for large-array applications;[60] these modules have successfully shown that solar-collector system costs can be at least halved by proper design of the collector with integrated support (ready for mounting on ground). The same basic absorber material (Granges strips) employed in the small traditional modules is used. The collector costs have been reduced by a factor of two; support and installation costs, by a factor of three; and plumbing costs, by a factor of five. Collector output has been increased by about 10%, and reduction of heat losses from interconnections is expected to add another 5% output compared with small-scale systems.

Another study has shown that the proper design of large site-built solar collectors can further reduce the array costs.[61] A combination of proper material and site-installation techniques produces an array design in which collector lengths equal the width of the field, so that collector interconnections, plumbing, insulation, etc. are no longer needed. With such collector designs, properly developed for large-scale arrays, a substantial reduction in FPC array costs can be expected.

A large-size module for ETCs similar to that for FPCs is difficult to imagine. The HP receiver does offer some hope of large-array applications, although problems with the expansion of larger header tubes might limit the total length of the module.

Line-focus collectors usually serve as an example of what long arrays can be installed, the array pipes serving at the same time as collector tubes. Module sizes surpass 100 m^2.

Central receivers represent the most advanced class of large-scale site construction, with reflecting units of about 40-50 m^2 (or even 100 m^2) placed on heliostats. Further developments and mass production might in the future bring down the costs such that these systems could be used in very large arrays (typically, some 100,000 m^2 of collecting surface) at a competitive level.

3.3 Energy Transport

The energy-transport system (ETS) for the collector subsystem of a CSHP would consist of all the hardware necessary to deliver the energy from the collector modules to the boundary of the field. The ETS would include all the pipes, fittings, valves, sensors, pumps, controllers, heat exchangers, vents, drains, drainback tanks, etc. required to make the system perform reliably and efficiently. Much of the design information is conventional and common to other applications. For example, much of the information contained in the report of Subtask 1(d)[62] will also apply to the collector energy transport. The main features that distinguish the transport system of a solar-collector array from other piping systems are the sensitivity of the collectors to flow maldistribution, the generally higher temperature levels, and the high economic value of the energy collected. The design of the transport system warrants considerable attention in both planning and installation. It might be necessary, for example, to introduce a daily storage capability on the collector site if the location of the seasonal storage or consumer is too remote from the collector field.

The design must be one that balances the many competing variables. The installation contractor must avoid mistakes that could negate important design features and cost the systems valuable energy.

Reference 15, a recent publication by SERI, is a useful handbook for IPH system design. It contains excellent and extensive sections on the design of transport and control systems and a guide for installation and set-up. It deals with FPCs, evacuated collectors, and PTCs. The recent SNLA publication by Meyer[50] contains very valuable information on ETS heat losses. This includes measurements of losses from the pipes, hand and control valves, pumps, pipe hangers, and supports. There is also a section on the elimination of losses due to thermosiphoning of fluid from warm parts of the piping to heat sinks.

Other relevant design and installation data may be found in Refs. 48, 49, and 55. There are also a number of sources that cite design errors in previous projects and lessons learned; these sources include Refs. 2, 3, 52, 53, 55, and 63-65.

3.4 Support and Mounting

Normally, the engineering data required for the design and installation of the collectors' support structure would be obtained from the manufacturer. However, due to the relatively high cost of this aspect of the system and its importance in determining the performance of tracking collectors, government-supported research and analysis has been substantial, and a body of information exists in the public domain. Much of the useful information is reviewed and reported in Refs. 15 and 49. Additional information may be found in Refs. 55, 64, and 66-69.

3.5 Collector-Subsystem Control Strategies

Information presented in this section was contributed by subtask participants M. Bruck, H. Zinko, and J. van Gilst.

3.5.1 General Considerations

The success of the design of a central solar-heating plant with seasonal storage (CSHPSS) depends very much upon the control strategies adopted. Because solar-energy use still has to be considered a "nonestablished" technology, it has not yet fully developed its own rules. Control strategies, therefore, tend to rely on existing devices in the conventional heating and climatization fields.

Traditionally, most of the control devices have dealt with monovalent energy resources (oil or gas or electricity, etc.). These conventional controllers are simple, cheap, and available. However, in solar installations with seasonal storage -- backed up by heat pumps, conventional heating systems, or both -- the control devices have to handle multivalent energy resources. Conventional control devices are not designed for this purpose.

It is necessary to distinguish between control strategies for the total solar-heating system, including collector-array, distribution, and storage subsystems (which might turn out to be a very involved problem), and the optimal operation of the collector array alone. As far as the total system is concerned, this might be a task for the next phases of Task VII. There are indications, however, that the difference between an optimal dynamic-control strategy (including stratification of storage) and a reasonably straightforward control applied to the same CSHPSS might mean a difference of 20% in collector area needed for the system.[70] Hence, it is worthwhile to invest considerable effort in the development of suitable strategic models.

3.5.2 Control Strategies for Large Arrays

The aim of every array control strategy is to improve the heat output and the solar fraction and to reduce the pumping energy. Two basic types of control strategies are commonly used: the so-called "on/off" and "proportional" types. With an on/off controller, the circulation pump is turned on or off, or a three-way valve is opened or shut, but the pump speed remains constant. With a proportional controller, the pump speed is varied in order to maintain a specific temperature at the collector absorber or the collector outlet. In practice, of course, both principles can be used simultaneously in order to define an optimal strategy.

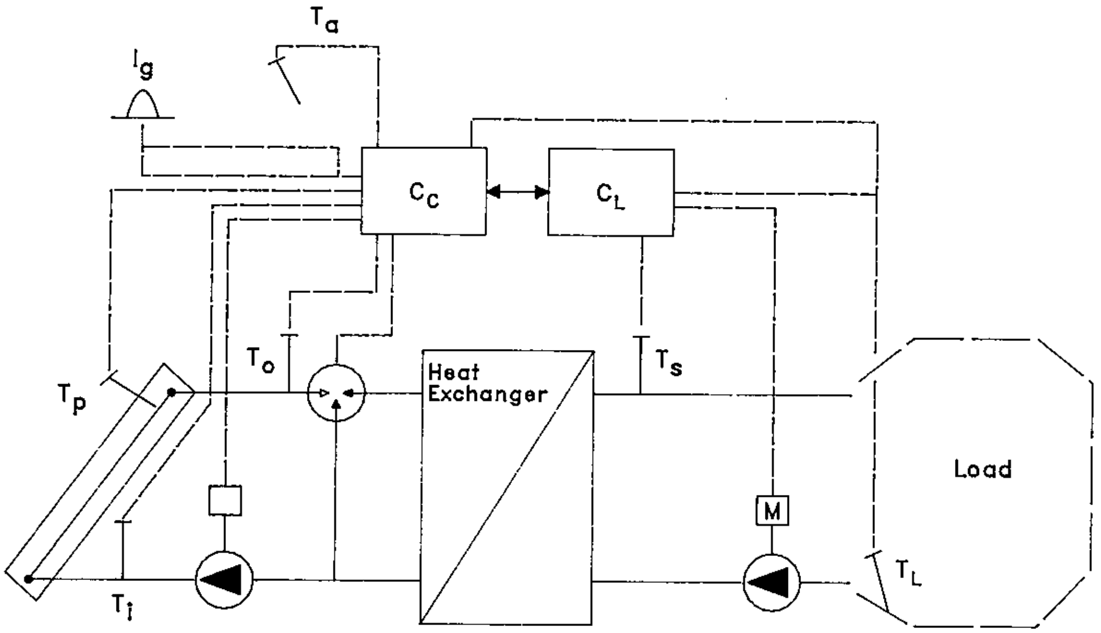
The simplest strategy is to compare the collector temperature (measured at a certain reference collector) with the storage temperature. Whenever the reference temperature exceeds the storage temperature by a specific amount, ΔT_{START}, the pump is turned on; when the measured temperature difference falls below a specific amount, ΔT_{STOP}, the controller turns the pump off.

Depending upon the heat capacity of the collector, loop temperature instabilities may cause high switching rates, and unnecessary energy losses may occur. In order to avoid such instabilities, one of the following measures can be taken:

- Increase ΔT_{START}. This would reduce the switching frequency, but it also could cause severe energy losses and drastically reduce the net heat output of the array.

- Install a bypass parallel to the heat exchanger (see Fig. 3.1). In this case, the circulation pump would be turned on according to the insolation level ($S_{on} \approx 150$ W/m^2)[71] or to the plate temperature (in a simpler control strategy). In a rather complex strategy, pump operation might depend on insolation level, storage-tank temperature, and ambient air temperature (calculating the actual collector efficiency with the help of a microprocessor). A three-way valve is opened when the bypass temperature exceeds the storage reference temperature by a certain amount (≈1.5 K).

Theoretical as well as practical results gained at Graz, Austria (photo laboratory with a total collector area of 1060 m^2),[71] indicate that considerable improvements in array performance (compared to that obtained



T_p ... plate temperature
T_i ... inlet temperature
T_o ... outlet temperature
T_a ... ambient air temperature

T_s ... storage temperature
T_L ... load temperature
I_g ... global irradiance
C_c ... collector loop
C_L ... load loop

Fig. 3.1 Possible Control System for a Large Solar-Collector Array [The functions of the control units for loop C_C and loop C_L can be combined in one unit.]

using the simple "on/off strategy" without bypassing the heat exchanger) can be achieved (up to 20% higher annual net heat output and up to 10% less pumping energy). In practice, for large array systems, it is not useful to vary the flow rate over a very broad range. Changing the flow rates affects the dynamic pressure balance within the array and, hence, the flow distribution; changes in flow distribution might result in unbalanced collector cooling and lower the array's efficiency. For example, the reduction of the flow rate from 0.5 L/min·m^2 to 0.2 L/min·m^2 can, for a given array, reduce the energy output by 3-15%, depending on array size, pressure-drop ratio of the header pipe to collector, and type of connection.[72]

Low flow rates also increase the heat-transfer time from collector to heat exchanger, so that the system's response time for varying radiation conditions increases. Finally, the flow rate affects the collector heat-removal factor, F, which can substantially decrease the collector efficiency. Experience at Sodertorn[59] showed that a flow-rate variation of between 40 and 100% (100% corresponding to design point) could be tolerated without significant changes in the energy produced by the array. (An efficiency decrease of 6% at most was detectable in the course of a day by decreasing the flow rate to 40%; however, a part of this effect can be attributed to changing temperatures and heat-capacity effects.) When the flow rate was decreased to 20%, a significant reduction of the collector efficiency (about 20%, related to the same collector temperature) was measured.

The influence of the control temperature differences has not been measured. However, optimal control depends on accurate temperature measurement, a requirement that very often is not fulfilled with commercially available control systems. Figure 3.2 illustrates this case.

Assume that the start/stop condition is controlled by temperature sensors (Fig. 3.1) measuring T_p and T_i. For a given irradiation, the absorber will reach the stagnation temperature T_p and the pump will start. The mass-flow rate will reduce the operating temperature to T_o. Larger mass-flow rates will result in lower T_o. The stop criterion can be set by the start criterion according to the following relationship:

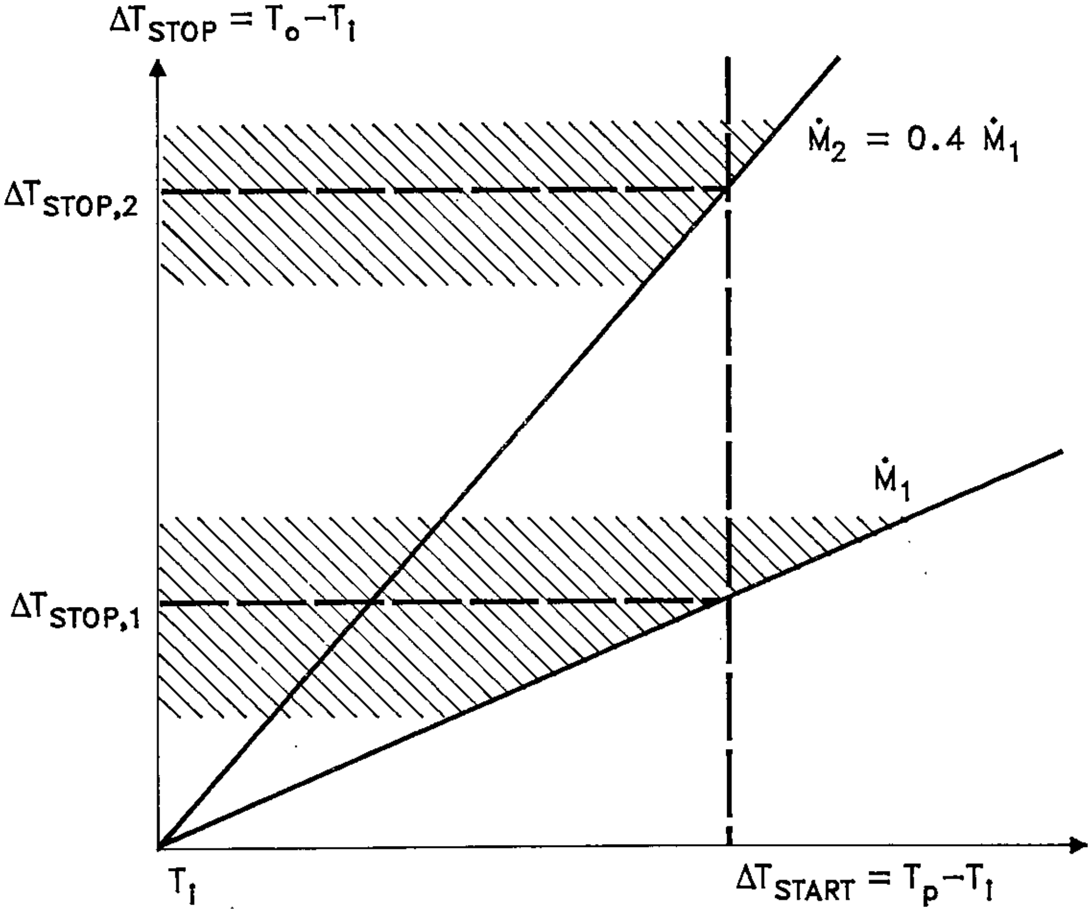


Fig. 3.2 Connection between Control Temperature Differences for Two Different Mass-Flow Rates (The shaded area indicates possible control margins when sensors measure wrong temperatures.)

$$\Delta T_{STOP} \leq \frac{K}{\dot{M}c_p} \cdot \Delta T_{START}$$

where:

K = Total heat loss from the array,

$\dot{M}$ = Mass-flow rate, and

c_p = Specific heat.

In practical cases, ΔT_{STOP} is rather small, which means that the temperature difference must be measured quite accurately in order to avoid oscillating system operation. In large-scale systems, it is worthwhile to use high-quality sensors for the control system when using calculated start/stop and temperature conditions. Decreasing the mass-flow rate near start/stop conditions increases the ΔT and thus decreases the accuracy requirements for the control sensors.

3.5.3 Example of a Large-Array Control Strategy

Assume that the collector array is connected to a constant-temperature load by means of a heat exchanger, as in Fig. 3.1. During the night, collectors and piping cool to ambient nighttime temperatures. At sunrise, the collectors are warmed up in a stagnated condition (without coolant flow). In a south-oriented array, the cosine law allows for only a slow increase in the irradiation incident upon the collectors until the theoretical start condition for the collectors is reached. However, the energy received during this period can be used to preheat the piping and array components, thus contributing the portion of daily energy production (approximately 10%) needed for the heating of the system; otherwise, this energy would be taken from the useful output.

The absorber temperature controller can be set to a temperature of the order of the expected operating temperature. The pumps then are activated at a lower speed (40%), and the three-way bypass valve diverts flow around the heat exchanger. Now the system operates in the warming mode. Whenever the temperature T_O at the bypass rises a few degrees above the expected load temperature, T_L, the three-way shunt opens to the heat exchanger and a low flow from the load passes through the load side of the heat exchanger. With increasing irradiation, the pump speed increases to a maximum and the three-way valve opens according to the set temperature from the collector loop.

With decreasing irradiation, the collector temperature decreases and (at a small temperature difference above the load temperature) the three-way valve and load-circuit control reduce flow to the heat exchanger. At a set value, the pump speed decreases toward a minimum, and when $T_O \leq T_L$ the flow through the heat exchanger is shut off. The solar-collector circuit is operated until the temperature T_O reaches a minimum-temperature set point.

It is essential for this type of control that the time constant for the controlled units is well matched to the size of the system and flow rates. In large systems the necessary control functions may be generated by means of a microcomputer controller. If solar radiation is treated as an additional control parameter, the pump speed can be controlled in a more rational way.

Experience with the kind of system control described here (in contrast to a simple on/off control) has shown a 10-15% higher array output on clear days. The control setting sequence is shown schematically in Fig. 3.3.

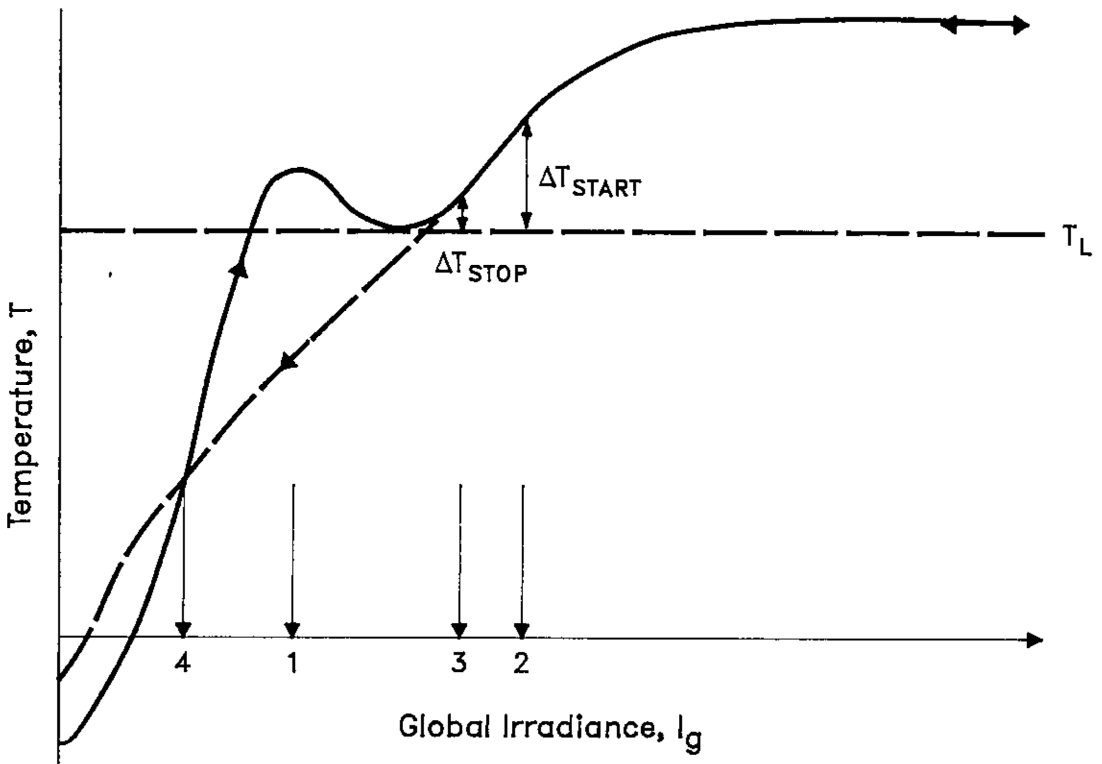
3.6 Safety and Environmental Considerations

Solar collectors are generally regarded as safe and environmentally benign. However, a large solar plant presents hazards much like those in any other industrial environment. The most obvious hazards are the presence of high temperatures, concentrated sunlight, and (in some plants) fluids or other materials that are flammable, toxic, or both. A thorough treatment of safety and environmental issues, including detailed references to U.S. and state legislation, is presented in the SERI handbook.[15] Additional information may be found in Refs. 73-75.

3.7 Installation and Start-Up

Special precautions are often needed for components of solar-energy systems to assure that they are not damaged during installation or start-up. For example, some collectors require protection from dry stagnation or from cold starts made from dry stagnation. Table 3.1 is a check list, extracted from the SERI handbook,[15] of things to consider in installing fields of solar collectors.

Additional information, restrictions, etc. will be supplied by the collector manufacturer. Clearly, starting up a large plant (such as a multimegawatt central-receiver plant) is not an operation to be undertaken lightly. Any such start-up requires careful planning and trained personnel.



1. Circulation pump starts
2. Heating Phase: circulation pump speeds up, 3-way-valve controls temperature, load pump stops
   Cooling Phase: circulation pump slows down
3. Heat exchanger by-passed; load pump stops (cooling phase)
4. Circulation pump stops

Fig. 3.3 Switch Points for a Large-Array Control System

Table 3.1 Checklist for Installation of Industrial Process-Heat Solar-Energy Systems

---

Documentation
- Piping and Instrument Diagram
- System Drawings
- Component Specifications and Drawings
- Equipment List
- Construction Codes
- Operation and Maintenance Manuals
- Progress Log
- Spare-Parts List

Flat-Plate and Evacuated-Tube Collectors
- Vegetation
- Support Structure
- Collector Alignment for Tilt and Azimuth
- Row Spacing
- Manifold Alignment
- Manifold Connectors, Installation and Materials
- Slope for Drainage
- Stagnation Cover during Construction
- Support Structure to Meet Specifications
- Rigidity of Support and Collector Attachment
- Access to Collector Field as Necessary

Line-Focus Collectors
- Collector Alignment for Azimuth
- Alignment of Receiver Tubes
- Row Spacing
- Access
- Support Structure
- Assembly of Receiver Tube and Cover
- Cleanliness of Receiver Tube and Cover
- Alignment and Support of Flexible Hoses
- Attachment of Flexible Hoses
- Alignment of Sun Trackers (check during fluid flow)
- Travel of Collector
- Shielding of Components from Concentrated Radiation

Piping, Fittings, and Insulation
- Provision for Thermal Expansion
- Piping and Fittings, Schedules and Material
- Orientation of Fittings to Flow
- Gaskets and Packing
- Short Bolting of Flanges
- Adequate Vents and Drains
- Valves for Oil System Installed Horizontally
- Relief Valves Installed Vertically, Vented to Safe Location, with Weep Hole
- Pipefitting Practices in Field (minimize pressure drop)
- Pipe Placement to Allow Access (but isolated from foot traffic)
- Heat-Tracing Check before Insulation is Installed
- Waterproofing of Insulation, Particularly Underground
- Pipe Supports (isolated from pipe)

Table 3.1 (Cont'd)

Heat Exchangers
  - Clearance for Disassembly
  - Connecting Piping Fully Supported
  - Thermal Expansion
  - Instrument Connections
  - Vents and Drains

Pumps
  - Foundations
  - Connecting Piping Fully Supported
  - Alignment of Pump and Motor
  - Flushing and Cooling Lines Sealed
  - Isolation Valves, Strainer, Check, Discharge-Pressure Gauge
  - Free and Correct Rotation
  - Grounding
  - Suction Head
  - Lubricating Oil
  - Bearing Temperatures, Discharge Pressure, Motor Current

Pressure Vessels and Storage Tanks
  - Foundations
  - Thermal Expansion
  - Conformity to Construction Drawings
  - Vessel Internals
  - Placement, Thickness, and Type of Backfill for Underground Tanks
  - Waterproofing
  - Thermosiphon Breakers
  - Safety-Valve Settings

Control System, Electrical System, and Instrumentation
  - Labeling of Instruments and Controllers
  - Wiring Shielded and Grounded
  - Fail-Safe Position of Valves
  - Free Movement of Valves
  - Orientation to Flow of Valves and Instruments
  - Immersion of Thermowells
  - Inlet and Outlet Pipe Lengths around Flow-Measuring Devices
  - Auxiliary Power Supply, Uninterruptible Power Supply, Battery Charger

Safety and Environmental Concerns
  - No Sharp Edges or Exposed Hot Piping
  - Guard Rails, Ladder Cages
  - Safety Showers, Eye Baths
  - Fire Extinguishers
  - Emergency-Shutdown Capability
  - Collection of Heat-Transfer Fluids
  - Personnel Training

Source: Ref. 15

4 OPERATION, MAINTENANCE, AND DURABILITY

Although small solar-energy systems have been in use for many years, systems on the scale of 10^3 m^2 have been built only in the last ten years. The body of knowledge relating to proper operation and maintenance of large solar-collector systems is growing rapidly. As the number and variety of systems in service grows, the feedback from operational experience on the design, installation, and operation of new systems generates rapid improvement.

Because the operational characteristics of systems may vary considerably from country to country, the format adopted for this chapter differs from that used in the rest of the report. Brief synopses of operational experience with various collector types and systems, based on reports submitted by the subtask participants, are followed by summaries of the important observations from these synopses.

4.1 Experience in Switzerland

This section consists of material adapted from an account submitted by Atlantis Energie A.G. (through Sorane, S.A.) for use in this report.

4.1.1 Flat-Plate Collectors

As of 1977, approximately 500 solar installations were registered in Switzerland. Since then it has been difficult to keep track of the exact number, because the number of new solar installations has increased rapidly. It is believed that several thousand installations are in operation in Switzerland by now. The applications of these installations can be classified as follows:

- Swimming-pool heating,
- Domestic water heating, and
- Low-temperature space heating.

The number of swimming-pool installations (and the potential for future installations) is relatively small in Switzerland. Most of the solar-energy installations were meant for domestic hot-water (DHW) heating. For this purpose, suppliers developed standard systems with collectors of about 10 m^2 surface area. Most of the experience was gained with systems of this sort, operating at temperatures of 40-60°C. The greatest future potential, however, is expected to be in both space heating and DHW heating, provided seasonal storage becomes feasible.

Experience with solar energy systems over approximately the last eight years has shown that some of the FPCs, especially those of the "homemade" or "small-series" types, did not meet the operational requirements and had to be taken out of operation after a short period. These types are gradually disappearing from the market.

The operation of "professional," mass-produced collectors, after the elimination of some initial problems, has been fairly satisfactory. The functioning and efficiency of these collectors seem to remain unchanged after several years of operation, although some failures have occurred. The operational time has been too short to make definite judgments about collector lifetimes. With the increasing number of solar installations, however, it has become necessary to speed up the operational experiences in order to better predict the lifetime expectancy, the operational costs, and the economics of solar heat generation. For this purpose, a test bench was built by the Engineering School at Rapperswil.

The test facilities were built at two locations, one of average, the other of extreme climatic conditions (high solar-radiation intensities, very low ambient temperatures). The tests are conducted under the most severe of operating conditions, collector stagnation (i.e., maximal achievable temperature, without heat removal). At present, ten different collector makes (some Swiss, some of foreign origin) have been tested. The function and performance of all key FPC components, as well as the collectors as a whole, are tested for inappropriate choice of materials and material combinations, wrong collector lay-outs, corrosion problems, transparency changes in the covers, durability of selective and nonselective coatings, etc.

After approximately six months of testing, one collector has exhibited corrosion failures (material and contact corrosion were investigated using various heat-transfer fluids, with anticorrosion additives at various concentrations). A seal between the absorber plate and the collector header of another collector has leaked, resulting in loss of heat-transfer fluid. The cover of one of the collectors broke because of a large temperature difference between the collector's two sides (caused by snow covering only half of the collector glazing). The performance of the selective and nonselective coatings showed little or no change at low temperatures, but at higher operating temperatures a coating foil of one collector separated from the absorber body, while the color of another one changed considerably (change of ε and α).

Since the first series of tests is not finished yet, no final judgments can be made. It can be seen, however, that failures occur even in the best collectors. It will take time before FPCs can be characterized as totally trouble-free over a lifetime of 20-30 years. On the other hand, experience with the collectors tested, as well as with the commercial collector installations, also has indicated that this goal can be achieved. Introducing better quality control during collector fabrication appears important, because usually failure occurred in one collector while others of the same make remained intact.

4.1.2 Evacuated Collectors

There has been very little experience with evacuated collectors in Switzerland, so little can be said about their life expectancy, operational difficulties, or maintenance.

It is expected that both life expectancy and performance of evacuated collectors should be good in Switzerland, because the influence of climatic conditions is likely to be minimal. Given good quality control during their production, the collectors could probably attain useful lifetimes typical of conventional heating systems (about 20 years).

The most important condition to be satisfied in order to assure long collector lifetimes is to keep the initial vacuum at a value of at least 10^{-4} torr. The competitive suppliers of evacuated collectors (Corning,* Philips, and Sanyo) also have many years' experience in manufacturing evacuated television tubes, and these tubes have maintained their vacuums over such periods. Therefore, it can be expected that this basic condition for collector lifetimes will be satisfied.

The other requirements for evacuated collectors are identical with those for FPCs.

4.1.3 Tracking Collectors

Because tracking concentrating collectors convert only beam irradiance to thermal energy, their basic cost should be lower than that of flat-plate or evacuated collectors in order to be competitive with them for heat generation in a temperature range of about 40-60°C. This was not the case in past years, and therefore concentrating collectors did not find such wide acceptance in Switzerland as did FPCs. The solar installations using concentrating collectors were very few, and experience was quite limited.

One plant, put into operation in 1979 for the generation of medium-temperature heat, used 100 m^2 of parabolic concentrating collectors for the generation of hot water at 80-90°C. Experience with this plant is summarized as follows:

- The concentrating-collector array generated sporadically, under ideal conditions, the same amount of heat as did an array of FPCs located at the same site.
- Actual conditions differed from the ideal most of the time, and the energy gain of the concentrating collectors over one year was only about half of the gain of the FPCs.

---

*Corning Glass Works, Corning, N.Y.

- Use of this particular collector to generate heat at temperatures above 80°C could not be recommended, because its efficiency decreased rapidly at higher temperatures. This deterioration in performance occurred because the heat-transfer medium flowed in a glass pipe that was not insulated from the environment. (The collectors are now equipped with an insulated absorber to make them more efficient above 80°C.)

The experience gained with the first Swiss concentrating collectors, therefore, was rather disappointing. The main problem was the high thermal loss factor of 3.6 $W/m^2 \cdot K$. Other problems included a lack of accuracy in sun tracking and excessive fluid capacity in the system (low system dynamic efficiency).

It is expected that the second generation of concentrating collectors will be free from most of the above problems. However, because no experience has been gained with this collector type on a larger scale, it remains to be seen whether the expectations will be confirmed in practice.

4.2 Experience in Sweden

This section is adapted from materials submitted by H. Zinko for use in this report.

4.2.1 Flat-Plate Collectors

In the past, FPCs were produced mostly for use in DHW systems, and the collector-module size was about 4 m^2 at the largest. About 30,000 m^2 of such collectors are in operation in Sweden. However, experience has shown that such collectors would not be the most economical solution for large-scale installations. Therefore, as early as 1977, site-built collector roofs (single-glass selective, constructed by Granges Aluminum and SOLLAB) were used for the 2,900-m^2 Lambohov CSHP. Since then, the Granges Aluminum absorber strips have been found to be very useful for the design of large-scale collectors. Both uncovered and single-glazed collector modules about 12 m^2 in area have been developed and used successfully in demonstration plants.[60] During the fall of 1982, a 1,920-m^2 solar district-heating installation with 12-m^2 modules and single-glazed covers was completed. The average operating temperature is around 55°C.

Near Uppsala, the local district-heating authority is constructing the Lyckebo CSHP with 4,320 m^2 of collectors of a new type.* Operating temperatures

---

*Scandinavian Solar AB.

will reach about 90°C during the summer, and a special anticonvection structure made of Teflon™* will be placed between the outer glass and the absorber.[76]

Finally, Granges Aluminum is developing a new large-scale design, based on its absorber strips, that uses an unconventional on-site installation technique for large collecting units (areas on the order of 100 m^2). This technique is expected to lead to a cost-benefit breakthrough for large solar-collector arrays.

Other FPCs of interest are under development. The Swedish rubber company Trelleborg AB is developing a black-rubber collector to be installed with or without a cover. This collector, which can be sized to fit the roof's dimensions, can replace ordinary roof covers. Consumer costs should be very low when it is used in newly constructed buildings.

Solar-collector costs (including support) for large-scale installations in 1982 are of the order of 0.6-0.7 SEK/kWh for temperatures around 30°C and 1.8-2.3 SEK/kWh for temperatures around 60°C. It is expected that the costs at 60°C can be decreased to 1.2 SEK/kWh. On the basis of the collectors mentioned above, the installation costs are expected to total about 3.5-4.5 SEK/kWh annually for the near-term installations and about 2-3 SEK/kWh annually for future installations.

However, all the collectors discussed above are recent developments. None has undergone sufficient tests or been operated sufficiently long to allow reliable prediction of degradation and other impacts affecting collector operating life.

4.2.2 Evacuated Collectors

In Sweden, evacuated collectors have been considered to be the most advantageous solar collectors for solar central heating and district heating. Three solar district-heating installations are in operation, with a total of eight systems containing different ETC types. The largest of these installations is operated by the Sodertorn district-heating authority, where about 150 m^2 of GE and Philips collectors are installed.[59] OI, GE, and Philips evacuated collectors are being tested at another district-heating plant at Knivsta (around 30 m^2 of each type),[65] while at Studsvik about 10 m^2 of both Corning and Philips ETCs (with and without back reflectors) are undergoing long-term tests.[77]

So far, the general experience with ETC collectors has been quite satisfactory. The collectors behave very well in the northern climate and respond to low solar-irradiation levels. The field comparisons between single-cover,

---

*"Teflon™" is a registered trade name of E.I. duPont de Nemours and Co., Wilmington, Del.

selective FPCs and ETCs at Sodertorn have given strong evidence that at temperatures around 60°C ETCs produce (on average) 40-80% more energy output than FPCs.

After initial troubles with boiling and blocking of the tubes had been overcome, the subsequent operation of the Sodertorn ETCs was without serious problems. The tube-breaking rate is far below 1%/yr even under severe conditions (with occasional stagnation and boiling). Thermal shocks might be a problem for some types of ETC, especially under nonoperational conditions (start-up after maintenance, stops, etc.). However, the learning period for achieving safe system operation has been no longer than for FPCs. References 59 and 65 provide more details from the experience gained at Sodertorn and Knivsta.

The higher energy output of ETC systems at $T > 60°C$ compared with FPC output still cannot compensate for the higher costs of ETCs. The tenders for Lyckebo show a considerably higher cost lever (cost per unit of energy delivered to the load) for ETC systems compared with the FPC installations (based on the heat delivered to a heat exchanger for a desired annual power production).

A rough estimate today indicates system costs to be about 6-8 SEK/kWh yearly, depending on type ($T = 60°C$). Annual costs are expected to decrease to 4-6 SEK/kWh in the near future. Hence, ETC systems have to be developed further in order to be competitive with large-scale FPC systems. (Not included in these calculations, of course, is the considerable credit from long-term durability expected from ETCs.)

4.2.3 Tracking Collectors

Experience with tracking concentrating collectors is very poor. There exists some uncertainty about the usefulness of PTCs for northern climatic conditions (high amounts of diffuse radiation, relatively low total irradiation). The first large-scale installation, 1250 m^2 of line-focus collectors at Vaxjo (See Sec. 4.2.4), produced energy considerably below the predicted values. Reasons for the poor performance included malfunction of the collectors, the imperfect system, and a larger measured amount of diffuse radiation at the site than the reference calculations, based on data from another site, had called for. Another line-focus collector (SUNTEC module, about 70 m^2) is operated by the Uppsala district heating authority, but reliable measurements are not available so far. Cost comparisons indicate that current PTC system costs should be close to those for ETC systems.

On the other hand, CPC collectors are operated very successfully by Studsvik Energiteknik AB. The Studsvik CSHP has been operating for four years with results close to predicted ones (See Sec. 4.2.4). The collectors have a concentration ratio of 4:1, and they are mounted on a rotating platform. The operating-temperature range is 40-70°C, and the annual production rate is about 300 kWh/m^2. Although the aluminized polyester reflectors show signs of different degrees of deterioration (slight to heavy), the total plant output so far has not been affected seriously. One reason for that could be that the light strikes the reflector sheets with a large angle of incidence, which results in high refractive beam reflection. Total installed costs for the collector are today around 4.5 SEK/kWh yearly (T = 60°C). Development of a low-cost system based on similar principles is in progress.

At Studsvik Energiteknik AB, a very large CPC array (75 m^2) mounted horizontally on a rotating platform is installed in an inflated, hemispherical plastic greenhouse. The collecting system promises a low-cost technology for solar-energy production at temperatures of about 80°C and above. This Giant Inflated Solar Collector demonstration installation will undergo a longer testing period before final conclusions about large-scale applications can be drawn.[77]

4.2.4 Systems with Seasonal Storage

The aim of Task VII, construction of CSHPSSs, was instigated in Sweden by several groups during the second half of the 1970s. The Council for Building Research approved grants for three projects with the same basic idea: medium-temperature (collector temperature > 50°C) solar collectors take in heat during the summer season (with about 1700-2000 sunshine hours annually) to supply energy for space heating and DHW production. Energy is stored in long-term water-based storage systems. Three systems, based on different schemes, have been built: one is a relatively small-scale pilot plant, while the two others are on a demonstration scale (see Table 4.1). These installations commenced operation during 1979 and 1980.[2]

Two other installations commenced operation in 1981. These two installations use uncovered or single-glazed solar collectors to produce low-temperature heat to be stored in low-temperature ground storage systems, essentially by means of heat-exchange tubes inserted into the ground. One of these two installations is on a pilot scale and incorporates heat recovery for a low-temperature space-heating system (T < 30°C). The other installation is demonstration-size and feeds a heat pump.

Finally, the largest installation is that of Lyckebo. The Lyckebo plant uses 4320 m^2 of FPCs, combined with a 100,000-m^3 rock cavern for storage. Lyckebo represents the 1982 state of the art in terms of CSHPSSs. Table 4.1 summarizes the essential features of all six installations.

4.2.4.1 Studsvik. The Studsvik system[78] uses a new, patented method for both storage and solar collectors. An excavated earth pit is insulated with mineral wool (side walls and bottom) and polyurethane (lid). The liner is made from a rubber sheet. The lid floats on the storage water and serves as a turntable, tracking the sun and supporting the solar collectors. Weakly concentrating (4:1) CPC solar collectors are installed on the rotating platform.

Table 4.1 Solar Central Heating Projects with Seasonal Storage in Sweden

	Collector			Storage			
Location	Type	Area (m^2)	Heat Pump	Type	Volume (m^3)	Planned Solar Contribution (%)	Application
Studsvik	CPC on rotating lid	120	No	Water in earth pit	640	100	Office building
Ingelstad	Line-focus PTC	1,250	No	Water in concrete tank	5,000	50	52 single-family houses
Lambohov	Single-glazed, selective FPC	2,900	Yes (storage to consumer)	Water in rock cavern	10,000	85	55 single-family houses
Sigtuna (Sunstore project)	Black FPC with one glass; black FPC uncovered	36 126	No	Rock, 40 bore holes	10,000	80	One large single-family house
Kingsbacka (Sunclay project)	Black FPC, uncovered	1,600	Yes (storage to consumer)	Clay, submerged U-tube	85,000	60	School for 800 students
Lyckebo	Selective FPC, covered by one glass and two Teflon™ sheets	4,320	Not yet decided	Rock cavern	100,000	15	500 dwellings

The solar collectors are handmade prototypes that consist of CPC profiles cut out of polyurethane and covered with aluminized polyester reflector sheets. The collectors are protected by single glass covers. Each collector unit has an area of about 2.4 m^2.

The installation has been in operation since 1979, over operating periods from the end of March to the beginning of October. In 1981 the installation produced 99% of the seasonal heating needs for a 500-m^2 office building. The collectors produced about 320 kWh/m^2, with an operating efficiency of about 40%. The maximum storage temperature was 60°C. A major problem with the collectors has been enhanced reflector degradation caused by condensation. Storage and tracking systems have worked well. A second-phase study for purposes of advanced system design is in progress.

4.2.4.2 Ingelstad. The Ingelstad plant[3] is much larger than that in Studsvik and uses 420 parabolic line-focus collectors tilted in the N-S direction (35°). The collectors are operated at high temperatures (>90°C). Heat is stored in a 5000-m^3 concrete tank insulated by 10 cm of foam glass and 10 cm of mineral wool. The solar-collector, storage, and distribution systems are separated by means of heat exchangers. All parts, except the solar collectors, function successfully. Initially, minerals leached from the concrete walls of the storage tank caused fouling in both collectors and heat exchangers, but this problem has diminished.

The parabolic line-focus collectors exhibit problems with both the tracking and focusing of solar radiation. Many collectors focus badly, and about 5% of the collectors are out of working order at any given time. The installation is also located at a site that has received considerably less direct radiation during the last few years than expected. The combination of all these effects has resulted in an energy production of about half of the predicted values.

4.2.4.3 Lambohov. The Lambohov facility is a distributed solar-collector system with a common central storage.[4] In total, 2900 m^2 of solar collectors (flat-plate, selective, single-cover) are mounted on the roofs of 55 houses. Solar collectors, heat-distribution systems, and storage systems are interconnected directly, without heat exchangers. Hot water for domestic use is stored in daily accumulators and transferred to the DHW supply by means of heat exchangers.

The heating water is distributed directly from the storage unit to the houses. When the temperature delivered from the tank sinks below 55°C, a heat pump is activated to boost the temperature of the circulating water. The storage is, in principle, similar to that at Studsvik; however, because of ground conditions, a cylindrical cavern was blasted out of the rock. The wall insulation consists of 40-cm porous ceramic bubbles (Leca) cast into foam concrete. The material for the top insulation is (floating) polyurethane; the lining is made of rubber.

In the Lambohov plant, problems arose with the conventional heat-distributing part of the system. Because of the absence of heat exchangers, some parts of the system reached subatmospheric pressures, and air leaked in as a result. This air, together with draining air from the solar collectors, caused both corrosion and bacteriological poisoning of vital equipment (the heat exchangers for the DHW, evaporators, pumps, etc.).

No reliable evaluation of performance data was possible. However, measurements made manually indicate that the solar collectors worked satisfactorily. The installation was reconstructed during 1981 and was restarted in the second half of 1982.

4.2.4.4 Lyckebo. In the village of Storvreta, 13 km north of Uppsala, a new housing area is under construction.[76] During 1981-1984, 550 houses will be built at Lyckebo. The houses will be heated by a separate district-heating system, supplied with solar energy from a seasonal-storage facility.

The project will be carried out in two phases. In the first phase only 15% of the required solar collectors will be installed; the rest of the energy will be simulated with an electric boiler connected to the storage facility. In the second phase, which is expected to be completed during the latter part of the 1980s, the remaining 85% of the solar collectors will be installed, so that approximately 100% of the needed energy will be supplied by solar energy.

The rock cavern is designed as a torus, 75 m in diameter and 30 m in height. The cavern roof is 30 m below ground. The pressure in the cavern is kept in balance with the surrounding ground water with the aid of a pressurizing and relief system.

There are two separate systems for water inlet and outlet, and the pipings can be adjusted according to the stratification of the storage. The temperature levels are 40°C in the bottom and 90°C in the top. The equipment needed for operation -- pumps and heat-exchangers for the "storage water" and pumps, expansion tanks, etc. for the district-heating network -- is situated in a tunnel between the storage and the rock surface. The control functions are handled by means of a computer; the control room is also situated in the tunnel.

The cavern was blasted out between August 1981 and April 1982; it was filled with water in September 1982. After all the installations were finished, the storage facility was to commence operation in the summer of 1983.

The first part of the solar-collector installation will consist of 4320 m^2 of FPCs made by Scandinavian Solar AB. Each collector is 12 m^2 in area. The absorber is an aluminum plate with a selective layer (Granges Sunstrip) and in the middle is a copper tube for the fluid. In each collector the "Sunstrips" are coupled in series, which gives a total length of 72 m. The water inlet is in the bottom of the collector and the outlet in the top.

To reach the desired high temperatures, three cover layers are used above the absorber: two layers of thin Teflon™ film and one 4-mm-thick glass cover. The back side is insulated with 10 cm of mineral wool, and the whole construction is mounted together in an aluminum frame. The weight of each collector is about 300 kg.

The collector installation also was to commence operation in the summer of 1983.

4.2.4.5 Deep Dry-Ground Storage Projects. Two projects are presently under way: Sunstore and Sunclay.[79] In both types heat is stored underground, in rock (Sunstore) and in clay (Sunclay). With Sunstore, heat is transferred by means of vertical distribution holes drilled into rock. Low-temperature heat is stored for seasonal use in combination with heat pumps. With the rock storage, temperatures might even be so high that the heat could be used for heating systems without use of heat pumps. In the Sunstore project at Sigtuna, boreholes are charged by a total of 160 m^2 of solar collectors. Heat is delivered to borehole storage and directly to the DHW system. Because of the high surface-to-volume ratio in Sigtuna, the system is backed up by electrical heating.

The Sunclay project also involves low-temperature storage.* U-shaped tubes inserted into clay are used as heat exchangers. A very simple method for introducing the tubes into the clay has been developed, and the system is expected to be low-cost even for small-scale applications. The heat is extracted by means of a heat pump. In the first application of the system, for a school, about 85,000 m^3 of clay (35 m deep, 36 m x 68 m ground surface) are used for heat storage in 612 U-tubes at temperatures between 12 and 20°C. Solar energy is predicted to cover about 60% of the annual heating requirements. A diesel-driven heat pump is used for temperature boosting, contributing the remaining 40% of the heat to the system. The system has been in operation since the winter of 1980-81; the solar-collector system (uncovered, flat, black aluminum plates with copper tubes) performs very well.

Boreholes in rocks can be spaced wider apart and charged to higher temperatures than tubes in clay. The initial costs for borehole drilling, however, are expected to be larger than for the Sunclay method. It appears probable that the Sunstore method can be used economically only on a large scale.

4.3 Experience in the United Kingdom

The following material was extracted from a brief article by Keith Hayward (Ref. 80), which was furnished by B. Rogers.

---

*High-temperature storage is, however, being tested in Kullavik.

"... With some 19,000 solar systems for heating domestic water having been installed over the last five years comes the opportunity for examining the durability of the solar collectors in these systems.

A survey of collectors carried out by the Solar Energy Unit at University College, Cardiff, found faults in every one. These ranged from broken cover glasses caused by thermal expansion to corrosion and condensation problems ..." (See Table 4.2.)

Table 4.2 Principal Faults Found in Ten Solar Collectors Examined by Solar Energy Unit, Cardiff[a,b]

Nature of Fault	Fault-Classification Code
Covers	
Dirt on the Outer Cover	A2/3
Deposit on the Inner Surface of Cover	B3
Breakage of Glass Cover	A1
Sagging of Plastic Cover	C1
Discoloration of Cover	C2
Condensation	C2
Cover/Enclosure Assembly	
Degradation of Seal	A1
Ineffective Seal	B1
Absorber Plate	
Degradation of Surface	A1
Corrosion of Plate	A1
Insulation	
Loose and Ineffective Insulation	B1
Dampness	B2
Enclosure and Supports	
Corrosion of Materials	A3
Pipe Connections	
Corrosion	C3
Poor Insulation	B1

[a] Source: Ref. 80.

[b] The Fault Classification Format was as follows: Defect was found in most installations, A; in several installations, B; in a single installation, C. Effect of defect on performance was considerable, 1; moderate, 2; slight, 3.

4.4 Experience in the United States

Information presented in this section is extracted from reports describing the operational experiences of major U.S. solar-energy programs (solar energy in commercial buildings and in industrial processes, conversion of solar energy to electrical power).

4.4.1 Solar-Collector-System Problems in the Commercial Demonstration Program

The material in this subsection is from an ANL report[81] that presents a failure analysis based on data obtained from 80 operating solar-heating-and-cooling systems; the work was sponsored by the DOE. Information on failures was obtained from National Solar Data Network (NSDN) reports on the status of instrumented solar-energy systems, as well as from monthly performance and narrative reports. Additional information came from DOE field-office reports and DOE Contractors' Reviews.

The 80 systems examined -- of different designs, sizes, and configurations -- were used to provide heating, cooling, and DHW. Data on ten of these systems cover the period between January 1977 and October 1979. The remaining 70 systems were installed after that time and provided data over periods ranging from nine to 21 months.

A component is said to have failed when a function other than that intended is performed. Components that failed ten or more times during the data-collection period are defined here as "critical components." "Major critical components" are those that experienced 40 or more failures. Table 4.3 ranks solar-energy-system components in terms of the number of failures experienced.

The collector subsystem experienced 74% of the 332 failures recorded. Of the 246 failures within the collector subsystem, about 46% were related to the collector itself, 19% to interconnections, 18% to controls, 7% to pumps, and 4% to valves. These five elements accounted for about 92% of the collector subsystem failures.

The combined failure incidence for the three major critical components -- collectors, controls, and interconnections -- and the three critical components -- pumps, valves, and storage containers -- accounted for 95% of the system failures. The remaining failures were caused by heat exchangers, dampers, chillers, heat pumps, and air handlers.

4.4.1.1 Collectors. Solar collectors were found to be the most critical component of solar-energy systems. Of the 80 systems reviewed, 52 had a total of 113 collector problems (see Table 4.4).

Table 4.3 Ranking of Component Failures

Component Ranking	Failure Incidence	% of Total Failures	Number of Affected Systems	% of Total Systems
Major Critical Components				
1 Collectors	113	34.0	52	65
2 Component Controls	86	25.9	43	54
3 Interconnections	49	14.8	31	39
Critical Components				
4 Pumps	28	8.4	28	35
5 Valves	19	5.7	19	24
6 Storage Containers	18	5.4	18	23
Other Components				
7 Heat Exchangers	8	2.4	8	10
8 Dampers	4	1.2	4	5
9 Chillers	4	1.2	2	3
10 Heat Pumps	2	0.6	2	3
11 Air Handlers	1	0.3	1	1

Source: Ref. 81.

With the exception of two sites where baseballs damaged one collector panel, the field data did not indicate the number of collector panels affected by a failure. For example, while there were 12 recorded instances of absorber-plate degradation, the actual number of collectors that experienced these problems could be ten to 100 times greater than the failure incidence recorded. Table 4.5 summarizes the failure incidences for four types of solar collectors.

Flat-plate collectors (air and liquid) are used in 86.3% of the 80 systems reviewed. Of the recorded problems, 75% were associated with this type of collector.

Freezing, which accounted for 17.7% of the collector problems, is associated with the design of the system rather than the design of the collector. Degradation of gaskets, seals, and absorber plates accounted for 37.5% of the

Table 4.4 Collector Problems Affecting 52 Solar-Energy Systems[a]

Problem	Incidence
Freezing	20
Tracking	
Motors and Controls	14
Alignment	6
Rotary Joints	2
Seals and Gaskets	18
Absorber Plate	
Coating Degradations	12
Leaks	3
Heat-Transfer-Tube Leaks	9
Outer Glazing (thermal expansion)	7
Insulation Outgassing	4
High-Wind Damage	4
Reflector Degradation	3
Air Bound[b]	2
Baseball Damage	2
Collector Deformation (thermal expansion)	2
Miscellaneous	5
Total	113

[a] Source: Ref. 81.

[b] Liquid flow blocked by pocket of air trapped in piping.

problems associated with FPCs. Insulation outgassing (four instances) appeared to be less of a problem on these 52 systems than the leaks that occurred at the joints between the absorber tubes and the internal manifolds (nine instances).

Some of the gasket and seal leaks could have been caused by the improper selection of materials, resulting in outgassing. The data available from the DOE field offices indicated only that seal or gasket leaks had occurred; the seals were replaced, and the glazings were cleaned and re-installed.

Degradation of the absorber-plate coating (12 instances) could have been caused by improper preparation of the coating surface or improper selection of materials. The data do not distinguish between these causes. The affected systems were returned to operational status by replacing or resurfacing the absorber plates and cleaning and re-installing the glazing.

Table 4.5 Classification of Collector Types Used by 80 Solar-Energy Systems

Collector Type	Number of Systems	Number of Affected Systems	Problem Incidence		Number of Collector Manufacturers
			Number	%	
Flat-Plate					
Liquid-Circulating	61	41	80	70.8	27
Air-Circulating	8	3	5	4.4	3
Tracking	7	6	25	22.1	4
Tubular	4	2	3	2.7	3
Total	80	52	113	100.0	37

Source: Ref. 81.

Although problems with tracking collectors accounted for only 22% of the collector malfunctions recorded, six out of the seven systems with tracking collectors experienced failures. These problems resulted from improper design of the tracking mechanisms. On all but two of the tracking systems, the collector manufacturer has replaced tracking motors and control circuit boards. On the remaining two systems, the tracking and alignment problems have been resolved by minor hardware adjustments.

Tubular collectors are used on four of the 80 solar-energy systems reviewed. Two of the four systems had collector problems. The small sample size does not permit a firm conclusion.

Sixty-six of the 113 collector failures can be related to design or material selection for insulation, absorber-plate coatings, and seals. System design -- the integration of the solar collector into the solar heating and cooling system -- accounted for 22 collector-related problems. Improper maintenance procedures accounted for ten failures, and installation practices affected six systems. The remaining nine problems were of miscellaneous nature.

4.4.1.2 Interconnections. Interconnection malfunctions occurred 49 times and affected 61% of the systems monitored. Ninety percent of the interconnection malfunctions affected more than one joint. Although the field information did not indicate the number of joints affected, all of the collector-to-collector or collector-to-manifold joints usually were replaced when these problems occurred. Solar-collector arrays at typical sites include large numbers of joints, and the actual number of interconnections that failed could have exceeded the total number of collector panels that were affected.

Ninety-eight percent of the interconnection problems occurred in the collector subsystems, while 2% occurred in the storage-to-heating subsystems. Table 4.6 summarizes the problem incidence with interconnections.

4.4.2 Early Operational Results from the Industrial Process-Heat Program

The material presented in this subsection is from Refs. 53 and 63.

In 1977 DOE began funding a series of field tests to gain operational experience in the application of solar energy to IPH requirements. Thirty-four design studies or actual installations were funded, using technologies ranging from FPCs to line-focus concentrators to industrial central-receiver systems. The types of solar-energy systems include hot-air, hot-water, and steam production, applied to a broad spectrum of industrial processes.

The early hot-air and hot-water projects, as well as two steam projects, are operational and are providing important feedback for the design of current systems. The operational systems on the whole have shown good reliability, but system thermal efficiency has been lower than predicted. Investigation points to a need for better design to reduce thermal and parasitic losses and for improvement of the solar-industrial process interface. Failure of routine nonsolar components (pumps, valves, controls) has been a continuing problem. Results to date have also clearly indicated that efficient and cost-effective reflector-cleaning techniques must be developed for concentrating collectors to insure good long-term performance.

Six of the early IPH projects were analyzed by SERI and reported by Kutscher and Davenport.[53] Table 4.7 lists the projects; Table 4.8 describes the problems and corrective actions; Tables 4.9-4.11 display the performance results.

Although the limited statistical basis available from the six projects made generalization difficult, some

Table 4.6 Interconnection Problems Affecting 32 Solar-Energy Systems

Problem	Incidence Number	Incidence %
Materials	13	26.5
Hose Clamps	10	20.4
Thermal Expansion	7	14.3
Solder	5	10.2
Lack of Insulation	4	8.2
Manifold Slope	3	6.1
Air-duct Leakage	2	4.1
Threaded Pipe Joints	2	4.1
Ground Movement	2	4.1
Flare Fitting	1	2.0
Total	49	100.00

Source: Ref. 81.

Table 4.7 Industrial Process-Heat Field Tests[a]

Project Site	Contractor	Application	Type of Collector	Collector Fluid	Collection Temperature (°F)	Process Temperature (°F)	Area (ft^2)	Thermal Storage
Hot-Water Projects								
Campbell Soup Co., Sacramento, Calif.	Acurex Corp., Mountain View, Calif.	Can washing	Solargenics Series 77 FPC and Acurex Model 3001-1 E-W PTC	Water	150	180-195	7,335	19,000 gal hot water
Riegel Textile Corp., LaFrance, S.C.	General Electric Co., Philadelphia, Pa.	Textile dyeing	GE TC-100 ETC	Water/ethylene glycol	270	190	6,680	8,000 gal hot water
York Building Products, Inc., Harrisburg, Pa.	AAI Corp., Baltimore, Md.	Concrete-block curing	AAI 24:1 Multiple-reflector linear concentrator	Water/ethylene glycol	135	135-180	9,216	50,000 gal hot water[b]
Hot-Air Projects								
Gold Kist, Inc., Decatur, Ala.	Teledyne-Brown Engineering, Huntsville, Ala.	Soybean drying	Solaron Series 2000 FPC	Air	140	155-175	13,104	None
J.A. LaCour Kiln Services, Inc., Canton, Miss.	Lockheed Missiles and Space Co., Huntsville, Ala.	Lumber drying	Chamberlain Model 11301 FPC	Water	142	110-160	2,520	5,000 gal hot water
Lamanuzzi and Pantaleo Foods, Fresno, Calif.	California Polytechnic State University, San Luis Obispo, Calif.	Fruit drying	Site-fabricated FPC	Air	145	140-150	21,000	14,000 ft^3 rock bin

[a] Source: Ref. 53.

[b] Storage is in the plant's rotoclave.

Table 4.8 Problems Encountered in Industrial Process-Heat Field Tests[a]

Project Site	Problem	Corrective Action
Gold Kist, Inc., Decatur, Ala.	Collector contamination by soybean chaff	Developed automatic sprinkler system
	Data logger failure due to low temperature	Defective car replaced; heater repaired
	Water seepage into insulation	None
	Plant operation schedule calling for maintenance during daytime	Changed operation schedule to use solar equipment more effectively
LaCour Kiln Services, Inc., Canton, Miss.	PVC[b] pipe failure due to overheating during nonload conditions	Replaced all PVC with steel pipe; installed high-temperature cutoff; installed larger-pressure relief valve
	Gravel in collector-loop piping	Replaced flowmeters, installed screens
	Flood damage to data-acquisition system	Damage being repaired
	Dust in disk drive	Placed computer in filter-equipped, air-conditioned room
	Erratic water flowmeters	Replaced flowmeters, added turbine flowmeters
	Poor turndown ratio on conventional heaters	None
	Inadequate collector-pipe slope to ensure draindown	Wooden supports added to prop up pipe
Lamanuzzi and Pantaleo Foods, Fresno, Calif.	Rain leakage into damper housings	Repaired damper motors
	Nonuniform rock storage bed	None
	Timeclock failures in data-acquisition system	Isolated clock with capacitors
	Lexan™ stress failure and yellowing[c]	None
	Vandalism	None
	Failure of solar-energy system microprocessor-based controller	None
Campbell Soup Co. Sacramento, Calif.	Data-logger failure	Exhaust fan installed
	Magnetic-tape-recorder failure	None
	Nonoperative flowmeter	Replaced with Kates control valve, as yet uncalibrated
	Broken glass cover tubes	Will be replaced
	Wind damage	Repaired damage
	Shutdown of can line while changing soup type	None

Table 4.8 (Cont'd)

Project Site	Problem	Corrective Action
Riegel Textile Corp., LaFrance, S.C.	Contamination of reflectors by boiler-stack effluents	None; effect is being studied
	Excessive night losses	Replace supply pipe with smaller-diameter pipe to reduce thermal mass
	Thermal shock-tube breakage	Installed overtemperature indicator; circuit box made less accessible
	Low flow rate through collector	Will install larger manifold fittings and will increase impeller diameter of pump
	Poor insulation in collector headers	Will replace leaky grommets and add more insulation
York Building Products, Inc., Harrisburg, Pa.	Failure of black chrome coating	Painted rusted areas with flat black paint
	Thermosiphon freeze-up	Installed check valves in collector-loop piping; replaced heat-exchanger tube bundle
	Mirror breakage (thermal)	Mirrors will be replaced
	Insufficient wire size for motors	Replaced wires with heavier gauge
	Drive motor grease too thick	Replaced grease with low-temperature grease
	Data logger not compatible with tape drive	Replaced data logger with different brand
	Mirror desilvering	None; effect is being studied to determine necessary number of coats of epoxy to mirror backs
	Dust problems with data logger	Relocated to building lobby

[a] Source: Ref. 53.

[b] PVC = Polyvinyl chloride.

[c] "Lexan™" is a registered trade name of General Electric Co., Schenectady, N.Y.

Table 4.9 System Performance in Industrial Process-Heat Field Tests[a]

Project	Number of Days of Data Collection	Energy (10^6 Btu/d)				Energy Delivered/Area (Btu/ft^2·d)	Fuel Displaced
		Incident[b]	Collected	Parasitic Use	Delivered		
Campbell Soup Co.	62	11.32	3.57	0.15	-	-	Natural gas
Riegel Textile Corp.[c]	3	11.0	2.01	0.068	1.07	160	Fuel oil
York Building Products, Inc.	262	11.05	1.30	0.051	1.09	118	Fuel oil
Gold Kist, Inc.	290	13.3	3.49	0.31	3.40	260	Fuel oil, natural gas
LaCour Kiln Services, Inc.	180	3.22	1.17	0.012	1.08	429	Natural gas
L and P Foods	181	47.8	10.5	1.00	9.49	452	Natural gas

[a] Source: Ref. 53.

[b] Daily total insolation in the plane of the collector array.

[c] Performance results available for this site are included for information, but the poor statistical basis should be noted.

Table 4.10 System Efficiencies in Industrial Process-Heat Field Tests (%)[a]

Project	System Utilization	System Availability	Efficiency Collector Array, η_c	Efficiency Thermal System, η_T	Efficiency Net System, η_S	Parasitic Fraction[b]
Campbell Soup Co.	81.5	82.0	31.5	-	-	4.2
Riegel Textile Corp.[c]	97.0	97.6	18.3	9.7	8.1	3.4
York Building Products, Inc.	100.0	91.6	11.7	9.8	8.6	3.9
Gold Kist, Inc.	63.5	100.0	26.2	25.6	19.7	8.7
LaCour Kiln Services, Inc.	100.0	94.0	36.3	33.5	32.5	1.0
L and P Foods	41.4	72.2	22.1	19.9	14.2	9.5

[a] Source: Ref. 53.

[b] (Parasitic Energy - Energy Collected) x 100%.

[c] Performance results available for this site are included for information, but the statistical basis (only three days of data collection) should be noted (for comparison, see Table 4.9).

Table 4.11 Predicted and Actual Energy Delivery in Industrial Process-Heat Field Tests

Project	Annual Energy Delivery: Predicted 10^6 Btu/yr	Annual Energy Delivery: Predicted 10^3 Btu/yr·ft^2	Annual Energy Delivery: Actual 10^6 Btu/yr	Annual Energy Delivery: Actual 10^3 Btu/yr·ft^2	Actual Delivery as Percent of Predicted Delivery (%)
Campbell Soup Co.	2156	290	-	-	-
Riegel Textile Corp.	1400	210	370	55	26
York Building Products, Inc.	1500	160	364	39	24
Gold Kist, Inc.	3700	280	788	60	21
LaCour Kiln Services, Inc.	900	360	370	147	41
L and P Foods	2300	110	1035	49	44

Source: Ref. 53.

conclusions that should prove useful in future projects were drawn from the SERI research. These conclusions are listed here:

- Collectors can prove to be a major problem in field application of solar projects. Degradation of absorber surfaces and glazings is still relatively common.

- Problems similar to those encountered in the solar heating and cooling of buildings occur in IPH applications. Better education in system design, engineering, and installation is needed to prevent the recurrence of such problems as thermal shocking of ETCs, heat-exchanger freezing due to thermosiphon heat loss, and improper pump selection.

- Parasitic power has been a major factor in the low system efficiency of the two systems employing air-circulating collectors.

- Thermal losses from piping, both during operation and overnight, can seriously degrade system performance.
- Data-acquisition systems have generally been very unreliable.
- Use of solar energy to obtain industrial process heat is not yet cost-effective. Although industrial managers are concerned about fuel curtailments, most do not yet view solar energy as a profitable investment.
- A considerable investment in maintenance is needed to approach predicted performance in first-generation projects.
- Environmental contaminants can seriously affect the performance of solar collectors.
- Certain adjustments in plant operation schedules, hardware, and control logic are often needed to optimize the use of a solar-energy system.
- Opportunities for energy conservation are abundant in industry, and many conservation measures have much more rapid payback periods than solar-energy systems. Just as in the solar heating and cooling of buildings, energy conservation should precede solar implementation.
- In some applications, solar energy may improve the quality of a final product, in addition to saving fossil fuel.

4.4.3 Recent Operational Experience in the Industrial Process-Heat Program

In 1979 and 1980, the DOE added a number of large, new IPH projects and refurbished several of the earlier demonstrations. Both the new and the refurbished systems are now operational, but no comprehensive evaluations have been conducted and performance data are still quite limited. Information presented at the May 1983 Semiannual Review of the DOE Solar Thermal Technology Program, however, indicates that the new systems have benefited from the lessons learned in the first generation. Most of these systems have experienced shake-down difficulties normally associated with new plants, and some of the more innovative system designs have encountered problems that had not arisen in the early work, but on the whole, the problems are less severe and the performance is better.

The newest IPH heat systems to go into operation have mostly been rather large (5000-m^2) steam systems using PTCs. Experience with these new arrays indicates that many of the early problems have been solved: Integration of solar heat with the process load has been achieved rather easily in most plants; problems related to field assembly have been reduced by much greater reliance on factory construction and larger module sizes; tracking devices and control systems have become automatic, simpler, and more dependable; and certain troublesome components have been replaced with more reliable equipment (e.g., flexible hoses are now expected to last seven to ten years). Exceptions to these generalizations have occurred, however, and new problems have been discovered.

At the Dow Chemical Co. plant in Dalton, Ga., the N-S troughs were installed on a 10° slope. The resulting thrust loads led to bearing failures, flexible-hose failures, and (perhaps) erratic tracking. The collectors also experienced problems with thermal expansion and limit-switch failures. Nevertheless, the system is in operation, most of the problems have been corrected, and reliable performance data are being collected. The clear-day efficiency of the system appears to be about 30%.

The 1500-m^2 steam system at the Johnson and Johnson plant in Sherman, Texas, also uses PTCs. The problems with this installation have been minor, and the array is operating routinely. However, reliable performance information appears to be unavailable for this collector array.

The installation at the Caterpillar Tractor plant in San Mateo, Calif., has 5000 m^2 of roof-mounted PTCs delivering steam to the process line. The plant, which is still in the shake-down phase, has had problems with inconsistent start-ups, dirty mirrors, poor tracker adjustment, etc. Although the system is instrumented and monitored, it appears that reliable performance results will not be obtained until the U.S. economy improves, because the capacity of the system exceeds the load of the factory at its current production level, and the collectors are defocused to reduce the output.

The system on the Lone Star Brewery in San Antonio, Texas, has been in operation a bit longer than the San Mateo system, and more performance data have been collected and analyzed. After some modeling effort, acceptable agreements between predictions and results have been obtained under ideal conditions. One of the major omissions in the early models was a "soiling model" for the mirror reflectivity. It was found that the reflectivity decreased at the rate of about 10% per month in dry weather. Most of the reflectivity loss is restored by hard rain or by a one-pass wash with high-pressure demineralized water. Problems at Lone Star have included tracking problems, excessive down-time for maintenance, system leaks, and visually poor condition of the receiver tube coating (such observations do not always correlate with thermal measurements).

The latest information on performance and operation of PTCs comes from the SNLA/SERI Project for Modular Industrial Steam Retrofit systems. In this project, four delta-T strings were built by contractors and installed (three at Sandia and one at SERI) for testing and evaluation. The troughs are based on the latest technology, and the modules have efficiencies comparable with the efficiency models assumed in this report (i.e., $\eta \approx 0.8$). The strings are carefully engineered and installed. Performance and operating data, when available, should establish the standards for future large systems.

4.4.4 Operational Results from Solar One

Solar One is the 10-MWe (megawatts-electric) solar power plant at Barstow, Calif., which has been operational since April 12, 1982. The plant has already met or exceeded design goals: efficiency, >20%; overall solar-to-electric power, 10.4 MWe; power from storage, 7.3 MWe; lower insolation level, 300-W/m^2 beam; and minimum operating power, 500 kWe. The plant has produced net power since April 1983. The period of negative power output resulted from shake-down problems; from high power consumption on site for construction, maintenance, training, etc.; and from a period of very low solar insolation (the beam radiation in 1982 was 25% below normal, and in 1983 the level started out even lower).

Most of the plant experience has been positive. The computerized control system works very well. The number of heliostats out of service has decreased from about 100 to 10 or 12 (out of 1818 units). Maintenance costs are decreasing, and start-up time has decreased.

There have been problems with the heliostat mirrors, but most of these problems are considered minor. About 100 mirror panels have fallen off because of inadequate bonding of the attachment plates (traced to improper handling of epoxy in the manufacturing of a few heliostats). After one year, about 400 mirrors show signs of corrosion, but the affected area is less than 0.01% of the total area. Soiling has been higher than expected, but restoration to within 1-2% of capacity occurs after a hard pelting rain or after washing with high-pressure demineralized water.

4.5 Experience in The Netherlands

The information in this section was submitted by C. den Ouden for use in this report.

4.5.1 Flat-Plate Collectors

Apart from the use of FPCs in combined solar-heating and DHW heating systems in approximately 50-100 demonstration projects and the use of unglazed solar collectors for heating swimming pools, the chief use of FPCs was in DHW systems.

There are 4-5 local manufacturers of FPCs, and solar water heaters have more than 90% of the small market. The FPC modules for solar water heaters range in size from 1.4-4 m^2, and the majority of absorber plates are made of stainless steel or ordinary steel (used in closed loops). The absorber surfaces are generally spectrally selective, chromium or cobalt oxide for stainless steel or tin oxide on black glass enamel for ordinary steel.

Recently, one collector and system manufacturer started producing collector modules using the "Sunstrip" absorber manufactured by Granges Aluminum (Sweden). A complete solar water heater can now be supplied for an installed price of approximately $1000. In general, cooperation between the small solar industry and the research institutes working on solar-energy development is good, and the number of unfavorable experiences is relatively small. The FPCs in use have functioned satisfactorily, sometimes for more than six years without any severe failures.

4.5.2 Evacuated-Tube Collectors

For higher temperatures (>60-70°C) and in certain applications, the use of ETCs can be advantageous.

In past years, the TNO-TH developed an evacuated FPC of special design. This design used specially developed techniques to seal double glazing in order to maintain low pressure and suppress convection. This collector is now further developed and is produced by a collector manufacturer.

Philips Laboratory has developed several types of ETCs that use heat pipes to transfer the solar heat to the transfer fluid in the solar installations. Especially for projects with interseasonal storage systems without heat pumps, the use of such high-performance collectors is required to maintain reasonable efficiency of the collectors in the summer.

The experience with ETCs in The Netherlands has only been gained over the last 3-4 years. Several current R&D projects involve solar-energy systems in which various types of Philips HP collectors are under study. Thus far, good experiences in using these collectors have been reported. The first large project, 100 solar houses with interseasonal storage, will be provided with Philips ETCs.

4.6 Experience in the Federal Republic of Germany

The information in this section was submitted by H. Riemer for use in this report.

Today, about 10,000 solar-energy systems are installed in the Federal Republic of Germany, with a total collector area of 200,000 m^2. Most of the systems are for DHW supply of one- and two-family houses and have collector areas of up to 10 m^2. Some larger systems with collector areas from 100 to 2500 m^2 have been installed; these systems supply public buildings or building areas with hot water or are used to heat water for swimming pools. Nearly all of the installed collectors are FPCs, which are partly selectively covered. No widespread operating experience has been obtained with HP collectors. Line-focus collectors or other concentrating collectors are not installed in Germany; instead, they are exported to countries where effective use is possible.

On the basis of experiences with FPCs that have been in operation for three to five years, no comments can be made about reliability or lifetime of the collectors.

Certain problems appeared within the planning phase, during and shortly after the installation of the collectors. These problems are mainly the following:

- Unfavorable site conditions for installation;
- Trade problems and failure by installation; and
- Unproven combination of materials for piping and collector.

If structural and architectural requirements set a standard, cost for installation increases considerably (up to 80% of the price of the collector). If the collectors were integrated as part of the roof, tightness could be a serious problem. Piping connections between the collector units are a weak point in collector fields. Thermal stress, imperfect installation, or both have led to degradation, cracking, and corrosion. Imperfect insulation and connection leakage has been confirmed. A very important problem in the operation of collector fields was and is venting of the systems (piping and collector). This problem has been identified in many systems.

The problems mentioned thus far can be overcome by well-trained personnel. Simplified mounting of collectors and preparation for mounting by the manufacturer could reduce installation costs and sources of failure.

Corrosion, a result of improper combinations of materials, was often found in absorbers and piping. Breakage of both plastic and glass collector covers occurred. Dirt was a problem only in extreme conditions, near the coast (salt and sand) or in industrial areas (dust). Condensation was often encountered. Most of these problems could be minimized and overcome with more experience. Unsatisfactory control and regulation of the collector circuit and of the total system was the most frequent cause of failures.

4.7 Experience in the Commission of the European Communities

Information in the following section was submitted by D. van Hattem for this report.

4.7.1 Flat-Plate Collectors

Flat-plate collectors have been used in Ispra for heating, cooling, and DHW heating. A 50-m^2 array has been used for heating for more than six years now. A 180-m^2 array has been operated with a seasonal-storage project. Generally, the collectors have proven reliable and performed as expected. The use of stationary flat reflectors has been very effective.

The chief instance of degradation has been the penetration of water into the collector casings. Such penetration results in condensation on the inside of the glass cover, degrades the insulation at the backside, and enhances the external corrosion of the absorber. Some leakage has occurred at the joints, which have not always been very well designed.

A very heavy hailstorm (stones with 4-cm diameters and wind velocities of more than 100 km/h) left the FPCs undamaged.

All of the collectors are operated with water-glycol solutions. Therefore, power or pump failures are very undesirable, because the glycol can degrade under stagnation conditions. No special maintenance is carried out; the collectors are kept sufficiently clean by rain.

For large arrays that operate at low temperatures (<70°C), very good experience has been obtained with the Pirelli Collector M158. This collector has a rubber absorber that withstands freezing, boiling, and corrosion. The absorber, which is 1 m wide, can be made more than 20 m long and can easily be integrated into roof structures.

4.7.2 Evacuated-Tube Collectors

Evacuated-tube collectors have been operated and tested for more than four years in Ispra. The "first-generation" collectors of this type (OI, Sanyo) performed well but had hydraulic characteristics that made them unattractive for large collector arrays.

The heat-pipe ETC (Philips) represents an important step forward. It has very low overall heat losses and a reasonable optical efficiency (0.64). The hydraulic part of the collector is extremely simple, which makes it easy to install and results in a very low pressure drop. Other advantages include the following:

- Individual tubes can be exchanged without interrupting the flow in the collector circuit.
- The collector has a low heat capacity.
- In moderate climates, the freezing protection can be accomplished by flushing.

4.8 Experience in Austria

Information in the following section was submitted by M. Bruck for use in this report.

Solar-energy and heat-pump systems are increasingly being considered for supplying heat to buildings in Austria. Compact systems with collectors or heat pumps are also of increasing interest for domestic water heating, and it is likely that they will prove valuable for practical use as present experience is applied to planning and design.

By the end of 1982, the market for solar and heat-pump systems in Austria was such that installed-collector area totaled about 113,900 m^2, as follows:

- Systems having up to 10 m^2 of collector area--24%
- Systems having 10-30 m^2 of collector area--56%
- Systems having 30-70 m^2 of collector area--12%
- Systems exceeding 70 m^2 of collector area--8%

A breakdown of solar plants according to their application shows that DHW heating plants accounted for 42%; swimming-pool-heating plants accounted for 54%; plants used for both swimming-pool heating and DHW heating accounted for 22%; and other uses accounted for 2%. Annual installation of solar collectors totalled 18,700 in 1982.

A total of 17,500 heat-pump systems had been installed in Austria by the end of 1981. Applications include the following:

- DHW heating--61%
- Space heating--31%
- Swimming-pool heating--3%
- Other--5%

At present, solar-energy systems in Austria are used mainly for DHW heating, for swimming-pool heating, and for combinations of the two functions. In the case of space heating by means of solar-energy systems, heat-pump systems, or both together, high demands are placed upon the heat insulation of the building and the heat-distribution system (low-temperature heating system). Several concepts are being tested at present, with special attention to their cost-effectiveness.

The thermal-energy output of a solar-energy system depends largely on insolation, ambient air temperature, and the working temperature of the collector system. This last item will always be kept as low as possible.

The gross heat outputs are in the range of about 250-350 kWh/m^2 for plastic collectors for swimming-pool heating (May to September), 300-400 kWh/m^2 annually for DHW systems with FPCs, and up to 650 kWh/m^2 for ETCs. These figures are confirmed by measurements taken at Austrian solar-energy test stations operated on behalf of the Austrian Federal Ministry for Science and Research.

The service life of FPCs meeting the Austrian standard ONORM M 7710 is expected to be more than 15 years.

It is estimated that 3-5% of total primary energy demand in Austria can be saved up to the year 2000, if the use of solar-energy and heat-pump technologies continues to increase. Statistically, the reduced consumption of commercial energy is indicative of the contribution of solar energy (including "passive" solar-energy systems and the use of ambient heat) to the energy supply.

4.9 Summary of Operational Experience and Maintenance Issues

Table 4.12 summarizes some of the operational problems that have been reported for the four collector types under consideration. Operational results for central receivers are still rather scarce.

Probably the greatest concerns of the designer and operator responsible for system maintenance are the following: maintenance of the integrity of the transport system, cleaning of mirrors and glazings, maintenance of proper fluid chemistry and exclusion of oxygen from the system, reliability of control elements, maintenance of the integrity of thermal insulation, reliability of the instruments and data systems, and maintenance of the site.

4.10 Anticipated Durability of Collectors

There appears to be general consensus that well-designed, well-made conventional FPCs (i.e., units with glass covers, metal absorber plates with copper tubing, aluminum boxes, and high-quality gaskets and insulation) will last 20-30 years if stagnation is avoided and the fluid chemistry is maintained within proper bounds. Lifetimes of collectors with major components made of polymers or elastomers have not been established.

Evacuated-tube collectors are expected to match or surpass FPCs in durability. Vacuum integrity is not a major concern, although helium diffusion will lead to some performance degradation in borosilicate tubes.

Parabolic-trough collectors equipped with glass mirrors are designed for 30-year lifetimes, but experience is too limited to make projections. Heliostats have the same sort of limitations. It is probable that the limiting factor for tracking-collector lifetimes will be degradation of performance below acceptable limits, rather than outright failures.

Table 4.12 Operational Problems with Various Collector Subsystems

	Collector Type			
System Component	Flat-Plate Collectors	Evacuated-Tube Collectors	Parabolic-Trough Collectors	Central Receivers
Optics	Outgassing Opacity of glazing Soiling	Soiling Delamination Corrosion	Soiling Delamination Corrosion Distortion Hail damage	Soiling Corrosion
Materials	Seals and gaskets Glazing degradation Stress corrosion Outgassing Absorber-coating failures	Corrosion of exposed fin Seals and grommets Insulation	Mirror degradation Absorber coating	Mirror degradation
Circulating Fluid	Fluid chemistry Corrosion Leakage Freezing	Thermal shock Drainage Large inventory	Cold pumping Thermosiphoning Flammability	NA[a]
Mechanical Structure	Thermal expansion Distortion	Thermal expansion High flow independence	Thermal expansion Distortion Flex hoses Wind damage	NA
Control	Pumps Solenoid valves	Pumps Valves Stagnation Restarting	Trackers-hunting Pumps	

[a] NA = not applicable.

5 COSTS

5.1 Methodology of Cost Estimation and Economic Assessment

The economic feasibility of alternative energy investments in the private and public sectors can be evaluated in a number of ways. All of these methods provide some explicit, quantitative way of combining the values of labor, capital, fuel, and other tangible costs (such as taxes) over some period of time.

The most popular assessment methods involve computation of net values, payback, and internal rate of return. Each of these methods requires conversion of all costs associated with the project to some form of levelized or annualized cash flow. To accomplish this conversion for a future date requires a knowledge of future prices, wages, and interest rates and is, therefore, accompanied by uncertainty. Such economic assessments are beyond the scope of Subtask 1(b) but will presumably be a part of the analysis and evaluation of the site-specific designs in Subtask 1(e). However, the principal result of the economic analyses used for large capital investments such as solar-heating plants is to connect the initial cost of the plant to an annualized cost of energy (recurring costs such as maintenance, taxes, etc. usually will be added to the capital costs, but they are often less sensitive to choice than initial costs). One method that has been used for analysis of IPH systems is that of Dickinson and Brown.[82] Their method involves a levelizing factor, M, defined as M = levelized cost of energy/investment. This factor depends on all the usual economic parameters; for a reasonable range of values, it is in the range of 0.1 to 0.2. A convenient rule of thumb, then, is that the annualized cost of energy is about one tenth the cost of the plant divided by its annual energy output. Therefore, a system or subsystem that cost $1/kWh annually should deliver energy at a cost of about $0.10/kWh.

In Subtask 1(b) we are primarily concerned with methods for obtaining estimates of the capital cost of the collector subsystem. In a mature industry with a solid base of cost history, this would be a straightforward process. Unfortunately, the solar industry has no sound basis for projecting future costs. The large systems that have been installed are first-of-a-kind designs and use many handmade components.

Thus, two uncertainties confront the system designer -- the cost of the components and the cost of construction. The future cost of collectors, on an individual basis, is discussed later in this chapter. In the remainder of this section, we present a method for estimating plant costs originally developed by Guthrie[83] and adapted for solar applications by Brown at SERI.[84] The modular method, as it is called, starts with the cost of the major component(s) of the system and then applies a series of multiplicative factors to account for associated materials, direct labor, indirect labor, and indirect costs. Costs are broken down into fairly standard categories and are easily adjusted for different regional or national conditions. The latter attribute is the main reason for including the method in this report; using the modular method, cost estimates made in one country should be convertible to another country's terms simply by adjusting the factors for labor rates, taxes, freight, etc. The modular method, as modified by Brown, is shown schematically in Fig. 5.1.* The values of the parameters were developed in 1980 and have not been updated or validated since that time.

The factor M_c/E_c will vary both with size of the collector array and with the cost of collector equipment. (M_c/E_c may also vary with temperature supplied, but adequate data on this effect are not available.) For available collectors at today's prices (\$100-200/m^2), we expect M_c/E_c values in the following range:

Flat Plate, Liquid--0.19

Flat Plate, Air--0.19

Evacuated Tube--0.21

Parabolic Trough--0.14

Size range represented among these collector types is approximately 2,000 to 200,000 m^2.

The factor L_c/M_c will vary in much the same manner as M_c/E_c. The appropriate ranges for L_c/M_c are as follows:

Flat Plate, Liquid--0.11

Flat Plate, Air--0.11

Evacuated Tube--0.12

Parabolic Trough--0.14

The factor e (engineering and office costs) normally ranges between 5 and 15% of M. This factor depends upon the degree of commonality between elements of the project design and previous projects, the complexity of the design, and the length of time required for design and construction. Experience suggests that a 6% allowance for engineering and office costs is appropriate for solar

---

*The symbols used in the figure and in the following discussion are not consistent with the nomenclature established for the rest of this report. The levelizing factor, M, has already been defined. Other important terms are defined as follows: M_c, cost of collector materials; L, cost of labor; E, cost of equipment; i/L, ratio of indirect to direct labor cost.

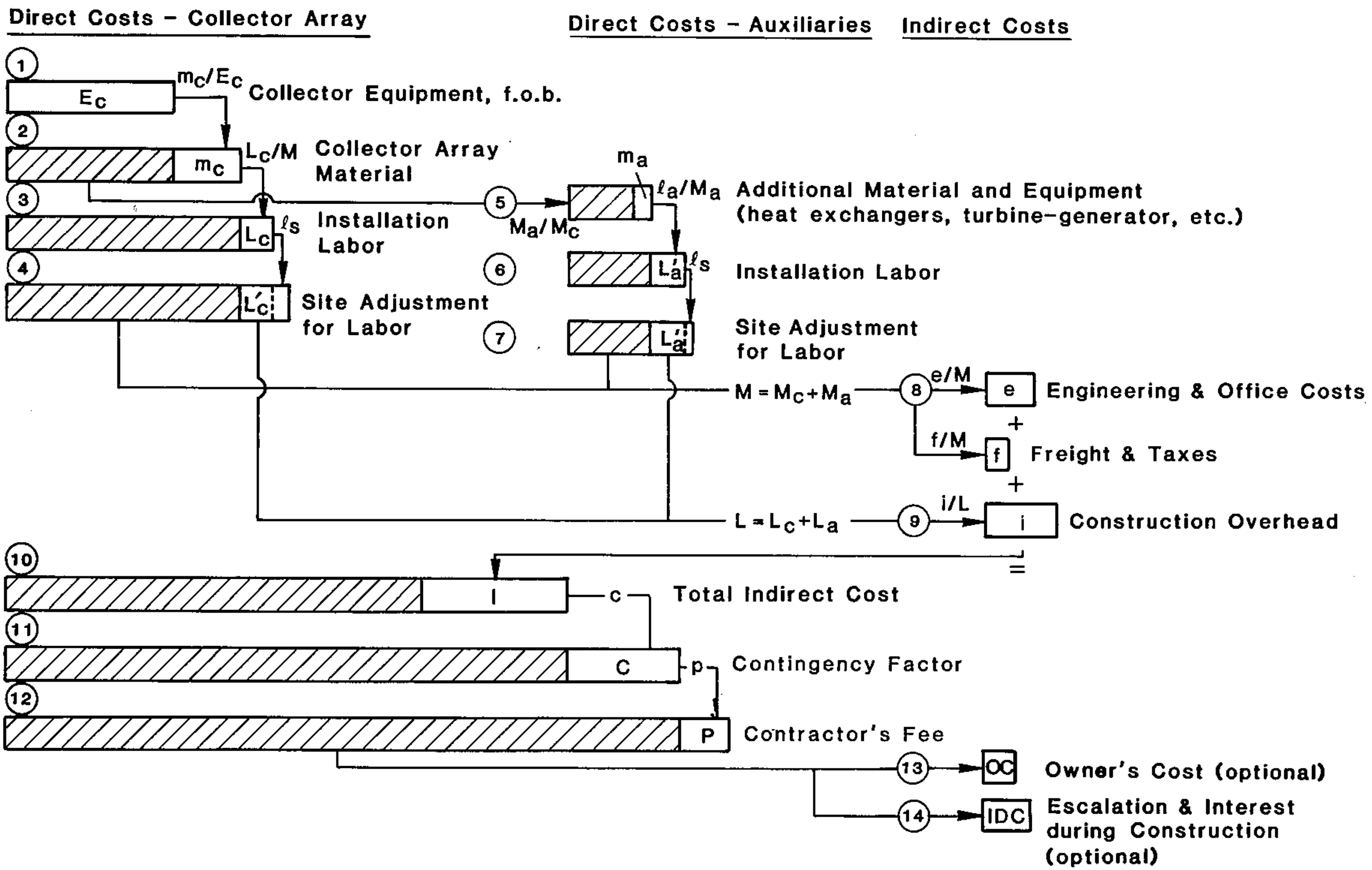


Fig. 5.1 Use of Modular Method to Estimate Costs for Solar Thermal System
[Note -- Use of symbols is not consistent with Nomenclature list]
(Source: Ref. 84)

process-heat systems, while a slightly higher allowance (8-10%) ought to be made for large solar-power projects. Freight and taxes (f/M) are generally quite close to 8% of total material costs in typical industrial construction, but f/M could be much lower for states where solar-energy systems are exempt from sales taxes. (Sales taxes are nominally taken as 3% of M in obtaining the 8% figure for f/M.) Indirect labor costs may vary between 45 and 80% of direct labor costs. In several recent solar IPH projects, indirect costs have been substantially higher than 80%; however, we propose that a value of 50% for i/L is appropriate for current or near-term solar projects. The contingency factor, c, is taken as 15%. This appears to be an appropriate mid-range estimate of contingency costs. The contractor's fee, p, should vary according to the following schedule:

Total Contract Value	Fee Factor (p)
<$1,000,000	0.10
$1,000,000 to $4,999,999	0.08
$5,000,000 to $9,999,999	0.07
≥ $10,000,000	0.05

The values selected for estimating 1985 costs and long-range costs are shown in Table 5.1.[85] One shortcoming of the method is that the multiplicative factors must be updated in a maturing industry where, say, the ratio of material costs to labor costs changes significantly.

In the remainder of this section, we develop some cost figures intended to be of use in Subtasks 1(a) and 1(e) and in Phase II.

5.2 Collector-Module Costs

The cost information we seek to develop in this work pertains to prices expected two or three years in the future. In a mature technology, such a projection would pose no problem. One would simply take today's cost and apply a reasonable factor for general inflation. This may, in fact, be the appropriate way to estimate solar equipment costs; it is certainly the conservative way. However, it has been the practice in the solar community to anticipate cost reductions that are expected to occur through technological advances, market forces, or high-volume production in estimating the cost of future projects. (Once a project actually enters the design phase, the designer must be very judicious in projecting cost reductions.) It is relatively easy to anticipate the ultimate cost reductions that could be achieved when equipment items such as solar collectors are manufactured in large volume. The simple way is to note the mass of material required and apply a simple multiplier for the cost of manufactured goods. A more sophisticated approach involves a detailed analysis of the production process and an overall optimization of cost of material, labor, and capital equipment as a function of the production volume. Such studies, carried out for several collector concepts, will be used in subsequent sections.

Table 5.1 Modular Cost-Estimate Factors for Solar-Collector Subsystems[a,b]

	Collector Type			
Factor	Flat-Plate Collector	Evacuated-Tube Collector	Parabolic-Trough Collector	Central Receiver
M_c/E_c	0.19	0.21	0.14	--[b]
L_c/M_c'	0.11	0.12	0.14	--[b]
e/M	0.06	0.06	0.06	0.06
f/M	0.08	0.08	0.08	0.08
i/L	0.50	0.50	0.50	0.50
c	0.15	0.15	0.15	0.15
p	0.05	0.05	0.05	0.05

[a] Source: Based on Ref. 85. Information received from K.C. Brown, 1981.

[b] Unknown.

Current costs are relatively easy to obtain directly from manufacturers, but it is more reliable to use actual data from recent projects or quotations on bona fide projects than to rely on inquiries or published prices.

Presumably the cost of products manufactured in 1985 will lie somewhere between manufacturers' estimates and actual cost data -- but where? Elaborate market-penetration theories and analysis could be evoked to shed some light on this question, but it is unlikely that this would substantially reduce our uncertainty. We will, therefore, rely upon intuition and the collective judgment of the participating experts to establish a reasonable expectation for each technology.

5.2.1 Nonconcentrating Collectors

The Subtask 1(b) interim report, an unpublished working document, suggested an installed cost of $270/m^2 for FPCs.* Recent evidence suggests this estimate may be slightly high. Mueller Associates, Inc., analyzed the costs of solar industrial-heat systems as part of a study for the U.S. Gas Research Institute (GRI).** Mueller found that 1981 quotations (from nine U.S. FPC manufacturers) on two commercial hot-water systems ranged from $12.01 to 18.88/ft^2, with an average of $14.77/ft^2 ($159/m^2). These costs include delivery but not mounting. Another set of Mueller data shows that bids for six hot-water projects of sizes from 100 to 400 m^2 in area ranged from $11.79 to 13.80/ft^2 and averaged $12.78/ft^2 ($137/m^2). We have, therefore, reduced the $137/m^2 by 8% for shipping to obtain our estimate of current costs, $127/m^2 F.O.B. ("freight on board," the price at the manufacturer's site).

The ultimate cost of FPCs was analyzed in 1980 by Booz Allen & Hamilton for the GRI.[86] They found that at production levels of about 10^6 m^2 for a single manufacturer, the factory sale price could drop to $8/ft^2 ($86/m^2). (At least two manufacturers producing at this volume would be required to make this price certain.) Other sources of cost data on FPCs include the committee for Advanced Program Research Requirements (APRR) and SERI.

We believe that the cost of FPCs has stabilized somewhat and that further decreases in the next five years will be modest. Therefore, we recommend that the 1985 factory sale price be held at $127/m^2.

5.2.2 Evacuated Collectors

For cost analysis, we have lumped concentrating and nonconcentrating evacuated collectors together.

The Subtask 1(b) interim report suggested an installed cost of $538/m^2. We now believe evacuated collectors can be installed for substantially less (with proper attention to the design of the support and plumbing systems). The 1982 Mueller study cites quotations from four evacuated-collector manufacturers for two hot-water projects; these quotations range from $18.01 to 28.60/ft^2. Since the $28.60/ft^2 bid was noncompetitive, we have chosen to use the low bid of $18.01/ft^2 as the basis for our cost estimates. After adjusting for shipping, the current F.O.B. cost is $180/m^2.

Booz Allen & Hamilton[86] also studied the ultimate mass-production cost of evacuated collectors and concluded that they could be manufactured less expensively than FPCs, for $5/ft^2. On the premise that no manufacturer would sell a high-performance collector for less than a low-performance

---

*U.S. dollars, 1981.

**Mueller Associates, Inc., unpublished information (1982).

collector, we place the ultimate cost of evacuated collectors at the same figure as that of FPCs, $\$86/m^2$.

Since the market for evacuated collectors for the next five years would appear to be quite limited, we expect no reduction from the 1981 cost of $\$180/m^2$ for the module.

5.2.3 Parabolic-Trough Collectors

In the interim report, subtask participants estimated current installed costs for PTCs to be $\$615/m^2$. Our current figures indicate this cost may be substantially lower.

Quotations cited by Mueller range from \$32 to $40/ft^2$ for installed IPH systems. The most recent cost figure on a real project was $\$21.80/ft^2$ at the job site. We believe that a manufacturer would sell quantities of 2,000 to 20,000 m^2 of second-generation troughs for about $\$200/m^2$ F.O.B.

At SNLA, Schimmel has estimated the ultimate production cost (at an annual production rate of 10^6 m^2/yr per manufacturer) to be $\$96/m^2$ F.O.B.[87] Adjusting to 1981 dollars yields our recommendation of $\$104/m^2$.

The current costs of PTCs reflect a recent, dramatic reduction. Another such reduction would not be expected in the next five years. Our 1985 cost estimate is $\$200/m^2$.

5.2.4 Central Receivers

Central receivers pose a special problem for any approach that presents collector-module and installation costs separately, because one major component of the collector is the site-built receiver tower. In this section, therefore, the discussion of collector modules will only pertain to heliostats.

Under the contract, the actual installed price of the 1818 heliostats that constitute the Barstow field was $\$27.90/ft^2$ (without motor, foundation, or controls, according to Brown). This figure for total cost seems a bit inconsistent, compared with the $\$30/ft^2$ installed price quoted by the supplier, Martin Marietta, in 1981. Battleson[49] cites still different values, $\$492/m^2$ for 1818 installed heliostats and an incremental cost (i.e., heliostat 1819) of $\$355/m^2$; Battleson states that these figures include adjustments for government-furnished equipment, wiring, etc. Hildebrandt and Lawrence use a figure of approximately $\$250/m^2$ for the incremental cost of the Barstow collectors.[88]

To be consistent with our treatment of the other collector categories, we have used a still different figure based on an analysis of a 40,000-ft^2 IPH system by Brown. In this analysis, a heliostat cost of $\$26/ft^2$ works out to a system cost (without storage) of $\$51.39/ft^2$. On the basis of the Barstow experience, we adjusted the cost upward to $\$28/ft^2$ for heliostats and $\$53/ft^2$ for the system.

The mass-production cost of heliostats has been the subject of in-depth study by two groups, PNL[89] and the Transportation Systems Center of General Motors* (GM).[90] Both groups agree that the cost of heliostats can be greatly reduced. The PNL results were \$91.89/m^2 at 25,000 units yearly and \$80.49/m^2 at 250,000 units yearly. The corresponding GM results were \$120.12/m^2 and \$89.48/m^2. Hildebrandt and Lawrence[88] adjusted these numbers to 1981 dollars and used two figures, \$134/m^2 near-term and \$98/m^2 long-term, to recalculate the cost of an IPH repowering project. The lowest of these costs was \$253/m^2 near-term and \$217/m^2 long-term, at heliostat costs of \$134 and 98/m^2, respectively. We accept the \$98/m^2 figure as representing the ultimate factory cost of heliostats in mass production.

Heliostat costs may decrease by 1985. As Hildebrandt points out, one commercial power plant would place a manufacturer in the position of producing more than 25,000 units.[88] Even a small number of modest-sized central-receiver plants between now and 1985 could motivate manufacturers to invest in the necessary production facilities. We have, therefore, adopted the guidance given by Sandia National Laboratory for the design of IPH and power-plant repowering projects, \$230/m^2, as our 1985 heliostat cost recommendation.

5.3 Collector-Subsystem Costs

No two studies seem to approach the estimation of installation costs in the same way. The breakdown of cost elements varies from one study to the next. Some studies lump plumbing with installation of collectors; some separate pumps, valves, controls, etc.; some include shipping and land- and site-preparation charges. Few studies include administrative and engineering charges, contingencies, overruns, and other factors that invariably escalate project costs. There are also wide differences in cost methodology. Many cost studies are made on the basis of inquiries to manufacturers or installers. This is normally a valid procedure, but there are no manufacturers or installers who have installed 20,000-m^2 arrays. They are more likely to have experience with DHW systems 4-5 m^2 in area.

Other studies go through detailed layouts of the collector fields and systematically tally the cost of every pipe and elbow required. This approach, too, is basically sound when the technology is mature, but it sometimes fails when applied to new applications. For example, there have been detailed studies of large arrays in which collectors were assumed to have the same characteristics as those normally used for DHW heating or other small-scale applications. These studies sometimes conclude that a certain generic collector type will not serve this application because the pumping power is too great. Such conclusions may be drawn without considering how the characteristics of the collector could be modified to better suit the application.

---

*General Motors Corp., Detroit, Mich.

5.3.1 Historical Cost Data

We have identified several sources of cost data on built projects that offer useful insight into the breakdown of direct and indirect costs. The categories in Tables 5.2-5.5 include most of the cost categories identified in the historical cost analyses we reviewed.

5.3.1.1 Collector Modules. Section 5.2 dealt only with the factory sale price of the collector modules. The other factors that influence the cost of the collectors to the end user are the distribution cost and profit and the cost of mounting the collectors on the support structure. These factors are included with the collector-module cost, because they are often part of the contract with the collector supplier.

The distribution and profit factor is seldom quoted explicitly and is not important if one works with supplier quotations in which it is included. We have included it in an effort to bridge the gap between predicted factory sale prices, based on theory and analysis, and the realities of the market.

The cost of mounting the collectors on the support structure is often included in the contract with the supplier. This item does not include any construction or plumbing.

The figures for FPCs (Table 5.2) were actually backed out of the cost of mounted collectors, using a distribution and profit factor of 30%. This factor seems reasonable for large installations, which are likely to be contracted with the manufacturer. Small systems purchased through a distributor would have higher costs.

5.3.1.2 Site Preparation. Very little information is available on site preparation from U.S. projects. One reason for the lack of information is that many of the industrial systems and almost all the commercial systems have been roof-mounted, and any costs associated with roof modifications have been included in the support-structure cost. Clearly, site-preparation costs can be important in large arrays.

5.3.1.3 Support Structure. Support-structure costs have been very high on some roof-mounted collector systems, both because of the structural limitations of the roof and because of the necessity for maintaining the weather-tightness of the building. Ground-mounted arrays should be less expensive, unless the situation is unusual or multifunctional support structures are needed. The cost of support structures is one that may improve with economies of scale in large systems.

5.3.1.4 Piping and Insulation. Plumbing (or transport-system) costs are the most straightforward to estimate. The costs of pipe, fittings, welding, and insulation are well known; these costs are documented for hot-water distribution systems in the report of Subtask 1(d), which also serves to

Table 5.2 Historical Cost Data for Flat-Plate Collector Systems: U.S. Experience with Building and Industrial Process-Heat Systems (1981 U.S. $\$/m^2$)

Cost Category	IEA VII (2nd Meeting, 1980)	IEA (Base Case, 1982)	Mueller (10 IPH Sites, 1981)	Mueller (6 Sites, 1982)	APRR (800 ft^2 Comm., 1982)	SERI (1980)
Collector Module						
Factory Sale	165.00	105.00		105.00	182.00	
Distribution and Profit	50.00	31.00		31.00	55.00	
Mounting	35.00	35.00		35.00	35.00	
Subtotal	250.00	171.00	284.00	171.00	272.00	188.00
Site Preparation	--[a]	27.00			--[a]	--[a]
Support Structure						
Materials		43.00			43.00	76.00
Field Labor		43.00			43.00	114.00
Subtotal	--[b]	86.00	84.00	312.00	86.00	190.00
Piping and Insulation						
Materials						22.00
Field Labor						10.00
Subtotal	32.00	74.00	135.00		74.00	32.00
Pumps, Controls, and Electrical Work						
Materials						1.60
Field Labor						2.75
Subtotal	6.00	3.80	--[b]		3.80	4.35
Total	288.00	361.80	503.00	483.00	435.80	414.35

[a] Negligible.

[b] Omitted.

Table 5.3 Historical Cost Data for Evacuated Collector Systems: U.S. Experience with Building and Industrial Process-Heat Systems (1981 U.S. $/m^2)

Cost Category	IEA VII (2nd Meeting, 1980)[a]	IEA (Base Case, 1982)	Mueller (10 IPH Sites, 1981)	Mueller (6 Sites, 1982)	APRR (800 ft^2 Comm., 1982)	SERI (1980)
Collector Module						
Factory Sale						
Distribution and Profit						
Mounting						
Subtotal		240.00	284.00	240.00	258.00	237.00
Site Preparation			27.00		--[b]	--[b]
Support Structure						
Materials		43.00			43.00	140.00
Field Labor		43.00			43.00	200.00
Subtotal		86.00	84.00	312.00	86.00	340.00
Piping and Insulation						
Materials						67.00
Field Labor						52.00
Subtotal		74.00	135.00		74.00	119.00
Pumps, Controls, and Electrical Work						
Materials						3.65
Field Labor						5.50
Subtotal		3.80	--[c]		3.80	9.15
Total	528.00	403.80	530.00	552.00	421.80	705.15

[a] No cost breakdown available.

[b] Negligible.

[c] Omitted.

Table 5.4 Historical Cost Data for Parabolic-Trough Collector Systems: U.S. Experience with Building and Industrial Process-Heat Systems (1981 U.S. $/m^2)

Cost Category	IEA VII (2nd Meeting, 1980)[a]	IEA (Base Case, 1982)	Mueller (10 IPH Sites, 1981)	Mueller (6 Sites, 1982)[a]	APRR (800 ft^2 Comm., 1982)[a]	SERI (1980)
Collector Module						
Factory Sale			234.00			
Distribution and Profit						
Mounting			73.00			
Subtotal		258.00	307.00			250.00
Site Preparation						13.00
Support Structure						
Materials						10.50
Field Labor						7.70
Subtotal			292.00			18.20
Piping and Insulation						
Materials						21.50
Field Labor						5.60
Subtotal						27.10
Pumps, Controls, and Electrical Work						
Materials						7.40
Field Labor						8.70
Subtotal						16.10
Total	615.00	475.00[b]	599.00	430.00	430.00	324.40

[a] No cost breakdown available.

[b] Aggregate of all costs not associated with collector module is \$217.00/m^2.

Table 5.5 Historical Cost Data for Central-Receiver Systems: U.S. Experience with Building and Industrial Process-Heat Systems (1981 U.S. $/m^2)

Cost Category	IEA VII (2nd Meeting, 1980)	IEA (Base Case, 1982)	Mueller (6 Sites, 1981)	SERI (1980)	Hildebrandt (22 designs , 1981)	Solar One, Barstow, Calif.
Collector						
Heliostat Factory Sale		230.00	230.00	183.00	98.00-134.00	350.00[a]
Heliostat Installation				81.00		
Site Preparation				1.70		
Collector Subsystem	350.00			265.70[b]		566.00[c]
Tower and Receiver	123.00			35.00		300.00
Pumps, Controls, and Electrical Work	--[d]			42.00		
Total	473.00	416.00[e]	416.00[e]	342.70	217.00-253.00[e]	866.00

[a] Installed cost, according to Martin-Marietta contract, was \$320/m^2.

[b] Subtotal of collector costs listed above.

[c] Module cost was known, but breakdown of other collector-subsystem costs (aggregate: \$216/m^2) was not known.

[d] Omitted.

[e] Module cost and total were known, but cost breakdown was not available.

establish the national variations.[62] The only difficulty is that the plumbing design is not straightforward. The performance of the array depends (sometimes strongly) on the design of the plumbing. Very few designers have considered the effects of flow distribution and fluid-temperature variations on the array performance or have optimized the array design to include these effects. The \$32/m^2 cost for plumbing an FPC or evacuated-collector array used in the Subtask 1(b) interim report is probably too low; the suggested value is now \$74/m^2.

5.3.1.5 Pumps, Controls, and Electrical Work. The cost of pumps and control elements represents a relatively small fraction of the array cost. This is fortunate, because the cost estimates vary considerably. Critical factors include the design of the array plumbing, the choice of working fluid, the fluid's temperature, and the control strategy. Where pumps, controls, and electrical work are considered as a separate item, typical costs seem to be from \$1 to 15/m^2.[91] Sandia has found that the use of variable-volume pumps, despite their higher initial cost, is cost-effective.[15]

5.3.2 Modular Cost Estimates

The foregoing discussion relies heavily upon U.S. experience, which includes the entire spectrum of collector technologies. However, a well-established market exists for FPCs, and sometimes for evacuated collectors, in most of the participating countries. Therefore, before recommending projected costs to be used in system design, let us compare cost experiences for flat-plate and evacuated collectors in these countries. Tables 5.6 and 5.7 show cost information obtained from the subtask participants. Costs are stated first in the national currency, if available, and then in U.S. dollars. These tables reveal wide variations in installed-collector cost between participating nations -- costs for both collector types vary by nearly a factor of two. There is also a surprising variation between the fraction of the total costs attributed to the module and the fraction attributed to installation. Some countries report module costs much higher than installation, some report nearly equal costs, and some find installation substantially more expensive than the modules themselves. It is not known whether this disparity reflects actual experience or is merely an artifact of the accounting procedures.

Information presented in Sec. 5.3.1, while it may help to illustrate the importance of the various subsystem cost categories, is not very useful for projecting costs for future systems. Such systems will use different components and will occupy different sites in different regions or countries. The modular cost-estimating method is more useful for such cost projections. We have, therefore, used the method of Fig. 5.1, the parameters of Table 5.1, and the projected collector-module costs of Tables 5.2-5.5 (IEA Base Case, 1982) to derive a set of recommended base-case costs for 1985 and future years (Tables 5.8 and 5.9). (Note: Modular cost-estimating factors were not available for the central-receiver system, so the cost recommended by Hildebrandt from Table 5.5 was used.)

Table 5.6 Recent Costs of Flat-Plate Collectors in Participating Countries, 1982-83 (cost per square meter)[a]

Participant and Currency	Cost per Square Meter, in Terms of National Currency: Module	Instal-lation	Total	Conver-sion Factor[b]	Total Cost (U.S. $/m²)
Austria, Sch	3500	1400	4300	17.00	230
Canada, U.S. $			273		273
CEC, U.S. $	135	20	155		155
Germany, DM			480	2.40	200
The Netherlands, fl	250	250	500	2.75	180
Sweden, SEK	700	650	1350	7.66	180
Switzerland, Fr	266	380	640	2.00	320
U.S.A., U.S. $	135	200	335		335
U.K., U.S. $	234	46	280		280

[a] Single-glazed, selective-surface FPCs.

[b] Note that these recent conversion rates differ substantially from those in Table 1.1.

Table 5.7 Recent Costs of Evacuated Collectors in Participating Countries, 1982-83 (cost per square meter)

Participant and Currency	Cost per Square Meter, in Terms of National Currency: Module	Instal-lation	Total	Conver-sion Factor[a]	Total Cost (U.S. $/m²)
Austria, Sch	7000	1400	8400	17.00	435
CEC, U.S. $	400	40	440		440
Germany, DM			1000	2.40	420
The Netherlands, fl			900	2.75	327
Sweden, SEK	2200	950	3150	7.66	410
Switzerland, Fr	600	900	1500	2.00	750
U.S.A., U.S. $	205	200	405		405

[a] Note that these recent conversion rates differ substantially from those in Table 1.1.

Table 5.8 Recommended Collector-Subsystem Costs for 1985 Conceptual Design (1980 U.S. $/m^2)

Cost Item	Flat-Plate Collector	Evacuated Collector	Parabolic-Trough Collector	Central Receiver
Collector Module	130.00	194.00	215.00	230.00
Collector Materials	25.00	40.74	30.00	
Subtotal	155.00	234.74	245.00	251.31
Direct Labor	17.05	28.16	34.30	
Indirect Costs on Materials	23.25	32.86	34.30	
Indirect Labor	8.52	14.08	17.05	
Total Direct and Indirect Costs	203.82	309.84	330.74	346.66
Contingency	30.57	46.47	49.61	
Fee	10.19	15.49	16.53	
Total	244.58	371.80	396.89	416.00
Recommendation	245.00	370.00	400.00	415.00

These recommended values can be easily modified to suit other conditions by adjusting the appropriate parameters in Table 5.1 to reflect local experience.

5.4 Operating and Maintenance Costs

Operating and maintenance (O&M) costs generally include the cost of direct production, scheduled and unscheduled maintenance, plant overhead, and purchased power. Some analysts, such as Dickinson, identify replacement and insurance costs explicitly. In an economic analysis, purchased power is included in the operating cost and should not be deducted from the system output (as it has been in the preceding performance analyses).

Most economic analyses of solar-energy projects estimate annual overall O&M costs as a percentage of the initial capital investment (usually 1-2%). Experience with first-of-a-kind systems has generally shown this allowance to

Table 5.9 Recommended Collector-Subsystem Costs for Future Mass Production (1980 U.S. $/m^2)

Cost Item	Flat-Plate Collector	Evacuated Collector	Parabolic-Trough Collector	Central Receiver
Collector Module	95.00	130.00	106.00	98.00
Collector Materials	18.05	27.30	14.84	
Subtotal	113.05	157.30	120.84	
Direct Labor	12.43	18.86	16.90	
Indirect Costs on Materials	15.82	22.02	16.91	
Indirect Labor	6.21	9.43	8.46	
Total Direct and Indirect Costs	147.51	207.61	163.11	
Contingency	22.13	31.14	24.46	
Fee	7.37	10.38	8.16	
Total	177.01	249.13	195.73	217.00[a]
Recommendation	175.00	250.00	195.00	215.00

[a] From Ref. 88 (see Table 5.5).

be inadequate, primarily because of the extra expenses incurred in correcting design and installation mistakes. The fixed-percentage approach is probably inadequate even in the post-development period, because it fails to take into account the diverse maintenance requirements of plants of different sizes and designs. A study conducted at PNL[16] used a more systematic approach to calculate the O&M requirements and costs for seven collector technologies, using five operating temperatures and four plant sizes.

Where information was available, PNL made manpower estimates for specific tasks and derived costs from these estimates. In other cases, costs were estimated as a percentage of the installed capital cost of the system. Estimates were then aggregated to obtain the total annual O&M expenditure for each plant. The total was multiplied by a fixed factor to obtain plant overhead costs. The elements of this analysis are described below.

5.4.1 Direct Production Costs

The PNL investigators estimated the direct production costs to account for the number of operators required to run the plant. They devised scenarios to project how plants of different sizes and configurations would be operated; these scenarios were used to determine the operators' numbers and skill levels. The plant sizes, which ranged from 50 to 600 MW (thermal), were larger than the 5-to-100-MW (thermal) CSHPs presently under consideration.

5.4.2 Purchased-Energy Costs

Purchased energy costs included the cost of all auxiliary energy needed to run the plant. Among the energy requirements were energy to run the pumps, motors, and collector tracking devices, as well as heat tracing for the transport system. The unit cost of electricity used by PNL was $0.043/kWh.

5.4.3 Maintenance Costs

Maintenance costs included the cost of a maintenance crew and the cost of materials used. Both scheduled and unscheduled maintenance tasks were assumed to be performed by an in-plant crew; it also was assumed that the plants had been designed to minimize unscheduled maintenance.

The costs of scheduled and unscheduled maintenance were estimated for the collector, transport, storage, interface, and instrumentation subsystems. Maintenance costs were estimated either as a percentage of installed equipment costs or as an aggregate of the estimated costs of performing maintenance tasks specific to a subsystem. To use the latter method, major maintenance tasks were identified. The size of the crew needed for each task was estimated, based on assumptions of the rate and frequency at which the task would be performed. Multiplying this estimate by the annual wage rate yielded the annual cost of the task. These task costs were aggregated to obtain the annual maintenance cost for the plant.

The major scheduled maintenance tasks identified for the collector subsystem included cleaning, lubricating, and manual adjusting or realigning of collectors. Cleaning was assumed to occur monthly. Lubrication was to be performed quarterly, and manual adjusting or realigning was assumed to occur monthly for the evacuated CPC collectors and quarterly for all other collector types. No specialized training appeared to be required to perform routine collector-maintenance tasks.

The principle maintenance requirements for the receiver subsystem included inspection and repair of heat-exchanger tubes, insulation, structures, and aperture shields. Maintenance would likely be performed by specialized personnel, such as pipefitters or steamfitters. Maintenance costs for receiver subsystems were calculated as a percentage of the capital cost.

Maintenance requirements for the transport subsystem included the equipment-maintenance costs and the cost of replacing the degraded heat-transfer fluid. Equipment-maintenance tasks were identified as inspection of valves, replacement or repacking of valves, and pump maintenance. Valve testing and pump maintenance were assumed to occur quarterly. Information on valve-failure rates was used to estimate the cost of replacing or repacking valves. Maintenance tasks for the transport subsystem would require specialized personnel, such as pipefitters or steamfitters.

The principal maintenance tasks for the interface subsystem included inspection and repair of heat-exchanger tubes; testing, replacement, or repacking of valves; and pump maintenance. The maintenance cost for this subsystem was estimated as a percentage of the initial capital cost. These tasks would likely be performed by either pipefitters or steamfitters.

The cost of maintaining instruments was estimated as a percentage of the installed capital cost of the plant instrumentation. This maintenance would likely be performed by instrument technicians or electricians.

Unscheduled maintenance costs were estimated as a percentage of installed-equipment costs; the estimated percentages were developed using information from cost-estimating guides and from other solar studies. The cost of maintenance materials was also estimated as a percentage of the installed-equipment cost, and the percentages again were based on information from cost-estimating guides and from other solar studies.

The estimated O&M costs for the 50-MW plants were all well below 1% in this study. The PNL estimates of O&M costs for the 150°C plants were 0.3, 0.5, and 0.4% for the evacuated-CPC, the parabolic-trough, and the central-receiver systems, respectively.[16] We would expect smaller plants to have higher fractional costs.

6 COMPARISON OF COLLECTOR SUBSYSTEMS

A series of calculations, at several levels of sophistication, was undertaken by the Subtask 1(b) group in order to guide the selection of the most promising collector types for various sites and system configurations. At early meetings, subtask participants compared the probable cost-effectiveness of collectors on the basis of costs and energy typically collected in other applications. Subsequent calculations introduced site-specific insolation and weather data, accurate collector-module modeling, more realistic loads, projected performance and cost estimates, and estimates of large-array effects. By this series of comparisons, the field of candidates has been reduced to four. This is as far as we believe it is reasonable to go without guidance from comprehensive system calculations (employing more detailed array models) and the associated sensitivity calculations.

6.1 Meteorological Data

Unfortunately, there is no unified meteorological data base for the countries participating in this task. Indeed, only the North American countries have produced a set of data for a large number of cities that can be accessed and used in a consistent way. Therefore, we have relied heavily on the U.S. data base, known as the typical-meteorological-year (TMY) tapes, which have been generated for 26 U.S. cities (subsequently expanded to more than 200).

The TMY is a hypothetical year, generated by patching together data for 12 "average" months with appropriate smoothing at the beginning and end of each month. This method was found to produce a year that better represented the performance of solar-energy systems than did the long-term averaging of yearly, daily, or hourly data or the arbitrary selection of a single year.

The TMY tapes contain hourly insolation and weather data for a complete year in a standard format; the data include values for the beam and total radiation on a horizontal surface, the ambient temperature, and the wind speed. The procedure for developing the TMY tapes, devised at SNLA, employs the Boes correlation between the total horizontal and beam radiation.[92] To supplement the U.S. data, we included a tape with data from Copenhagen, which had been used by IEA Task I in previous systems-analysis work and was known to be reliable. The Copenhagen tape contains only radiation on a horizontal surface and must be used with a correlation to obtain the beam radiation; the Boes correlation was used in our calculations. Results shown in this report are for Albuquerque, N.M.; Boston, Mass.; and Copenhagen, Denmark. These calculations were made before Madison, Wis., was adopted for design studies. Additional meteorological data have been supplied by some of the participating countries in graphical or tabular form and are included in this report for comparison.

The annual-insolation distributions calculated from the TMY tapes for Albuquerque and Boston are shown in Figs. 6.1 and 6.2. Figure 6.3 shows the insolation from the IEA Copenhagen tape, and Figs. 6.4-6.6 show national database insolation results for Kew (U.K.), Hamburg, and Stockholm. Four insolation quantities are presented:

- Total insolation on a horizontal surface (the most frequently measured quantity),
- Direct normal or beam radiation,
- Total radiation on a fixed surface inclined at the latitude angle, and
- The total radiation incident on a normal surface (this represents the maximum solar resource available to a two-axis tracking collector with a 2 π acceptance angle).

The annual integrals are tabulated in Table 6.1, along with the annual degree days and the total residential load used in the seasonal-storage calculations.

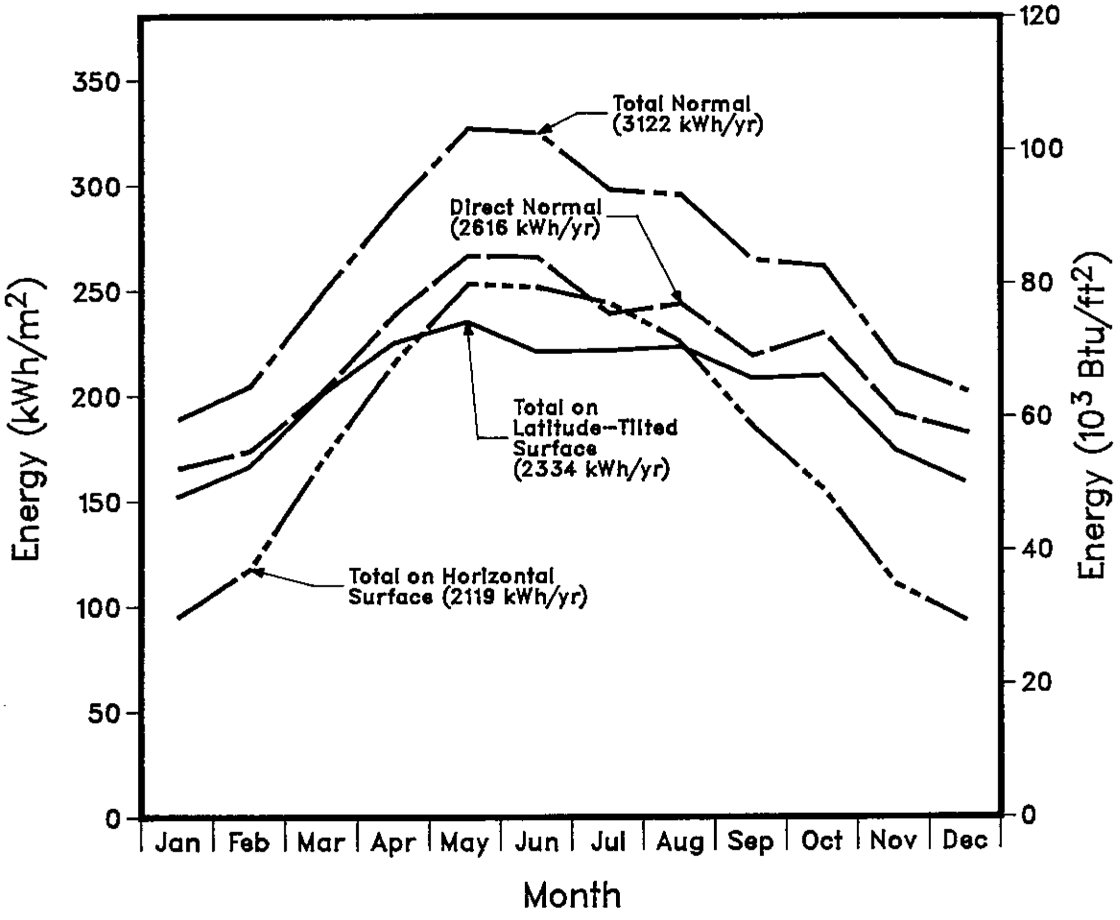


Fig. 6.1 Solar-Radiation Data for Albuquerque, New Mexico (TMY)

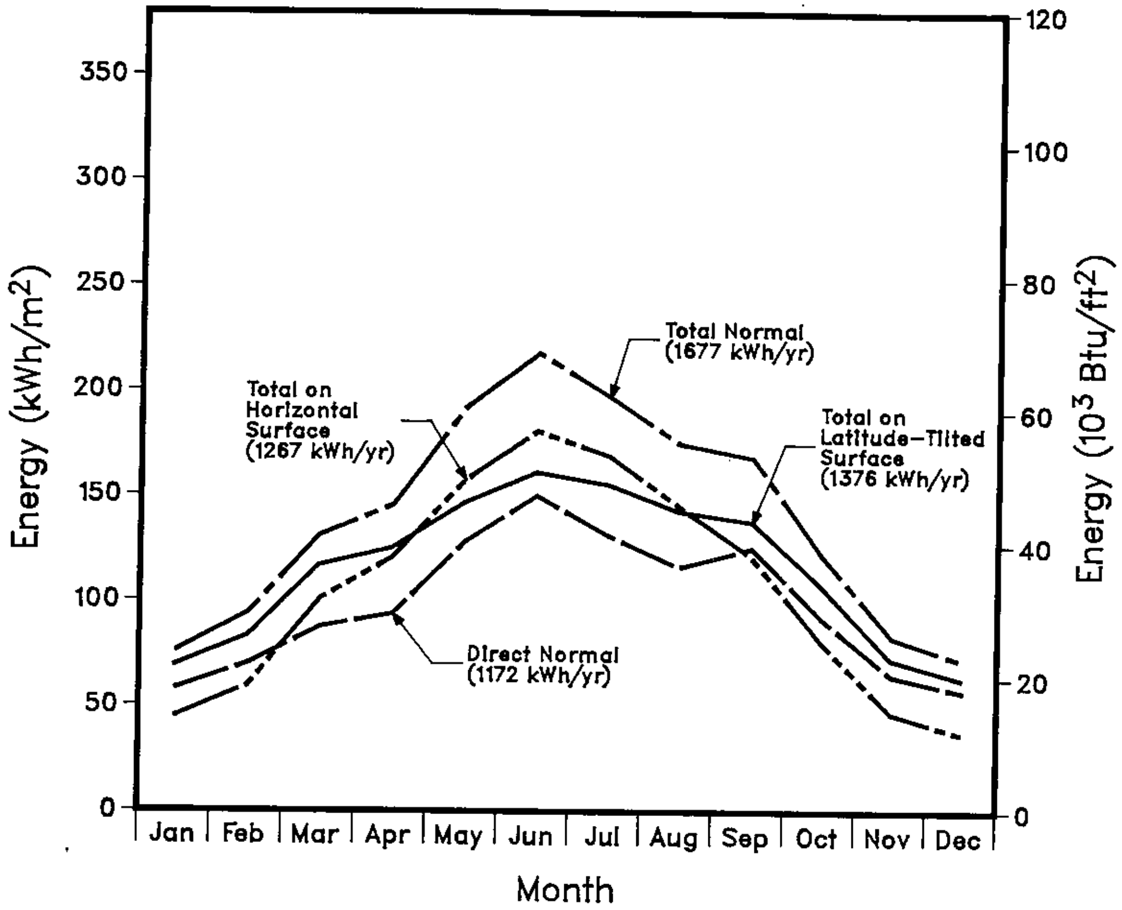


Fig. 6.2 Solar-Radiation Data for Boston, Massachusetts (TMY)

The fact that Albuquerque has more than twice the annual insolation available in Boston and three times the direct normal radiation in Kew is not surprising, nor is this fact the point of the comparison. The direct normal radiation in Copenhagen is relatively large compared with radiation on a fixed surface. This means that the weather is clear enough that collector strategies that accept the wide range of sun positions found at maximum latitudes (i.e., one- or two-axis tracking) may be attractive in Copenhagen. Kew, on the other hand, receives so little beam radiation that the use of concentrating collectors, with their lesser ability to use diffuse light, is questionable.

6.2 Annual Energy Delivery

Two basic methods of comparison were employed in this study. In the first method, the annual energy delivered by a collector fed from an infinite storage system at constant temperature was calculated by integrating the hourly output of collectors, described by the insolation models in Chapter 2, and ambient conditions read from the weather tapes. These isothermal calculations were performed for temperatures of 30, 60, 75, 90, and 120°C. The daily sums were also stored and used in subsequent calculations.

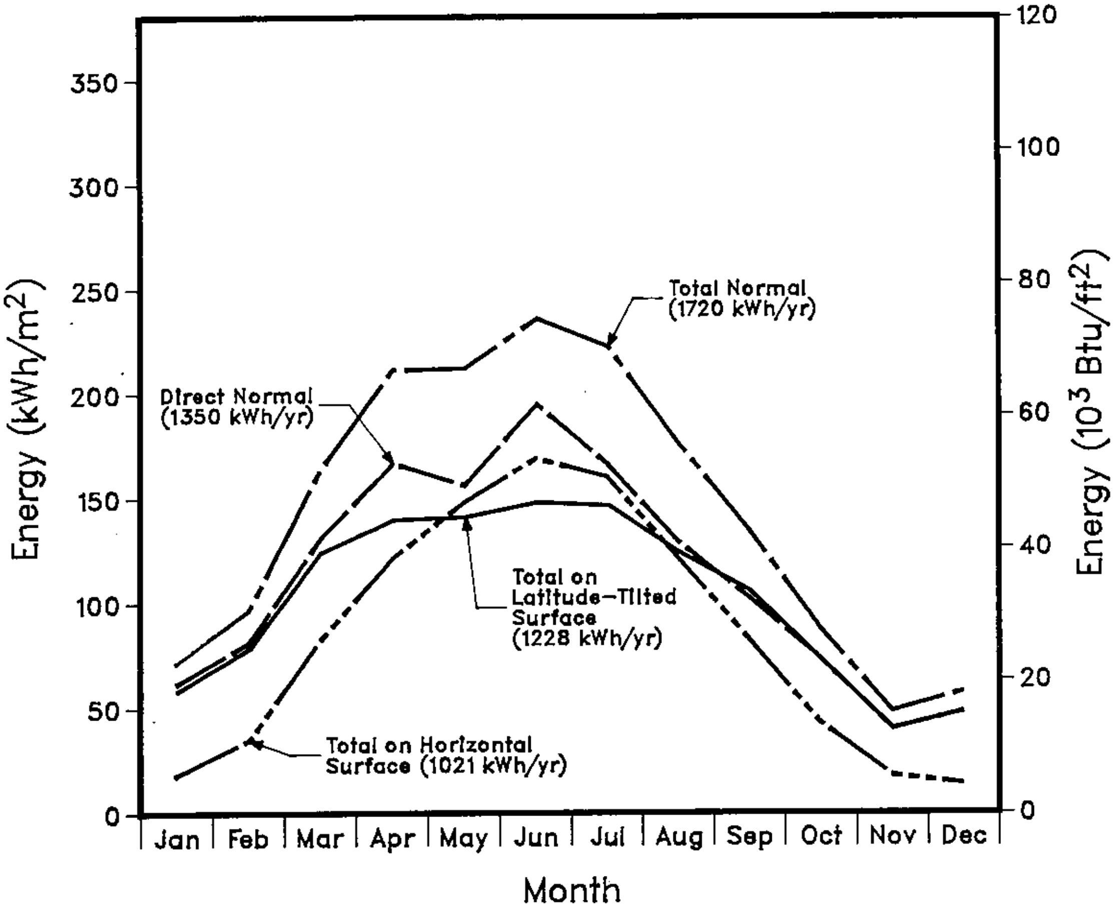


Fig. 6.3 Solar-Radiation Data for Copenhagen, Denmark
(IEA Task I Weather Tape)

A second set of comparisons was made for an ideal system, in which a lossless water-storage tank and a unit residential load were connected to the collector subsystem by means of a lossless distribution and transmission system. The load, intended to be representative of a small, well-built individual residence, was 4.24 kWh per degree-day (DD), where the degrees are measured in terms of the Celsius scale, plus 11.7 kWh/d for DHW. The number of degree days was calculated from the weather tapes using a room temperature of 18°C. The storage volume and collector area required to drive this load with a prescribed annual temperature swing of 60°C (from 40-100°C) were calculated. A calculation for FPCs showed that 60°C was approximately the optimal swing for this idealized system.

6.2.1 Fixed Storage Temperature

The annual energy collected per unit area of a collector module operating at a fixed inlet temperature is compared for a number of collectors in Albuquerque, Boston, Copenhagen, Coronation, Hamburg, Ispra, Kew, The Netherlands, and

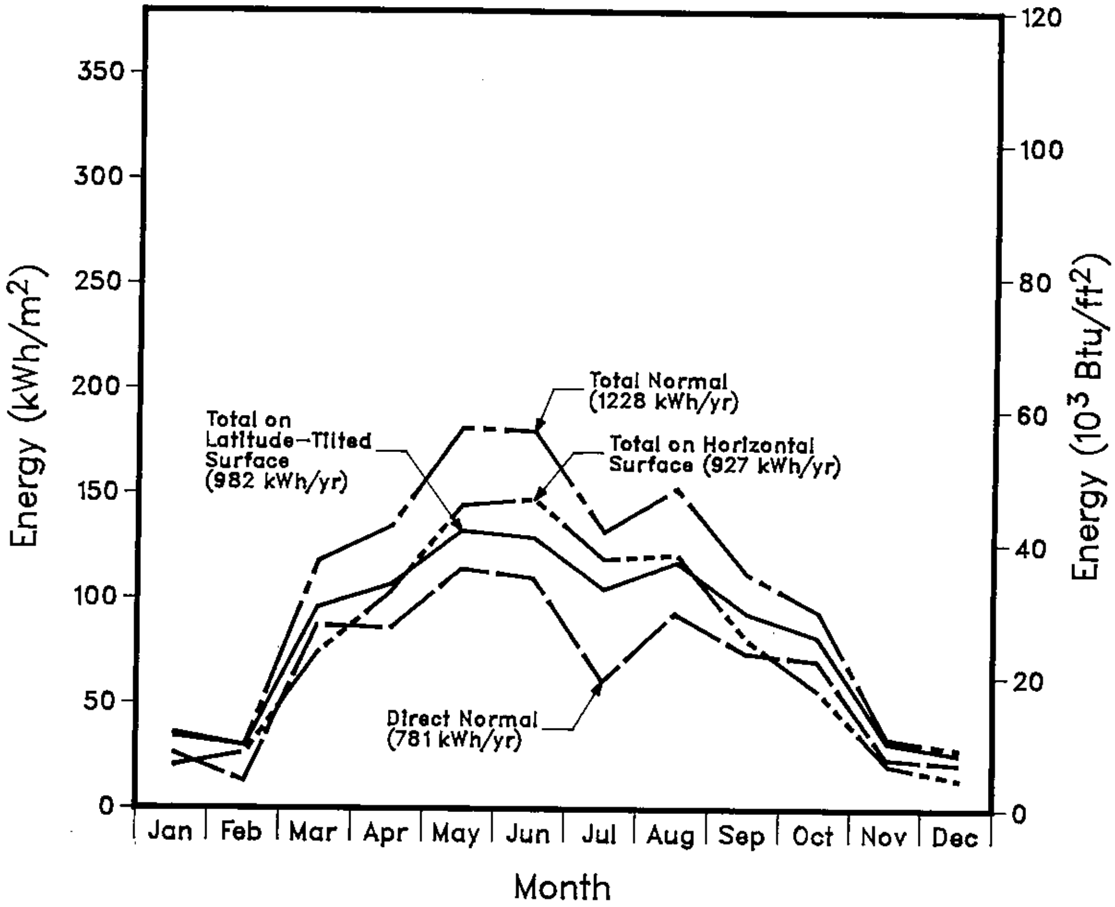


Fig. 6.4 Solar-Radiation Data for Kew, United Kingdom (U.K. Data Base)

Stockholm in Figs. 6.7 through 6.15. (The use of inlet temperature in the efficiency correlation, according to Ref. 18, implies that the flow rate is near that used in testing and high enough that only a small temperature rise occurs in the collector.) The calculations for the U.S. cities, Copenhagen, Kew, and Stockholm used the models discussed in Chapter 2. The remaining calculations were carried out by the subtask participants, using slightly different equations for collector efficiencies. Table 6.2 summarizes the results of most of the available calculations at fixed temperatures of 30, 50, 70, and 90°C.

The tracking collectors capture and retain substantially more energy at all temperatures than do the fixed collectors, with the notable exception of the advanced evacuated collectors. This is true even in Boston, where there is considerable cloudiness (but crossovers do occur at temperatures of around 30°C). As one would expect, the crossover between the FPC and the commercial evacuated collector moves to lower temperatures in the colder, cloudier climates. The calculations for Kew show virtually no energy collected by the shallow pond and a relatively high crossover for the evacuated collectors and

Table 6.1 Annual Radiation and Heating Loads

Parameter	Innsbruck, Austria (47° N)	Ispra, Italy (CEC) (46° N)	Copenhagen, Denmark (56° N)	Hamburg, W. Germany (54° N)	DeBilt, The Netherlands (52° N)
Direct Normal Radiation					
kWh/m^2			1,350		
Percent of Total Normal			78		
Total Radiation on Horizontal					
kWh/m^2	1,085	1,205	1,021	952	957
Percent of Total Normal	63		59	71	
Total Radiation on Latitude Tilt					
kWh/m^2	1,182		1,228	1,033	1,015
Percent of Total Normal	65		71		
Total Radiation on Normal					
kWh/m^2	1,819		1,720	1,350	
J/m^2	6,550		6,192	4,860	
10^3 Btu/ft^2	6,070		5,870	4,505	
Degree Days					
Base Temperature	20/18.5				
Celsius Scale	4,334		3,818		3,210
Fahrenheit Scale	7,800		6,872		5,780
Heating and DHW Load for a Small Residence					
kWh/unit	15,000[a]		20,386		
10^6 Btu/unit			70		

Table 6.1 (Cont'd)

Parameter	Stockholm, Sweden (59° N)	Zurich, Switzerland (47° N)	Albuquerque, N.M., U.S. (35° N)	Boston, Mass., U.S. (42° N)	Kew, U.K. (51° N)
Direct Normal Radiation					
kWh/m^2	1,316	850	2,616	1,172	781
Percent of Total Normal	71	63	83	70	64
Total Radiation on Horizontal					
kWh/m^2	980	1,127	2,119	1,267	927
Percent of Total Normal	53	83	68	76	75
Total Radiation on Latitude Tilt					
kWh/m^2	1,110	1,135	2,394	1,228	981
Percent of Total Normal	60	84	77	71	80
Total Radiation on Normal					
kWh/m^2	1,843	1,354	3,122	1,720	1,228
J/m^2		4,875	11,240	6,192	4,421
10^3 Btu/ft^2		4,621	10,655	5,870	4,192
Degree Days					
Base Temperature	18.6				18.3
Celsius Scale	4,246	3,660	2,464	3,209	3,062
Fahrenheit Scale	7,642	6,588	4,435	5,776	5,512
Heating and DHW Load for a Small Residence					
kWh/unit		19,716	14,669	17,813	17,200
10^6 Btu/unit		67	50	61	59

[a] Typical for small residences erected since 1880.

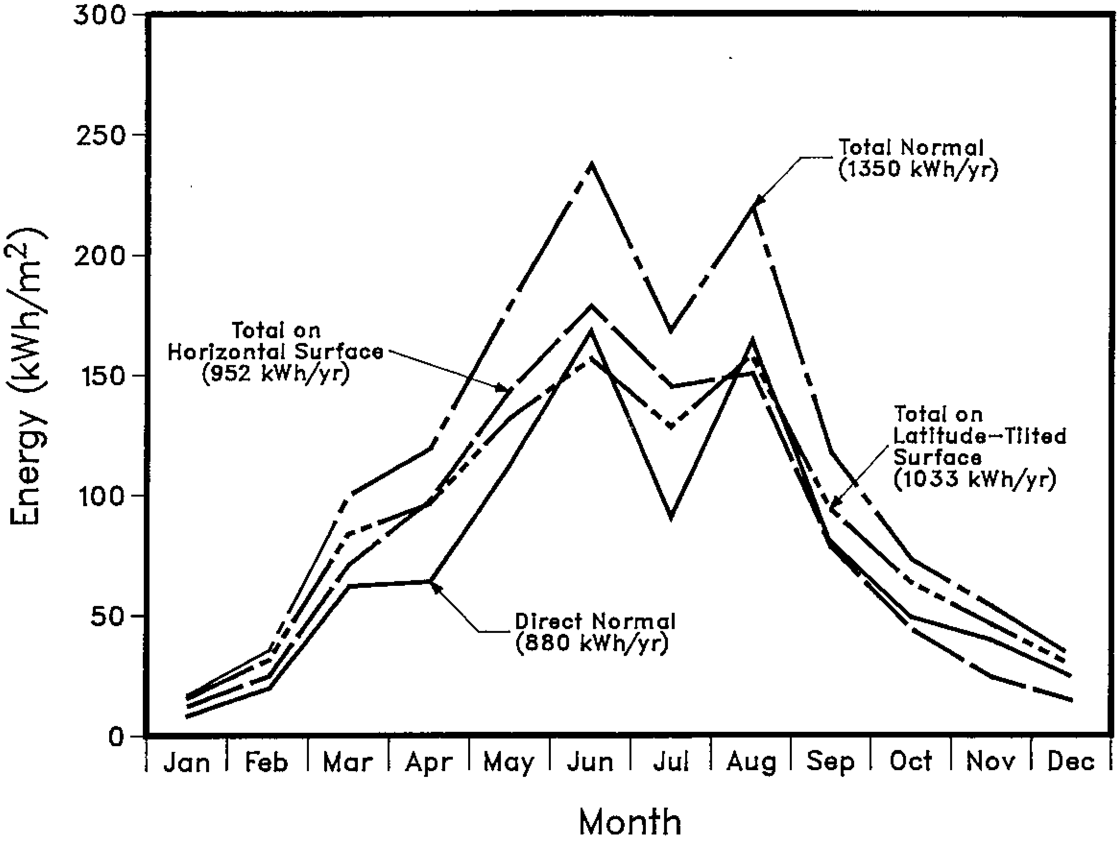


Fig. 6.5 Solar-Radiation Data for Hamburg, West Germany (German Data Base)

the FPCs. The tracking collectors deliver the most energy at the highest temperatures, but the stationary systems are competitive at temperatures below 50°C. It is not clear from Fig. 6.13 which system will perform best in actual use.

6.2.2 Fixed Annual Load

Figure 6.16 shows the results of a calculation of the collector area and storage volume required to fully satisfy the annual load requirements specified (4.24 kWh/DD, plus 11.7 kWh/d for DHW). The collector is a single-glazed, selective-absorber flat plate. The storage medium is water, which is allowed to vary between 40 and 100°C. The location is Boston. The fluctuating curves depict the incident solar energy collected daily and the building load. The smooth curves meeting at the right-hand boundary are integrals of the collected energy and the load. In this case, the solar-energy system provides 100% of the load, so the two integrals must balance.

The sinusoidal curve is the storage temperature, which is constrained to vary between 40 and 100°C. The collector area and storage volume necessary to

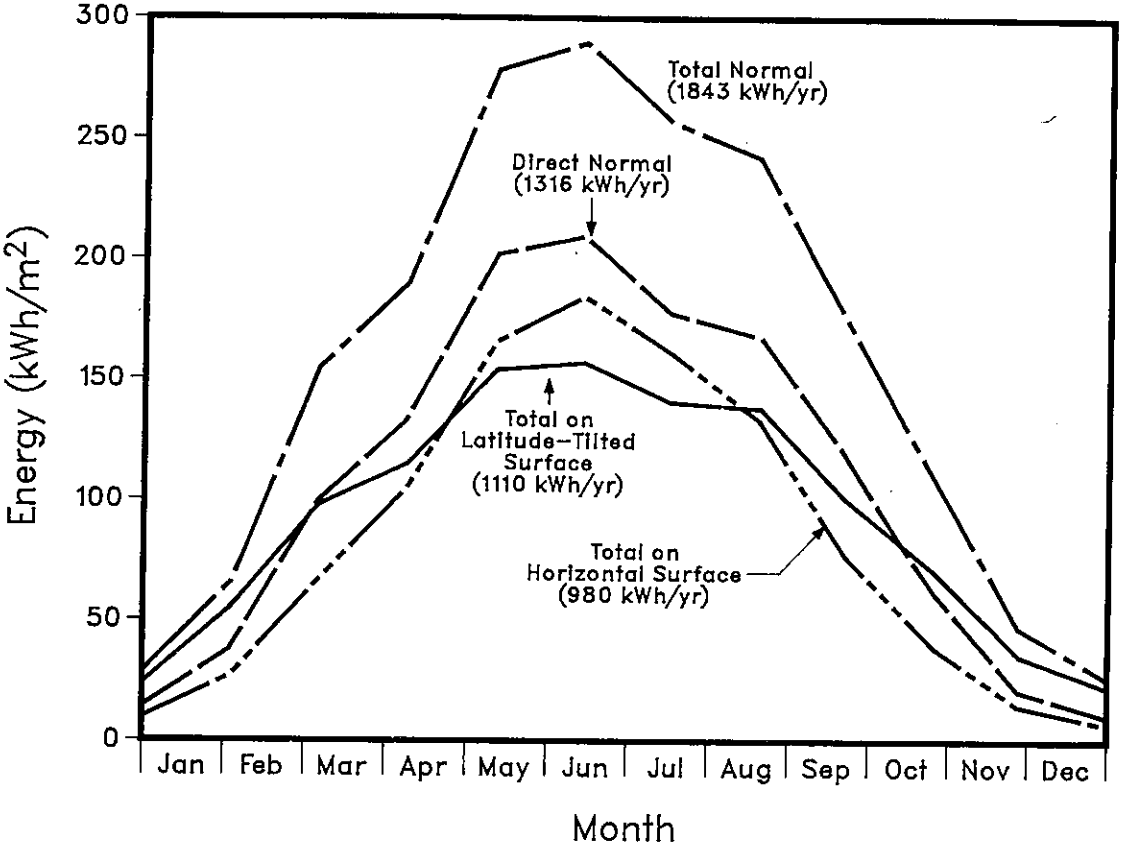


Fig. 6.6 Solar-Radiation Data for Stockholm, Sweden
(Swedish Data Base)

balance the load and collected energy, subject to the storage-temperature constraint, are displayed in the upper part of the figure. In this instance, it was determined that 42 m^2 of collector would supply the entire load of 17,813 kWh if connected to an ideal storage system (one without losses) containing 117 m^3 of water per residential unit (i.e., per 17,813-kWh load). Solar-energy collection peaks early in the year, when the collector temperature is near its minimum. This places a premium on highly efficient storage systems that will retain energy collected in the spring and summer months until it is needed in the fall.

Similar calculations were performed for each collector model in each of the three cities; the results are tabulated in Table 6.3. The collector-array-output energy-reduction factors from Table 2.8 were then applied to obtain an improved estimate of the areas required to deliver the fixed annual load. The collector areas and storage volumes, now adjusted for array losses, are displayed in Figs. 6.17 and 6.18. (Although the collector area required to meet the fixed load is quite sensitive to collector type and location, the required storage volume is relatively insensitive to these parameters.)

Table 6.2 Ideal Annual Energy Collected at Fixed Temperature (kWh/m^2)

Fixed Temperatures, System Types, and Radiation Levels	Innsbruck, Austria[a] (47° N)	Coronation, Canada[a] (52° N)	Ispra, Italy (CEC)[a] (46° N)	Copenhagen, Denmark (56° N)	Hamburg, W. Germany[a] (54° N)	DeBilt, The Netherlands[a] (52° N)
30°C						
Flat Plate at Latitude Tilt						
Single-Glazed, Selective	620	740	740	660		550
Double-Glazed, Selective	540			610		620
Evacuated Tube			770			570
Stationary Concentrators						
Conventional Evacuated Tube		710		490		
Advanced Evacuated Tube		1070		712		
Tracking Concentrators						
E-W Parabolic Trough		760		710		
Central Receiver		1160		874		
50°C						
Flat Plate at Latitude Tilt						
Single-Glazed, Selective	410	510	485	475	500	375
Double-Glazed, Selective	440			465		480
Evacuated Tube	680		660		620	480
Stationary Concentrators						
Conventional Evacuated Tube		670		425		
Advanced Evacuated Tube		1040		665		
Tracking Concentrators						
E-W Parabolic Trough		740		700		
Central Receiver		1160		975		
70°C						
Flat Plate at Latitude Tilt						
Single-Glazed, Selective		310	294	350	340	250
Double-Glazed, Selective				330		380
Evacuated Tube			565		550	410
Stationary Concentrators						
Conventional Evacuated Tube		600		370		
Advanced Evacuated Tube		1010		610		
Tracking Concentrators						
E-W Parabolic Trough		710		680		
Central Receiver				875		
90°C						
Flat Plate at Latitude Tilt						
Single-Glazed, Selective	130	170	157	220	230	160
Double-Glazed, Selective	160			260		290
Evacuated Tube	390		480		500	345
Stationary Concentrators						
Conventional Evacuated Tube		560		320		
Advanced Evacuated Tube		1000		670		
Tracking Concentrators						
E-W Parabolic Trough		760		660		
Central Receiver		1160		875		
Total Radiation on Latitude Tilt	1182			1228	1033	1015
Direct Normal Radiation				1350	880	

Table 6.2 (Cont'd)

Fixed Temperatures, System Types, and Radiation Levels	Stockholm, Sweden (59° N)	Zurich, Switzerland (47° N)	Albuquerque, N.M., U.S. (35° N)	Boston, Mass., U.S. (42° N)	Kew, U.K. (51° N)
30°C					
Flat Plate at Latitude Tilt					
Single-Glazed, Selective	666	646	1590	800	497
Double-Glazed, Selective	648	599	1420	740	461
Evacuated Tube	646				
Stationary Concentrators					
Conventional Evacuated Tube	514	508	1110	560	289
Advanced Evacuated Tube	760	740	1580	810	458
Tracking Concentrators					
E-W Parabolic Trough	705	475	1560	690	412
Central Receiver	820	514	1750	780	383[a,b]
50°C					
Flat Plate at Latitude Tilt					
Single-Glazed, Selective	474	462	1300	600	323
Double-Glazed, Selective	487	452	1220	575	322
Evacuated Tube	553				
Stationary Concentrators					
Conventional Evacuated Tube	433	434	1030	490	234
Advanced Evacuated Tube	692	674	1500	755	391
Tracking Concentrators					
E-W Parabolic Trough	676	459	1530	680	394
Central Receiver	820	514	1750	785	383[a]
70°C					
Flat Plate at Latitude Tilt					
Single-Glazed, Selective	341	325	1040	440	202
Double-Glazed, Selective	367	340	1020	435	222
Evacuated Tube	471				
Stationary Concentrators					
Conventional Evacuated Tube	370	373	930	434	192
Advanced Evacuated Tube	631	615	1420	695	337
Tracking Concentrators					
E-W Parabolic Trough	649	444	1520	660	375
Central Receiver	820	514	1750	650	383[b]
90°C					
Flat Plate at Latitude Tilt					
Single-Glazed, Selective	235	221	800	290	118
Double-Glazed, Selective	282	252	820	340	147
Evacuated Tube	385				
Stationary Concentrators					
Conventional Evacuated Tube	315	323	860	380	156
Advanced Evacuated Tube	575	564	1370	650	292
Tracking Concentrators					
E-W Parabolic Trough	624	428	1500	650	354
Central Receiver	820	514	1750	650	383
Total Radiation on Latitude Tilt	1110	1135	2334	1376	982
Direct Normal Radiation	1316	850	2616	1172	781

[a] Calculation employed national collector models.

[b] $\frac{1}{f}$ (51.3).

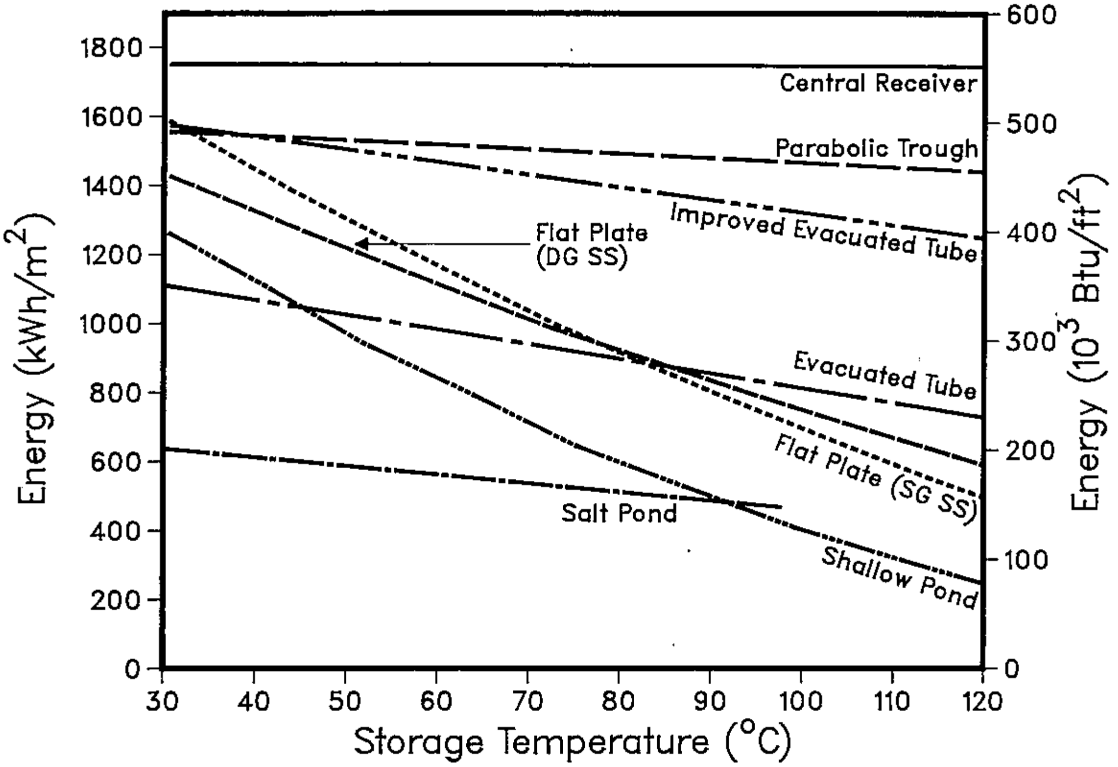


Fig. 6.7 Annual Energy Collected at Fixed Storage Temperature for Albuquerque, New Mexico

6.2.3 Comparison of Fixed-Temperature and Fixed-Load Results

Table 6.4 compares the calculated annual energy collected at a constant mean temperature of 70°C (the mean storage temperature for the seasonal calculation) for Albuquerque, Boston, and Kew.

The energy collected at 70°C was read from the graphs in an earlier section, while the seasonal-storage results came from Table 6.3. In general, the seasonal-storage calculations show less energy collected than the isothermal calculation. The largest difference is observed in the evacuated collector, where the seasonal-storage results are 13-16% lower than the constant-temperature results. The central-receiver results are as close as can be read from the graphs (as expected, since the heat losses from the central receiver were neglected). The flat-plate results, however, are surprisingly close in Albuquerque and Boston. The fact that the evacuated-collector results are more affected by the seasonal-storage conditions than are the flat-plate results is rather surprising and, at this writing, unexplained.

The implication of this comparison is that constant-temperature calculations, which are already available in many of the participating countries, may be used to estimate the collector area required for seasonal-storage systems with little loss of accuracy, if the mean seasonal temperature is used.

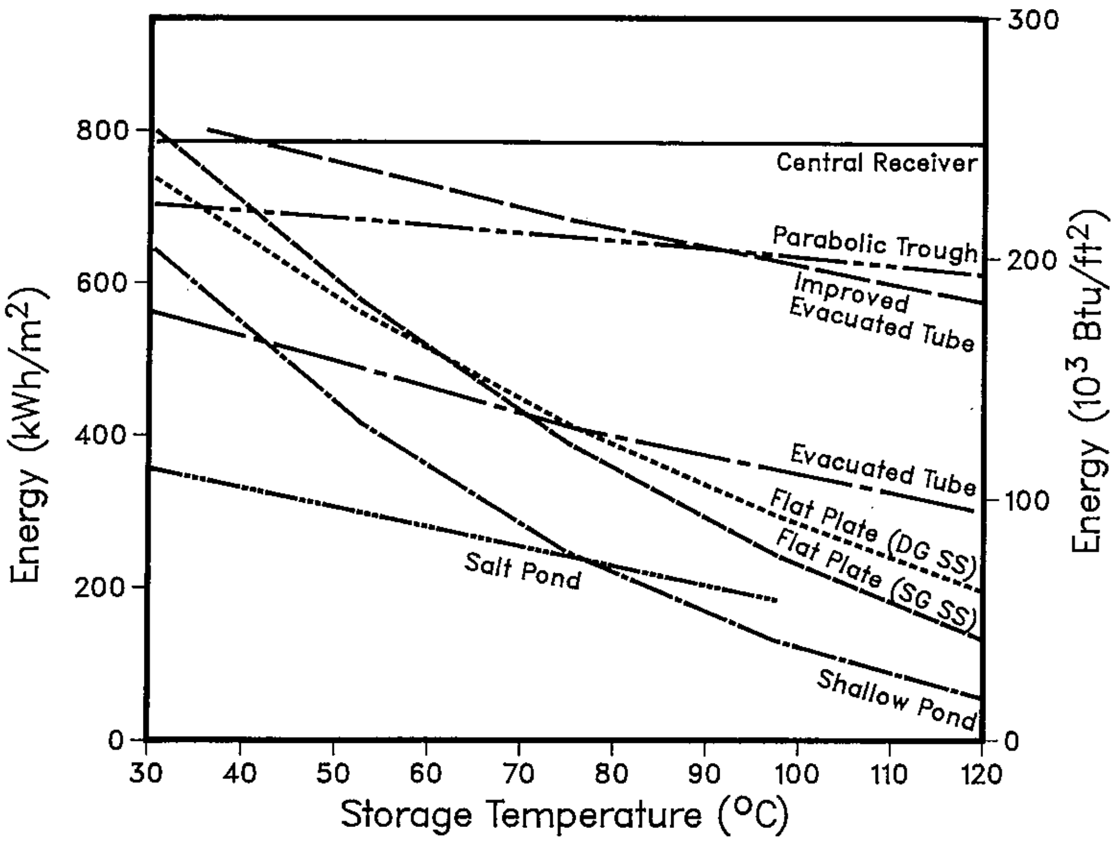


Fig. 6.8 Annual Energy Collected at Fixed Storage Temperature for Boston, Massachusetts

6.3 Comparison of Collector-Subsystem and System Costs

A simple cost comparison for the collector subsystem can be made by combining the cost recommendations of Tables 5.6 and 5.7 with the fixed-temperature energy-collection results of Table 6.2. To make the comparison more realistic, the collector-array-output reduction factors of Table 2.8 are also included in the calculation. Figures 6.19 and 6.20 show the approximate subsystem costs calculated in this way for distributed and central receivers for Albuquerque, Boston, and Copenhagen (based on the 1985 and future cost estimates). The figures show the most cost-effective distributed collector for each time period. For the 1985 cost estimate, FPCs are the most cost-effective, whereas in long-range (future) projections, parabolic troughs are expected to prevail. On the basis of subsystem (collector) costs alone, the FPC can compete with the central receiver in the near term if the temperature is below 40 to 50°C. Such low-temperature systems are feasible; however, the cost of heat pumps, larger heat exchangers, and larger distribution-system piping could negate the collector-subsystem savings. These issues must be examined in the broader context of overall system design

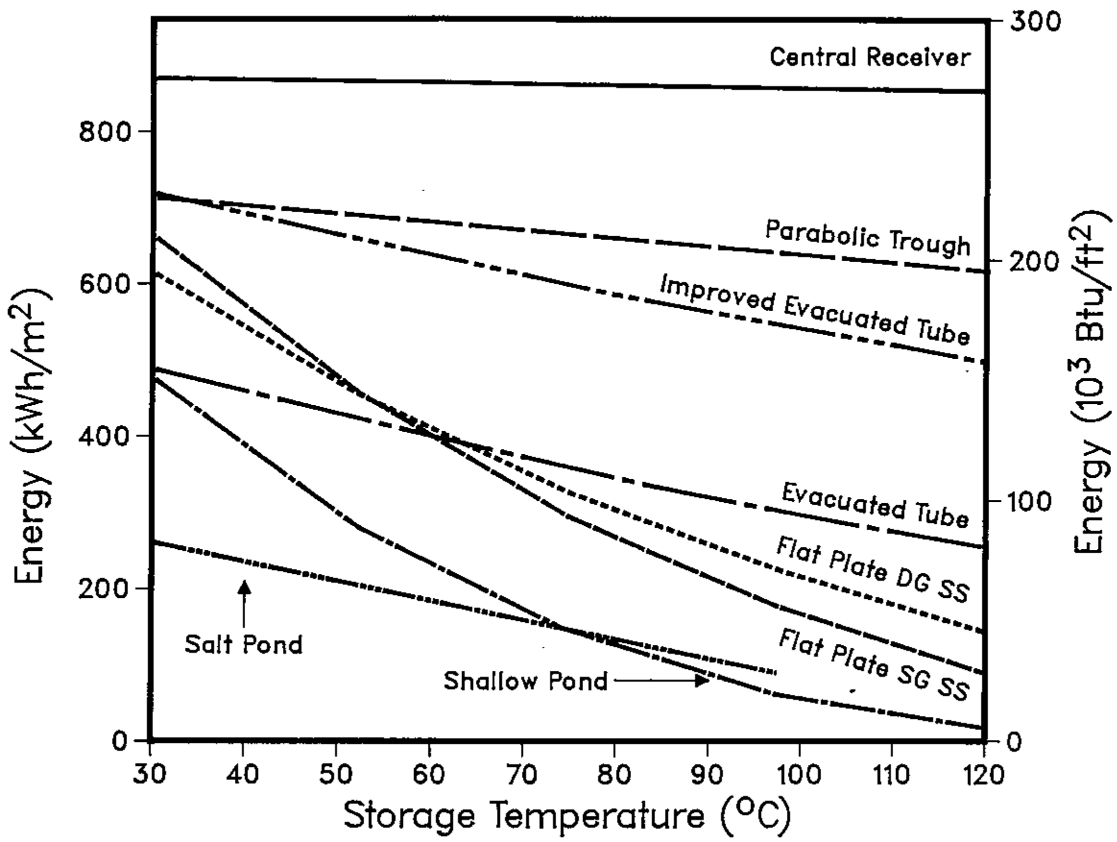


Fig. 6.9 Annual Energy Collected at Fixed Storage Temperature for Copenhagen, Denmark (U.S. calculation)

and optimization. If, in fact, future costs of tracking collectors are as low as or lower than stationary collectors, the collector-subsystem costs will be essentially independent of temperature, and other considerations will dictate the temperature level.

A system-cost comparison is obtained by combining the results of the seasonal-storage performance estimates from Table 6.3 with the recommended cost figures from Tables 5.6 and 5.7. The unit costs for storage were \$60/m^3 (current costs) and \$8/m^3 (long-range projections), corresponding roughly to underground concrete-tank storage and natural-aquifer storage, respectively. The cost of the distribution system was taken to be \$3000/unit. The basis for comparison is the combined cost of collectors and distribution. Tables 6.5-6.7 show the results for all three cities and three cost levels. Estimates are provided for the collector-subsystem cost, the complete-system cost, the collector and system capacity costs, and the approximate levelized cost of energy delivered. The levelized cost was obtained arbitrarily by assuming a value of 0.1 for the levelizing factor, M, of Dickinson and Brown.[82]

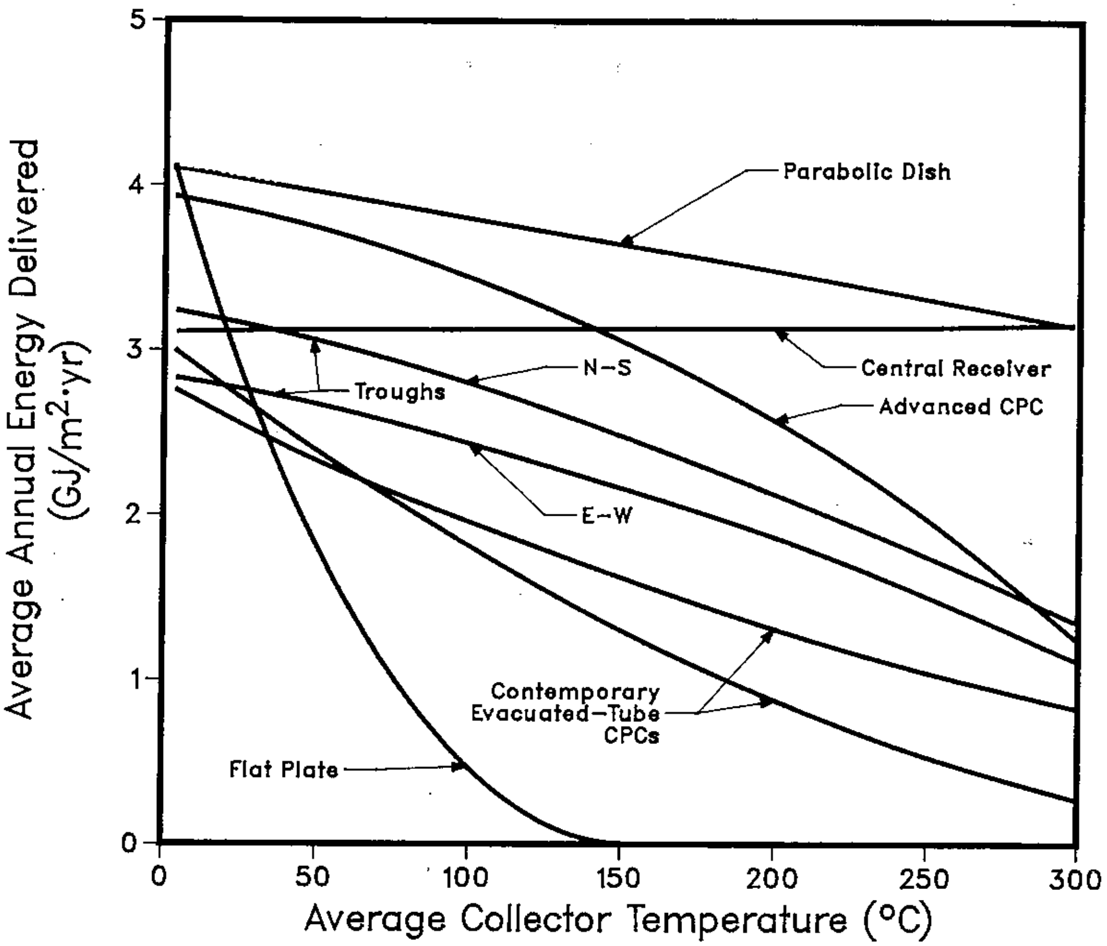


Fig. 6.10 Annual Energy Collected at Fixed Storage Temperature for Coronation, Canada

In the mass-production scenario, the tracking collectors hold a decided advantage in all locations. At current and projected 1985 costs the stationary collectors are cost-competitive, but the central receiver still appears more attractive. The variation in system cost between technologies is not very large. (For Albuquerque, the spread is only 34%.)

Our procedure has led us to conclude that the central-receiver technology has potential advantages in performance and cost-effectiveness at all three locations (Albuquerque, Boston, and Copenhagen). The high thermal efficiency of the central receiver, a result of its large concentration factor and its absence of field transport-system losses, is responsible for its performance advantage. This advantage leads directly to the central receiver's superior cost-effectiveness, because all the technologies included in this study ultimately have approximately the same costs per unit area. (For example, the spread in collector area required per unit in Boston is over 100%, but the

Table 6.3 Collector Areas and Storage Volumes Required to Meet Fixed Annual Load

Collector Type	Collector Area (m^2)	Storage Volume (m^3)	Energy Collected (kWh/m^2)
Albuquerque[a]			
Flat Plate DG SS[b]	14.5	87.2	1,015
Evacuated Tube	18.0	82.4	815
Central Receiver	8.4	77.9	1,752
Parabolic Trough	10.0	76.5	1,472
Flat Plate SG SS[c]	14.2	88.7	1,032
Shallow Pond	21.0	116.4	698
Improved Evacuated Tube	11.0	80.7	1,329
Boston[a]			
Flat Plate DG SS	39.6	115.6	450
Evacuated Tube	49.3	110.1	361
Central Receiver	24.2	107.8	736
Parabolic Trough	27.9	104.6	638
Flat Plate SG SS	41.7	117.2	427
Shallow Pond	64.7	156.4	275
Improved Evacuated Tube	28.0	109.0	636
Copenhagen[a]			
Flat Plate DG SS	59.4	106.3	343
Evacuated Tube	67.6	101.3	301
Central Receiver	37.2	120.8	549
Parabolic Trough	31.6	99.3	646
Flat Plate SG SS	65.6	101.1	311
Shallow Pond	138.7	185.1	147
Improved Evacuated Tube	37.1	104.1	549

[a] For Albuquerque, total annual load per residential unit (Q_{Load}) was 14,699 kWh. For Boston, Q_{Load} = 17,813 kWh, and for Copenhagen, Q_{Load} = 20,386 kWh.

[b] DG SS = double-glazed selective surface.

[c] SG SS = single-glazed selective surface.

Table 6.4 Energy Collected Annually at Fixed Temperature and Fixed Annual Load (kWh/m^2)

	Albuquerque		Boston		Kew	
Collector Type	70°C	40-100°C	70°C	40-100°C	70°C	40-100°C
Central Receiver	1750	1752	800	796	383[a]	383
Parabolic Trough	1530	1472	670	638	375	372
Advanced Evacuated Tube	1430	1329	700	636	337	334
Evacuated Tube	930	815	420	361	192	186
DG Flat Plate	1020	1015	440	450	222	195
SG Flat Plate	1050	1032	420	427	202	162
Shallow Solar Pond	710	698	280	275	26	15

[a] $\frac{1}{f}$ (51.3).

subsystem capacity costs vary by 43%. The comparison fails to show a near-term advantage for the more established technologies. In fact, the spread is nearly the same for current and mass-production costs, and less when our 1985 estimates are applied. This is probably a result of more rapid cost movement in the less mature technologies.)

Our figures show a clear dominance of the collector subsystem in the system costs in "current" scenarios. The "future" scenarios indicate that collector and storage costs could be comparable in areas where aquifers are not available and that these major subsystems become nearly equally important in the cost equation.

The purpose in presenting these cost estimates is solely to aid in the comparison of different solar-collector types. We have tried to treat each technology in a uniform, unbiased, and objective way, but the resulting cost figures are not to be construed as realistic estimates of system costs to be compared with those for conventional systems. In general, we would regard all the cost figures as optimistic; we have tried to choose performance and cost models that are indicative of the best results that could be expected independently of one another (i.e., the highest efficiency and the lowest cost) within each technology. It is certainly probable that, at least in early systems, assuring top performance will require large investments.

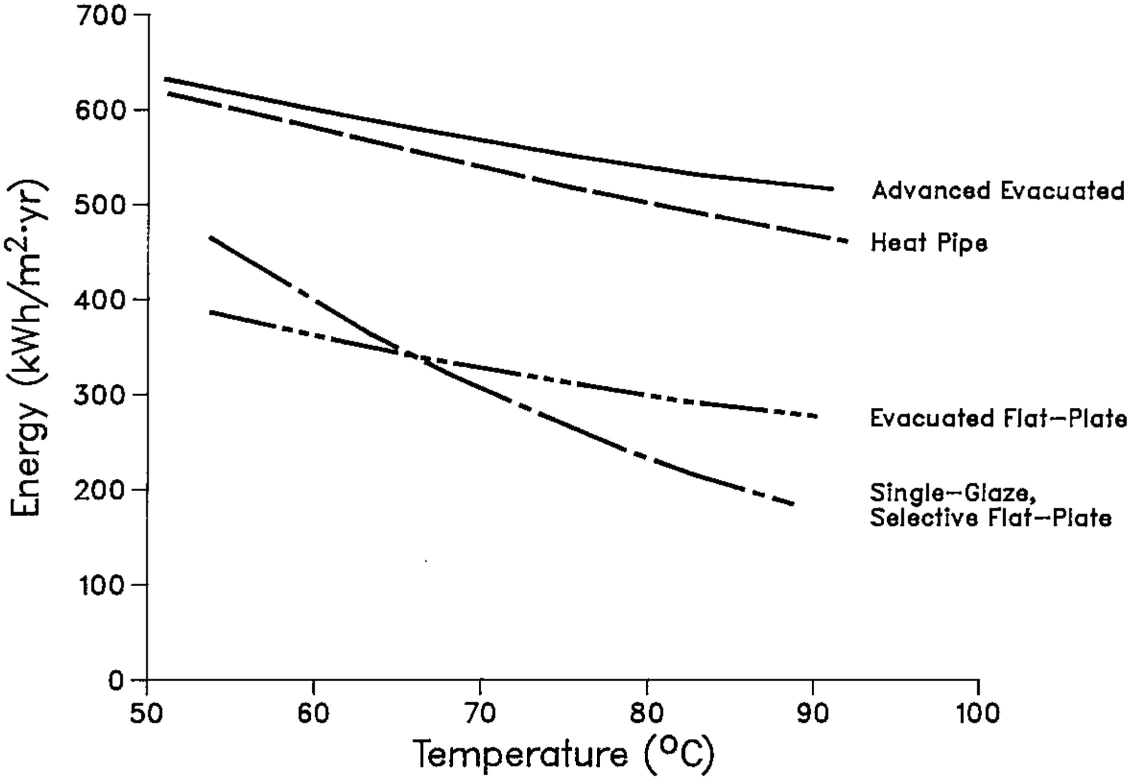


Fig. 6.11 Annual Energy Collected at Fixed Storage Temperature for Hamburg, West Germany

6.4 National Variations

We have not undertaken international comparisons of collector-subsystem costs in this report, although we have included most of the necessary information. The tables of the preceding sections contain information on energy productivity for fixed temperatures for some collector types in most of the subtask countries. On the basis of Sec. 6.2.3, these results could be used along with the array effects in Table 2.8 to estimate the performance of the subsystem in a seasonal-storage system. The collector-module costs from Table 5.8 can be used along with the modular estimation method of Sec. 5.1 to estimate the array costs. This level of detail may be adequate for the work of Subtasks 1(a) and possibly even 1(e). The design studies of Phase II will require more thorough, detailed performance and cost analysis.

Table 6.5 Cost-Effectiveness of Central Solar Heating Plants for Five Collector Subsystems: Boston, Massachusetts[a,b]

	Collector Type				
Performance and Cost Parameters	Flat-Plate, Single-Glazed	Flat-Plate, Evacuated Tube	Advanced Evacuated Stationary Concentrator	E-W Parabolic Trough	Central Receiver
Ideal Collector-Module Output (kWh/m^2)	450		636	638	736
Array Output-Reduction Factor	0.66	0.72	0.69	0.78	0.85
Estimated Array Output (kWh/m^2)	--	297	439	470	626
Required Collector Area (m^2/unit)	60		40.0	36	28
Required Lossless Storage Volume (m^3)	115		109	105	108
Collector Costs (\$/m^2)					
Current[c]	335	405	405	475	415
Future[d]	175	250	250	195	217
1985[e]	245	270	370	475	415
Collector-Subsystem Costs (\$/unit)					
Current[c]	20,100		16,200	17,100	11,600
Future[d]	10,500		10,000	7,000	6,100
1985[e]	14,700		14,800	17,100	11,600
Collector-Subsystem Capacity Costs [\$/(kWh/yr)]					
Current[c]	1.12		0.91	0.96	0.66
Future[d]	0.59		0.56	0.39	0.34
1985[e]	0.82		0.83	0.95	0.66
Storage-Subsystem Costs (\$/unit)					
Current, \$60/m^3[c]	6,936		6,540	6,276	6,468
Future, \$8/m^3[d]	920		870	840	860
1985, \$60/m^3[e]	6,936		6,540	6,276	6,468
Distribution-Subsystem Costs (\$/unit)	3,000		3,000	3,000	3,000
Total System Costs (\$/residential unit)					
Current[c]	30,040		25,740	26,376	21,068
Future[d]	14,420		13,670	10,840	9,960
1985[e]	24,636		24,340	26,376	21,068
System Capacity Costs [\$/(kWh/yr)]					
Current[c]	1.69		1.45	1.48	1.19
Future[d]	0.81		0.78	0.61	0.56
1985[e]	1.38		1.37	1.48	1.19
Approximate Levelized Energy Cost, M = 0.1 (\$/kWh)					
Current[c]	0.17		0.14	0.15	0.12
Future[d]	0.08		0.08	0.06	0.06
1985[e]	0.14		0.14	0.15	0.12

---

[a] Latitude of Boston = 42° N. Load = 17,813 kWh/yr.

[b] All comparisons are based on ideal (lossless) storage and distribution systems. Collector-subsystem costs and performance are based on models recommended in this report.

[c] Based on 1981 experience.

[d] Mass-production basis.

[e] Conceptual design.

Table 6.6 Cost-Effectiveness of Central Solar Heating Plants for Four Collector Subsystems: Copenhagen, Denmark[a,b]

	Collector Type			
Performance and Cost Parameters	Flat-Plate, Single-Glazed	Advanced Evacuated Stationary Concentrator	E-W Parabolic Trough	Central Receiver
Ideal Collector-Module Output (kWh/m^2)	311	549	646	875
Array Output-Reduction Factor	0.66	0.69	0.78	0.85
Estimated Array Output (kWh/m^2)	205	380	500	745
Required Collector Area (m^2/unit)	99	54	41	27
Required Lossless Storage Volume (m^3)	101	101	99	121
Collector Costs (\$/m^2)				
Current[c]	335	405	475	415
Future[d]	175	250	195	217
1985[e]	245	270	475	415
Collector-Subsystem Costs (\$/unit)				
Current[c]	33,165	21,870	19,475	11,205
Future[d]	17,325	13,500	7,995	5,860
1985[e]	24,255	14,580	19,475	11,205
Collector-Subsystem Capacity Costs [\$/(kWh/yr)]				
Current[c]	1.62	1.07	0.96	0.55
Future[d]	0.85	0.66	0.39	0.29
1985[e]	1.19	0.72	0.96	0.55
Storage-Subsystem Costs (\$/unit)				
Current, \$60/m^3[c]	6,060	6,060	5,940	7,260
Future, \$8/m^3[d]	808	808	792	968
1985, \$60/m^3[e]	6,060	6,060	5,940	7,260
Distribution-Subsystem Costs (\$/unit)	3,000	3,000	3,000	3,000
Total System Costs (\$/residential unit)				
Current[c]	42,225	30,930	28,415	21,465
Future[d]	21,133	17,310	16,935	9,830
1985[e]	33,315	23,640	28,415	21,465
System Capacity Costs [\$/(kWh/yr)]				
Current[c]	2.07	1.51	1.39	1.05
Future[d]	1.04	0.85	0.83	0.48
1985[e]	1.63	1.16	1.39	1.05
Approximate Levelized Energy Cost, M = 0.1 (\$/kWh)				
Current[c]	0.21	0.15	0.14	0.11
Future[d]	0.10	0.09	0.08	0.05
1985[e]	0.16	0.12	0.14	0.11

---

[a] Latitude of Copenhagen = 56° N. Load = 20,386 kWh/yr.

[b] All comparisons are based on ideal (lossless) storage and distribution systems. Collector-subsystem costs and performance are based on models recommended in this report.

[c] Based on 1981 experience.

[d] Mass-production basis.

[e] Conceptual design.

Table 6.7 Cost-Effectiveness of Central Solar Heating Plants for Four Collector Subsystems: Albuquerque, New Mexico[a,b]

Performance and Cost Parameters	Collector Type Flat-Plate, Single-Glazed	Advanced Evacuated Stationary Concentrator	E-W Parabolic Trough	Central Receiver
Ideal Collector-Module Output (kWh/m^2)	1,015	1,329	1,472	1,750
Array Output-Reduction Factor	0.66	0.69	0.78	0.85
Estimated Array Output (kWh/m^2)	670	917	1,148	1,490
Required Collector Area (m^2/unit)	22	16	13	10
Required Lossless Storage Volume (m^3)	87	81	77	78
Collector Costs $(\$/m^2)$				
Current[c]	335	405	475	415
Future[d]	175	250	195	217
1985[e]	245	270	475	415
Collector-Subsystem Costs $(\$/unit)$				
Current[c]	7,370	6,480	6,175	4,150
Future[d]	3,850	4,000	2,535	2,170
1985[e]	5,390	4,320	6,175	4,150
Collector-Subsystem Capacity Costs $[\$/(kWh/yr)]$				
Current[c]	0.50	0.44	0.41	0.28
Future[d]	0.26	0.27	0.17	0.14
1985[e]	0.37	0.29	0.41	0.28
Storage-Subsystem Costs $(\$/unit)$				
Current, $\$60/m^3$[c]	4,820	4,490	4,260	4,320
Future, $\$8/m^3$[d]	696	648	616	624
1985, $\$60/m^3$[e]	4,820	4,490	4,260	4,320
Distribution-Subsystem Costs $(\$/unit)$	3,000	3,000	3,000	3,000
Total System Costs $(\$/residential\ unit)$				
Current[c]	15,190	13,970	13,540	11,470
Future[d]	7,550	7,650	6,150	5,790
1985[e]	10,478	11,810	10,020	11,470
System Capacity Costs $[\$/(kWh/yr)]$				
Current[c]	1.04	0.95	0.92	0.78
Future[d]	0.51	0.52	0.41	0.39
1985[e]	0.71	0.80	0.92	0.78
Approximate Levelized Energy Cost, $M = 0.1$ $(\$/kWh)$				
Current[c]	0.10	0.10	0.09	0.08
Future[d]	0.05	0.05	0.04	0.03
1985[e]	0.07	0.08	0.09	0.08

[a] Latitude of Albuquerque = 35° N. Load = 14,669 kWh/yr.

[b] All comparisons are based on ideal (lossless) storage and distribution systems. Collector-subsystem costs and performance are based on models recommended in this report.

[c] Based on 1981 experience.

[d] Mass-production basis.

[e] Conceptual design.

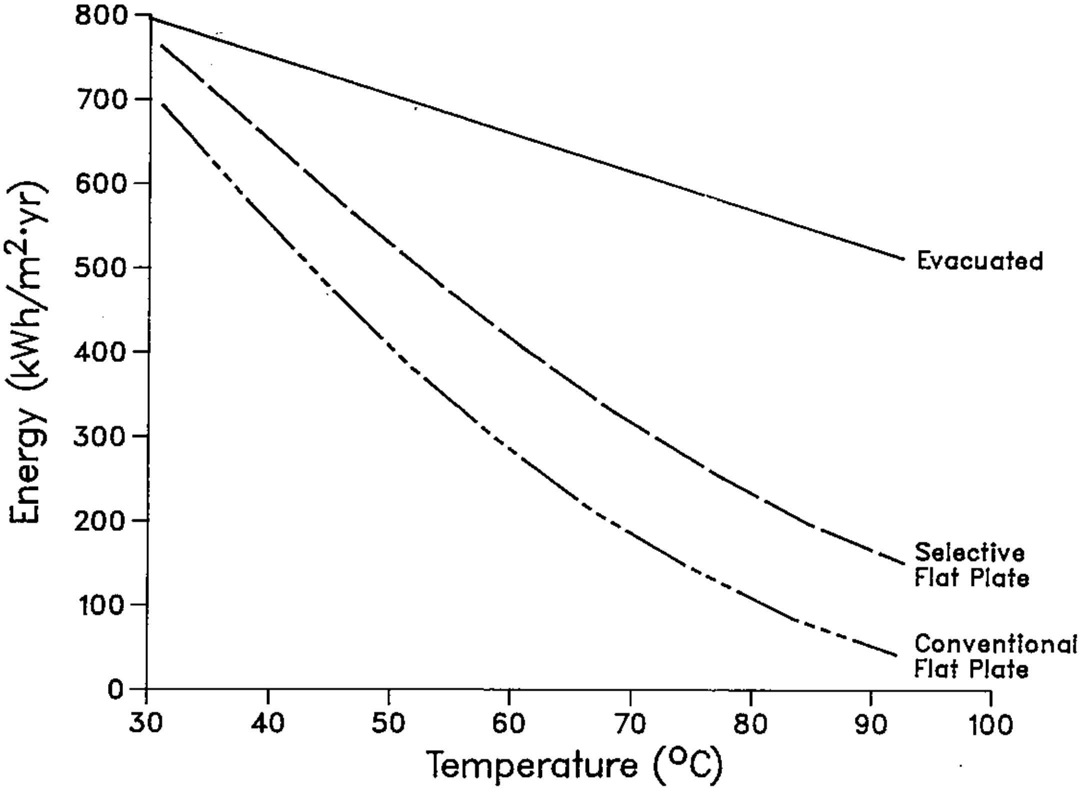


Fig. 6.12 Annual Energy Collected at Fixed Storage Temperature for CEC, Ispra, Italy

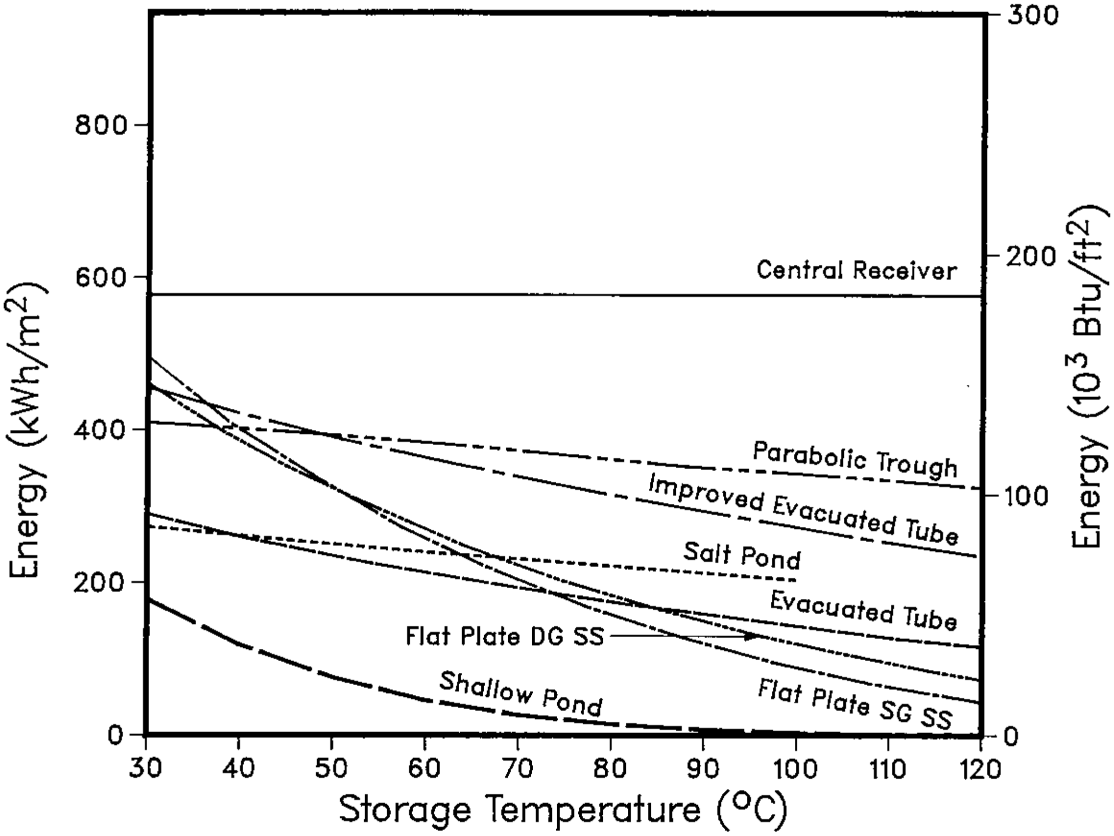


Fig. 6.13 Annual Energy Collected at Fixed Storage Temperature for Kew, United Kingdom

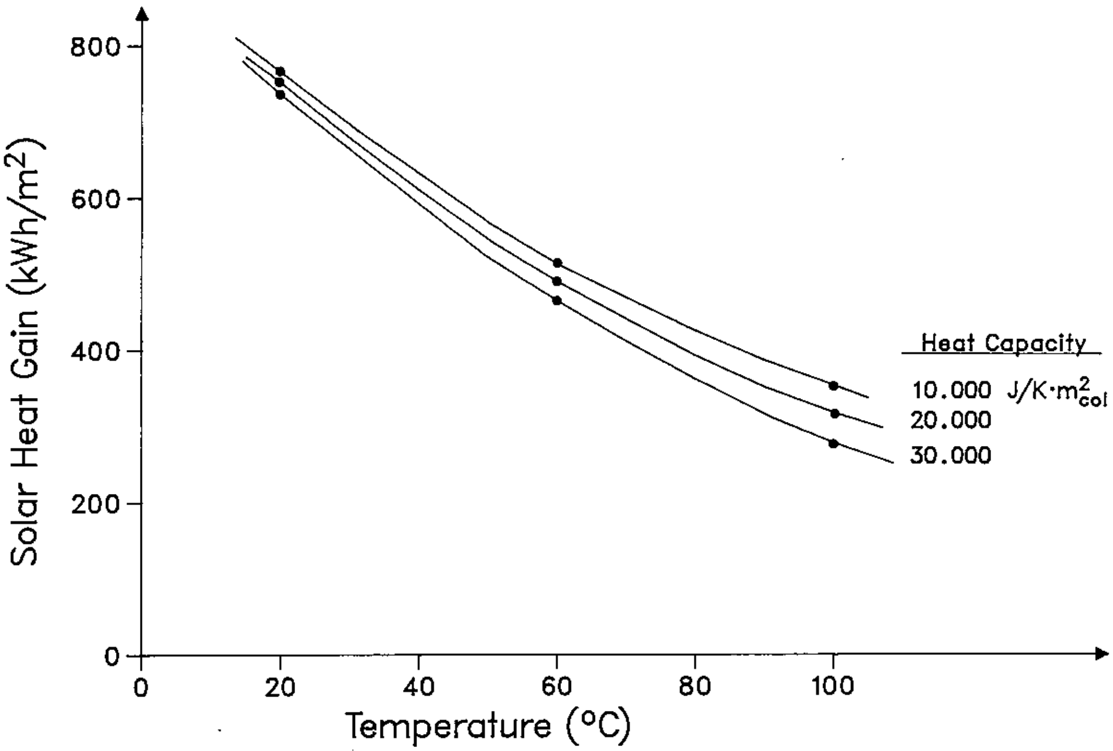


Fig. 6.14 Annual Energy Collected at Fixed Storage Temperature for The Netherlands

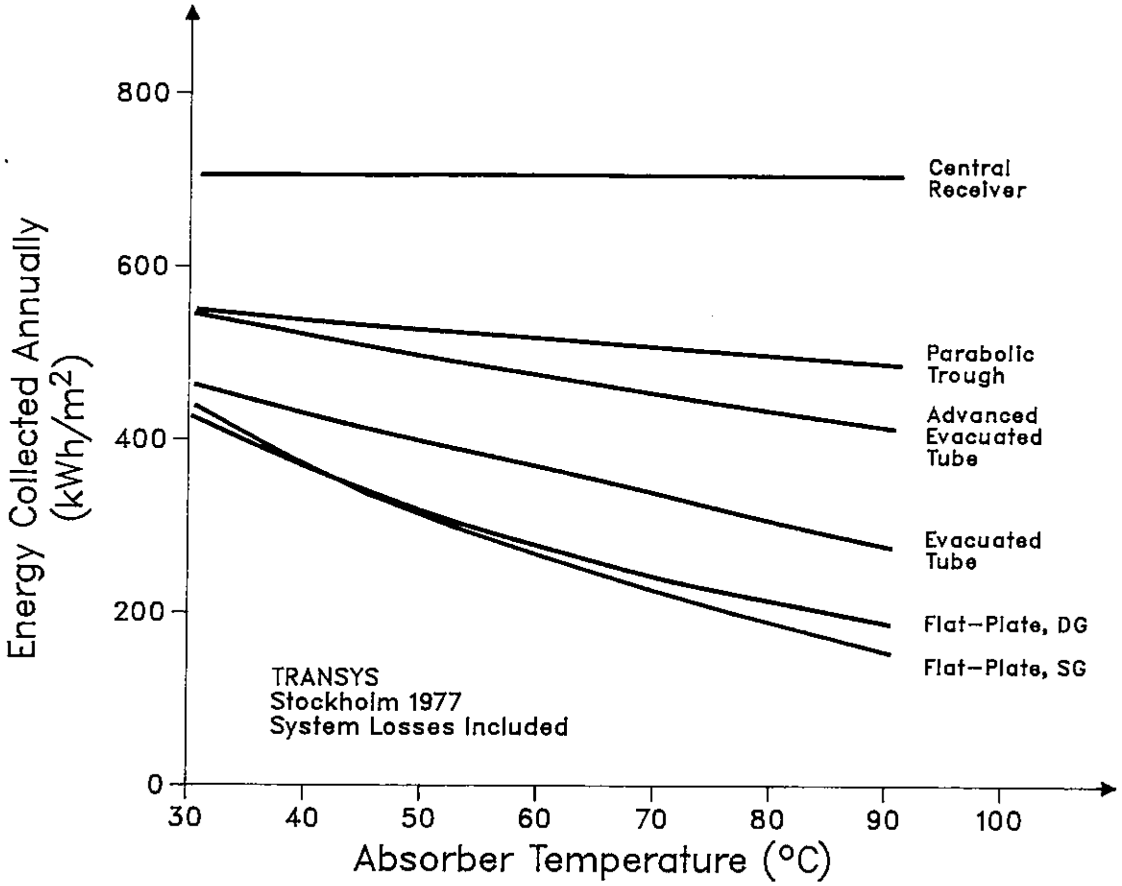


Fig. 6.15 Annual Energy Collected at Fixed Storage Temperature for Stockholm, Sweden

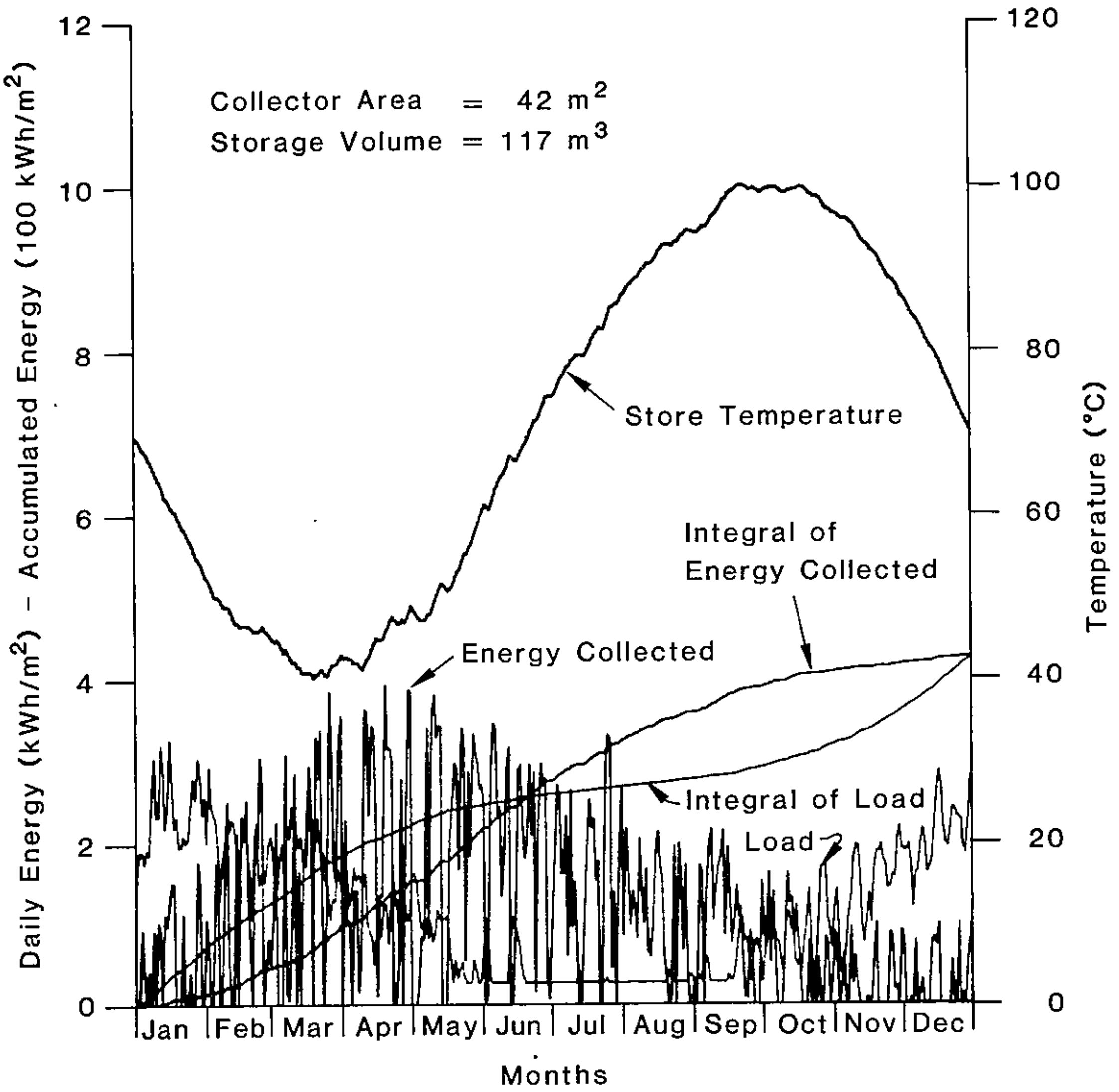


Fig. 6.16 Annual Energy Collected and Storage Temperatures for Ideal System with Fixed Annual Load

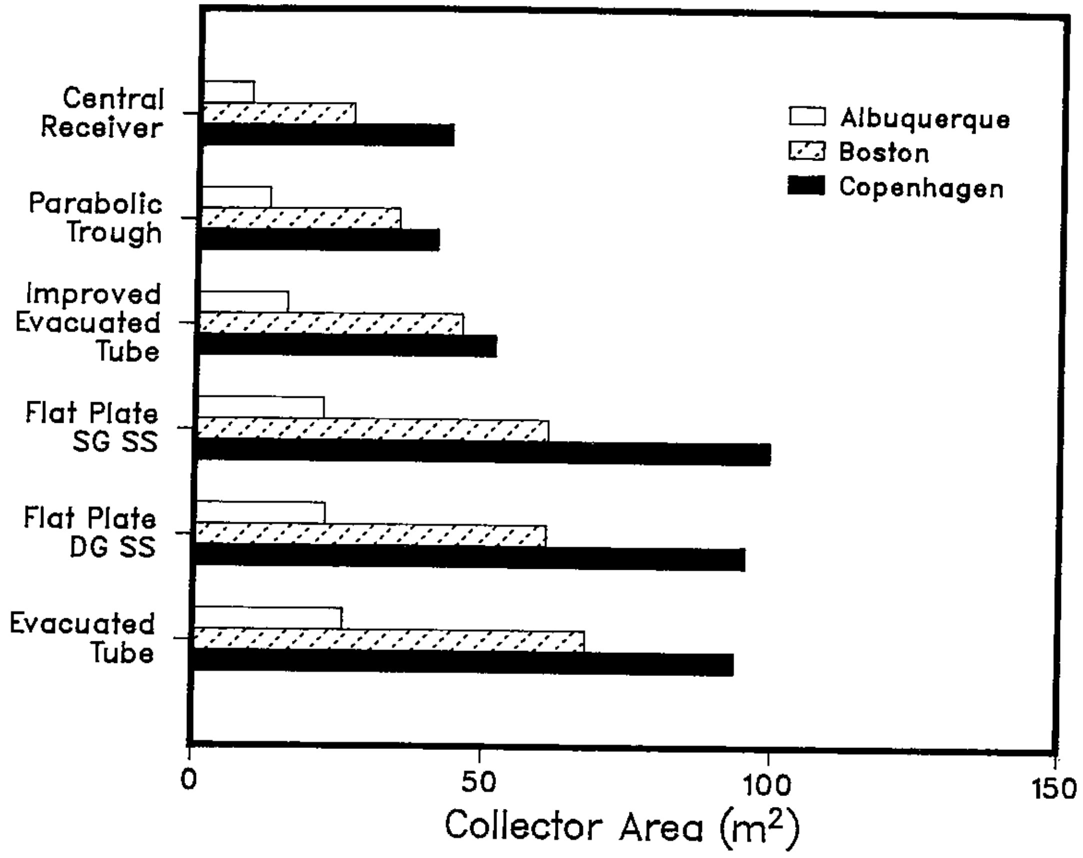


Fig. 6.17 Collector Areas Required to Meet Fixed Annual Load

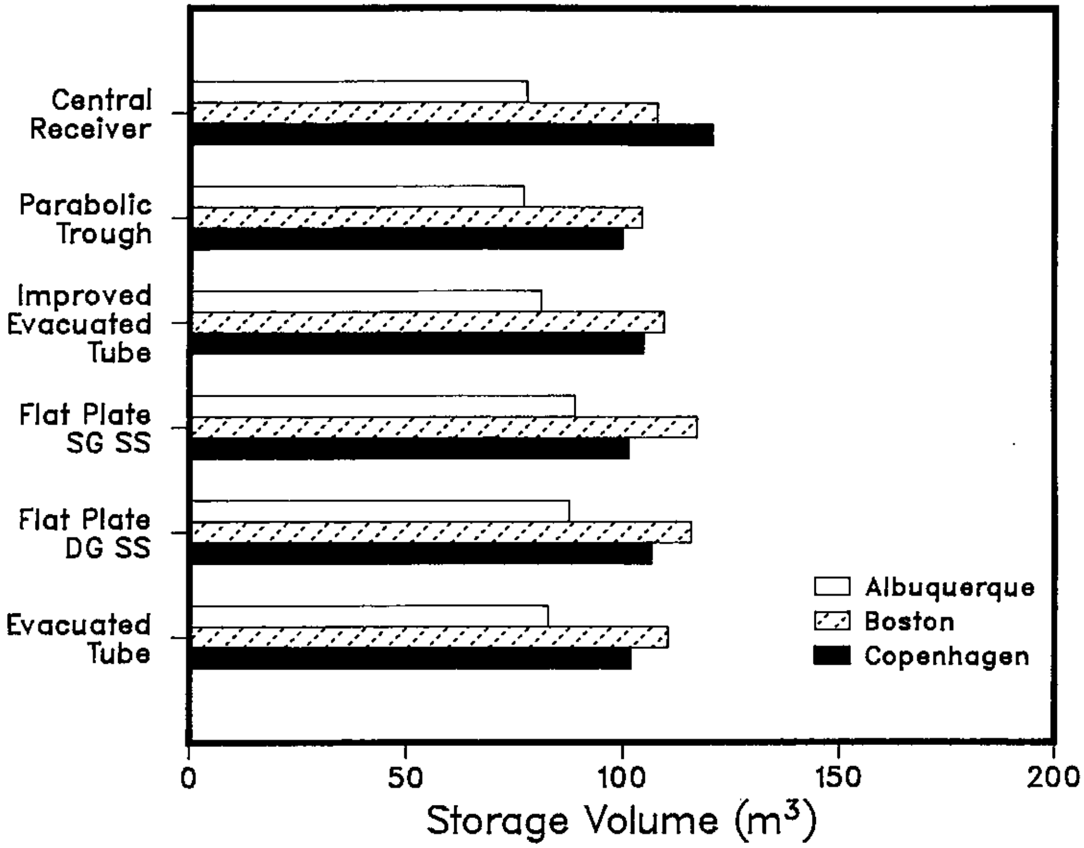
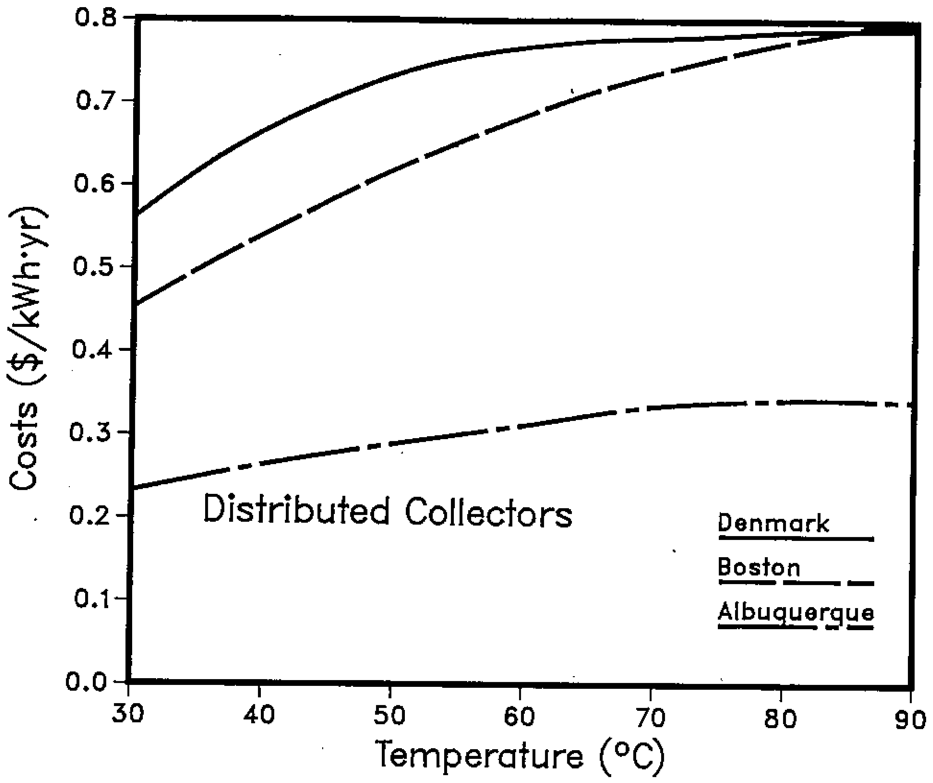


Fig. 6.18 Storage Volumes Required to Meet Fixed Annual Load



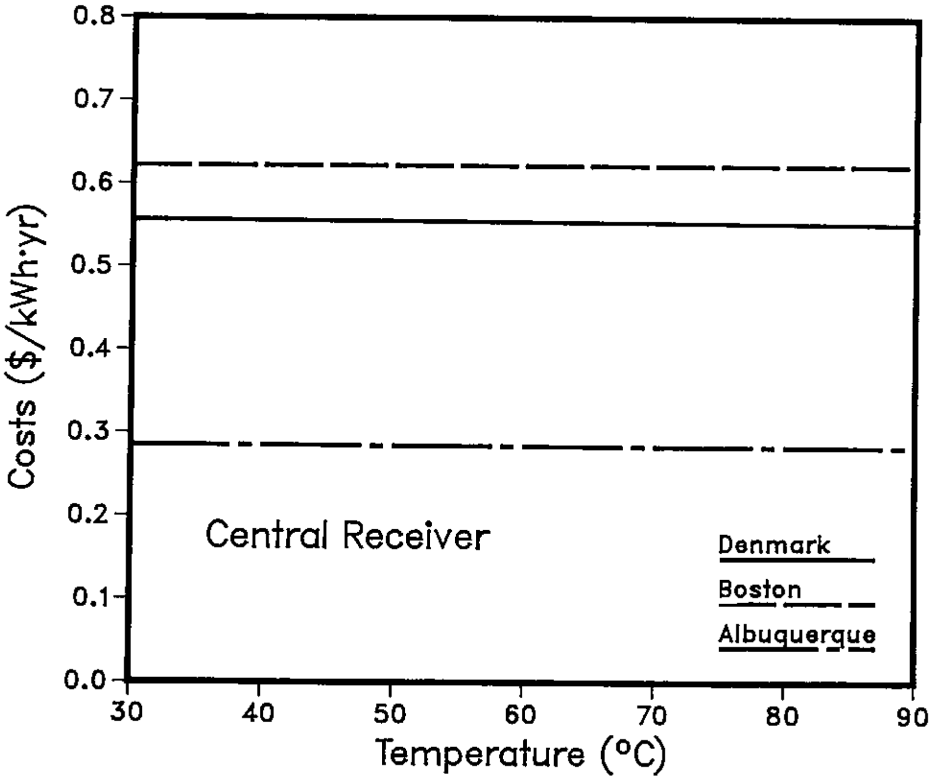


Fig. 6.19 Subsystem Costs for Large Arrays in 1985

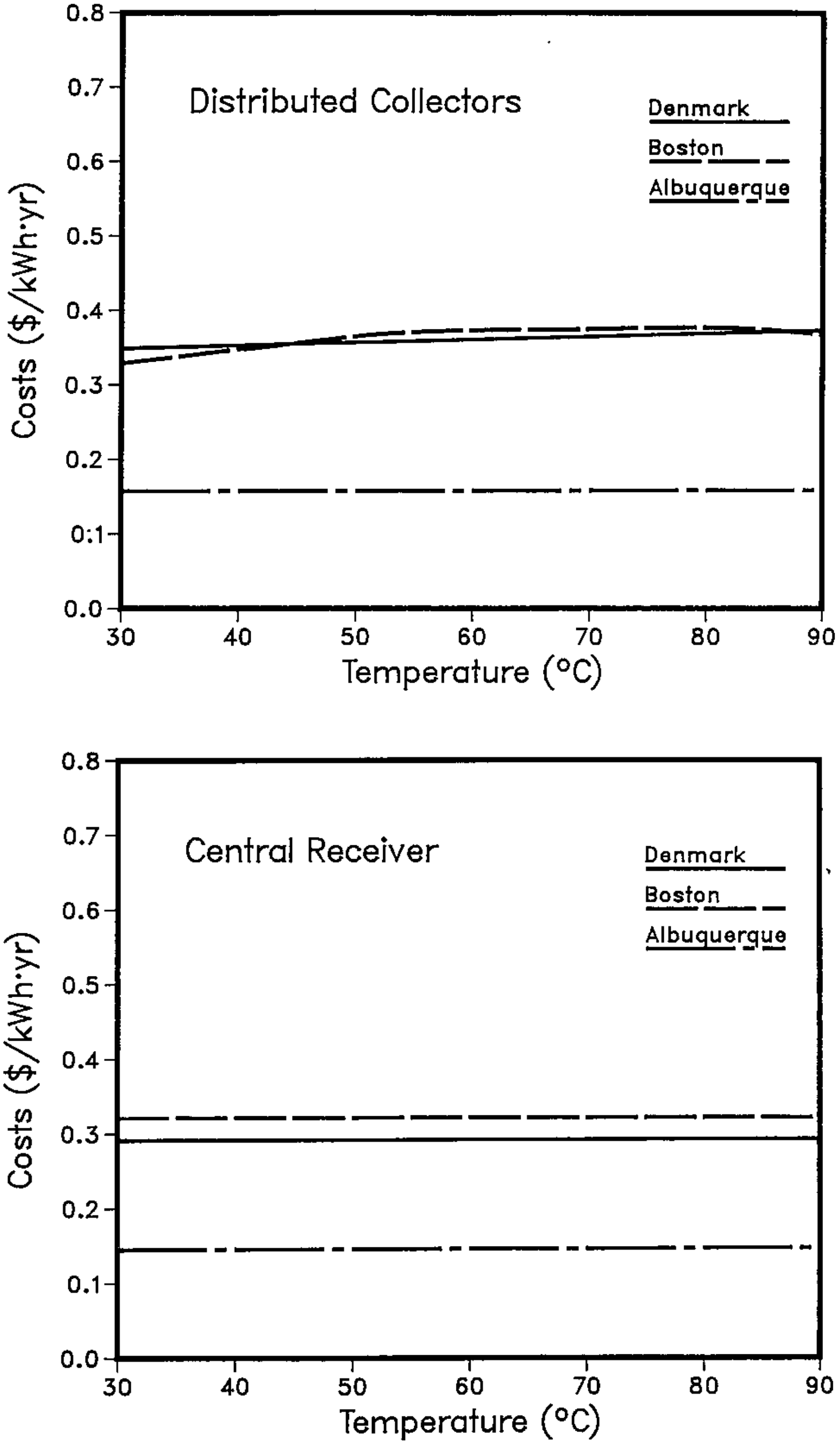


Fig. 6.20 Subsystem Costs for Future Large Arrays

7 INFORMATION ON MODELS

7.1 Collector-Subsystem Models for MINSUN

A primary objective of the work of Subtask 1(b) was to provide reliable performance and cost models for use in system-optimization studies using the MINSUN system-optimization code developed by Subtask 1(a) for the Task VII studies. Tables 2.4-2.6 and 2.8 constitute the basis for the performance models developed for use with MINSUN; however, the nature of the calculational procedures employed by MINSUN makes an additional step necessary for implementation. MINSUN works with relatively large time steps (usually a day or a week); therefore, this code does not keep track of the time of day or the sun angles during its integration cycle. Because these variables are essential to proper calculation of the collector output, a preliminary calculational step was required in which the energy output of the collector for various inlet (storage) fluid temperatures was calculated by hour-by-hour simulation of the collectors represented in Tables 2.4-2.6. The daily integrals were then stored in three-dimensional arrays (collector, day, temperature) for each site under consideration for use in MINSUN. The results were then modified by applying the collector-array output-reduction factors from Table 2.8.

The collector-output integration program was originally written in Basic by Jim Hedstrom at LANL. The Basic program output was written onto magnetic tape and sent to Canada for use with the MINSUN program. This procedure did not allow users of MINSUN to adjust parameters of the collector models to fit national experience, so the collector code was translated from Basic to FORTRAN and integrated into the MINSUN preprocessor routine UMSORT by the Canadian 1(a) group. The FORTRAN listing of the computer program is Appendix A of this report.

7.2 Collector Models for TRNSYS

TRNSYS is a quasi-steady system-simulation code that calculates energy flow and fluid state points for steady flow in an arbitrary set of components (such as collectors, pumps, valves, tanks, etc.) in response to slowly varying boundary conditions (solar insolation and ambient temperature). The time interval is arbitrary, but it should generally be large compared to the time constants of the components in order to justify the quasi-steady assumption; because insolation data are frequently presented on an hourly basis, TRNSYS is frequently used with one-hour time steps. The authors of TRNSYS (University of Wisconsin) have built a great deal of modeling flexibility into the code.[93] There are some 30 subroutines available to model components. At least five calculational algorithms for collectors were available when this project started, but several of these were based upon theoretical models that are not applicable to all collectors considered here. One subroutine, Mode 5, allows collector efficiencies and incident-angle modifiers to be entered in tabular form and can, therefore, be used to couple any analytical or numerical collector models to the TRNSYS code. We have not constructed any specific models for TRNSYS, but we recommend the use of Mode 5 as the most straightforward method of adapting the models of Tables 2.4-2.6 and 2.8.

7.3 Cost Models

The basic data for cost modeling are contained in the tables of Chapter 5. We have not attempted to produce computer-language models for use in MINSUN, but the procedure is straightforward using methods similar to the modular estimating method shown in Fig. 5.1. A computer code based on the modular method, ECONMAT, is available from SERI.[94]

W. Whitman, Boston Redevelopment Authority
A. Wijsman, Institute of Applied Physics, Delft, The Netherlands (2)
W. Wilson, Sandia National Laboratory, Livermore, Calif.
B. Winn, Solar Environmental Engineering Co., Fort Collins, Colo.
P. Woodbury, National Park Service, Boston
S. Yuan, George Washington University, Washington, D.C.
A. Zaidi, W.L. Wardrap and Associates, Winnipeg, Canada
M. Zarea, Universidad Simon Bolivar, Caracas, Venezuela
D. Zaslavsky, Ministry of Energy and Infrastructure, Jerusalem, Israel
H. Zinko, Studsvik Energiteknik AB, Nykoping, Sweden (2)

T. Noguchi, Government Industrial Research Institute -- AIST, MITI, Nagoya, Japan (2)
E. Ofverholm, Swedish Council for Building Research, Stockholm (2)
M. Older, Boston Redevelopment Authority, Boston
I. Oliker, Burns and Roe, Inc., Oradell, N.J.
M. Olszewski, Oak Ridge National Laboratory, Tenn.
P. Petersen, Ministry of Energy, Copenhagen (2)
S. Pinkerton, Massachusetts Office of Energy Resources, Boston
R. Potter, Los Alamos National Laboratory, N.M.
G. Purcell, Electric Power Research Institute, Palo Alto, Calif.
V. Rabl, Electric Power Research Institute, Palo Alto, Calif.
B. Rawlings, McLachlan Group, Melbourne, Australia
K. Reed, National Bureau of Standards, Washington, D.C.
H. Riemer, Kernforschungsanlage Julich, Federal Republic of Germany
B. Rogers, University College, Cardiff, U.K. (2)
R. Rogers, Power Kinetics, Inc., Troy, N.Y.
D. Rose, Charlestown Navy Yard, National Park Service, Boston
F. Salvesen, A/S Miljoplan, Sandvika, Norway (2)
G. Schaffar, Institut fur Allgemeine Physik, Vienna (2)
G. Schnee, The Greater Roxbury Development Corp., Roxbury, Mass.
F. Scholz, Kernforschungsanlage Julich, Federal Republic of Germany
G. Schriber, Federal Office of Energy, Bern, Switzerland (2)
S. Schweitzer, U.S. Department of Energy, Washington, D.C.
P. Sens, Netherlands Energy Research Foundation, Petten, The Netherlands (2)
A. Sigmund, Austrian Institute for Building Research, Vienna (2)
A. Smart, Department of National Development and Energy, Canberra, Australia (2)
W. Soderberg, University of Minnesota, Minneapolis
G. Spielmann, Austrian Institute for Building Research, Vienna (2)
A. Strub, Commission of the European Communities, Brussels, Belgium (2)
R. Sundberg, Minnesota Department of Energy, Planning and Development, Minn.
S. Swaile, Boston Redevelopment Authority
C.J. Swet, Mount Airy, Md.
R. Tabors, Massachusetts Institute of Technology, Cambridge
H. Talarek, Kernforschungsanlage Julich, Federal Republic of Germany (2)
G. Tenet, Solar Energy Industries Assn., Washington, D.C.
W. Tolbert, U.S. Air Force, Golden, Colo.
R. Torrenti, Ecole des Mines, Valbonne, France (2)
C. Tsang, Lawrence Berkeley Laboratory, Calif.
J. van Gilst, Sorane S.A., Lausanne, Switzerland (2)
D. van Hattem, Joint Research Center, Ispra, Italy (2)
A.V. Verganelakis, Ministry of Research and Technology, Athens, Greece (5)
T. Vijverman, National Program for Energy R&D, Brussels, Belgium (2)
F. Vivona, Consiglio Nazionale Ricerche, Rome (5)
M. Wahlig, Lawrence Berkeley Laboratory, Calif.
P. Wattiez, International Energy Agency, Almeria, Spain

G. Hellstrom, University of Lund, Sweden (2)
T. Hirono, Agency of Industrial Science and Technology -- MITI, Tokyo (2)
P. Holst, Studsvik Energiteknik, Nykoping, Sweden
M. Holtz, National Assn. of Home Builders Research Foundation, Westminster, Colo. (2
H. Jacobs, Interatom, Almeria, Spain
D. Jardine, Kaman Sciences Corp., Colorado Springs
T. Jilar, Chalmers University of Technology, Goteborg, Sweden
A. Kalt, DFVLR, Koeln, Federal Republic of Germany
P. Kando, National Assn. of Home Builders Research Foundation, Rockville, Md.
S. Kaneff, The Australian National University, Canberra
L. Kannberg, Battelle Pacific Northwest Laboratory, Richland, Wash. (2)
S. Karaki, Colorado State University, Fort Collins
P. Karlsson, Swedish State Power Board, Vallingby, Sweden (2)
M. Karnitz, Oak Ridge National Laboratory, Tenn.
D. Kash, University of Oklahoma
P. Kjaerboe, Viak AB, Vallingby, Sweden
E. Kjellsson, Uppsala Kraftvarme AB, Uppsala, Sweden (2)
H. Klein, Ministry for Research and Technology, Bonn-Bad Godesburg, Federal Republic of Germany (2)
V. Korsgaard, Technical University of Denmark, Lyngby (2)
F. Kreith, Solar Energy Research Institute, Golden, Colo.
D. Krischel, Interatom, Bergisch-Gladbach, Federal Republic of Germany (2)
R. LaFontaine, Oscar Faber & Partners, St. Albans, Herts, U.K. (2)
A. Lannus, Electric Power Research Institute, Palo Alto, Calif.
R. LeChevalier, U.S. Department of Energy, Oakland, Calif.
T. LeFeuvre, National Research Council, Ottawa, Ontario, Canada (4)
G.O.G. Lof, Solaron, Denver
G. Long, Harwell Atomic Enerkgy Research Establishment, Oxfordshire, U.K. (2)
V. Lottner, Kernforschungsanlage Julich, Federal Republic of Germany (5)
K.G. Lund, National Research Council, Ottawa, Ontario, Canada
C.C. Mangold, U.S. Department of Energy, Washington, D.C.
P. Margen, Margen-Consult, Nykoping, Sweden
J. Martin, Oak Ridge National Laboratory, Tenn.
J. Martin, University of Lowell/International Energy Agency, Almeria, Spain
A. McGarity, Swarthmore College, Penn.
D. McKay, Atmospheric Environment Services, Downsview, Ontario, Canada (2)
T. McMahon, Australian Delegation to Organization for Economic Cooperation and Development, Paris (2)
L. Mims, Chicago
J. Mitchell, University of Wisconsin, Madison
C. Moore, Center for Community Technology, Madison, Wis.
E. Morofsky, Public Works Canada, Ottawa, Ontario
F. Morse, U.S. Department of Energy, Washington, D.C. (10)
R. Mounts, U.S. Conference of Mayors, Washington, D.C.
D. Neeper, Los Alamos National Laboratory, Los Alamos
J. Nilsson, Riksbyggen, Stockholm (2)

T. Bostrom, Swedish Council for Building Research, Stockholm (2)
R. Bourne, Solar Concept Development Corp., Davis, Calif.
A. Boysen, Hidemark Danielson Ark. HB, Stockholm (25)
D. Breger, Solar Thermal Storage Program, Allston, Mass. (2)
B.J. Brinkworth, University College, Cardiff, U.K. (2)
T. Bruce, Sodertalje Energiverk, Sodertalje, Sweden (2)
M. Bruck, Austrian Solar and Space Agency, Vienna (2)
B. Butler, Science Applications, Inc., La Jolla, Calif.
R. Carmona, International Energy Agency, Almeria, Spain
M. Cederstrom, Swedish State Power Board, Vallingby, Sweden
V. Chant, Hickling Management Consultants, Ltd., Ottawa, Ontario, Canada (2)
P. Chuard, Sorane S.A., Lausanne, Switzerland (2)
J. Claesson, University of Lund, Sweden
C. Cluff, University of Arizona, Tucson, Ariz.
T. Cole, Jet Propulsion Laboratory, Pasadena, Calif.
D. Corrsin, Boston Redevelopment Authority, Mass.
R. Dahl, Kernforschungsanlage Julich, Federal Republic of Germany
W. D'Alessandro, Solar Age, Harrisville, N.H.
K. Davidson, Gas Research Institute, Chicago
A. Davis, Alternate Energy Resources, Inc., El Paso, Texas
E. DeMora Fiol, Spanish Delegation to Organization for Economic Cooperation and Development (OECD), Paris (2)
C. den Ouden, Institute of Applied Physics, Delft, The Netherlands (10)
F. de Winter, Atlas Corp., Santa Cruz, Calif.
B. Dikkers, National Bureau of Standards, Washington, D.C.
M. Donn, Victoria University of Wellington, New Zealand (2)
W. Duff, Colorado State University, Fort Collins (2)
H. Eder, Eder Solar and Public Solar Power Coalition, Los Angeles, Calif.
K. Eriksson, Energiverken I Goteborg, Sweden
R. Engwall, Swedish Council for Building Research, Stockholm
G. Faninger, Austrian Solar and Space Agency, Vienna (2)
S. Fralick, San Diego Gas and Electric Co., Calif.
J.F. Friedrich, Kernforschungsanlage Julich, Federal Republic of Germany (2)
W. Gerant, U.S. League of Cities, Washington, D.C.
J.H. Gibbons, Office of Technology Assessment, U.S. Congress
J. Gleason, Self Reliance District Heating Group, Washington, D.C.
P. Golobic, Ministry of Energy, Toronto, Ontario, Canada
J. Goya, INTA, Madrid, Spain (2)
J. Guertin, Massachusetts Office of Energy Resources, Boston
H. Gurney, Boston National Historical Park, Mass.
I. Gyuk, U.S. Department of Energy, Washington, D.C.
J. Hadorn, Sorane S.A., Lausanne, Switzerland (25)
R. Hakansson, Studsvik Energiteknik AB, Nykoping, Sweden (2)
K. Hansen, Technical University of Denmark, Lyngby, Denmark (4)
T. Hansen, Danish Solar Energy Testing Laboratory, Taastrup, Denmark
T. Haskill, DSIR, Wellington, New Zealand (2)
P. Heinzelmann, International Energy Agency, Paris (2)

Distribution for ANL/ES-139

Internal:

J.W. Allen
J.G. Asbury
F.C. Bennett
R.L. Cole
E.J. Croke
J.J. Dzingel
A.J. Gorski
P.R. Hirsch
J.R. Hull
D. Karvelas
A.S. Kennedy
A.B. Krisciunas
K.S. Macal
A.I. Michaels (12)
R.B. Poeppel
D. Ramaswami
J.J. Roberts
W.W. Schertz (5)
J.F. Tschanz
R.W. Weeks
ANL Contract Copy
ANL Libraries
TIS Files (6)

External:

U.S. Department of Energy Technical Information Center,
for distribution per UC-59a (324)
Manager, U.S. Department of Energy, Chicago Operations Office (DOE-CH)
Chief, Office of Patent Counsel, DOE-CH
Energy and Environmental Systems Division Review Committee:
H.J. Barnett, Washington University
R.S. Berry, The University of Chicago
B.A. Egan, Environmental Research and Technology, Inc., Concord, Mass.
W.H. Esselman, Electric Power Research Institute, Palo Alto, Calif.
M.H. Kohler, Bechtel Group, Inc., San Francisco
N.C. Mullins, Indiana University
J.J. Stukel, University of Illinois, Urbana
J.J. Wortman, North Carolina State University
P. Achard, Ecole des Mines, Valbonne, France
D. Aitken, Western Solar Utilization Network, Portland, Ore.
R. Aldwinckle, National Research Council, Ottawa, Ontario, Canada (5)
R. Allen, University of Maryland, College Park
K. Anderson, Office of Senator E.M. Kennedy, Boston
H. Andersson, Swedish Council for Building Research, Stockholm
J. Andrews, Brookhaven National Laboratory, Upton, N.Y.
S. Angus, Hooper and Angus Associates, Ltd., Toronto, Ontario, Canada
E. Aranovitch, Joint Research Center, Euratom, Ispra, Italy (2)
B. Baeyens, National Program for Energy R&D, Brussels, Belgium (2)
C. Bankston, Washington, D.C. (10)
W. Barnes, U.S. Air Force Academy, Colorado Springs
S. Baron, Burns and Roe, Inc., Oradell, N.J.
J. Bigger, Electric Power Research Institute, Palo Alto, Calif.
R. Biggs, National Research Council, Ottawa, Ontario, Canada (2)
J. Birk, Electric Power Research Institute, Palo Alto, Calif.
W. Blanchette, Boston National Historical Park
S. Blum, TPI, Inc., Beltsville, Md. (2)

β	Surface tilt (0 to +90°; positive if normal to surface points toward equator)
γ	Azimuth of a surface (0 to 360°; clockwise from North)
ε	Infrared emittance of a surface
η	Efficiency
	η_c, collector efficiency η_t, system thermal efficiency η_o, collector optical efficiency η_d, collector optical efficiency for diffuse radiation
θ	Incident angle (0 to +90°; measured from perpendicular)
	θ_{EW}, measured in east-west plane normal to collector θ_{NS}, measured in north-south plane normal to collector
θ_c	Acceptance angle of CPC collector
θ_z	Zenith angle (0 to +90°)
κ	Time constant
λ	Altitude of sun (0 to +90°)
ρ_s	Reflectance for solar radiation
σ	Stefan-Boltzmann constant (5.67×10^{-8} W/m$^2 \cdot$ K^4)
τ	Transmittance
$\tau\alpha$	Transmittance-absorptance product of a collector
ϕ	Latitude (0 to ±90°; North is positive)
ω	Hour angle of sun (0 to 360°; noon is 0°, afternoon is positive)
ψ	Collector coverage (aperture area divided by ground area)

Q	Energy (J)
	Q_c, energy collected Q_ℓ, energy lost Q_s, energy stored
r	Reflectivity
S_{on}	Insolation level (W/m^2)
t	Time (s)
T	Temperature (K or °C)
	T_a, ambient temperature T_c, collector temperature T_i, inlet temperature T_L, load temperature T_p, plate temperature in flat-plate collector T_s, storage temperature T, long-term average (annual)
U	Thermal conductance (W/m^2 · K)
U_L	Overall collector heat-loss coefficient (W/m^2 · K)
V	Speed (m/s)

Secondary Subscripts

f	Fluid
i	Inlet, inside
m	Mean
o	Outlet, outside
START	Refers to collector-pump start condition
STOP	Refers to collector-pump stop condition

Greek Symbols

α	Absorptance of receiver

NOMENCLATURE

A	Area (m^2) A_c, collector aperture area A_g, ground area covered by collector array
b_o	Incident-angle modifier coefficient
C	Concentration ratio
c_p	Constant-pressure specific heat (J/kg · K)
f	Row shading factor
F	Collector heat-removal efficiency factor F_R, based on collector inlet temperature F_o, based on collector outlet temperature
I	Irradiance (W/m^2) I_a, irradiance available to a collector I_b, beam irradiance I_d, diffuse irradiance I_g, global irradiance I_h, global irradiance on a horizontal surface
K	Total heat loss from an array
$K_{\alpha\tau}$	Incident-angle modifier (flat plate)
$K_{\rho\alpha\tau}$	Correction factor for incident-angle modifier (evacuated tube and parabolic trough)
L	Length (m)
$\dot{m}_c$	Collector mass-flow rate per unit collector area (kg/s · m^2)
M	Total mass (kg)
$\dot{M}$	Total mass-flow rate (kg/s) $\dot{M}_c$, collector mass-flow rate
N	Number of collector rows

INITIALISMS

ANL	Argonne National Laboratory
APRR	Advanced Program Research Requirements
BNL	Brookhaven National Laboratory
CEC	Commission of the European Communities
CMHC	Canada Mortgage and Housing Corp.
CPC	Compound parabolic concentrator
CSHP	Central solar-heating plant
CSHPSS	Central solar-heating plant with seasonal storage
DD	Degree day
DG	Double-glazed
DG SS	Double-glazed, selective surface
DHW	Domestic hot water
DOE	U.S. Department of Energy
DSET	Desert Solar Exposure Test Laboratory
ETC	Evacuated-tube collector
ETS	Energy-transport system
E-W	East-West
F.O.B.	Freight on board
FPC	Flat-plate collector
GE	General Electric Co.
GM	General Motors Corp.
GRI	Gas Research Institute
HP	Heat pipe
IEA	International Energy Agency
IPH	Industrial process heat
JPL	Jet Propulsion Laboratory
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
N-S	North-South
NAHB	National Association of Homebuilders
NBS	U.S. National Bureau of Standards
NSDN	National Solar Data Network
OECD	Organization for Economic Cooperation and Development
OI	Owens-Illinois, Inc.
O&M	Operating and maintenance
PNL	Battelle Pacific Northwest Laboratory
PTC	Parabolic-trough collector
R&D	Research and development
SERI	Solar Energy Research Institute
SG	Single-glazed
SG SS	Single-glazed selective surface
SNLA	Sandia National Laboratory at Albuquerque (N.M.)
SNLL	Sandia National Laboratory at Livermore (Calif.)
TMY	Typical meteorological year
TNO/TH	Institute of Applied Physics (Delft, The Netherlands)

APPENDIX B: LIST OF TASK VII REPORTS

Tools for Design and Analysis, Verne G. Chant and Ronald C. Biggs, National Research Council, Canada, available as CENSOL1 from Technical Information Office, Solar Energy Program, National Research Council, Ottawa, Canada, K1A OR6 (Dec. 1983).

The MINSUN Simulation and Optimization Program: Application and User's Guide, edited by Verne G. Chant and Rune Hakansson, National Research Council, Canada, available as CENSOL2 from Technical Information Office, Solar Energy Program, National Research Council, Ottawa, Canada, K1A OR6 (Dec. 1983).

Basic Performance, Cost, and Operation of Solar Collectors for Heating Plants with Seasonal Storage, Charles A. Bankston, Argonne National Laboratory, USA, available as ANL/ES-139 from National Technical Information Services, 5285 Port Royal Road, Springfield, Va. 22161, USA (May 1983).

Heat Storage Models: Evaluation and Selection, Pierre Chuard and Jean-Christophe Hadorn, Eidgenossische Drucksachen und Material Zentrale, Bern, Switzerland, available from EDMZ, Switzerland.

Cost Data and Cost Equations for Heat Storage Concepts, Pierre Chuard and Jean-Christophe Hadorn, Eidgenossische Drucksachen und Material Zentrale, Bern, Switzerland, available from EDMZ, Switzerland (June 1983).

Heat Storage Systems: Concepts, Engineering Data and Compilation of Projects, Pierre Chuard and Jean-Christophe Hadorn, Eidgenossische Drucksachen und Material Zentrale, Bern, Switzerland, available from EDMZ, Switzerland.

Basic Design Data for the Heat Distribution System, Tomas Bruce, Lennart Lindeberg, and Stefan Roslund, Swedish Council for Building Research, Sweden, available as D22:1982 from Svensk Byggtjanst, Box 7853, S-10399, Stockholm, Sweden (Oct. 1982).

APPENDIX B:

LIST OF TASK VII REPORTS

```
C
      WRITE(LUW,150)
  150 FORMAT(1X,130(1H*))
C
      WRITE(LUW,200)
  200 FORMAT(1H ,'*       MONTH        *   J   *   F   *   M   *'
     $,'   A   *   M   *   J   *   J   *   A   *   S   *   O   *'
     $,'   N   *   D   **   YEAR   *')
      WRITE(LUW,150)
C
      WRITE (LUW,250) (SUMA(IC,1,K),K=1,13)
  250 FORMAT(1H ,'* AMB. TEMPERATURE   *',12(F5.1,3H  *),1H*,F6.1
     $,5H    *)
C
      WRITE(LUW,300) (SUMA(IC,2,K),K=1,13)
  300 FORMAT(1H ,'* TEMP. FOR LOAD MOD *',12(F5.1,3H  *),1H*,F6.1
     $,5H    *)
      WRITE(LUW,150)
C
      WRITE(LUW,350) (SUMA(IC,3,K),K=1,13)
  350 FORMAT(1H ,'* DIRECT NORMAL RAD. *',12(F6.0,2H *),1H*,F8.0,3H  *)
C
      WRITE(LUW,400) (SUMA(IC,4,K),K=1,13)
  400 FORMAT(1H ,'* TOTAL HORIZONTAL   *',12(F6.0,2H *),1H*,F8.0,3H  *)
      WRITE(LUW,150)
C
      WRITE(LUW,450) (SUMA(IC,5,K),K=1,13)
  450 FORMAT(1H ,'* TOTAL INCIDENT     *',12(F6.0,2H *),1H*,F8.0,3H  *)
      WRITE(LUW,150)
C
      DO 1000 N=1,5
      M=N+5
      WRITE(LUW,500) TEMP(N),(SUMA(IC,M,K),K=1,13)
  500 FORMAT(1H ,'* COLLECTED AT ',F5.0,2H *,12(F6.0,2H *),1H*,F8.0
     $,3H  *)
 1000 CONTINUE
C
      WRITE(LUW,150)
C
      DO 1100 N=1,5
      M=N+10
      WRITE(LUW,550) TEMP(N),(SUMA(IC,M,K),K=1,13)
  550 FORMAT(1H ,'* OP. HOURS AT ',F5.0,2H *,12(F6.0,2H *),1H*,F8.0
     $,3H  *)
 1100 CONTINUE
C
      WRITE(LUW,150)
C
      RETURN
      END
```

```
      GO TO 1525
 1530 IF (J .GE. JA) GO TO 500
      J = J + 1
      GO TO 422
C.  BAD CONTROL CARD
  453 INDERR = 1
C    WHEN ICHECK = -2, READIN HAS BEEN CALLED TO FETCH AN OPTIONAL
C    SPECIFICATION FROM CARD.
      IF (ICHECK .EQ. -2) GO TO 500
      IERR=IERR+1
      WRITE (LUW,1100)
      WRITE (LUW,1101)
      WRITE (LUW,1001) (ICARD(I),I=1,80)
      WRITE (LUW,1002) (IBLK,I=1,ICH1),IMARK
      GO TO 500
C.  BAD DATA CARD.  TEST FOR FIRST NON-BLANK
  463 DO 473 K=1,ICH
      IF (ICARD(K).NE.IBLK.AND.ICARD(K).NE.ICOM) GO TO 483
  473 CONTINUE
  483 IF (K.EQ.ICH) GO TO 1483
      INDERR=1
      IERR=IERR+1
      WRITE (LUW,1100)
      WRITE (LUW,1102)
      WRITE (LUW,1001) (ICARD(I),I=1,80)
      WRITE (LUW,1002) (IBLK,I=1,ICH),IMARK
      GO TO 500
C.  POSSIBLE MISSING DATA CARD
 1483 INDERR=-1
      IERR=IERR+1
      WRITE (LUW,1100)
      WRITE (LUW,1103)
      GO TO 500
C.  PRINT CURRENT CARD
  405 WRITE (LUW,1001) (ICARD(I),I=1,80)
      WRITE (LUW,1002) (IBLK,I=1,ICH1),IMARK
      GO TO 500
C  PRINT OUT COMMENT CARDS FROM TOP OF DECK
700   WRITE(LUW,701)
701   FORMAT(1H1)
      IF (LSAVE .LE. 0) GO TO 730
      DO 710 L = 1,LSAVE
710   WRITE(LUW,1001) (HEADNG(I,L),I = 1,80)
730   DO 740 L = 1,NSAVE
      DO 740 I = 1,80
      HEADNG(I,L) = 0
740   CONTINUE
  500 CONTINUE
      RETURN
 1000 FORMAT (80A1)
 1001 FORMAT (1X,80A1)
 1002 FORMAT (82A1)
 1100 FORMAT (/1X,15H*****ERROR*****)
 1101 FORMAT (1X,35HBAD OR MISSING DATA ON CONTROL CARD)
 1102 FORMAT (1X,13HBAD DATA CARD)
 1103 FORMAT (1X,17HMISSING DATA CARD)
      END
C SUMMARY
C
C
      SUBROUTINE SUMARY(LUW,IC,ICITY)
C
      COMMON/PRT/SUMA(6,15,13),TEMP(5)
C
      WRITE(LUW,100) IC,ICITY
  100 FORMAT(1H1,///,20X,' * IEA * UMSORT OUTPUT SUMMARY *',//
     $,                20X,'       FOR COLLECTOR NUMBER  :',I3,/
     $,                20X,'       FOR LOCATION          :',A4,//
     $,'  - TEMPERATURES       IN     DEGREES CELCIUS',/
     $,'  - ALL ENERGIES       IN     MEGAJOULES/MONTH OR YEAR',//)
```

```
      ISIGN=2
      GO TO 6
   14 CONTINUE
      DO 7 N=1,10
      IF (ICARD(K).EQ.IDIG(N)) GO TO 493
    7 CONTINUE
      GO TO 433
C.   A NUMBER HAS BEEN DETECTED
  493 XNUM=FLOAT(N-1)
      L=L+1
      GO TO (21,22,23),ISET
   21 ARRAY(J)=ARRAY(J)*10.0+XNUM
      GO TO 6
   22 LD=LD+1
      ARRAY(J)=ARRAY(J)+XNUM*10.0**(-LD)
      GO TO 6
   23 EX=EX*10.0+XNUM
      GO TO 6
   24  IEX=IFIX(SIGN(2)*EX+SIGN(2)*0.01)
       ARRAY(J)=SIGN(1)*ARRAY(J)*10.0**IEX
      ICH1=ICH
      IF (J.GE.JA) GO TO 500
      J=J+1
      ISIGN=1
      SIGN(1)=1.0
      SIGN(2)=1.0
      ISET=1
      L=0
      EX=0.0
      II = ICH+1
    6 CONTINUE
      GO TO (500,500,453,443,500,500), NOPT
C.  READ A NEW CARD
  443 READ (LU,1000) (ICARD(I),I=1,80)
      ICARD(81)=IBLK
      ICH=1
      IF (ICARD(1).NE.ISTAR) GO TO 423
      IF (ILIST) WRITE (LUW,1001) (ICARD(I),I=1,80)
      GO TO 443
C.  NON-NUMERIC CHARACTER FOUND
  433 ICH1=ICH
      IF (ICH.EQ.II .AND. (NOPT.EQ.3.OR.NOPT.EQ.4)) GO TO 1500
434   GO TO (500,500,453,463,500,500), NOPT
C   CHECK TABLE FOR USER DEFINED CONSTANT (SUBSTITUTE FOR NUM. DATA)
1500  DO 1502 L = 1,26
      IF (ICARD(ICH) .EQ. LETTER(L)) GO TO 1510
1502  CONTINUE
      GO TO 434
C    GET THREE LETTER CONSTANT NAME
1510  ICON2 = IBLK
      ICON3 = IBLK
      IC = ICH + 1
      IF (ICARD(IC).EQ.IBLK .OR. ICARD(IC).EQ.ICOM) GO TO 1512
      ICON2 = ICARD(IC)
      IC = IC + 1
      IF (ICARD(IC).EQ.IBLK .OR. ICARD(IC).EQ.ICOM) GO TO 1512
      ICON3 = ICARD(IC)
      IC = IC + 1
C    CHECK LIST L FOR CONSTANT NAME
1512  L1 = HEADER(L)
1515  IF (L1 .EQ. 0) GO TO 434
      IF (ICHAR2(L1).EQ.ICON2 .AND. ICHAR3(L1).EQ.ICON3) GO TO 1520
      L1 = LINK(L1)
      GO TO 1515
C    USE VALUE FROM TABLE
1520  ARRAY(J) = VALUE(L1)
      ICH = IC
      ICH1 = ICH
C    SKIP CHARACTERS UNTIL A BLANK OR COMMA IS FOUND
1525  IF (ICARD(ICH).EQ.IBLK .OR. ICARD(ICH).EQ.ICOM) GO TO 1530
      ICH = ICH + 1
      ICH1 = ICH
```

```
  400 GO TO (401,402,403,403,405,401), NOPT
C.  GET CHARACTERS UNTIL NEXT BLANK, COMMA, OR EQUAL SIGN
  401 J=1
      ICH1=ICH
      I=ICH
      DO 411 ICH=I,81
      IF (ICARD(ICH).EQ.IBLK.OR.ICARD(ICH).EQ.ICOM.OR.ICARD(ICH).EQ.IEQ)
     .              GO TO 421
      IARRAY(J)=ICARD(ICH)
      J=J+1
  411 CONTINUE
C.  BLANK FILL REST OF ARRAY
  421 DO 431 K=J,81
  431 IARRAY(K)=IBLK
      GO TO 500
C.  GET REST OF CARD
  402 J=1
      I=ICH
      DO 412 ICH=I,81
      IARRAY(J)=ICARD(ICH)
      J=J+1
  412 CONTINUE
      ICH=81
C.  BLANK FILL REST OF ARRAY
      DO 432 K=J,81
  432 IARRAY(K)=IBLK
      GO TO 500
C.  ZERO AND READ IN DATA ARRAY
  403 ICH1=ICH
      JA=IARRAY(1)
      IF (JA.LE.0) GO TO 500
      DO 413 J=1,JA
  413 ARRAY(J)=0.
      J=1
  422 ISIGN=1
      SIGN(1)=1.0
      SIGN(2)=1.0
      ISET=1
      L=0
      EX=0.0
  423 I=ICH
      II = ICH
      DO 6 ICH=I,81
      K=ICH
      IF (ICARD(K).NE.IPLUS) GO TO 15
       IF(K.LE.1) GO TO 6
       IF(ICARD(K-1).NE.ICOM.AND.ICARD(K-1).NE.IBLK)  ISET=3
       GO TO 6
15    IF (ICARD(K).NE.IBLK.AND.ICARD(K).NE.ICOM.AND.ICARD(K).NE.IEQ)
     .        GO TO 11
C.  A COMMA, EQUAL SIGN OR BLANK SPACE HAS BEEN DETECTED
      IF (L.GT.0) GO TO 24
      II = ICH + 1
      GO TO 6
   11 IF (ICARD(K).NE.NS) GO TO 12
C.  A NEGATIVE SIGN HAS BEEN DETECTED
       IF(K.LE.1) GO TO 10
       IF(ICARD(K-1).EQ.ICOM.OR.ICARD(K-1).EQ.IBLK.OR.ICARD(K-1).EQ.IEQ)
     .                GO TO 10
       ISIGN=2
       ISET=3
10    SIGN(ISIGN)=-1.0
      GO TO 6
   12  IF (ICARD(K).NE.IDP) GO TO 13
C.  A DECIMAL POINT HAS BEEN DETECTED
      ISET=2
      LD=0
      GO TO 6
   13  IF (ICARD(K).NE.E) GO TO 14
      IF (L .EQ. 0) GO TO 433
C.  E FORMAT NOTATION HAS BEEN DETECTED
      ISET=3
```

```
C.  IOPT=0  READ A NEW CARD
C.  IOPT=1  IGNORE LEADING BLANKS, GET CHARACTERS UNTIL NEXT BLANK.
C.  IOPT=2  GET REST OF CHARACTERS ON CARD.
C.  IOPT=3  GET DATA FROM CONTROL CARD, INHIBIT READ
C.  IOPT=4  GET DATA FROM DATA CARD
C.  IOPT=5  PRINT ENTIRE CARD
C.  IOPT=6  SAME AS 1 EXCEPT INHIBIT READ
C.  IOPT=7  PRINT OUT COMMENT CARDS FROM TOP OF DECK
C.  IF IOPT IS NEGATIVE, A NEW CARD IS READ BEFORE PROCESSING BEGINS.
C.  INDERR INDICATES SUCCESS OR FAILURE WHEN PROCESSING DATA.
C.  INDERR=0  OK
C.  INDERR=1  NON-NUMERIC CHARACTER FOUND IN DATA.
C.  INDERR=-1 FIRST NON-BLANK CHAR ON DATA CARD WAS NON-NUMERIC.
C.  COMMA ARE ALWAYS TREATED AS BLANKS.
C.
      LOGICAL ILIST,SAVE
      INTEGER E,HEADNG,HEADER
      DIMENSION ICARD(81),ARRAY(1),IARRAY(81),IDIG(10),SIGN(2)
      COMMON /LUNITS/ LUR,LUW,IFORM
      COMMON /LIST/ ILIST,NSAVE,HEADNG(80,8)
      COMMON /CONST/ LETTER(26),HEADER(26),NCON
      COMMON /STORE/ NSTORE,IAV,ICHAR2(50),ICHAR3(50),VALUE(50),LINK(50)
      COMMON /ERRS/ ITMAX,IQTMAX,ITRACE,IERR,IEMAX,ICT,NCALLS,CALLED(50)
      DATA IDIG/1H0,1H1,1H2,1H3,1H4,1H5,1H6,1H7,1H8,1H9/
      DATA IBLK/1H /,ICOM/1H,/,IDP/1H./,NS/1H-/,E/1HE/,IPLUS/1H+/
      DATA ISTAR/1H*/,IMARK/1H$/,IEQ/1H=/,SAVE/.TRUE./,LSAVE/0/
      DATA ICH1/1/,ICH/1/,LD/0/
      ICHECK = INDERR
      INDERR=0
      IOPT=IOPT1
      LU=LUR
      IF(IOPT1.GT.-7) GO TO 195
      LU=-10-IOPT1
      IOPT=-4
195   CONTINUE
      NOPT=IABS(IOPT)
      IF (IOPT.GT.0) GO TO 200
C.  READ A NEW CARD AND CHECK FOR COMMENT
  201 READ (LU,1000) (ICARD(I),I=1,80)
      ICH=1
      ICARD(81)=IBLK
      IF (ICARD(1).NE.ISTAR) GO TO 200
      IF (ILIST) WRITE (LUW,1001) (ICARD(I),I=1,80)
      IF (.NOT. SAVE) GO TO 201
      LSAVE = LSAVE + 1
      DO 202 I = 1,80
202   HEADNG(I,LSAVE) = ICARD(I)
      SAVE = (LSAVE .LT. NSAVE)
      GO TO 201
  200 CONTINUE
      SAVE = .FALSE.
      IF (NOPT.EQ.0) GO TO 500
      GO TO (301,302,400,400,400,301,700), NOPT
C.  SKIP LEADING BLANKS
  301 I=ICH
      ICH1=ICH
      DO 311 ICH=I,81
      IF (ICARD(ICH).NE.IBLK.AND.ICARD(ICH).NE.ICOM) GO TO 400
  311 CONTINUE
      GO TO (201,400,201,201,400,321), NOPT
C..  MISSING KEYWORD
  321 IF (ICHECK .EQ. -2) GO TO 322
C     IF ICHECK IS -2, READIN HAS BEEN CALLED TO LOOK FOR
C     OPTIONAL FIELD ON CARD.
      INDERR = 1
      GO TO 500
  322 DO 323 II = 1,10
  323 IARRAY(II) = IBLK
      GO TO 500
C.  SKIP ONE BLANK
  302 IF (ICARD(ICH).NE.IBLK.AND.ICARD(ICH).NE.ICOM) GO TO 400
      IF (ICH.LE.81) ICH=ICH+1
```

```
      ALT=COSE(ALAT)*COSE(DEC)*COSE(HR)+SINE(ALAT)*SINE(DEC)
C
      CSH=ALT
      ALT=ARCSIN(ALT)
      HRCRIT=90
      CHRCR=TANG(DEC)/TANG(ALAT)
      IF(CHRCR.GT.1)GO TO 100
C
      HRCRIT=ARCCOS(CHRCR)
  100 AZIM=COSE(DEC)*SINE(HR)/COSE(ALT)
C###  THE FOLLOWING LINES ADDED TO UMSORT.ORG
      IF(AZIM.GT.1..AND.AZIM.LT.1.0001) AZIM=1.
      IF(AZIM.LT.-1..AND.AZIM.GT.-1.0001) AZIM=-1.
C###
      AZIM=ARCSIN(AZIM)
C
      BB=ABS(HR)
      CC=ABS(AZIM)
C
      IF(BB.GT.HRCRIT)AZIM=(180-CC)*AZIM/CC
C
      RETURN
      END
      SUBROUTINE INTER1(XA,YA,NI,X,Y)
      DIMENSION X(NI),Y(NI)
C
C
C
      IF(XA.GE.X(NI))GO TO 1000
      IF(XA.LT.X(1))GO TO 2000
      JJ=NI-1
      KK=JJ
      DO 3000 I=1,JJ
 3000 IF(XA.GE.X(I).AND.XA.LT.X(I+1))KK=I
      M=KK
      YA=Y(M)+(Y(M+1)-Y(M))*(XA-X(M))/(X(M+1)-X(M))
      RETURN
 1000 YA=Y(NI)
      RETURN
 2000 YA=Y(1)
      RETURN
      END
      SUBROUTINE INTER2(XA,XB,YA,NI,NJ,X1,X2,Y)
      DIMENSION X1(NI),X2(NJ),Y(NI,NJ)
C
C
C
      JJ=NI-1
      KK=JJ
      DO 1000 I=1,JJ
 1000 IF(XA.GE.X1(I).AND.XA.LT.X1(I+1))KK=I
C
      LL=NJ-1
      MM=LL
      DO 2000 L=1,LL
 2000 IF(XB.GE.X2(L).AND.XB.LT.X2(L+1))MM=L
C
      I=KK
      J=MM
      Y1=Y(I,J)+(Y(I+1,J)-Y(I,J))*(XA-X1(I))/(X1(I+1)-X1(I))
      Y2=Y(I,J+1)+(Y(I+1,J+1)-Y(I,J+1))*(XA-X1(I))/(X1(I+1)-X1(I))
      YA=Y1+(Y2-Y1)*(XB-X2(J))/(X2(J+1)-X2(J))
      RETURN
      END
      SUBROUTINE READIN(IOPT1,ARRAY,IARRAY,INDERR)
C.  SUBROUTINE READIN PERFORMS THE FUNCTION OF FREE-FORMAT CARD
C.  READING.  THE VARIABLES TO BE READ IN (FROM 80 CHARACTER CARDS)
C.  CAN BE IN ANY FORMAT, BUT THEY MUST BE SEPARATED BY ONE OR MORE
C.  COMMAS OR BLANK SPACES.  E-FORMAT INPUT IS PERMISSIBLE.
C.  MULTIPLE DATA CARDS WILL BE USED IF NECESSARY.
C.  READIN IS CAPABLE OF PROCESSING BOTH DATA AND CHARACTER STRINGS.
C.  THE FOLLOWING OPTIONS ARE AVAILABLE.  NEW CARDS ARE READ IF NEEDED.
```

```
C
      AKAT=1
      ETTILT=TILT
      IF(TILT.EQ.0) ETTILT=ALAT
      GAMMA=DIR-AZIM
C
      CALL SOLRAD(ETTILT,DIR,RHO)
      AKNS=1-BO*(1/COSE(TNS)-1)
C
      IF(AINS.GT.90.OR.TNS.GT.90)AKNS=0
C
      CALL INTER1(TEW,AKEW,7,XI,YI)
C
      IF(TEW.GT.90)AKEW=0
      AKAT=AKEW*AKNS
      QINC=QDERC+QSKY+QGRND
      QINCC=QINC
      DTUI=(TCIN-TA)/QINCC
      QCL=QINCC*(UL1*DTUI+UL2*DTUI**2)
      QCIN=TALPHA*(AKAT*QDERC+.72*QSKY+.72*QGRND)
      QCOUT=QCIN-QCL
C
      IF(QCOUT.LT.0)QCOUT=0
C
      RETURN
      END
C  THIS VERSION OF SUBROUTINE WEATH HAS BEEN MODIFIED TO PRODUCE OUTPUT
C  IN SI UNITS.
C
      SUBROUTINE WEATH(RDAY)
      COMMON/A/RMON,DAY,TIME,HR,DEC,CSH,ALT,AZIM,ALAT,QSP,EOT
                  SINE(XX)=SIN(XX/57.29578)
C
C  RETURNS EOT,QSP,WHETR ARRAY FOR ONE DAY OF DATA
C
      AA=(RDAY+7)*180/111
      BB=(RDAY-106)*180/59
      CC=(RDAY-166)*180/80
      DD=(RDAY-247)*180/113
      EE=360*(272.1+RDAY)/365
C
C
C
      IF(RDAY.GT.0.AND.RDAY.LE.106)EOT=-14.2*SINE(AA)
      IF(RDAY.GT.106.AND.RDAY.LE.166)EOT=4*SINE(BB)
      IF(RDAY.GT.166.AND.RDAY.LE.246)EOT=-6.5*SINE(CC)
      IF(RDAY.GT.246.AND.RDAY.LE.365)EOT=16.4*SINE(DD)
C
      QSP=426.9833-13.949995*SINE(EE)
C     ORIGINALLY CALCULATED IN BRITISH UNITS - CONVERT TO SI
      QSP = QSP * 11.356576
C
      RETURN
      END
      SUBROUTINE ALTAZ
      COMMON /A/RMON,DAY,TIME,HR,DEC,CSH,ALT,AZIM,ALAT,QSP,EOT
            COSE(XX)=COS(XX/57.29578)
            SINE(XX)=SIN(XX/57.29578)
            TANG(XX)=TAN(XX/57.29578)
            ARCCOS(XX)=57.29578*ACOS(XX)
            ARCSIN(XX)=57.29578*ASIN(XX)
            ARCTAN(XX)=57.29578*ATAN(XX)
C
C
C
      DLONG=2
      HR=15*(12-(TIME+EOT/60-4/60*DLONG))
      ADEC=RMON+DAY/32-1
C
      AA=30*(ADEC-5.7)
C
      DEC=23.279*COSE(AA)
```

```
C
      DATA Y(1,1)/0.0/,Y(1,2)/.384/,Y(1,3)/.701/,Y(1,4)/.789/
      DATA Y(1,5)/.814/,Y(1,6)/.811/,Y(1,7)/.723/
      DATA Y(2,1)/0.0/,Y(2,2)/.404/,Y(2,3)/.687/,Y(2,4)/.771/
      DATA Y(2,5)/.814/,Y(2,6)/.806/,Y(2,7)/.729/
      DATA Y(3,1)/0.0/,Y(3,2)/.366/,Y(3,3)/.576/,Y(3,4)/.662/
      DATA Y(3,5)/.757/,Y(3,6)/.754/,Y(3,7)/.748/
      DATA Y(4,1)/0.0/,Y(4,2)/.330/,Y(4,3)/.495/,Y(4,4)/.584/
      DATA Y(4,5)/.708/,Y(4,6)/.753/,Y(4,7)/.726/
      DATA Y(5,1)/0.0/,Y(5,2)/.300/,Y(5,3)/.429/,Y(5,4)/.521/
      DATA Y(5,5)/.661/,Y(5,6)/.724/,Y(5,7)/.730/
      DATA Y(6,1)/0.0/,Y(6,2)/.240/,Y(6,3)/.367/,Y(6,4)/.445/
      DATA Y(6,5)/.603/,Y(6,6)/.689/,Y(6,7)/.736/
      DATA Y(7,1)/0.0/,Y(7,2)/.212/,Y(7,3)/.315/,Y(7,4)/.391/
      DATA Y(7,5)/.544/,Y(7,6)/.642/,Y(7,7)/.736/
C
C
C
      QCOUT=0
      QINCC=QDNI
      IF(QINCC.EQ.0)GO TO 1000
C
      AA=ABS(AZIM)
      BB=ABS(ALT)
      CALL INTER2(AA,BB,AO,7,7,X1,X2,Y)
      EFF=TALPHA*AO
      QCOUT=QINCC*EFF
      IF(QCOUT.LT.0)QCOUT=0
 1000 RETURN
      END

      SUBROUTINE SHPO(TALPHA,UL1,UL2,BO,TCIN,QINC,QINCC,QCOUT)
      COMMON /A/RMON,DAY,TIME,HR,DEC,CSH,ALT,AZIM,ALAT,QSP,EOT
      COMMON /B/AINS,TNS,TEW,QH,QDNI,QSKY,QGRND,QDERC,QDER,QDIF,TA
                COSE(XX)=COS(XX/57.29578)
C
C
C
      TILT=0
      DIR=0
      GAMMA=DIR-AZIM
      RHO=0
      CALL SOLRAD(TILT,DIR,RHO)
      ZEN=90-ALT
      AA=ABS(ZEN)
      SPRB=COSE(90*(AA/90)**1.24)
      QINCC=QDNI*SPRB+QDIF
      DT=TCIN-TA
      QCL=UL1*DT
      QCIN=TALPHA*QINCC
      QCOUT=QCIN-QCL
      IF(QCOUT.LT.0)QCOUT=0
      RETURN
      END
      SUBROUTINE EVAC(TALPHA,UL1,UL2,BO,TILT,DIR,RHO,
     1                TCIN,QINC,QINCC,QCOUT)
      COMMON /A/RMON,DAY,TIME,HR,DEC,CSH,ALT,AZIM,ALAT,QSP,EOT
      COMMON /B/AINS,TNS,TEW,QH,QDNI,QSKY,QGRND,QDERC,QDER,QDIF,TA
C
C
C
      DIMENSION XI(7),YI(7)
      DATA XI(1)/0.0/,XI(2)/15.0/,XI(3)/30.0/,XI(4)/45.0/
      DATA XI(5)/60.0/,XI(6)/75.0/,XI(7)/90.0/
      DATA YI(1)/1.0/,YI(2)/1.08/,YI(3)/1.14/,YI(4)/1.11/,YI(5)/.94/
      DATA YI(6)/.65/,YI(7)/0.0/
              COSE(XX)=COS(XX/57.29578)
C
C
C
C
```

```
C
C
C
      TILT=0
      DIR=0
      AKAT=0
      AINS=90-ALT
      IF (ALT.NE.0 .AND. AINS.LT.90)
     *    AKAT=1-BO*(1/COSE(AINS)-1)
      QINCC=QH
      DT=TCIN-TA
      QCL=UL1*DT
      QCIN=TALPHA*AKAT*QINCC
      QCOUT=QCIN-QCL
      RETURN
      END
      SUBROUTINE PART(TALPHA,UL1,UL2,BO,DIR,RHO,
     1                TCIN,QINC,QINCC,QCOUT)
      COMMON /A/RMON,DAY,TIME,HR,DEC,CSH,ALT,AZIM,ALAT,QSP,EOT
      COMMON /B/AINS,TNS,TEW,QH,QDNI,QSKY,QGRND,QDERC,QDER,QDIF,TA
C
C
C
      DIMENSION XI(9),YI(9)
      DATA XI(1)/0.0/,XI(2)/10.0/,XI(3)/20.0/,XI(4)/30.0/
      DATA XI(5)/40.0/,XI(6)/50.0/,XI(7)/60.0/,XI(8)/70.0/
      DATA XI(9)/90.0/,YI(1)/1./,YI(2)/1./,YI(3)/1./,YI(4)/.99/
      DATA YI(5)/.95/,YI(6)/.88/,YI(7)/.82/,YI(8)/.68/,YI(9)/0.0/
              SINE(XX)=SIN(XX/57.29578)
              COSE(XX)=COS(XX/57.29578)
              TANG(XX)=TAN(XX/57.29578)
              ARCCOS(XX)=57.29578*ACOS(XX)
              ARCSIN(XX)=57.29578*ASIN(XX)
              ARCTAN(XX)=57.29578*ATAN(XX)
C
      QCOUT=0
      GAMMA=DIR-AZIM
      TILT=90-ARCTAN(TANG(ALT)/COSE(GAMMA))
      GAM=ABS(GAMMA)
      IF(GAM.GT.90)TILT=TILT-180
C
      CALL SOLRAD(TILT,DIR,RHO)
      CALL INTER1(AINS,AKAT,9,XI,YI)
C
      IF(AINS.GT.90)AKAT=0
      QINCC=QDERC
      IF(QINCC.EQ.0)GO TO 1000
      DTUI=(TCIN-TA)/QINCC
      QCL=QINCC*(UL1*DTUI+UL2*DTUI**2)
      QCIN=TALPHA*AKAT*QINCC
      QCOUT=QCIN-QCL
      IF(QCOUT.LT.0)QCOUT=0
 1000 RETURN
      END
C  82-06-22
C  THIS VERSION OF SUBROUTINE CENT HAS BEEN MODIFIED TO REMOVE THE FISH
C  FUDGE FACTOR FOR LATITUDE IN ACCORDANCE WITH THE LATEST DOCUMENTATION
C  IT HAS ALSO HAD THE BAD TABLE ENTRIES CORRECTED TO AGREE WITH THE
C  DOCUMENTATION
C
      SUBROUTINE CENT(TALPHA,UL1,UL2,BO,TCIN,QINC,QINCC,QCOUT)
      COMMON /A/RMON,DAY,TIME,HR,DEC,CSH,ALT,AZIM,ALAT,QSP,EOT
      COMMON /B/AINS,TNS,TEW,QH,QDNI,QSKY,QGRND,QDERC,QDER,QDIF,TA
C
C
C
      DIMENSION X1(7),X2(7),Y(7,7)
      DATA X1(1)/0.0/,X1(2)/30.0/,X1(3)/60.0/,X1(4)/75.0/
      DATA X1(5)/90.0/,X1(6)/110./,X1(7)/130./
      DATA X2(1)/0.0/,X2(2)/5.0/,X2(3)/15.0/,X2(4)/25.0/
      DATA X2(5)/45.0/,X2(6)/65.0/,X2(7)/89.5/
```

```
      COSHR=COSE(HR)
      SINAZM=SINE(DIR)
      SINHR=SINE(HR)
C
C
C
      CSI=SINDEC*SINLAT*COSSLP-SINDEC*COSLAT*SINSLP*COSAZM
      CSI=CSI+COSDEC*COSLAT*COSSLP*COSHR+COSDEC*SINLAT*SINSLP*
     1COSAZM*COSHR
      CSI=CSI+COSDEC*SINSLP*SINAZM*SINHR
      IF (CSI.GT.1.0 .AND. CSI.LT.1.0001) CSI=1.0
      AINS=ARCCOS(CSI)
C
C  DEBUG SECTION
C
C     IF(AINS.LE.0.OR.AINS.GE.90)WRITE(15,101)CSI,AINS,RMON,DAY,TIME
C 101 FORMAT(' AINS ANGLE VIOLATION  CSI=',E10.4,' AINS=',E10.4,2X,
C    1' RMON-DAY-HR=',3F4.0)
C
      RB=CSI/CSH
      IF(CSI.LT.0.017)RB=0
      X=AINS
      IF(X.EQ.90)GO TO 4000
      TV=ARCTAN(TANG(ALT)/COSE(GAMMA))
      TV1=TV+TILT
      IF(TV.LT.0)TV=180+TV
      TV=TV+TILT
C
      AA=ABS(90-TV)
C
      IF(AA.LT.0.1)THOR=90-AINS
      IF(AA.LT.0.1)GO TO 4000
      TP=90-AINS
C
C  DEBUG SECTION  -  EXCEPTION HANDLING
C
      FFF=(TANG(TP)/TANG(TV))
C     IF(FFF.GT.1.0.OR.FFF.LT.-1.0)WRITE(15,106)
C    1FFF,RMON,DAY,TIME,TP,TV
C106  FORMAT(' ARCCOS VIOLATION=',E10.4,'  RMON-DAY-HR',3F4.0,
C    1' TP-TV',E10.4,3X,E10.4)
      IF(FFF.GT.1.0.OR.FFF.LT.-1.0)FFF=1.0
      PPP=TANG(ARCCOS(FFF))
C     IF(PPP.EQ.0.)WRITE(15,200)PPP,RMON,DAY,TIME,TV,TP
C 200 FORMAT(' DENOM VIOL=',E10.4,'  RMON-DAY-HR',3F4.0,
C    1' TV-TP',E10.4,3X,E10.4)
      IF(PPP.EQ.0)PPP=1.0E-38
      THOR=ARCTAN(TANG(TV)/PPP)
C
C
C     THOR=ARCTAN(TANG(TV)/TANG(ARCCOS(TANG(TP)/TANG(TV))))

 4000 TNS=TV-90
      TEW=90-THOR
 3000 QSKY=.5*(1+COSE(TILT))*QDIF
      QGRND=.5*(1-COSE(TILT))*RHO*QH
      QDERC=QDER*RB
C
C
      RETURN
      END
C 82-06-17
C  THIS VERSION OF SUBROUTINE POND HAS BEEN MODIFIED TO REMOVE (HOPEFULLY) THE
C  SIN/COS ARGUMENT TOO GREAT ERROR ENCOUNTERED ON THE P1400.
C  COS IS NOW CALLED ONLY IF THE ARGUMENT IS .LT. PI/4 ... ALL RESULTING VALUES
C  SHOULD BE IDENTICAL - ONLY THE INTERNAL LOGIC HAS CHANGED.
C
      SUBROUTINE POND(TALPHA,UL1,UL2,BO,TCIN,QINC,QINCC,QCOUT)
      COMMON /A/RMON,DAY,TIME,HR,DEC,CSH,ALT,AZIM,ALAT,QSP,EOT
      COMMON /B/AINS,TNS,TEW,QH,QDNI,QSKY,QGRND,QDERC,QDER,QDIF,TA
                COSE(XX)=COS(XX/57.29578)
```

```
      QINC=QDERC+QSKY+QGRND
      QINCC=QINC
      IF(QINCC.EQ.0)GO TO 100
      DTUI=(TCIN-TA)/QINCC
      QCL=QINCC*(UL1*DTUI+UL2*DTUI**2)
  100 QCIN=TALPHA*AKAT*QINCC
      QCOUT=QCIN-QCL
C
C
      IF(QCOUT.LT.0)QCOUT=0
C
      RETURN
      END
C  THIS VERSION OF SOLRAD INCLUDES ALL BRITISH AND GERMAN MODIFICATIONS
C  MADE UP TO 82-06-17 AND HAS ALSO BEEN MODIFIED TO PRODUCE OUTPUT IN
C  SI UNITS
C
C
C
      SUBROUTINE SOLRAD(TILT,DIR,RHO)
      COMMON /A/RMON,DAY,TIME,HR,DEC,CSH,ALT,AZIM,ALAT,QSP,EOT
      COMMON /B/AINS,TNS,TEW,QH,QDNI,QSKY,QGRND,QDERC,QDER,QDIF,TA
      COMMON /C/IBOZ
             SINE(XX)=SIN(XX/57.29578)
             COSE(XX)=COS(XX/57.29578)
             TANG(XX)=TAN(XX/57.29578) + 1.E-30
             ARCSIN(XX)=57.29578*ASIN(XX)
             ARCCOS(XX)=57.29578*ACOS(XX)
             ARCTAN(XX)=57.29578*ATAN(XX)
C
C
C
      BOES=0
      IF(IBOZ.EQ.1)BOES=1
      AINS=0
      TNS=0
      TEW=0
      RB=0
      IF(QH.EQ.0)RETURN
C
C  BOES DIFFUSE MODEL
C
      IF(BOES.EQ.0)GO TO 1000
      QEXT=CSH*QSP
      PP=QH/QEXT
      IF(PP.LT.0.3073)QDN=0
      IF(PP.GT.0.3073.AND.PP.LE.0.8659)QDN=1.79*PP-.55
      IF(PP.GT.0.8659)QDN=1
      QDN=QDN*317.21
C     THE ABOVE ORIGINAL CALCULATION WAS DONE IN BRITISH UNITS - NOW
C     CONVERT FROM BTU/H.FT**2 TO KJ/H.M**2
      QDN=QDN*11.356576
      QDER=QDN*CSH
      GO TO 2000
C
C
C
 1000 QDER=QDNI*CSH
 2000 QDIF=QH-QDER
      IF(QDER.EQ.0)GO TO 3000
      IF(ALT.LT.0)GO TO 3000
C
C
      GAMMA=DIR-AZIM
      SINDEC=SINE(DEC)
      SINLAT=SINE(ALAT)
      COSSLP=COSE(TILT)
      COSLAT=COSE(ALAT)
      SINSLP=SINE(TILT)
      COSAZM=COSE(DIR)
      COSDEC=COSE(DEC)
```

```
     1YRLEN,TROOM,THAMB,(TEMP(I),I=1,5),(DYMON(J),J=1,12)
      IF(RDAY.EQ.1.AND.ION(5).EQ.1)WRITE(LUE,231)
     1YRLEN,TROOM,THAMB,(TEMP(I),I=1,5),(DYMON(J),J=1,12)
      IF(RDAY.EQ.1.AND.ION(6).EQ.1)WRITE(LUF,231)
     1YRLEN,TROOM,THAMB,(TEMP(I),I=1,5),(DYMON(J),J=1,12)
  231 FORMAT(I8,7F6.0,/,12I5)
C
C
C
      IRDAY=RDAY
      IF(ION(1).EQ.1)WRITE(LUA,216)IRDAY,IHR24,
     1(QFLPT(M),M=1,5),AAA,BBB,
     2(HFLPT(M),M=1,5)
      IF(ION(2).EQ.1)WRITE(LUB,216)IRDAY,IHR24,
     1(QPOND(M),M=1,5),AAA,BBB,
     2(HPOND(M),M=1,5)
      IF (ION(3).EQ.1)WRITE(LUC,216)IRDAY,IHR24,
     1(QEVAC(M),M=1,5),AAA,BBB,
     2(HEVAC(M),M=1,5)
      IF(ION(4).EQ.1)WRITE(LUD,216)IRDAY,IHR24,
     1(QCENT(M),M=1,5),AAA,BBB,
     2(HCENT(M),M=1,5)
      IF(ION(5).EQ.1)WRITE(LUE,216)IRDAY,IHR24,
     1(QPART(M),M=1,5),AAA,BBB,
     2(HPART(M),M=1,5)
      IF(ION(6).EQ.1)WRITE(LUF,216)IRDAY,IHR24,
     1(QSHPO(M),M=1,5),AAA,BBB,
     2(HSHPO(M),M=1,5)
  216 FORMAT(I6,I6,7F8.2,5F4.0)
      IF(ADAY.EQ.DYMON(AMON))GO TO 750
      GO TO 730
C
C  END OF DAY LOOP
C
  900 CONTINUE
C
      DO 1010 K=1,6
      DO 1010 N=1,12
      SUMA(K,1,13)=SUMA(K,1,13)+SUMA(K,1,N)/12.
      SUMA(K,2,13)=SUMA(K,2,13)+SUMA(K,2,N)/12.
      DO 1020 I=3,10
 1020 SUMA(K,I,N)=SUMA(K,I,N)/1000.
C
      DO 1030 I=3,15
 1030 SUMA(K,I,13)=SUMA(K,I,13)+SUMA(K,I,N)
 1010 CONTINUE
C
      DO 1100 K=1,6
      IF (ION(K).EQ.1) CALL SUMARY(LUW,K,ICITY)
 1100 CONTINUE
C
C
      WRITE(LUW,765)
  765 FORMAT(' END OF IEADATA PROCESSING')
      STOP
      END
      SUBROUTINE FLPT(TALPHA,UL1,UL2,BO,TILT,DIR,RHO,
     1                  TCIN,QINC,QINCC,QCOUT)
      COMMON /A/RMON,DAY,TIME,HR,DEC,CSH,ALT,AZIM,ALAT,QSP,EOT
      COMMON /B/AINS,TNS,TEW,QH,QDNI,QSKY,QGRND,QDERC,QDER,QDIF,TA
                      COSE(XX)=COS(XX/57.29578)
C
C
C
      FPTILT=TILT
      IF(TILT.EQ.0) FPTILT=ALAT
C
      CALL SOLRAD(FPTILT,DIR,RHO)
C
      AKAT=1-BO*(1/COSE(AINS)-1)
C
      IF(AINS.GT.90)AKAT=0
```

```
     1RHO(1),TCIN,QINC(K,1),QINCC(K,1),QCOUT(K,1))
      QFLPT(K)=QFLPT(K)+QCOUT(K,1)
      IF(QCOUT(K,1).GT.0.0)HFLPT(K)=HFLPT(K)+1.0
      IF (K.EQ.1) SUMA(1,5,AMON)=SUMA(1,5,AMON)+QINC(K,1)
      SUMA(1,5+K,AMON)=SUMA(1,5+K,AMON)+QCOUT(K,1)
      IF (QCOUT(K,1).GT.0.0) SUMA(1,10+K,AMON)=SUMA(1,10+K,AMON)+1.0
C
  310 IF(ION(2).EQ.0)GO TO 311
      CALL POND(TALPHA(2),UL1(2),UL2(2),BO(2),TCIN,
     1QINC(K,2),QINCC(K,2),QCOUT(K,2))
      QPOND(K)=QPOND(K)+QCOUT(K,2)
      IF(QCOUT(K,2).GT.0.0)HPOND(K)=HPOND(K)+1.0
      IF (K.EQ.1) SUMA(2,5,AMON)=SUMA(2,5,AMON)+QINCC(K,2)
      SUMA(2,5+K,AMON)=SUMA(2,5+K,AMON)+QCOUT(K,2)
      IF (QCOUT(K,2).GT.0.0) SUMA(2,10+K,AMON)=SUMA(2,10+K,AMON)+1.0
      IF(QH.LE. 50.0)GO TO 300
C
  311 IF(ION(3).EQ.0)GO TO 312
      CALL EVAC(TALPHA(3),UL1(3),UL2(3),BO(3),TILT(3),DIR(3),
     1RHO(3),TCIN,QINC(K,3),QINCC(K,3),QCOUT(K,3))
      QEVAC(K)=QEVAC(K)+QCOUT(K,3)
      IF(QCOUT(K,3).GT.0.0)HEVAC(K)=HEVAC(K)+1.0
      IF (K.EQ.1) SUMA(3,5,AMON)=SUMA(3,5,AMON)+QINC(K,3)
      SUMA(3,5+K,AMON)=SUMA(3,5+K,AMON)+QCOUT(K,3)
      IF (QCOUT(K,3).GT.0.0) SUMA(3,10+K,AMON)=SUMA(3,10+K,AMON)+1.0
C
  312 IF(ION(4).EQ.0)GO TO 313
      CALL CENT(TALPHA(4),UL1(4),UL2(4),BO(4),TCIN,
     1QINC(K,4),QINCC(K,4),QCOUT(K,4))
      QCENT(K)=QCENT(K)+QCOUT(K,4)
      IF(QCOUT(K,4).GT.0.0)HCENT(K)=HCENT(K)+1.0
      IF (K.EQ.1) SUMA(4,5,AMON)=SUMA(4,5,AMON)+QINCC(K,4)
      SUMA(4,5+K,AMON)=SUMA(4,5+K,AMON)+QCOUT(K,4)
      IF (QCOUT(K,4).GT.0.0) SUMA(4,10+K,AMON)=SUMA(4,10+K,AMON)+1.0
C
  313 IF(ION(5).EQ.0)GO TO 314
      CALL PART(TALPHA(5),UL1(5),UL2(5),BO(5),DIR(5),RHO(5),TCIN,
     1QINC(K,5),QINCC(K,5),QCOUT(K,5))
      QPART(K)=QPART(K)+QCOUT(K,5)
      IF(QCOUT(K,5).GT.0.0)HPART(K)=HPART(K)+1.0
      IF (K.EQ.1) SUMA(5,5,AMON)=SUMA(5,5,AMON)+QINCC(K,5)
      SUMA(5,5+K,AMON)=SUMA(5,5+K,AMON)+QCOUT(K,5)
      IF (QCOUT(K,5).GT.0.0) SUMA(5,10+K,AMON)=SUMA(5,10+K,AMON)+1.0
C
  314 IF(ION(6).EQ.0)GO TO 315
      CALL SHPO(TALPHA(6),UL1(6),UL2(6),BO(6),TCIN,
     1QINC(K,6),QINCC(K,6),QCOUT(K,6))
      QSHPO(K)=QSHPO(K)+QCOUT(K,6)
      IF(QCOUT(K,6).GT.0.0)HSHPO(K)=HSHPO(K)+1.0
      IF (K.EQ.1) SUMA(6,5,AMON)=SUMA(6,5,AMON)+QINCC(K,6)
      SUMA(6,5+K,AMON)=SUMA(6,5+K,AMON)+QCOUT(K,6)
      IF (QCOUT(K,6).GT.0.0) SUMA(6,10+K,AMON)=SUMA(6,10+K,AMON)+1.0
C
  315 CONTINUE
  300 CONTINUE
C
C  END OF COLLECTOR LOOP
C
C
  200 CONTINUE
C
C  END OF HOUR LOOP
C
      HRS=24
      IF(RDAY.EQ.1.AND.ION(1).EQ.1)WRITE(LUA,231)
     1YRLEN,TROOM,TMAMB,(TEMP(I),I=1,5),(DYMON(J),J=1,12)
      IF(RDAY.EQ.1.AND.ION(2).EQ.1)WRITE(LUB,231)
     1YRLEN,TROOM,TMAMB,(TEMP(I),I=1,5),(DYMON(J),J=1,12)
      IF(RDAY.EQ.1.AND.ION(3).EQ.1)WRITE(LUC,231)
     1YRLEN,TROOM,TMAMB,(TEMP(I),I=1,5),(DYMON(J),J=1,12)
      IF(RDAY.EQ.1.AND.ION(4).EQ.1)WRITE(LUD,231)
```

```
C
      READ(4,802)DATE,(WEATR(1,IN),IN=1,24)
      READ(4,802)DATE,(WEATR(2,IN),IN=1,24)
      READ(4,802)DATE,(WEATR(3,IN),IN=1,24)
      READ(4,802)DATE,(WEATR(4,IN),IN=1,24)
      READ(4,802)DATE,(DUMMY(IN),IN=1,24)
  802 FORMAT(F6.0,24F7.2)
C
C  DEGREE HOUR MODEL CALCULATIONS
C
      DO 8001 J=1,24
      AMB(J)=WEATR(3,J)
 8001 CONTINUE
C
      TAMD=0
      TAMC=0
      DO8003 K=1,24
      DHM(K)=AMB(K)
      IF(AMB(K).GE.TMAMB)DHM(K)=TROOM
      TAMC=TAMC+AMB(K)
      TAMD=TAMD+DHM(K)
 8003 CONTINUE
C
      AAA=TAMC/24
      BBB=TAMD/24
      I=DATE/10000
      RMON=I
      J=(DATE/100)-100*I
      DAY=J
C
      DO 1000 K=1,6
      SUMA(K,1,AMON)=SUMA(K,1,AMON)+AAA/DYMON(AMON)
 1000 SUMA(K,2,AMON)=SUMA(K,2,AMON)+BBB/DYMON(AMON)
C
      TAMAX=-100
      TAMIN=1000
C
C  START OF HOUR LOOP
C
      DO 200 L=1,24
      TIME=L
      QH=WEATR(2,L)
      QDNI=WEATR(1,L)
      TA=WEATR(3,L)
      VEL=WEATR(4,L)
      IF(TA.GT.TAMAX)TAMAX=TA
      IF(TA.LT.TAMIN)TAMIN=TA
      DO 212 J=1,6
      SUMA(J,3,AMON)=SUMA(J,3,AMON)+QDNI
      SUMA(J,4,AMON)=SUMA(J,4,AMON)+QH
      DO 212 I=1,5
      QCOUT(I,J)=0
      QINC(I,J)=0
      QINCC(I,J)=0
  212 CONTINUE
C     NOTE THAT THE QUANTITY 50.0 KJ/HM2 IN THE FOLLOWING
C     LINES IS ARBITRARY
      IF(QH.GT. 50.0)CALL ALTAZ
C
C  START OF COLLECTOR LOOP-DONE 5 TIMES FOR EACH HOUR
C  TEMPERATURES ARE IN DEGREES F
C
      DO 300 K=1,5
      TCIN=TEMP(K)
      IF(QH.LE. 50.0 .AND.ION(2).EQ.1)GO TO 310
      IF(QH.LE. 50.0)GO TO 300
C
C
C
      IF(ION(1).EQ.0)GO TO 310
      CALL FLPT(TALPHA(1),UL1(1),UL2(1),BO(1),TILT(1),DIR(1),
```

```
      ALAT=   DUMMY(1)
      DLONG=  DUMMY(2)
      TEMP(1)=DUMMY(3)
      TEMP(2)=DUMMY(4)
      TEMP(3)=DUMMY(5)
      TEMP(4)=DUMMY(6)
      TEMP(5)=DUMMY(7)
      TMAMB=  DUMMY(8)
      TROOM=  DUMMY(9)
C
      WRITE(LUW,108)ALAT,DLONG,TEMP(1),TEMP(2),TEMP(3),TEMP(4),
     1TEMP(5),TMAMB,TROOM
  108 FORMAT(1H0'ALAT=',F5.2,' DLONG=',F5.2,' TEMPS=',5F4.0,/,
     1'  TMAMB=',F3.0,'  TROOM=',F3.0)
C
      IF (IQRS.NE.0) STOP 9999
C       **** IQRS=0 IF NO INPUT ERRORS DETECTED ****
C
      READ(4,120) ICITY
  120 FORMAT(A4)
C
      IF (ION(1).EQ.1) WRITE(LUA,121) ICITY,IBOZT
      IF (ION(2).EQ.1) WRITE(LUB,122) ICITY,IBOZT
      IF (ION(3).EQ.1) WRITE(LUC,123) ICITY,IBOZT
      IF (ION(4).EQ.1) WRITE(LUD,124) ICITY,IBOZT
      IF (ION(5).EQ.1) WRITE(LUE,125) ICITY,IBOZT
      IF (ION(6).EQ.1) WRITE(LUF,126) ICITY,IBOZT
  121 FORMAT('IEA ',10X,A4,2X,A4,10X,'FLAT PLAT')
  122 FORMAT('IEA ',10X,A4,2X,A4,10X,'SALT POND')
  123 FORMAT('IEA ',10X,A4,2X,A4,10X,'EVAC TUBE')
  124 FORMAT('IEA ',10X,A4,2X,A4,10X,'CENT RECV')
  125 FORMAT('IEA ',10X,A4,2X,A4,10X,'PARB TROF')
  126 FORMAT('IEA ',10X,A4,2X,A4,10X,'SHAL POND')
C
C  PROCESSING BEGINS
C
      AMON=0.
      RDAY=0.
C
C  START OF MONTH LOOP
C
  750 AMON=AMON+1.
      ADAY=0.
C
C  START OF DAY LOOP
C  INITIALIZE HOUR ARRAYS TO ZERO
C
  730 DO 725 N=1,5
      QFLPT(N)=0
      HFLPT(N)=0
      QPOND(N)=0
      HPOND(N)=0
      QEVAC(N)=0
      HEVAC(N)=0
      QCENT(N)=0
      HCENT(N)=0
      QPART(N)=0
      HPART(N)=0
      QSHPO(N)=0
  725 HSHPO(N)=0
      RDAY=RDAY+1.
      ADAY=ADAY+1.
C
C  WEATH CALCULATES EOT AND QSP
C  WEATHER DATA READ INTO WEATR ARRAY
C
C  EXIT IF YEAR END
C
      IF(AMON.EQ.13)GO TO 900
      CALL WEATH(RDAY)
      DAY=ADAY
```

```
   50 FORMAT('    IEA DATA PROGRAM VERSION 1')
C
C     READ(LUR,100)(DYMON(I),I=1,12)
C 100 FORMAT(12F2.0)
      IDUMMY(1)=12
  100 CALL READIN (-4,DUMMY,IDUMMY,IQR)
      IQRS=IQRS+IQR
      IF (IQR.NE.0) CALL READIN (5,DUMMY,IDUMMY,IQR)
      YRLEN=0
      DO 99 J=1,12
      YRLEN=YRLEN+DUMMY(J)
   99 DYMON(J)=DUMMY(J)
C
      WRITE(LUW,101)(DYMON(I),I=1,12)
  101 FORMAT('     MONTH END DAYS',12(1X,I3))
C
C     READ(LUR,110)(ION(I),I=1,6),IBOZ
C 110 FORMAT(7I1)
      IDUMMY(1)=7
  110 CALL READIN (-4,DUMMY,IDUMMY,IQR)
      IQRS=IQRS+IQR
      IF (IQR.NE.0) CALL READIN (5,DUMMY,IDUMMY,IQR)
      DO 111 J=1,6
  111 ION(J)=DUMMY(J)
      IBOZ=DUMMY(7)
      IBOZT=IBOZN
      IF (IBOZ.EQ.1) IBOZT=IBOZY
C
      WRITE(LUW,115)(ION(I),I=1,6),IBOZ
  115 FORMAT('      COLLECTOR SWITCHES 1=ON,0=OFF ',//,
     1'      FLAT PLATE=',I1,' SALT POND=',I1,' EVAC TUBE=',I1,/,
     2'      CENTRAL RECV=',I1,' PARB TROUGH=',I1,' SHAL POND=',I1,/,
     3'    BOES MODEL=',I1)
C
C  READ COLLECTOR PARAMETERS
C
      DO 109 I=1,6
C
C     READ(LUR,102)(TALPHA(I),UL1(I),UL2(I),BO(I))
C 102 FORMAT(4(1X,F8.4))
      IDUMMY(1)=7
  102 CALL READIN (-4,DUMMY,IDUMMY,IQR)
      IQRS=IQRS+IQR
      IF (IQR.NE.0) CALL READIN (5,DUMMY,IDUMMY,IQR)
      TALPHA(I)=DUMMY(1)
      UL1(I)=   DUMMY(2)
      UL2(I)=   DUMMY(3)
      BO(I)=    DUMMY(4)
      TILT(I)=  DUMMY(5)
      DIR(I)=   DUMMY(6)
      RHO(I)=   DUMMY(7)
C
      IF(I.EQ.1)WRITE (LUW,211)
  211 FORMAT(1H0,'        ALPHA         UL1         UL2',
     1'      BO          TILT         DIR          RHO')
      WRITE(LUW,103) TALPHA(I),UL1(I),UL2(I),BO(I),
     1    TILT(I),DIR(I),RHO(I)
  103 FORMAT(7(3X,E10.4))
C     CONVERT W/M**2K INPUT TO KJ/HM**2K NEEDED FOR COMPUTATION
      UL1(I)=UL1(I)*3.6
      UL2(I)=UL2(I)*3.6**2
  109 CONTINUE
C
C  READ IN LAT AND TEMP STEPS FOR A SINGLE CITY
C
C 105 READ(LUR,107)ALAT,DLONG,TEMP(1),TEMP(2),TEMP(3),TEMP(4),
C    1TEMP(5),THAMB,TROOM
C 107 FORMAT (2(1X,F5.2),7(1X,F3.0))
      IDUMMY(1)=9
  105 CALL READIN (-4,DUMMY,IDUMMY,IQR)
      IQRS=IQRS+IQR
      IF (IQR.NE.0) CALL READIN (5,DUMMY,IDUMMY,IQR)
```

APPENDIX A: FORTRAN LISTING OF COLLECTOR SUBSYSTEM CODE FROM MINSUN

```
C  THIS VERSION OF THE UMSORT MAIN PROGRAM HAS BEEN MODIFIED TO ACCEPT ALL INPUT
C  AND TO PRODUCE ALL OUTPUT IN SI UNITS.
C  THE FORMAT OF THE INPUT AND OUTPUT HAS ALSO BEEN MODIFIED TO ALLOW FOR
C  MORE ACCURACY.
C
C  PROGRAM IEADATA
C  PROGRAM TO PRODUCE OUTPUT DATA FOR IEAMINSUN
C  UP TO SIX COLLECTOR TYPES CAN BE SELECTED
C
C  BASED ON LOS ALAMOS SCIENTIFIC LABORATORY'S CANADA FILE
C  PROGRAM
C
      BLOCK DATA
      COMMON /LUNITS/LUR,LUW,IFORM
      COMMON /PRT/SUMA(6,15,13),TEMP(5)
      DATA SUMA/1170*0./
      DATA LUR/5/,LUW/6/
      END
C
C
C  MAIN LINE PROGRAM FOR UMSORT
C
      INTEGER YRLEN,AMON,DYMON
      COMMON /A/RMON,DAY,TIME,HR,DEC,CSH,ALT,AZIM,ALAT,QSP,ECT
      COMMON /B/AINS,TNS,TEW,QH,QDNI,QSKY,QGRND,QDERC,QDER,QDIF,TA
      COMMON /C/IBOZ
      COMMON /LUNITS/ LUR,LUW,IFORM
      COMMON/PRT/SUMA(6,15,13),TEMP(5)
      DIMENSION WEATR(4,24),ION(6),AMB(24),DHM(24)
      DIMENSION QFLPT(5),HFLPT(5)
      DIMENSION QPOND(5),HPOND(5)
      DIMENSION QEVAC(5),HEVAC(5)
      DIMENSION QCENT(5),HCENT(5)
      DIMENSION QPART(5),HPART(5)
      DIMENSION QSHPO(5),HSHPO(5)
      DIMENSION TALPHA(6),UL1(6),UL2(6),BO(6)
      DIMENSION TILT(6),DIR(6),RHO(6)
      DIMENSION DYMON(12)
      DIMENSION QINC(5,6),QINCC(5,6),QCOUT(5,6)
      DIMENSION DUMMY(24),IDUMMY(81)
      DATA LUA/7/,LUB/8/,LUC/9/,LUD/10/,LUE/11/
      DATA LUF/12/,IHR24/24/
      DATA IBOZN/'    '/,IBOZY/'BOES'/
      DATA IQRS/0/
C
C
C
C  DATA ELEMENTS ARE AS FOLLOWS
C  DYMON-LAST DAY OF EACH MONTH
C
C  TALPHA,UL1,UL2,BO- COLLECTOR INPUT PARAMETERS
C  AMON,RDAY,ADAY-MONTH AND DAY COUNTERS
C  WEATR- WEATHER DATA ARRAY
C
C  READ PARAMETER SECTION
C  READ IN DAY OF MONTH-END FOR CONTROL LOOP
C  AND SET COLLECTOR SWITCHES
C
      WRITE(LUW,50)
```

APPENDIX A:

FORTRAN LISTING OF COLLECTOR–SUBSYSTEM CODE FROM MINSUN

Ratzel, A.C., and C.E. Simpson, *Heat Loss Reduction Techniques for Annual Solar Receiver Designs*, Sandia National Laboratory Report SAND 78-1769, Albuquerque, N.M. (Feb. 1979).

Ratzel, A.C., *Evaluation of the Evacuated Solar Annular Receivers Used at the Mid-Temperature Solar Systems Test Facility (MSSTF)*, Sandia National Laboratory Report SAND 78-0983, Albuquerque, N.M. (1979).

Sillman, S., *The Trade-off between Collector Area, Storage Volume, and Building Conservation in Annual Storage Solar Heating Systems*, Solar Energy Research Institute Report SERI/TR-721-907, Golden, Colo. (March 1981).

Solar Energy System Construction Cost, Mueller Associates, Inc., Draft Report 81-183 (Aug. 1981).

The Solar Thermal Report, Vol. 2, No. 1, published by Solar Energy Research Institute, Golden, Colo., SERI/SP-633-1060 (Winter 1981).

The Solar Thermal Report, Vol. 2, Nos. 2-8, published by Jet Propulsion Laboratory, Pasadena, Calif., JPL 5106-10/1 through 10/7 (undated).

The Solar Thermal Report, Vol. 3, No. 1, published by Jet Propulsion Laboratory, Pasadena, Calif., JPL 5106-10/9 (Jan. 1982).

Survey and Evaluation of Available Thermal Insulation Materials for Use on Solar Heating and Cooling Systems, Versar, Inc., interim technical report under Contract No. EM-78-C-04-5363 (May 1979).

Tabor, H., *Letter to the Editor*, Solar Energy *24*:113-15 (1980).

Thornton, J., et al., *Comparative Evaluation of Solar Thermal Systems for Thermal Applications*, Solar Energy Research Institute Report SERI/TR-253-1706, Golden, Colo. (in press).

Waksman, D., E. Streed, and J. Seiler, *NBS Solar Collector Durability/ Reliability Test Program Plan*, U.S. National Bureau of Standards Technical Note 1136, Washington, D.C. (Jan. 1981).

Williams, J., S. Whitney, and H. Ball, *Solar-Augmented Applications in Industry, Final Report for 1979*, Gas Research Institute, Chicago, Ill., 82 pp. (Feb. 1980).

Wilson, W.G., *Central Receiver Technology Development: Heliostats: Quarterly Review Presentation*, Sandia National Laboratory, Livermore, Calif. (Sept. 1981).

Wyman, C., J. Castle, and F. Krieth, *A Review of Collector and Energy Storage Technology for Intermediate Temperature Applications*, Solar Energy *34*:519-40 (undated).

Linn, J.K., *Analysis of Collectors for Process Heat Applications*, Sandia National Laboratory Report SAND 78-1977, Albuquerque, N.M. (Feb. 1979).

Lumsdaine, E., *Solar Technology Assessment Project, Vol. V: Solar Industrial Process Heat*, available from Florida Solar Energy Center, Cape Canaveral, Fla., 78 pp. (April 1981).

Lundgren, R.G., and J.V. Otts, *Central Receiver Test Facility (CRTF) Cost History*, Sandia National Laboratory Report SAND 80-2477, Albuquerque, N.M. (May 1981).

McGarity, A.E., W.R. McIntire, and J.W. Allen, *Simulation Modeling of Solar Heating Systems with CPC Collectors*, Progress in Solar Energy, Proc. of the American Solar Energy Society 5:507-511 (1982).

McGarity, A.E., J.W. Allen, and W.W. Schertz, *Side-by-Side Testing of Solar Heating Systems with CPC Collectors*, Progress in Solar Energy, Proc. of the American Solar Energy Society 5:437-442 (1982).

Mavec, J.A., et al., *Reliability and Maintainability Evaluation of Solar Collector and Manifold Interconnections*, Argonne National Laboratory Report ANL/SDP-TM-79-4 (U.S. Department of Energy Report SOLAR/0902-79/70) (March 1979).

Morse, T., *Product Class Evaluation: Concentrating Solar Collectors*, Hittmann Associates, Inc., Columbia, Mo. (1981).

O'Gallagher, J.J., and R. Winston, *Dramatic Improvement in Cost and Performance for LCNT (Low Concentration Nontracking or CPC) Arrays through Proper Receiver Design and Transport Network Layout*, Enrico Fermi Institute (The University of Chicago), Chicago, Ill., 4 pp. (Jan. 1982).

O'Gallagher, J.J., J.C. Church, and R. Winston, *Expected Energy Delivery of Generic Solar Energy Collectors Deployed at Five Locations in Canada*, Enrico Fermi Institute (The University of Chicago), Chicago, Ill., 54 pp. (Feb. 1982).

Otts, J.V., *Midtemperature Solar System Test Facility Program Status Report*, Sandia National Laboratory Report SAND 80-1681, Albuquerque, N.M. (Aug. 1980).

Peters, R.R., *Solar Energy Systems Design - A Simple Method for Sizing the Collector Field and Thermal Storage*, Sandia National Laboratory Report SAND 81-1541, Albuquerque, N.M. (July 1981).

Proceedings of the First Semi-Annual Distributed Receiver Systems Program Review, Lubbock, Texas, Jan. 22-24, 1982, 255 pp., published by Jet Propulsion Laboratory, Pasadena, Calif. (April 1980).

Graham, B.J., *A Survey and Evaluation of Current Design of Evacuated Collectors - Final Technical Report*, U.S. Department of Energy Report ALO/15350-1, Albuquerque, N.M. (Sept. 1979).

Harrison, T.D., and W.H. McCulloch, *Midtemperature Solar Systems Test Facility (MSSTF) Project Test Results: Phase IVA MSSTF System Operation*, Sandia National Laboratory Report SAND 78-1088, Albuquerque, N.M. (Nov. 1978).

Harrison, T.D., *Midtemperature Solar Systems Test Facility Test Results: Effects of Severe Hailstorm on August 9, 1978*, Sandia National Laboratory Report SAND 78-2182, Albuquerque, N.M. (Nov. 1979).

Harrison, T.D., G.N. Bond, and A.C. Ratzel, *Design Considerations for a Proposed Passive Vacuum Solar Annular Receiver*, Sandia National Laboratory Report SAND 78-0982, Albuquerque, N.M. (April 1979).

Harrison, T.D., K.D. McAllister, and J.A. Sisneros, *Measurement of Incident Angle Modifiers for the Solar Kinetics T-100 Line-Focusing, Parabolic Trough Solar Collector Reflector Surface, 050 Inch Corning 03117 Chemcor Glass*, Sandia National Laboratory, Albuquerque, N.M., 7 pp. (May 1980).

Hildebrandt, A.F., and S. Dasgupta, *Survey of Power Tower Technology*, J. of Solar Energy Engineering *102*:91-104 (May 1980).

Interim Reliability and Materials Design Guidelines for Solar Domestic Hot Water Systems, Argonne National Laboratory Report ANL/SDP-9 (U.S. Department of Energy Report SOLAR/0907-80/70) (Sept. 1980).

Knapp, C.L., and T.L. Stoffel, *Direct Normal Solar Radiation Data Manual: Longterm Monthly Mean, Daily Totals for 235 National Weather Service Stations: Addendum to the Insolation Data Manual*, Solar Energy Research Institute Report SERI/SP-281-1658, Golden, Colo. (July 1982).

Leonard, J.A., *Linear Concentrating Solar Collectors - Current Technology and Applications*, Sandia National Laboratory Report SAND 78-0949, Albuquerque, N.M. (July 1978).

Line-Focus Concentrating Collector Technology Development and Applications Management: Summary Presentation, Sandia National Laboratory, Albuquerque, N.M. (Sept. 1981).

Line-Focus Solar Thermal Energy Technology Development, FY79 Annual Report for Department 4720, K.D. Bergeron, R.L. Champion, and R.W. Hunke, eds., Sandia National Laboratory Report SAND 80-0865, Albuquerque, N.M. (April 1980).

Beach, C.D., *A Solar Collector Testing Program, Part I: Efficiency and Exposure Tests*, Florida Solar Energy Center Report FSEC-RD-79-2, Cape Canaveral, Fla. (May 1979).

Beveridge, B. (compiler), *Parabolic Dish Concentrator Designs and Concepts*, brochure prepared by the Jet Propulsion Laboratory, Pasadena, Calif., for the U.S. Department of Energy, JPL 400-98, 29 pp. (1980).

Bilgen, E., *A Feasibility Study on Solar Utility Total Energy Systems*, ASME Paper 80-WA/Sol-22, American Society of Mechanical Engineers, New York (1980).

Brandvold, G.E., *Distributed Collector Technology Development*, Sandia National Laboratory, Albuquerque, N.M. (Nov. 1981).

Britt, J.F., C.W. Schulte, and H.L. Davey, *Heliostat Production Evaluation Cost Analysis*, Solar Energy Research Institute Report SERI/TR-8052-1, Golden, Colo. (Dec. 1979).

Chopra, P.S., *Reliability and Materials Performance of Solar Heating and Cooling Systems*, Argonne National Laboratory Report ANL/SDP-TM-79-8 (U.S. Department of Energy Report SOLAR/0906/79-76) (June 1979).

Darnell, A.J., W.P. Marlatt, and J.K. Roberts, *TC-100 Solar Collector Review Program Final Report Summary*, Energy Technology Engineering Center, Canoga Park, Calif., 52 pp. (1981).

Department of Energy Solar Central Receiver Semiannual Meeting, October 15-16, 1980, Sandia National Laboratory Report SAND 80-8049 (1980).

Dudley, V.E., and R.M. Workhoven, *Summary Report - Concentrating Solar Collector Test Results, Collector Module Test Facility (CMTF), January-December 1978*, Sandia National Laboratory Report SAND 78-0977, Albuquerque, N.M. (March 1979).

Dudley, V.E., and R.M. Workhoven, *Performance Testing of the FMC Tresnel - Belt Concentrating Solar Collector*, Sandia National Laboratory Report SAND 80-0011, Albuquerque, N.M. (Jan. 1980).

Dudley, V.E., and R.M. Workhoven, *Performance Testing of the Scientific Atlanta Faceted Fixed Mirror Solar Concentrator*, Sandia National Laboratory Report SAND 80-0012, Albuquerque, N.M. (Jan. 1980).

Forkelson, L., and D. Larson, *1980 Annual Report of the Coolidge Solar Irrigation Project*, Sandia National Laboratory Report SAND 80-2378, Albuquerque, N.M. (Feb. 1981).

SWITZERLAND

IEA/CRO Solar Heating and Cooling Program: Central Solar Heating Plants with Seasonal Storage: Proposal for a Format for Data Specifications, Atlantis Energie A.G., Bern, Switzerland, 9 pp. (April 1980).

IEA - Task VII Central Solar Heating Plants with Seasonal Storage, Subtask 1(b): Information about Solar Collectors of the Following Types, Flat Plate, Evacuated, Parabolic Troughs, Atlantis Energie A.G. (Aug. 1982).

UNITED KINGDOM

Cross, B.M., and C.M.A. Johansson, *Solar Collector Manufacture and Performance in the U.K.*, University College, Cardiff, U.K., 6 pp. (undated).

Hayward, K., and R.W. Rawcliffe, *Durability Testing of Solar Collectors*, University College, Cardiff, U.K., 5 pp. (undated).

Wozniah, S.J., *Cost and Performance of Solar Water Heating Systems in the U.K.*, Building Research Establishment, Garston, Watford, U.K., 4 pp. (Aug. 1981).

UNITED STATES

Active Solar Energy System Design Practice Manual, U.S. Department of Energy Report SOLAR/0802-79/01, Washington, D.C. (Oct. 1979).

Assessment of Solar Collector Economies of Scale, Science Applications, Inc., Huntsville, Ala., SAI-79-697-HU, 11 pp. (Aug. 1978).

Barnhart, J.S., *Energy Transport System Optimization for Distributed Networks of Solar Collectors*, presented at the Energy Sources Technology Conf. and Exhibition, Houston, Tex., Jan. 1981, ASME Paper 81-SOL-1, American Society of Mechanical Engineers, New York (1981).

Bankston, C.A., *Central Solar Heating Plants with Seasonal Storage: Basic Cost and Performance Data for the Solar Collector Subsystem*, Interim Report of Subtask 1(b), IEA Task VII (April 1982).

Baylin, F., R. Monte, and S. Sillman, *Annual-Cycle Thermal Energy Storage for a Community Solar System: Details of a Sensitivity Analysis*, Solar Energy Research Institute Report SERI/TR-721-575, Golden, Colo. (July 1980).

Baylin, F., et al., *Economic Analysis of Community Solar Heating Systems that Use Annual Cycle Thermal Energy Storage*, Solar Energy Research Institute Report SERI/TR-721-898, Golden, Colo. (Feb. 1981).

COMMISSION OF EUROPEAN COMMUNITIES

The Solar Energy Programme at the Joint Research Centre - Ispra Establishment, Commission of the European Communities, 4 pp. (1979).

van Hattem, D., *Pressure Drop Calculations in Large Solar Collector Systems*, Subtask 1(b), IEA Task VII Report (Oct. 1981).

1980 Annual Status Report: Solar Energy, Commission of the European Communities Report EUR 7253 EN (1980).

FEDERAL REPUBLIC OF GERMANY

Bruno, R., et al., *Analysis and Optimization of Solar Hot Water Systems*, Energy Research 1:329-40. (June 1977).

SWEDEN

Abrahamsson, T., S. Jonson, and K. Lagerkvist, *Heat from Solar Energy and Air with Storage in Water and Ice*, Swedish Council for Building Research Report D11: 1981, Stockholm, Sweden (1981).

Åstrand, L., et al., *The Knivsta District Heating Project, Sweden, Interim Report*, IEA Solar R & D, 43 pp. (1982).

Bruce, T., *An Energy Utility Viewpoint*, City of Sodertalje Energy Authority, Sweden (1978).

Margen, P., *Giant Inflated Solar Collector (GIS)*, Studsvik Energiteknik AB, STV-Report 79-6834, Nykoping, Sweden (Dec. 1980).

Margen, P., *Economics of Solar District Heating*, Sumoored 4(4):128-34 (1980).

Schnittger, J.R., *Reliability Engineering for Solar Heating Plants. A Method Study for the Lambohov Project in Linkoping*, Swedish Building Research Summaries S30:1979 (Summary of R117:1979), Stockholm, Sweden (1979).

Zinko, H., *Performance and Costs of Solar Collectors*, Studsvik Energiteknik AB Report 1981-02-28, 20 pp. (1981).

Zinko, H., *National Solar Collector Experiences - Sweden Flat Plate Collectors - FPC*, Studsvik Energiteknik AB Report 1982-09-19, 5 pp. (1982).

BIBLIOGRAPHY

AUSTRIA

Bruck, M., P. Blum, and E. Held, *The Solar House "OBDACH" — Experiences with a Solar Ground-Coupled Storage System*, Proc. of the IEA Workshop on Solar Ground-Coupled Heat-Pump Systems, Ispra, Italy (1982).

Bruck, M., et al., *Optimization of Solar Heating Systems*, Solar Energy '82: Proc. of the Summer School held at Igls, Austria, 28 July - 6 Aug. 1982, European Space Agency Report ESA SP-181, pp. 215-20 (1982).

Bruck, M., *Performance Analysis of a Large Flat-Plate Collector System*, Austrian Solar and Space Agency (1983).

Faninger, G., *Solar Heating and Cooling Systems in Austria*, Austrian Solar and Space Agency (1980).

Schaffar, G., *Correction Factors for Thermal Inertia and Shading Effects of Flat-Plate Collector Systems*, Austrian Institute for Building Research, Vienna (1983).

CANADA

Aliker, I., *Heat Transport System for the Canadian Central Receiver Solar Utility*, Burns and Roe, Oradell, N.J., 48 pp. (Dec. 1979).

Arjomand, S., et al., *Assessment of the Industrial and Commercial Applications of the Central Receiver in Canada: Vol. I - Economics and Market Survey*, Canada Mortgage and Housing Corp., Ontario, Canada (April 1981).

Arjomand, S., et al., *Assessment of the Industrial and Commercial Applications of the Central Receiver in Canada: Vol. II - Technical Summary of Central Solar Receiver Technology*, Canada Mortgage and Housing Corp., Ontario, Canada (April 1981).

Bilgen, E., *Solar Utility Total Energy System*, Exregy Research Corp., Montreal, Canada, 42 pp. (Jan. 1980).

Tilton, B.E., G.L. Keller, and J.F. Best, *Central Receivers for Cogeneration Applications in Canada*, Canada Mortgage and Housing Corp., Ontario, Canada, 83 pp. (Dec. 1980).

Urguhart, D.A., *Implications of Vacuum Protected and Photovoltaic Solar Collectors Re Feasibility of the Central Receiver Solar Utility*, Spectral Engineering, Ltd., Toronto, Ontario (Dec. 1979).

92. Hall, I., et al., *Generation of Typical Meteorological Years for 26 Solmet Stations*, Sandia National Laboratory Report SAND 78-1601 (Aug. 1978).

93. *TRNSYS, A Transient Simulation Program*, Solar Energy Laboratory, The University of Wisconsin at Madison, Madison, Wisc., Report 38 (April 1981).

94. Stadjuhar, S., *PROSYA/ECONMAT User's Guide: Solar Industrial Process Heat Feasibility Evaluation*, Solar Energy Research Institute Report SERI/TR-733-724, Golden, Colo. (Feb. 1982).

80. Hayward, K., *Highlighting the Faults in Solar Collectors*, Building Service and Environmental Engineer (Aug. 1981).

81. Wolosewicz, R.M., and P.S. Chopra, *Freezing Problems and Other Reliability Concerns in Operational Solar Demonstration Sites*, Proc. of the U.S. Department of Energy Contractors' Review for Solar Heating and Cooling Demonstration Program, San Diego, Calif. (Dec. 1978).

82. Dickinson, W.C., and K.C. Brown, *Economic Analysis of Solar Industrial Process-Heat Systems: A Methodology to Determine Annual Required Revenue and Internal Rate of Return*, Lawrence Livermore Laboratory Report UCRL-52814 (Aug. 1979).

83. Guthrie, K.M., *Capital Cost Estimating*, Chemical Engineering, pp. 114-33 (March 24, 1969).

84. Brown, K.C., *End-Use Matching for Solar Industrial Process Heat*, Solar Energy Research Institute Report SERI/TR-34-091, Golden, Colo. (Jan. 1980).

85. *The Analysis of Construction Costs of Ten Industrial Process-Heat Systems*, Mueller Associates, Inc., Report MAI-210 (Dec. 1980).

86. *Evaluation of Residential and Commercial Solar/Gas Heating and Cooling Technologies*, prepared by Booz Allen & Hamilton for the Gas Research Institute, Chicago, Ill., GR-79/0105 (1980).

87. Schimmel, W.P., *Focus on Goals Revisited, A Report of the Solar Thermal Cost Goals Committee Presented to the DOE Division of Solar Thermal Energy Systems*, Sandia National Laboratory, Albuquerque, N.M. (1980).

88. Hildebrandt, A.F., and C.L. Lawrence, *Solar Technology Assessment Project, Vol. 9: Heliostat Systems — Technical and Economic Assessment*, University of Houston, Houston, Texas (1981).

89. Drumheller, K., *The Cost of Heliostats in Low Volume Production*, prepared by Battelle Pacific Northwest Laboratory, Richland, Wash., for Solar Energy Research Institute, Golden, Colo., SERI/TR-8043-2 (Jan. 1980).

90. Britt, J.F., *Heliostat Production Evaluation and Cost Analysis*, General Motors Corp. Transportation Systems Center, Warren, Mich., EP-80026 (March 1980).

91. *Proc. of the Distributed Solar Collector Summary Conf. — Technology and Applications*, R.L. Aluis, ed., Sandia National Laboratory Report SAND 83-0137c (March 1983).

68. Randall, D.E., D.D. McBride, and R.E. Tate, *Steady-State Wind Loading on Parabolic-Trough Solar Collectors*, ASME Paper 80-C2/Sol-20, American Society of Mechanical Engineers, New York (1980).

69. Peterka, J.A., J.M. Sinou, and J.E. Cermar, *Mean Wind Forces on Parabolic-Trough Solar Collectors*, Sandia National Laboratory Report SAND 80-7023 (1980).

70. Lenoir, Y., *Optimization de la Gestion des Stocks de la chaleur par des Algorithmes de programmation Dynamique*, Centre d'Automatique et d'Informatique Ecole des Mines, Paris (1980).

71. Bruck, M., *Performance Analysis of a Large Flat-Plate Collector System*, Austrian Solar and Space Agency (1983).

72. Jensen, L., *Flow Distribution Efficiency in Solar Collector Systems*, Lunds Tekniska Hogskola, Rapport BKL, 1981:6.

73. *Intermediate Minimum Property Standards for Solar Heating and Domestic Hot Water Systems*, U.S. National Bureau of Standards Report NBSIR 76-1059 (April 1976).

74. Waksman, D., and J. Holton, *Environmental and Safety Considerations for Solar Heating and Cooling Applications*, U.S. National Bureau of Standards Report NBSIR 78-1532 (Sept. 1978).

75. *Hazardous Properties and Environmental Effects of Materials Used in Solar Heating and Cooling (SHAC) Technologies: Interim Handbook*, J.Q. Searcy, ed., Sandia National Laboratory Report SAND 78-0842 (Aug. 1978).

76. Kjellson, E., and L. Åstrand, *The Lyckebo Project, Solar District Heating with Seasonal Storage*, IEA Task VII Report, Uppsala Kraftvarme (Jan. 1983).

77. Zinko, H., and C. Eriksson, *The Experimental Solar Collector First Field at Studsvik*, BFR Report, Sweden (1983).

78. Roseen, R., and B. Perers, *Integral Seasonal Storage Solar Heating Plant*, Solar World Forum, Proc. of the Fourth Solar Energy Society Congress, Vol. 1, D. Hall and J. Morton, eds., Pergamon Press, New York, pp. 697-702 (1981).

79. Hultmark, G., *The Sunclay Project: Seasonal Storage of Solar Heat in Clay*, Swedish Council for Building Research Report R38:1980, Stockholm, Sweden (1980).

55. *Proceedings of the Line-Focus Solar Thermal Energy Technology Development — A Seminar for Industry,* R.L. Champion, ed., Sandia National Laboratory Report SAND 80-1666 (Feb. 1981).

56. Randall, D.E., *Initial Experience and Preliminary Results — Solar Collector Materials Exposure to the IPH Environment,* Sandia National Laboratory Report SAND 81-0920 (May 1981).

57. Boes, E.C., *Fundamentals of Solar Radiation,* Sandia National Laboratory Report SAND 79-0490 (Dec. 1979).

58. Dickinson, W.C., *Annual Available Radiation for Fixed and Tracking Collectors,* Solar Energy *21*:249-51 (1978).

59. Karlsson, N.G., R. Hakansson, and H. Zinko, *Solar District Heating Facility at Sodertorn BFR,* Sweden (1982).

60. Hultmark, G., *The Solar District Heating System at Torvalla,* Swedish Council for Buiding Research, Stockholm, Sweden (1982).

61. Wilson, G., *A Large-Scale Solar Collector,* internal report prepared for Granges Aluminum, Sweden (1982).

62. Bruce, T., L. Lindeberg, and S. Roslund, *Central Solar Heating Plants with Seasonal Storage: Basic Design Data for the Heat Distribution System,* Swedish Council for Building Research Report D22:1982, Stockholm, Sweden [distribution restricted to participants in IAE Task VII] (Oct. 1982).

63. Kearney, D.W., *Status of Current IPH Applications,* Solar Energy Research Institute Report SERI/TR-632-1123, Golden, Colo. (1981).

64. Myers, S., *An Assessment of the Field Status of Active Solar Systems,* U.S. Department of Energy Report DOE/SF/11485-1 (Feb. 1982).

65. Kjellson, E., et al., *Solar District Heating with Evacuated Collectors: First-Year Experience of the Knivsta Plant,* Swedish Council for Building Research Report D10:1982, Stockholm, Sweden (1982).

66. Auld, H.E., and P.F. Lodde, *Study of Foundation Designs for Single-Axis Tracking Solar Collector Systems under Reduced Loading Conditions,* Sandia National Laboratory Report SAND 79-7016 (May 1979).

67. Auld, H.E., *Analysis of Field Test Results for Single-Axis Tracking Solar Collector Foundations,* Sandia National Laboratory Report SAND 79-7023 (July 1979).

42. van Hattem, D., *Yearly Collector Performance in Northern Italy*, Subtask 1(b), IEA Task VII Report, International Energy Agency (Sept. 1981).

43. Zinko, H., and R. Hakansson, *Annual Energy Production with Solar Collectors: TRNSYS Simulation*, Studsvik Energiteknik AB, 1981-09-15, 21 pp. (1981).

44. Steinmueller, B., *Performance of Collector Arrays under Ideal and Nonideal Conditions*, 18 pp. (1981).

45. Zinko, H., B. Perers, and E. Kjellson, *Dynamic System Response of the Solar Energy System at Knivsta*, Studsvik Energiteknik AB, EI-82/83, Nykoping, Sweden (1982).

46. Harrigan, R.W., *Handbook for the Conceptual Design of Parabolic-Trough Solar Energy Systems: Process-Heat Applications*, Sandia National Laboratory Report SAND 81-0763 (July 1981).

47. *Survey of Mirrors and Lenses and Their Required Accuracy, Final Report*, prepared by Honeywell, Inc., DE-AC04-78CS3548 (Feb. 1980).

48. Hudson, S.L., *Design Aspects and Optimization of Intermediate Temperature Solar Industrial Process Heat Systems*, ASME Paper 80-C2/Sol-18, American Society of Mechanical Engineers, New York (1980).

49. Battleson, K.W., *Solar Power Tower Design Guide: Solar Thermal Central Receiver Power Systems, A Source of Electricity and/or Process Heat*, Sandia National Laboratory Report SAND 81-8005 (April 1981).

50. Meyer, R.D., *Energy Transmission System Heat Losses*, Sandia National Laboratory Report SAND 82-1138 (Oct. 1982).

51. Menuchin, Y., et al., *Optimal Flow Configuration in Solar Collector Arrays*, Proc. of the 1981 Annual Meeting of the American Section of the International Solar Energy Society, Inc., Philadelphia, Penn. (1981).

52. McCumber, W.H., and M.W. Weston, *The Analysis and Comparison of Actual to Predicted Collector Array Performance*, IBM J. of Research and Development *23*(3):253 (May 1979).

53. Kutscher, C., and R. Davenport, *Preliminary Operational Results of the Low-Temperature Solar Industrial Process-Heat Field Tests*, Solar Energy Research Institute Report SERI/TR-632-385, Golden, Colo. (June 1980).

54. Mikkelson, E., *The Influence of Dynamic Effects on Useful Solar Output*, Technical University of Denmark (1982).

32. Harrison, T.D., *Midtemperature Solar Systems Test Facility Predictions for Thermal Performance of the Acurex Solar Collector with EEK 244 Reflector Surface*, Sandia National Laboratory Report SAND 80-1964/3 (1980).

33. Harrison, T.D., *Midtemperature Solar Systems Test Facility Predictions for Thermal Performance Based on Test Data: Sun-Heet Nontracking Solar Collector*, Sandia National Laboratory Report SAND 80-1964/4 (March 1981).

34. Harrison, T.D., *Midtemperature Solar Systems Test Facility Predictions for Thermal Performance Based on Test Data: AAI Solar Collector with Pressure-Formed Glass Reflector Surface*, Sandia National Laboratory Report SAND 80-1964/5 (March 1981).

35. Harrison, T.D., *Midtemperature Solar Systems Test Facility Predictions for Thermal Performance Based on Test Data: Acurex Solar Collector with Glass Reflector Surface*, Sandia National Laboratory Report SAND 80-1964/6 (March 1981).

36. Harrison, T.D., *Midtemperature Solar Systems Test Facility Predictions for Thermal Performance Based on Test Data: Solar Kinetics T-700 Solar Collector with Glass Reflector Surface*, Sandia National Laboratory Report SAND 80-1964/7 (March 1981).

37. Harrison, T.D., *Midtemperature Solar Systems Test Facility Predictions for Thermal Performance Based on Test Data: Alpha Solarco Model 104 Solar Collector with 0.125 Low-Iron Glass Reflector Surface*, Sandia National Laboratory Report SAND 80-1964/8 (April 1981).

38. Harrison, T.D., *Midtemperature Solar Systems Test Facility Program for Predicting Thermal Performance Based on Test Data: Solar Kinetics T-600 Solar Collector with EEK 244 Reflector Surface*, Sandia National Laboratory Report SAND 80-1964/9 (undated).

39. Dudley, V.E., and R.M. Workhoven, *Variation of Collector Efficiency and Receiver Thermal Loss as a Function of Solar Irradiance*, preprint of American Society of Mechanical Engineers paper (June 1982).

40. Gaul, H.W., and A. Rabl, *Incidence Angle Modifier and Average Optical Efficiency of Parabolic Trough Collectors*, J. of Solar Energy Engineering, Transactions of the American Society of Mechanical Engineers, Vol. 1 (1980).

41. Jones, R.E., and J.F. Burkhart, *Shading Effects of Collector Rows Tilted Toward the Equator*, Solar Energy *26*:563-65 (Dec. 1980).

22. O'Gallagher, J.J., et al., *A Stationary Evacuated Tube with Integrated Concentrator for 100 °C to 300 °C*, Proc. of the 1981 Annual Meeting of the American Section of the International Solar Energy Society, Inc., Philadelphia, Penn. (May 1981).

23. O'Gallagher, J.J., K. Snail, and R. Winston, *An Evacuated CPC Solar Collector Tube for Industrial Process Applications*, Proc. of the Annual Meeting of the International Solar Energy Society, Inc., Brighton, U.K. (Aug. 1981).

24. Winston, R., and J.J. O'Gallagher, *Design Optimization Studies for Nonimaging Concentrating Solar Collector Tubes*, The University of Chicago, Chicago, Ill. (Nov. 1982).

25. McIntire, W., and K. Reed, *Incident-Angle Modifiers for Evacuated-Tube Collectors*, Proc. of the 1981 Annual Meeting of the American Section of the International Solar Energy Society, Inc., Philadelphia, Penn., p. 282 (May 1981).

26. Wiesenmaier, B.L., *Test Results on Vacuum Tube Collectors*, Annual DOE Active Solar Heating and Cooling Contractors' Review Meeting, U.S. Department of Energy, Washington, D.C., 3 pp. (March 1980).

27. Winston, R., and J.J. O'Gallagher, *Nonimaging Concentrators for Solar Thermal Energy*, Enrico Fermi Institute (The University of Chicago), Chicago, Ill., 92 pp. (1980).

28. Winston, R., and J.J. O'Gallagher, *Fundamentals and Techniques of Nonimaging Optics for Solar Energy Conversion*, Enrico Fermi Institute (The University of Chicago), Chicago, Ill., 44 pp. (1980).

29. Harrison, T.D., *Midtemperature Solar Systems Test Facility Program for Predicting Thermal Performance of Line-Focusing, Concentrating Solar Collectors*, Sandia National Laboratory Report SAND 80-1964 (Nov. 1980).

30. Harrison, T.D., *Midtemperature Solar Systems Test Facility Predictions for Thermal Performance of the Solar Kinetics T-700 Solar Collector with EEK 244 Reflector Surface*, Sandia National Laboratory Report SAND 80-1964/1 (Nov. 1980).

31. Harrison, T.D., *Midtemperature Solar Systems Test Facility Predictions for Thermal Performance of the Suntec Solar Collector with Heat-Formed Glass Reflector Surface*, Sandia National Laboratory Report SAND 80-1964/2 (Nov. 1980).

12. *Cost-Effectiveness Comparison of Solar Collector Candidates for the Solar Utility, Section II,* prepared by Hooper and Angus Associates, Ltd., for the Canada Mortgage and Housing Corp., Ontario, Canada, 51 pp. (Dec. 1980).

13. *Cost-Effectiveness Comparison of Solar Collector Candidates for the Solar Utility, Section I* (draft version), prepared by Spectral Engineering, Ltd., for the Canada Mortgage and Housing Corp., Ontario, Canada, 101 pp. (Nov. 1980).

14. *Cost-Effectiveness Comparison of Solar Collector Candidates for the Solar Utility, Section I* (final report), prepared by Spectral Engineering, Ltd., for the Canada Mortgage and Housing Corp., Ontario, Canada (Nov. 1981).

15. Kutscher, C., et al., *Design Approaches for Solar Industrial Process-Heat Systems: Nontracking and Line-Focus Collector Technologies,* Solar Energy Research Institute Report SERI/TR-253-1356, Golden, Colo. (Aug. 1982).

16. Bird, S.P., et al., *Assessment of Generic Solar Thermal Systems for Large Power Applications, Vol. 2: Analysis of Thermal Energy Production Costs for Systems from 50 to 600 MWt,* Battelle Pacific Northwest Laboratory Report PNL-3533-Vol. 2, UC-62c, Richland, Wash. (June 1981).

17. Iannucci, J.J., and P.J. Eicker, *Comparison of Solar Thermal Systems for Process-Heat Applications,* Sandia National Laboratory, Livermore, Calif., 3 pp. (Feb. 1979).

18. *Methods of Testing to Determine the Thermal Performance of Solar Collectors,* American Society of Heating, Refrigerating, and Air-Conditioning Engineers, ASHRAE Standard 93-77, New York (1977).

19. Jenkins, J.P., and J.E. Hill, *A Comparison of Test Results for Flat-Plate Water-Heating Solar Collectors Using the BSE and ASHRAE Procedures,* ASME Paper 79-WA/Sol-4, American Society of Mechanical Engineers, New York (1979).

20. Clark, A.F., and W.C. Dickinson, *Shallow Solar Ponds,* Chapter 12 in Solar Energy Technology Handbook, W.C. Dickinson and P.N. Cheremisinoff, eds., Marcel Dekker, Inc., New York (1980).

21. McIntire, W., and R. Winston, *Design Considerations for Reducing Optical Losses due to Gaps between Absorbers and their Reflectors,* Proc. of the 1981 Annual Meeting of the American Section of the International Solar Energy Society, Inc., Philadelphia, Penn., Vol. 4.1, p. 27 (May 1981).

REFERENCES

1. *Cost-Effectiveness Comparison of Solar Collector Candidates for the Solar Utility*, prepared by Spectral Engineering, Ltd., for the Canada Mortgage and Housing Corp., Ontario, Canada (Sept. 1981).

2. Dalenback, J., E. Gabrielsson, and B. Ludvigsson, *Three Swedish Group Solar Heating Plants with Seasonal Storage: A Summary of Experience from the Studsvik, Lambohov and Ingelstad Plants up to the End of 1980*, Swedish Council for Building Research Report D5:1981, Stockholm, Sweden (1981).

3. Finn, L., *A Swedish Solar Heating Plant with Seasonal Storage in the Ingelstad Project: Design and Construction Stage*, Swedish Council for Building Research, Stockholm, Sweden, 73 pp. (1979).

4. Norrback, K., and J. Hallenberg, *A Swedish Group Solar Heating Plant with Seasonal Storage: Technical-Economic Description of the Lambohov Project*, Swedish Council for Building Research Report D36:1980, Stockholm, Sweden (1980).

5. Zinko, H., *Experience from Central Solar Heating System with Seasonal Storage in Sweden*, Studsvik Energiteknik AB, 1982-02-04 (1982).

6. Margen, P., *Seasonal Thermal Storage: Swedish Practice, Developments and Cost Projections*, Swedish Council for Building Research Report D4:1981, Stockholm, Sweden (1981).

7. Åstrand, L., *Solar Energy in Uppsala*, Uppsala Kraftvarme AB, 1981-10-15 (1981).

8. *The Potential Thermal Performance and Economic Viability of Solar Utilities in Canada*, prepared by Dilworth, Secord, Meagher, and Associates, Ltd., Ottawa, Canada Mortgage and Housing Corp., Ontario, Canada, 37 pp. (Jan. 1979).

9. *Security and a Price Ceiling for Home Heating: The Potential of Solar Utility for Stabilizing the Price of Low-Grade Energy and Ensuring its Continuous Availability*, Canada Mortgage and Housing Corp., Ontario, Canada, 23 pp. (Aug. 1979).

10. *The Canadian Central Receiver Solar Utility Concept*, Canada Mortgage and Housing Corp., Ontario, Canada, 21 pp. (Oct. 1979).

11. *Strategic Plan for the Implementation of the Solar Utility Concept*, Canada Mortgage and Housing Corp., Ontario, Canada, 19 pp. (Feb. 1980).

8.2.4 Solar-Collector Design Work

In general, the systems evaluated in this task use large collector arrays. It has been learned from examples in several countries that proper collector design for large-scale applications is an important factor in reducing collector-system costs. Large-area, site-built or factory-built collector modules that can be quickly and easily installed are especially effective in reducing array heat losses, as well as overall installed subsystem costs. Hence, we recommend strongly that participants encourage national efforts for development work on large-scale collectors according to the specifications in their national design studies.

8.1.3 Validity of Cost Information

The cost data supplied in this report, assembled from a variety of sources and adapted to fit the needs of our Phase I study, are not to be construed as representing real costs for any past or future projects. Additional cost information could be acquired from recent large projects; such information might at least validate the trends noted in Chapter 5, and perhaps it might confirm the applicability of the modular estimation method to a variety of sites.

8.1.4 Validity of Operational Information

Throughout this report we have stressed the limitations of operational experience with large systems and with the collectors they would employ. We have attempted to provide some guidance to the literature to aid the designer and owner. Until there is greater experience with large solar-energy systems, the designers and operators will have to rely heavily upon experience with conventional plants and district heating systems.

8.2 Recommendations

8.2.1 Phase I Work

We recommend the performance and cost information contained in this report be used for the test cases and national design studies of Phase I. We recommend that all participants include an analysis employing the base-case costs presented in Chapter 5 to facilitate subsequent comparison and evaluation of results. We suggest that participants may also wish to modify the base-case costs (and perhaps the performance data as well) to reflect national experience for use in the Phase I projects.

8.2.2 Phase II Work

The information contained in this report is adequate for initial design and trade-off studies. However, we do not recommend final design or component selection be undertaken without further investigation.

8.2.3 Workshop on Large Collector Arrays

We recommend an international workshop be held by experts in the design, performance, and operation of large solar-collector arrays. The workshop should be structured to provide answers to the many questions raised by investigations of early solar-energy installations. It should result in a compilation, in a consistent and useful form, of the latest and most relevant information from field installations.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

8.1.1 Collector Technologies

We have examined the technical and economic aspects of a wide range of solar collectors for use in CSHPSS. At least four of the technologies appear to be viable: FPCs, stationary concentrators, PTCs, and central receivers. The choice among these four depends upon system variables (including temperature, size, storage efficiency, and insolation) and upon site-specific economic considerations (including the cost of land, power, freight, labor, etc.). Two concentrating tracking-collector technologies, PTCs and central receivers, emerge as top contenders in what is basically a low-temperature application. The reasons for this lie partly in the use of seasonal storage -- which means that energy collected on clear days can be used during a long period of overcast days -- and partly in the economic assumptions. We have postulated the existence of a mass-produced product some time in the future and assumed some progress toward the size of markets that would make mass-production costs realistic. Adoption of central solar heating is perhaps the fastest and most beneficial route to fulfillment of the mass-production scenario.

A number of innovative collector concepts that may be viable for central-plant applications were not examined in any depth in this study. Concepts that may emerge as attractive candidates for some sites include the large-module FPCs and the plastic-dome-covered CPC collectors under development in Sweden and the plastic-film collectors and various types of ponds under consideration in the U.S.

8.1.2 Validity of Performance Information

The guidelines for this study permitted the consideration of technologies that are still in the development stage; the performance of such technologies has not yet been confirmed by field tests of commercial products. Investors would certainly insist on more thorough demonstrations of promise. Nevertheless, the performance data cited in this report for individual collector modules are based on sound evidence (mostly experimental) and should be confirmed by further investigation.

The subtask participants are less confident about the performance of large collector arrays; experience with early systems in all countries has been disappointing. Measured outputs often fall short of expectations by factors of two or three. In many cases this is a result of overly optimistic expectations, inadequate design and installation practices, or both; we expect the gap to be narrowed by experience. In addition, the importance of the transport system in determining the overall performance of the array has not been fully appreciated. We believe it is important to resolve the disparity between field performance and design estimates in order to improve both.

This report is part of the work within the IEA Solar Heating and Cooling Program,
Task VII: Central Solar Heating Plants with Seasonal Storage
Subtask I b): Solar-Collector Subsystems

This report — prepared as a part of the International Energy Agency's Solar Heating and Cooling Program, Task VII (Central Solar Heating Plants with Seasonal Storage [CSHPSS]), Subtask 1(b) (Solar-Collector Subsystems) — reviews the performance and cost of, as well as operating experience with, collector subsystems suitable for CSHPSS application. The types of collectors considered include horizontal collectors (solar ponds), stationary non-concentrating collectors, stationary concentrating collectors, distributed line-focus tracking collectors, and central-receiver tracking collectors. Design, installation, and operational considerations are discussed, and performance and cost models are recommended for use in the preliminary design phase of Task VII. Comparing the collector subsystems in terms of idealized CSHPSS use, the subtask participants find the tracking collectors to be most attractive for many locations.

Document ANL/ES-139
Energy and Environmental Systems Division, Argonne National Laboratory
Argonne, Illinois 60439, USA