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Design Guidelines for Evacuated Collector Solar Energy Systems

A Report of Task VI:
The Performance of Solar Heating, Cooling, and Hot Water Systems Using Evacuated Collectors

December 1986

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Table of Contents

ABSTRACT

This report assembles the results of the six year experimental phase of the International Energy Agency Task on the Performance of Solar Heating, Cooling, and Hot Water Systems Using Evacuated Collectors into a form that can be used by architects and engineers in designing, constructing and maintaining solar energy systems. The report is primarily addressed to design professionals with experience in designing solar energy systems. The purpose of the report is to familiarize designers with the very different characteristics of different types of evacuated collectors, to indicate where evacuated collectors are appropriate in a solar energy system, and to provide design guidelines to aid in integrating evacuated collectors into a system.

1. INTRODUCTION

This document deals with the design, construction, and maintenance of solar heating systems utilizing evacuated tubular collectors. It covers systems of all sizes that are engineered on an individual basis. It does not deal with pre-engineered packaged systems. It addresses concerns relating to the most popular types of evacuated tubular collectors currently available. A description of the types of collectors is included in Section 2.

The contents of this document are based on findings from the International Energy Agency Solar Heating and Cooling Programme Task VI work. All technical data included in this report is a direct result of work undertaken by the members of this task. System and component costs were not a part of the research purpose of the task. For this reason, costs are not discussed in the document.

The objectives of this document are:

- to familiarize solar system designers with the characteristics of evacuated tubular collectors,
- to indicate where evacuated tubular collector arrays are appropriate in a solar system design,
- to provide design guidelines to aid in integrating evacuated tubular collectors into a solar energy system design.

The document is primarily addressed to design professionals with experience in the design of solar heating systems and therefore it deals only with those portions of a solar heating system whose design is directly influenced by evacuated tubular collectors. Some general concepts of the design, construction, commissioning and maintenance of a solar energy system are included as Appendix A.

The design guidelines presented in Section 3 are laid out in a fashion that corresponds to the overall design process generally encountered in the building industry.

2. BACKGROUND

The ideal collector for use in any solar heating system would be one that:

- has a high efficiency, independent of climate and system characteristics
- is reliable and maintenance free
- is compact, light and easy to handle
- can be integrated into a system in a simple, reliable and cost-effective way.

A well designed evacuated tubular collector comes the closest to meeting this ideal of any other collector technology available.

Experience from Task VI work indicates that in most applications the energy delivered from an evacuated tubular collector array can be expected to be at least 50 percent greater than the energy delivered from a flat plate collector array of equal aperture area. More specifically, four major differences between evacuated tubular collectors and flat plate collectors must be understood:

1. Under almost all circumstances evacuated tubular collectors have a significantly higher energy output per unit of collector aperture area.
2. The output from an evacuated tubular collector is less dependent on the temperature difference between the collector and the ambient air, and hence, higher operating temperatures are practical.
3. Evacuated tubular collectors display a very high degree of reliability and lower maintenance costs than single glazed selective flat plate collectors.
4. With lower operating thresholds, tubular collectors will collect energy when single glazed selective flat plate collectors cannot operate.

2.1. Solar Energy System Loads

Evacuated tubular collector arrays can be used with all types of loads including:

- industrial process heat
- domestic water heating
- space heating
- space cooling
- various combinations of these loads.

The loads least suited for the use of evacuated tubular collectors are low temperature applications such as for swimming pool heating where the required output temperatures from the collectors are low relative to ambient temperatures for such applications.

At high insolation levels, the performance of evacuated tubular collectors is as good as that of flat plate collectors. However, under a wide variety of circumstances, the performance of evacuated tubular collectors far exceeds that of flat plate types.

Loads particularly suited to evacuated tubular systems, as opposed to flat plate systems, are those for which

- the required heat delivery temperatures are high
- the average ambient temperatures are low
- the insolation levels are low
- the collector array is subjected to high average wind velocities
- the required solar fraction is high.

For comparative purposes, Figure 2.1.1 is included to illustrate the general performance differences between evacuated tubular collectors and flat plate collectors.

The input/output characteristics illustrated in this figure indicate the daily output from a solar collector based on the total daily radiation reaching the collector aperture area.

Flat plate collector performance lies mainly in the darkly shaded area to the right. The very best performer, a large area triple glazed design where the inner two glazings are teflon, lies midway between the two boundaries in the lighter shaded area. The performance of most evacuated collectors lies in the darkly shaded area to the left, with some poor designs lying midway between the two boundaries.

2.2. Cascading Effects

When considering which type of collector to use, a designer must go beyond a simple comparison of the collector array area required to supply the required amount of energy for the load. He should be aware of several major cascading effects.

- The first cascading effect results from a smaller and lighter collector array. Because of the smaller required collector aperture area, the support structure for holding the collector array can be proportionally smaller and lighter.

  The smaller and lighter support structure results in fewer roof penetrations for a roof-mounted collector array, or smaller foundations for a ground-mounted array.

  In many cases where the mounting of a flat plate solar collector array on an existing building is not practical due to structural considerations, an evacuated tubular array may be possible. The smaller collector array also results in decreased amount collector array piping. The reduced piping requirement results in smaller pumps and a smaller heat transfer fluid inventory.

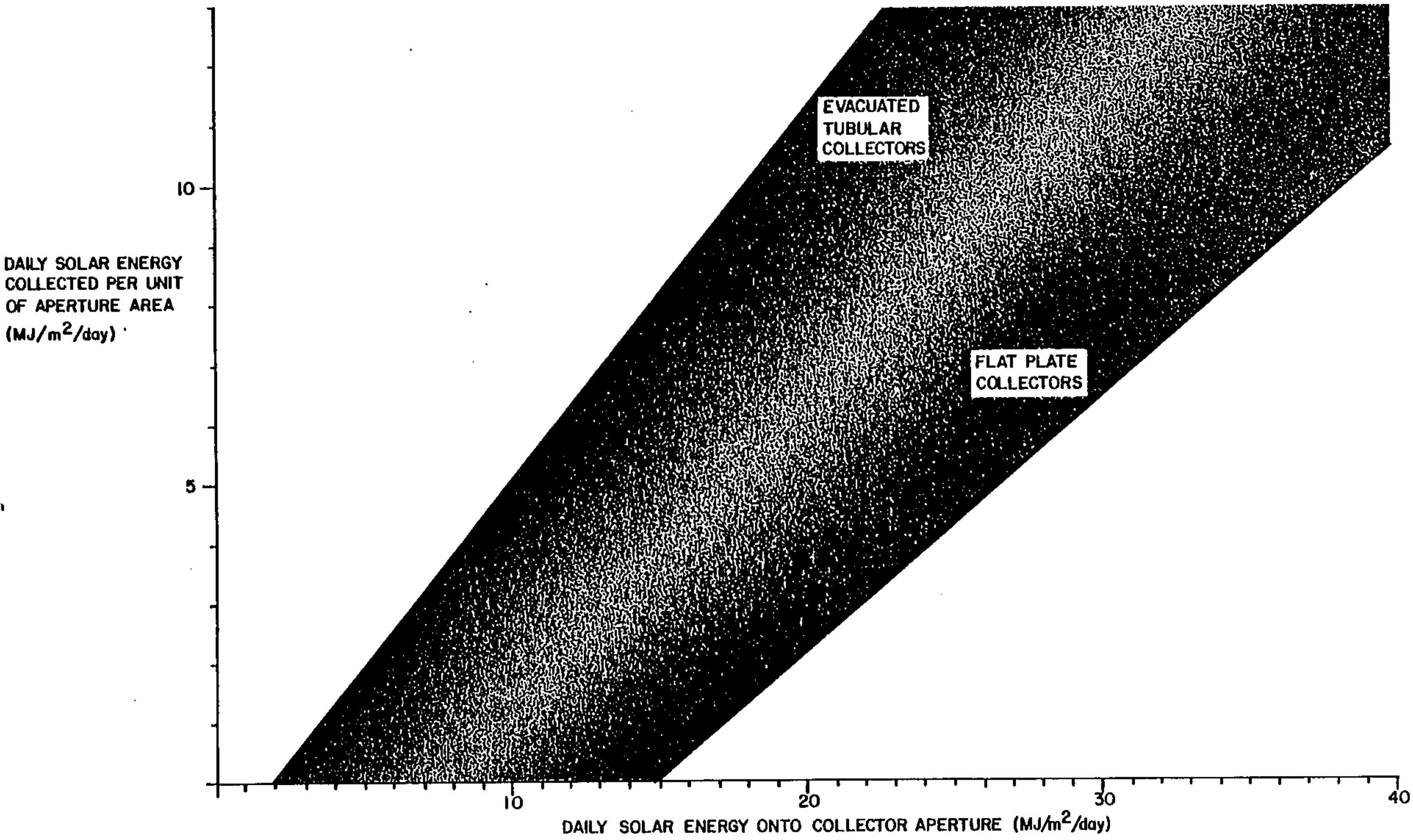


Figure 2.1.1 COMPARISON OF THE AVERAGE DAILY PERFORMANCE OF EVACUATED TUBULAR COLLECTOR MODULES AND FLAT PLATE COLLECTORS AT OPERATING TEMPERATURE DIFFERENCES BETWEEN 40°C AND 60°C

- The second cascading effect results from the fact that evacuated tubular collectors are relatively insensitive to operating temperatures when compared with flat plate collectors. Because higher collector temperatures can be tolerated, collector flow rates can be lower, resulting in smaller pumps, pipes and a smaller fluid inventory. Heat exchanger effectiveness becomes a less important consideration and, as a result, cheaper heat exchangers can be used. Storage temperatures can be higher, resulting in smaller storage volumes.
- A third cascading effect results from the overall smaller size of the system and components. This results in lower operating and maintenance costs.
- The first two cascading effects are illustrated schematically in Figure 2.1.2 and the third cascading effect is illustrated schematically in Figure 2.1.3.
- The overall results of the use of evacuated tubular collectors can be a significantly smaller, less complex and cheaper solar heating system to build and a simpler and cheaper system to operate.

2.3. Evacuated Tubular Collectors

Although improvements are still being made, the currently available collectors have remarkable good records in the area of reliability and performance. The durability of these current collectors allows some designs to be filled with cold water when the collectors are at the stagnation temperature without sustaining any damage.

Most early collector designs which exhibited failure problems are no longer manufactured.

2.3.1. The Misconception

Evacuated tubular collectors are currently tested and rated using methods specifically developed for flat plate collectors. These testing methods are not directly appropriate for evacuated tubular collectors whose operating characteristics are dependent on the levels of insolation, and hence, unjustly penalise their performance ratings.

Current collectors test procedures call for the testing of collectors at only one insolation level. Test results are displayed in the form of a collector efficiency curve as illustrated in Figure 2.2.1. This curve represents the test results for a typical evacuated tubular collectors module using the currently accepted test methods.

Although the curve was developed using only one level of insolation, this type of curve is still valid for other insolation levels when applied to flat plate collectors over their normal operating range where values of $\Delta T / I$ are less than 0.1 K$-$m^2/W. Essentially, for a constant value of $\Delta T / I$, the collector efficiency is assumed to be independent of the insolation level and collector operating ΔT.

For evacuated tubular collectors, however, this simplication does not represent their performance over their normal operating range where $\Delta T / I$ values can be well in excess of 0.2 K$-$m^2/W. The simplification becomes less valid as $\Delta T / I$ becomes larger.

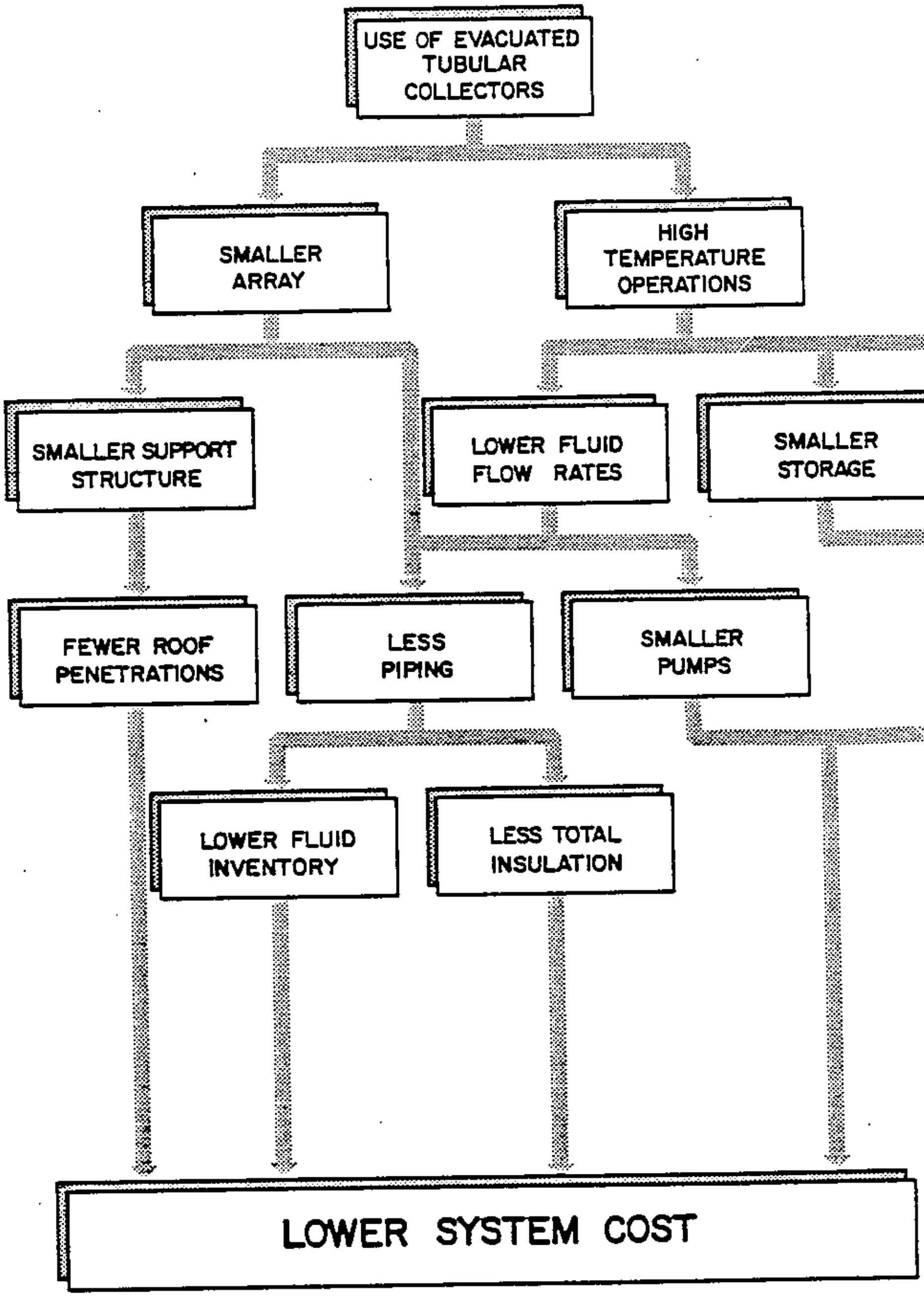


Figure 2.1.2 THE POTENTIAL CASCADING EFFECTS
System Cost

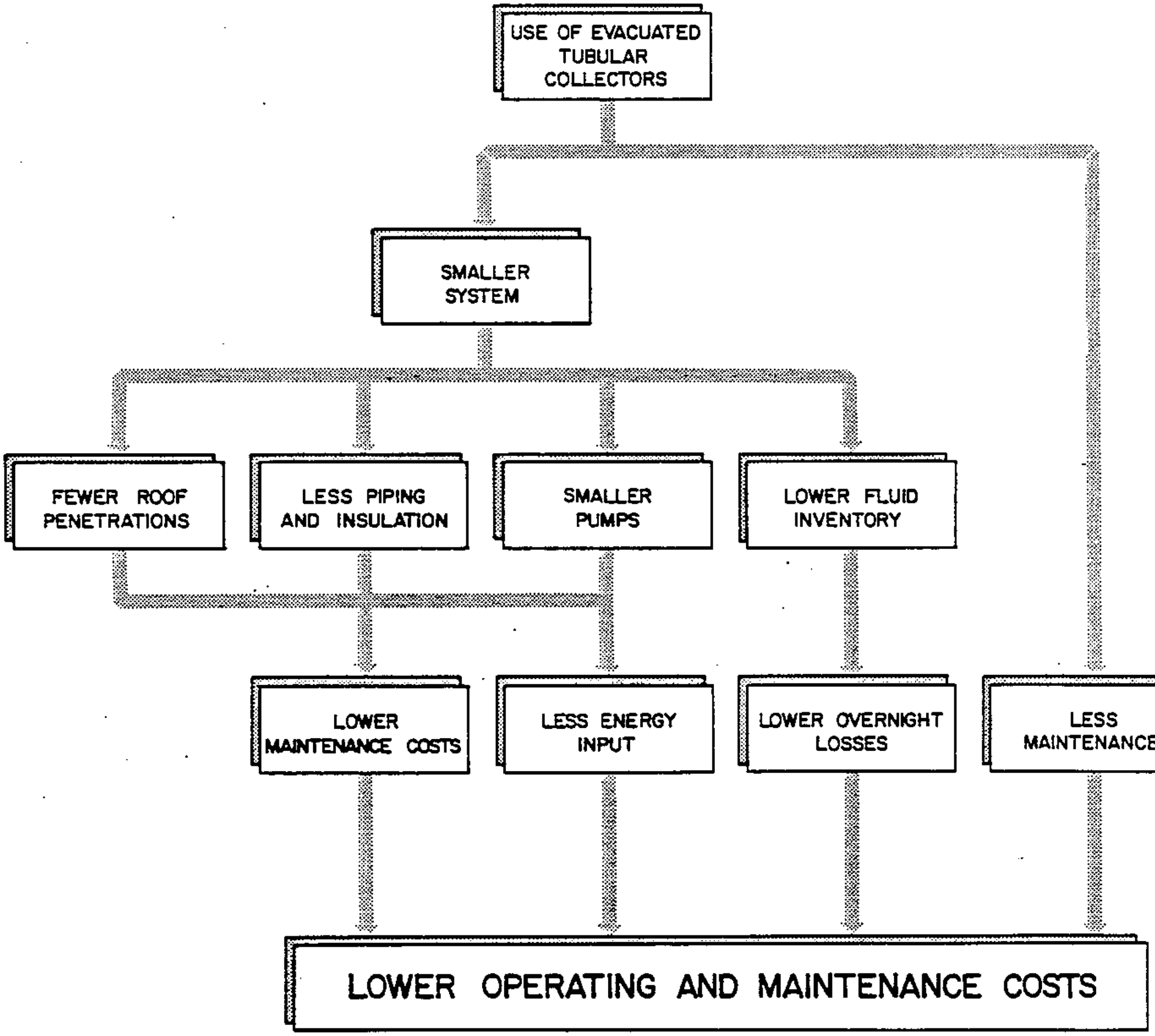


Figure 2.1.3 THE POTENTIAL CASCADING EFFECTS
Operating and Maintenance Costs

For a constant value of $\Delta T / I$, the collector efficiency varies significantly with the insolation rate and collector operating ΔT. To adequately display the efficiency characteristics of an evacuated tubular collector, a family of curves would be required. Figure 2.2.2, an efficiency plot of a typical evacuated tubular collector module, illustrates this point.

2.3.2. Evacuated Collector Tube Designs

Evacuated collector tubes are manufactured on a production, preproduction, and experimental basis in a wide variety of forms. All designs consist of an absorber surface directly or indirectly surrounded by a vacuum and a mechanism by which heat, absorbed by the absorber surface, can be removed from the collector tube.

All current evacuated tubular collector designs can be categorized into two groups.

- The first group is referred to as Dewar type collectors, and the second group, metal fin in vacuum type collectors. A large variety of variations of these two basic approaches are possible and have been tried. Of the five collectors currently available on a production basis, and manufactured by the Sunmaster Corporation in the USA, the Solartech collector manufactured by Solartech Ltd. in Canada and the Sydney University collector from Australia are of the Dewar type, while the Cortec manufactured by Corning in France, and the Philips VTR manufactured by Philips in the Netherlands are of the metal fin in vacuum type design. Illustrations of these five collectors are included as Figures 2.2.3 to 2.2.12. Dewar type evacuated tubular collectors may or may not have the heat transfer fluid in direct contact with the vacuum jacket. The Sunmaster and Solartech collectors are examples of Dewar type collectors where the heat transfer fluid is in direct contact with the vacuum jacket. The inner surface of the vacuum jacket forms the absorber plate of the collector. The heat transfer fluid enters the open end of the Dewar flask wetting the entire inner surface of the flask, and returns through a return pipe placed in the middle of the collector tube. In this type of collector, the inventory of fluid in the collector during operation is relatively high.

  An alternate design for Dewar flask type collectors is to insert a metal fin into the Dewar flask to which a heat transfer fluid pipe is attached. The inner tube of the vacuum jacket serves as a substrate for the absorber coating. From here, the absorbed energy is transferred through the glass wall to the cylindrical metal fin and, ultimately, to the copper transfer tube by conduction. It is important to note that, in this case, the circulating fluid does not contact the Dewar flask. The Sydney University collector is an example of this type of construction.

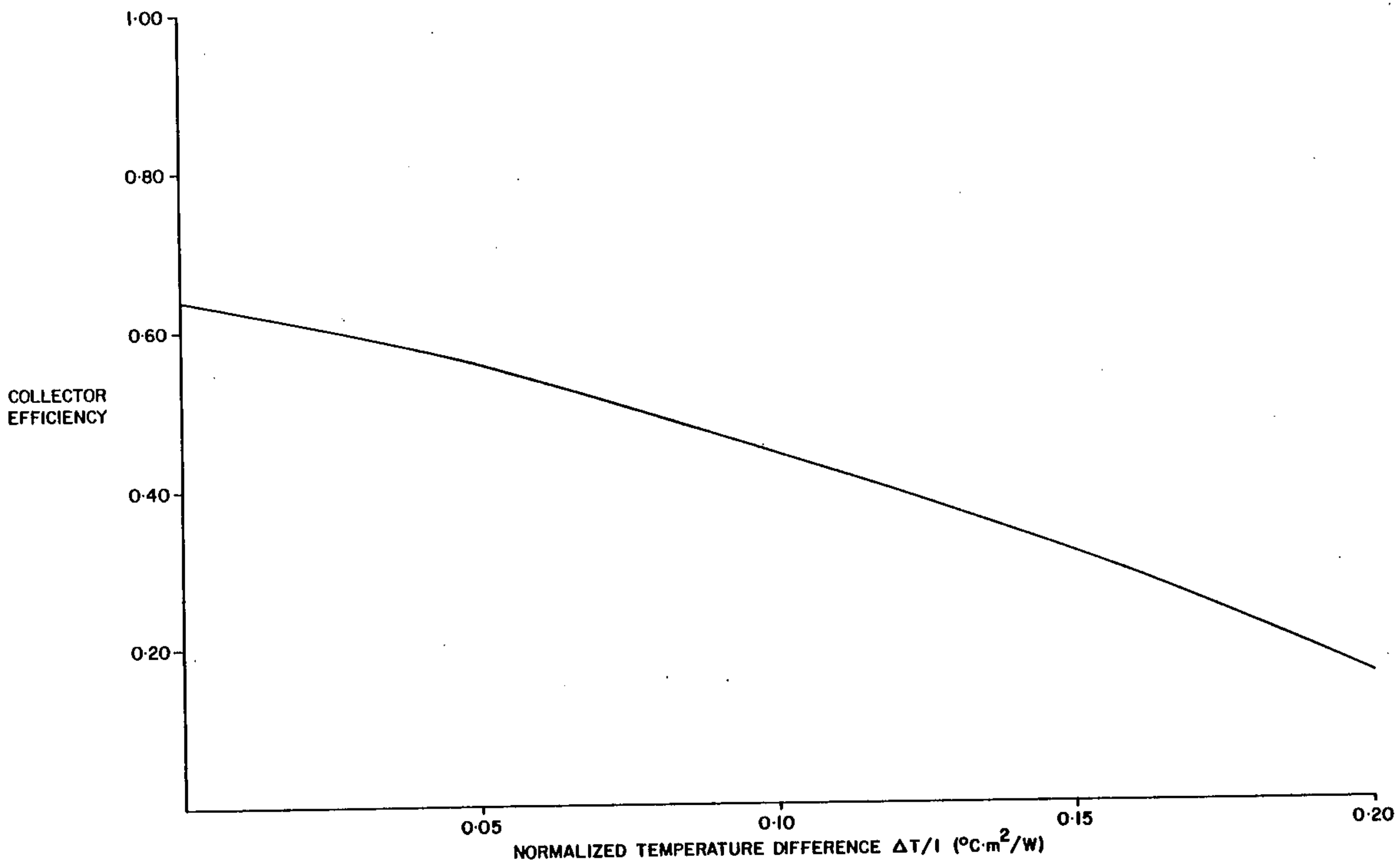


Figure 2.2.1 STANDARD EVACUATED TUBULAR COLLECTOR MODULE EFFICIENCY CURVE

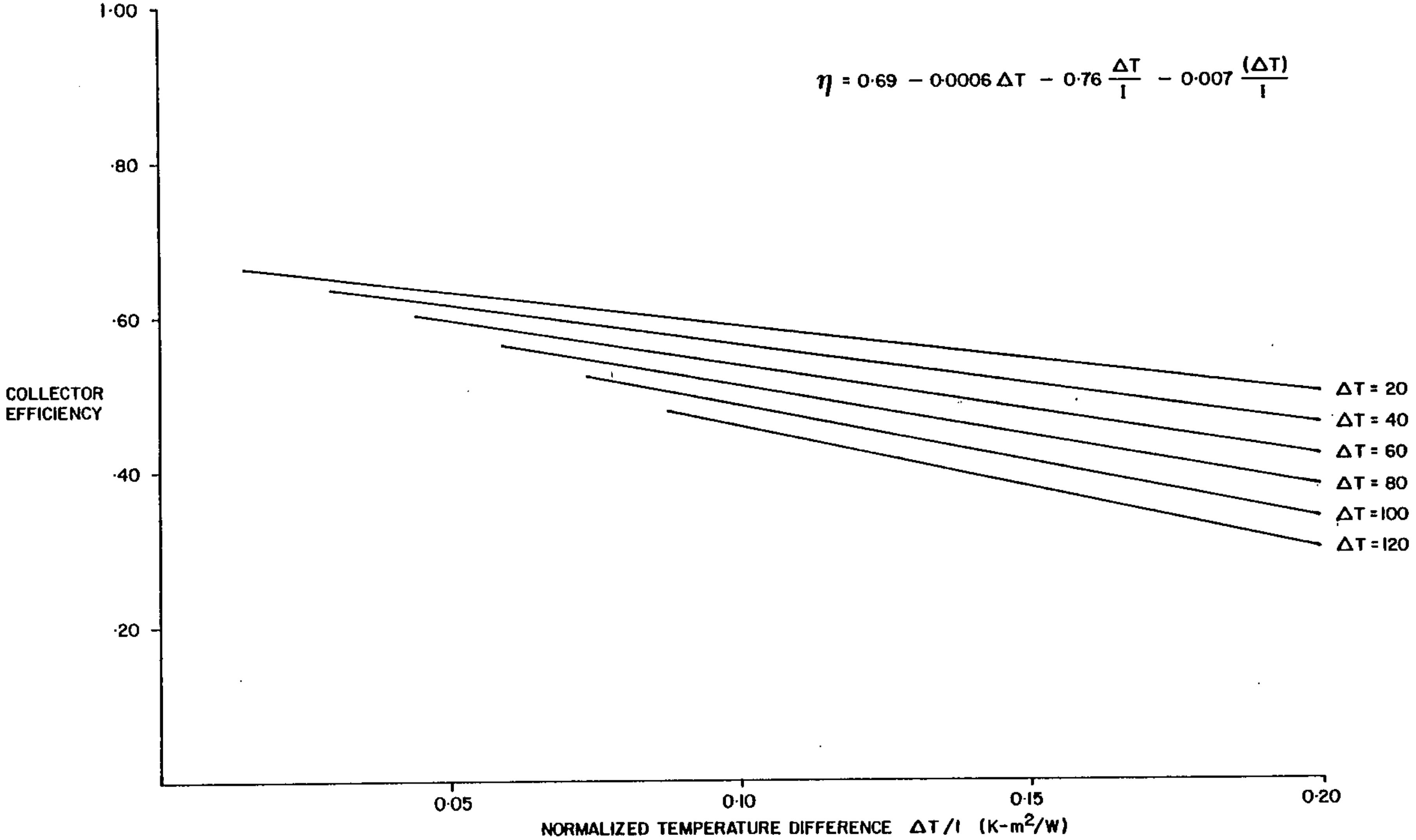


Figure 2.2.2 EFFICIENCY CHARACTERISTICS OF A TYPICAL EVACUATED TUBULAR COLLECTOR MODULE

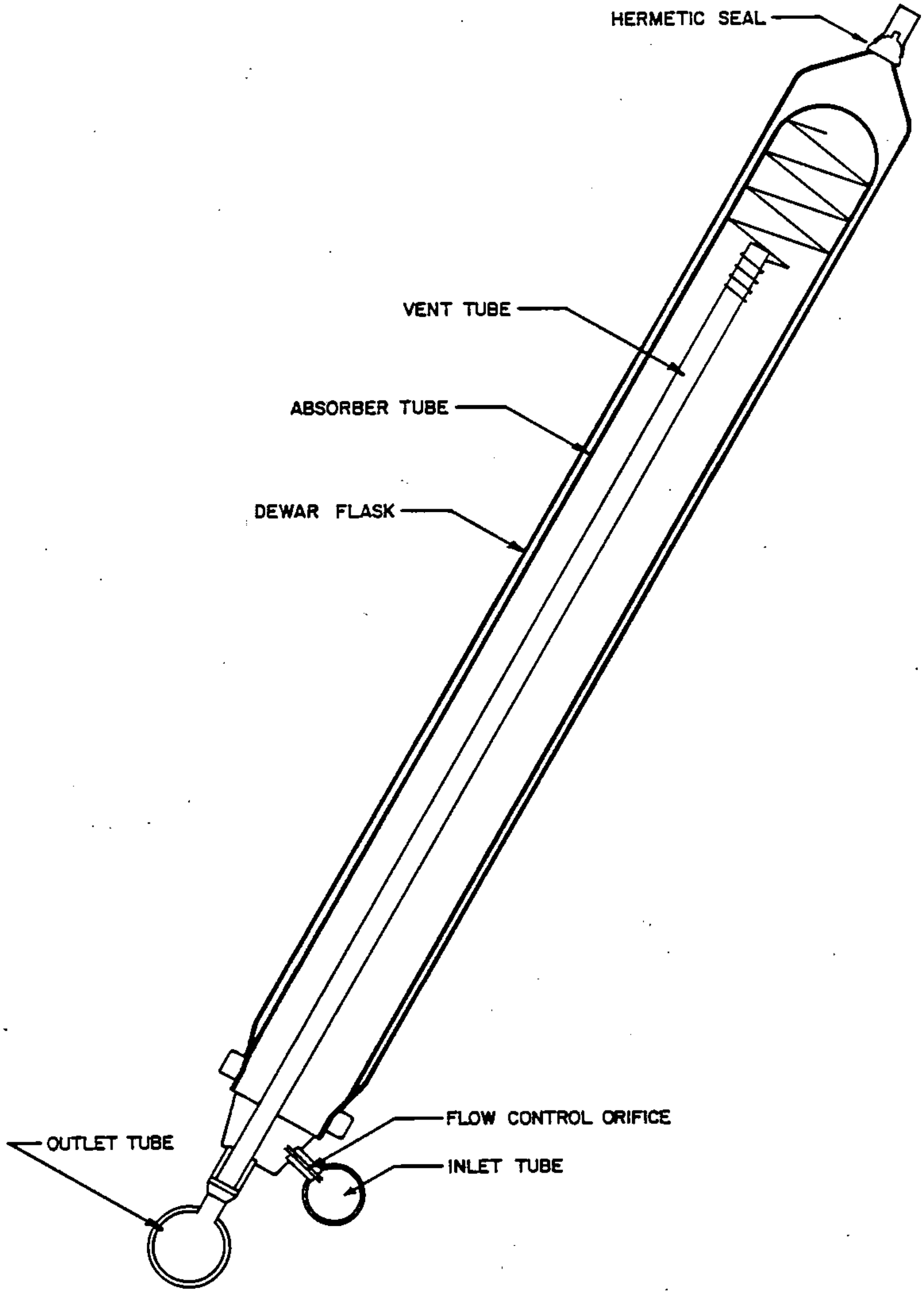


Figure 2.2.3 SUNMASTER COLLECTOR TUBE

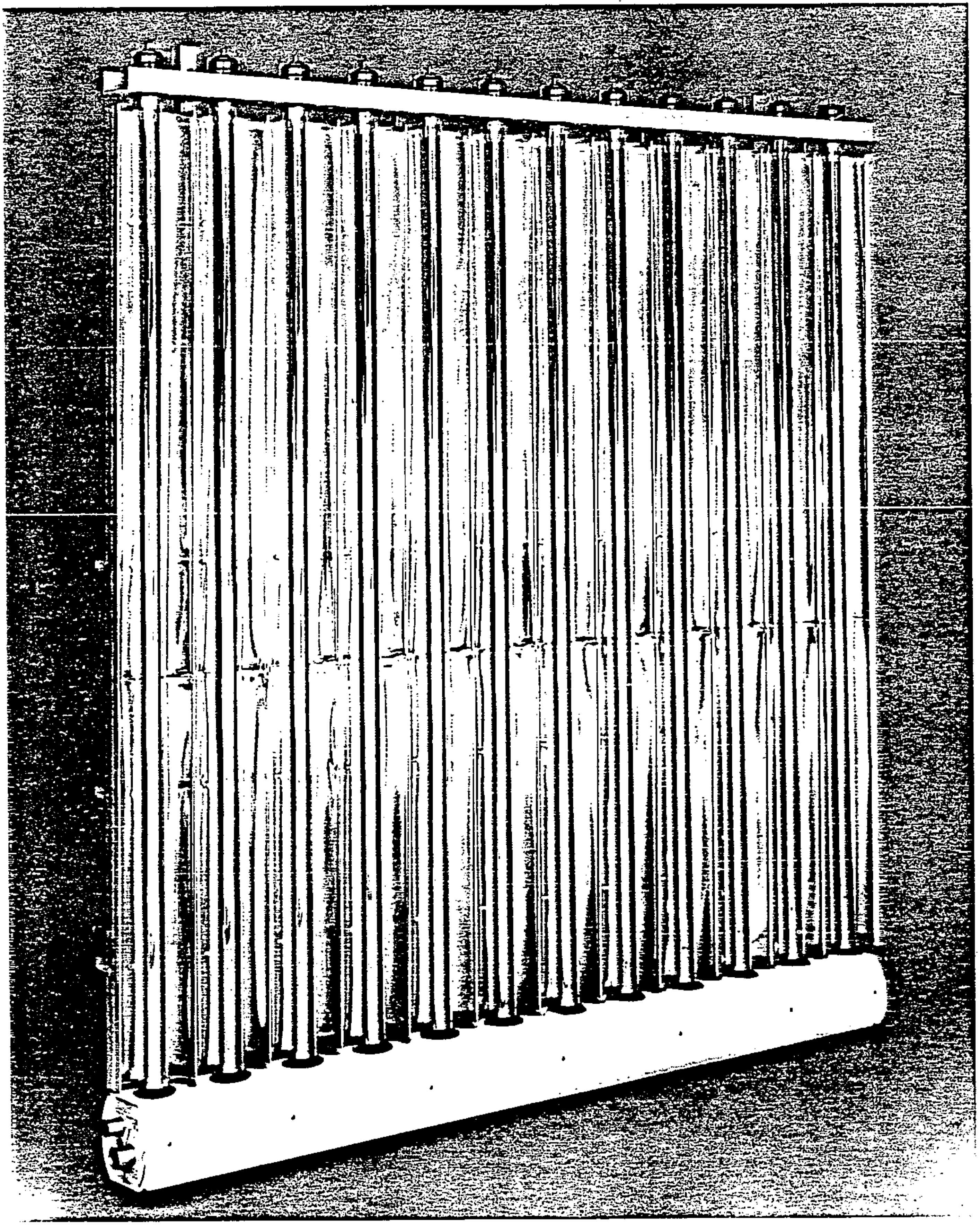


Figure 2.2.4 SUNMASTER COLLECTORS

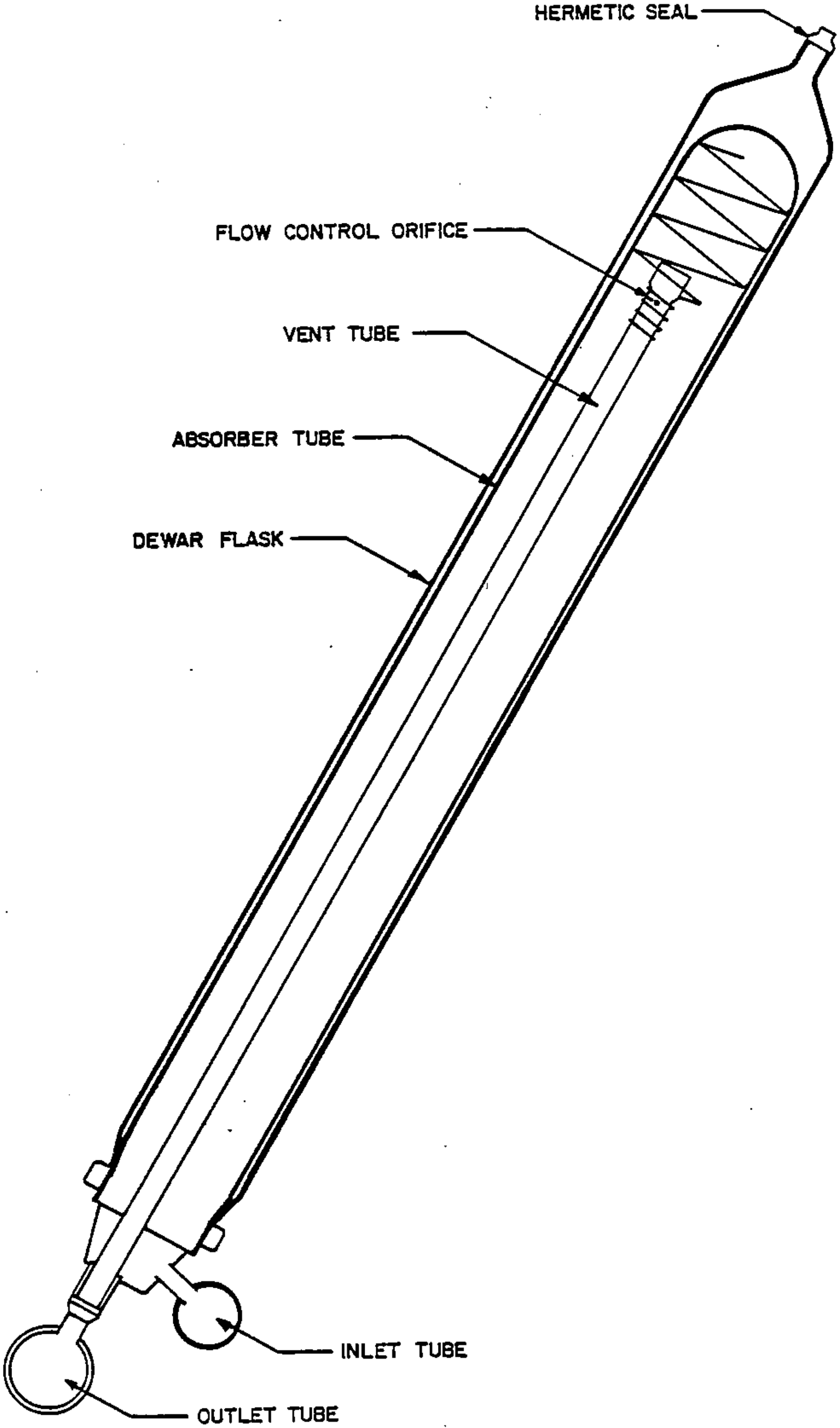


Figure 2.2.5 SOLARTECH COLLECTOR TUBE

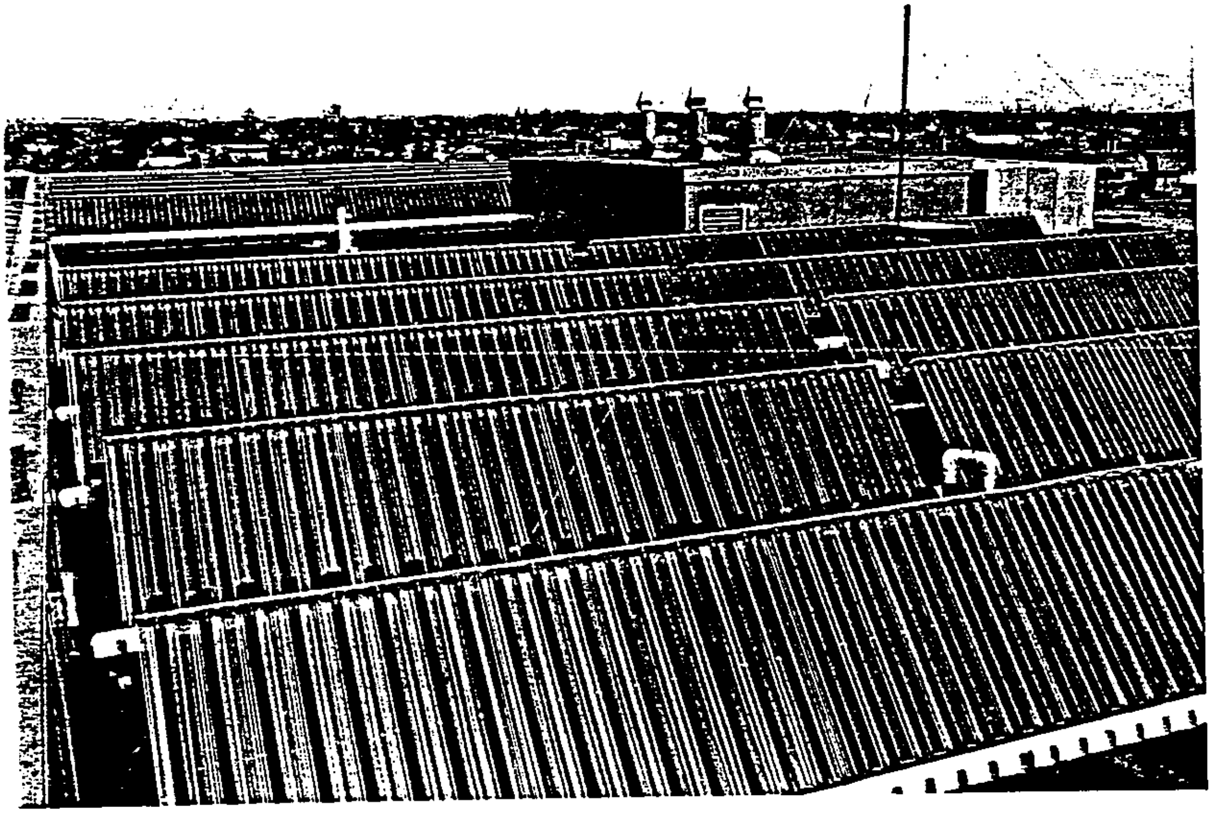


Figure 2.2.6 SOLARTECH COLLECTORS

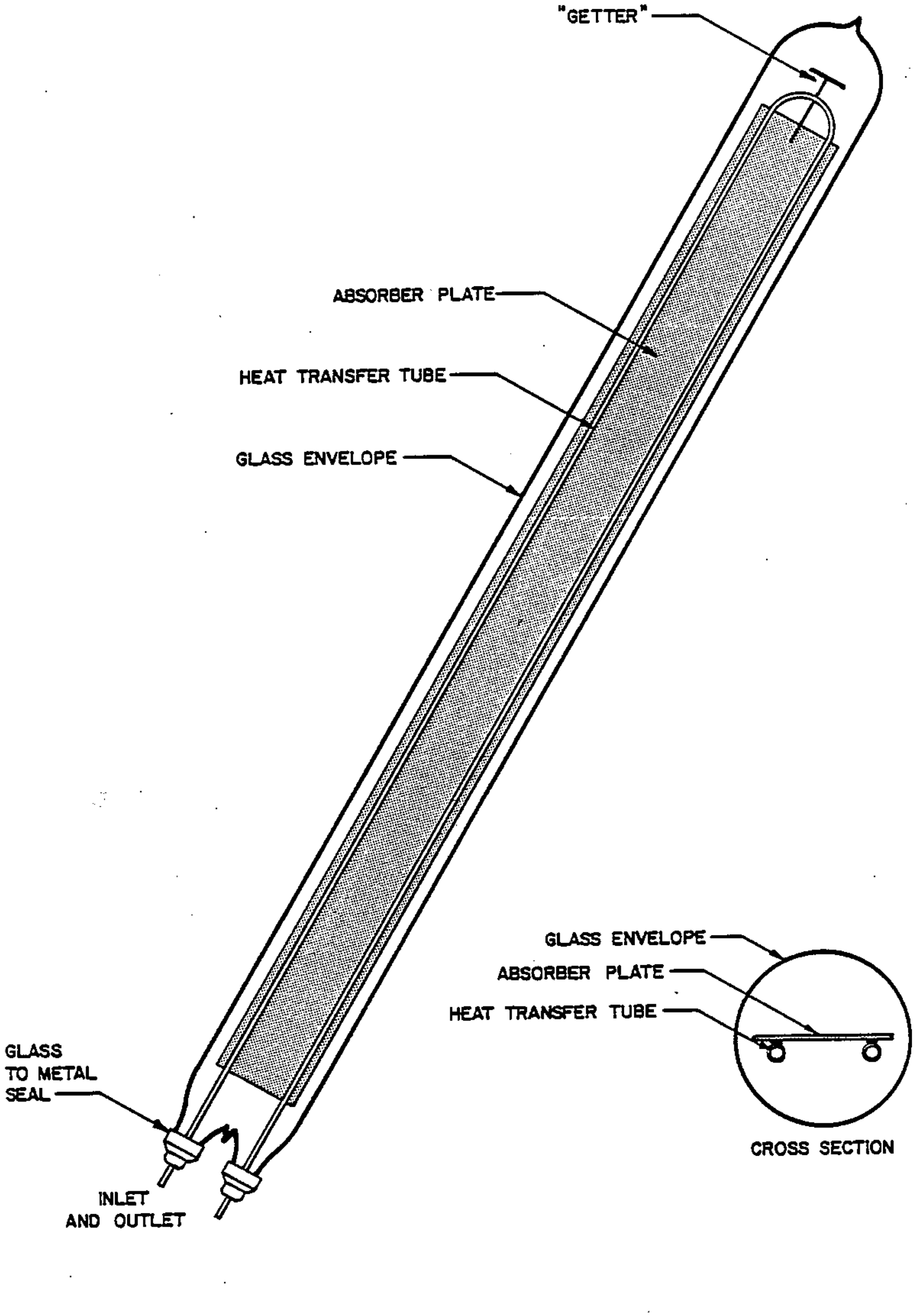


Figure 2.2.7 CORTEC COLLECTOR TUBE

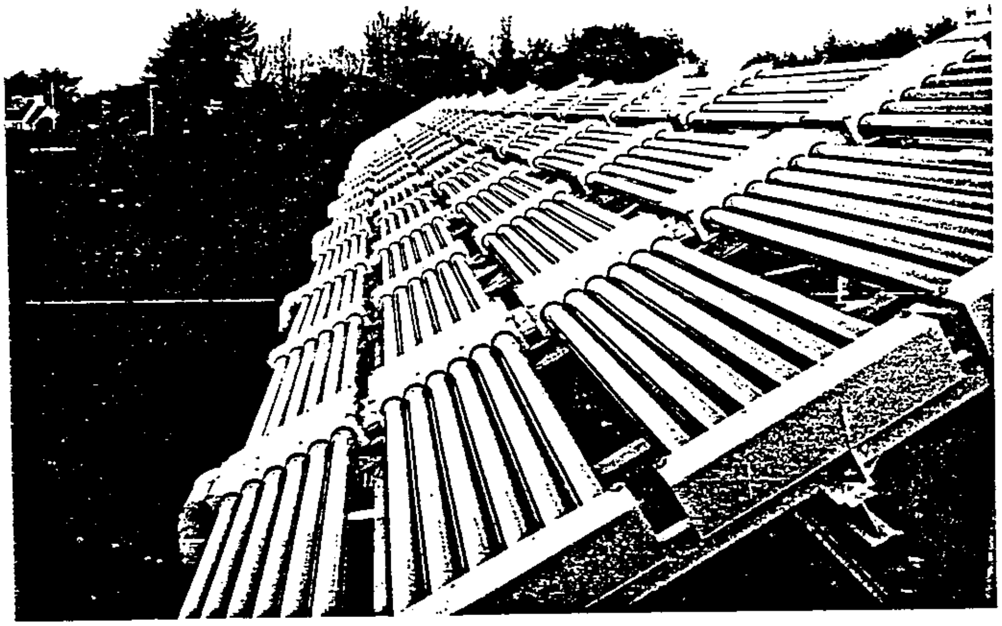


Figure 2.2.8 CORTEC COLLECTORS

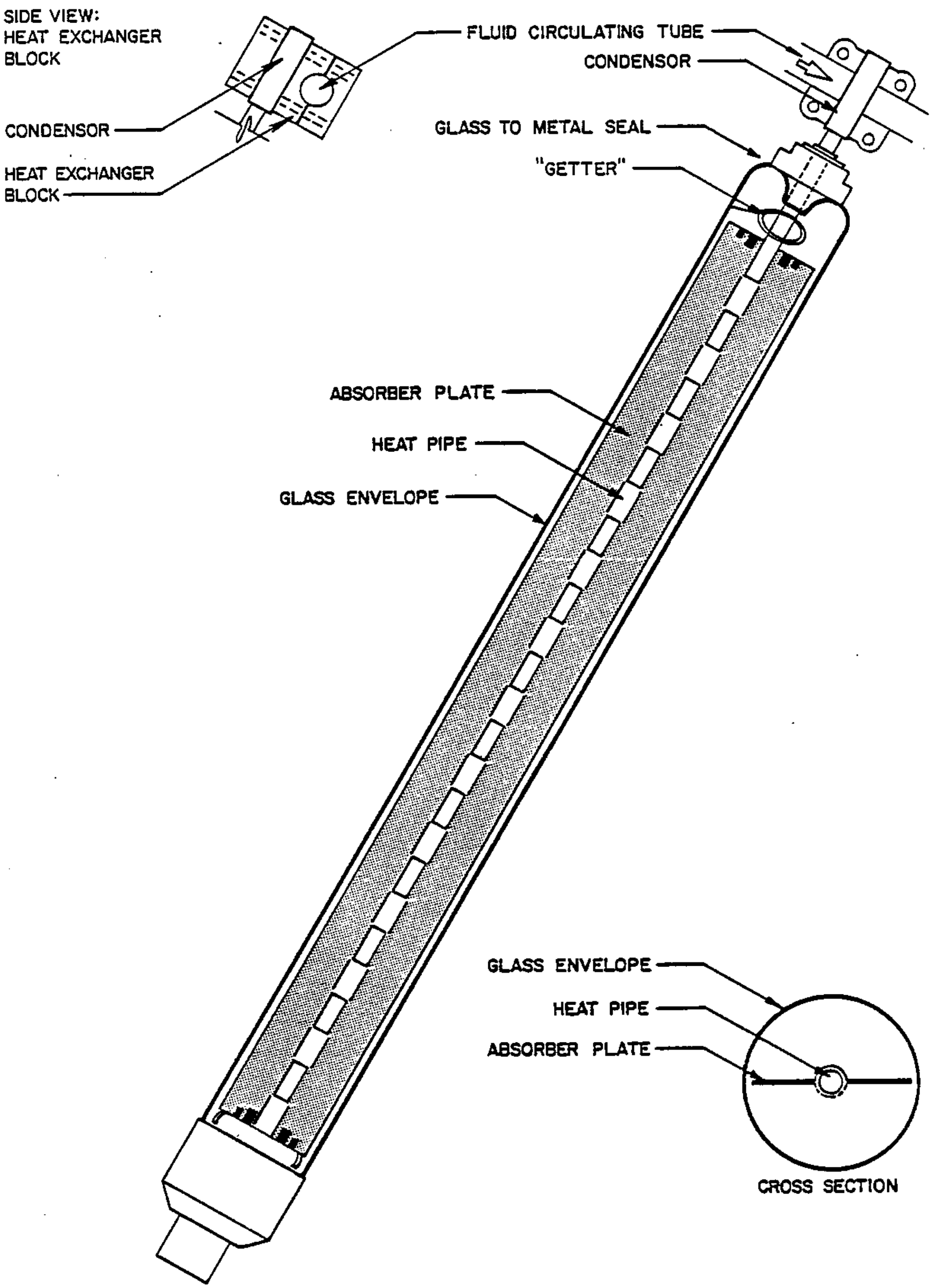


Figure 2.2.9 PHILIPS VTR 361 COLLECTOR TUBE

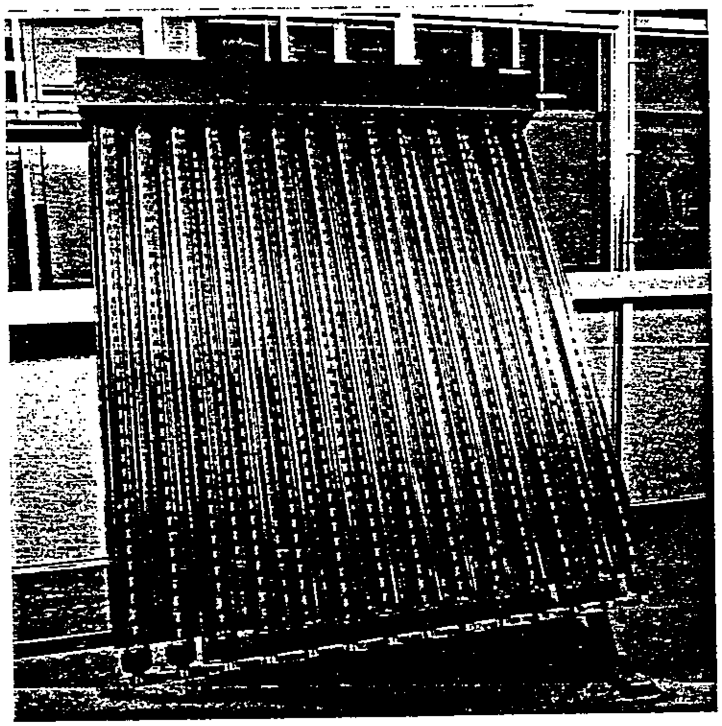


Figure 2.2.10 PHILIPS VTR COLLECTORS

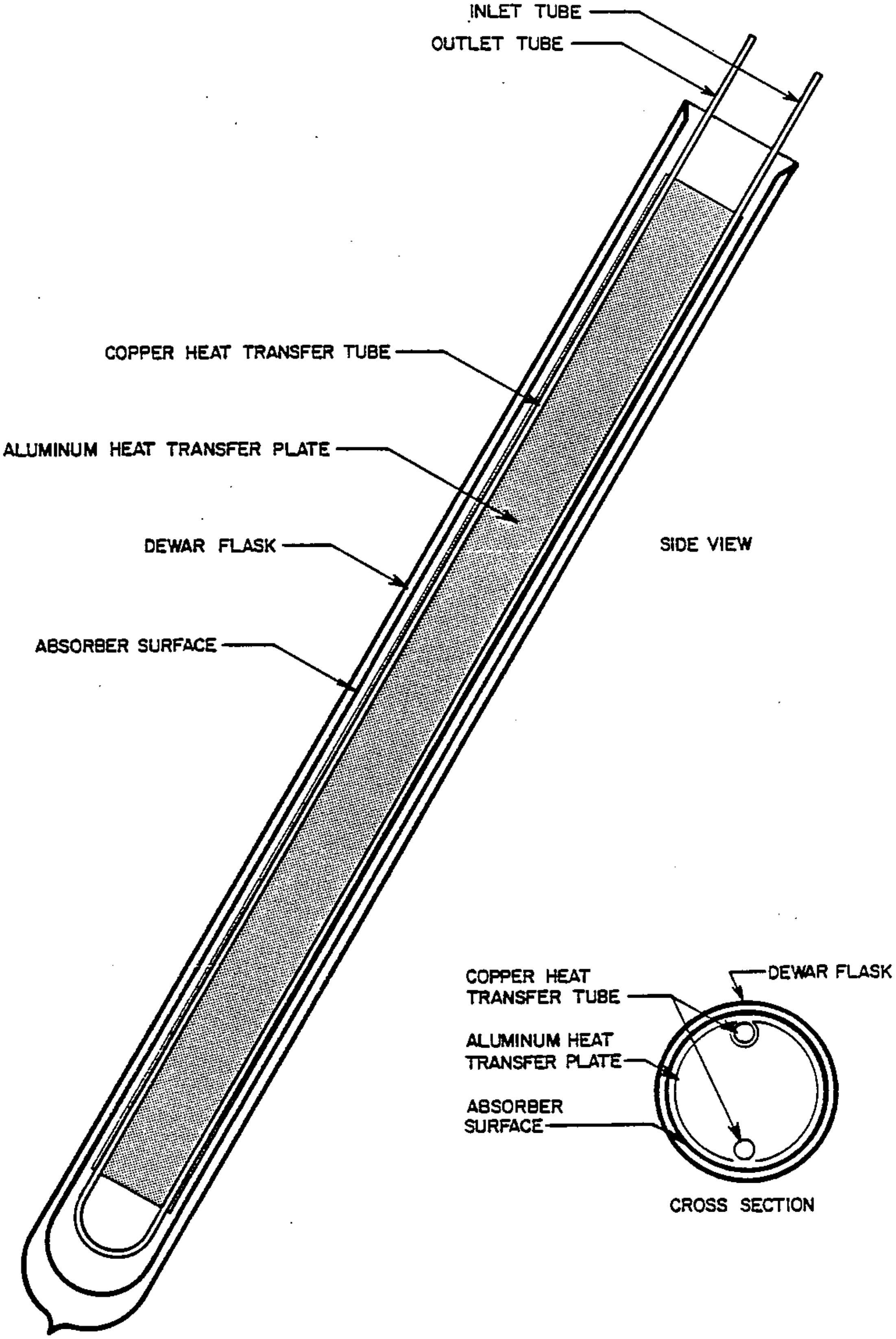


Figure 2.2.11 SYDNEY UNIVERSITY COLLECTOR TUBE WITH U-TUBE MANIFOLD

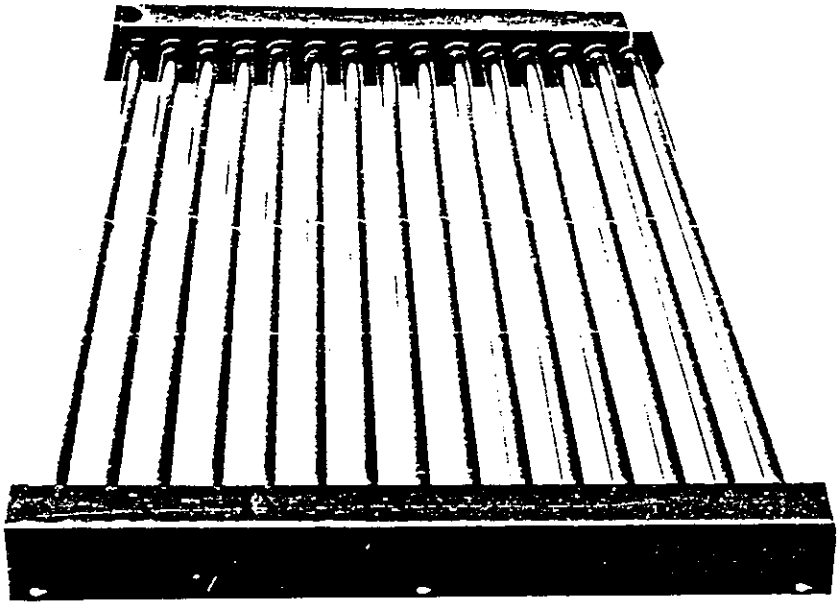


Figure 2.2.12 SYDNEY UNIVERSITY COLLECTORS WITH U-TUBE MANIFOLD

- The second group, the metal fin in vacuum type evacuated tubular collectors, shares one common design characteristic; all must incorporate a glass-to-metal vacuum seal in one form or another. In a metal tube in vacuum type collector design, a metal absorber plate is inserted in the evacuated portion of the collector tube with a path for heat transfer penetrating through the wall of the vacuum jacket. Numerous variations of this arrangement are possible. The Cortec collector incorporates two glass-to-metal seals. In a U-tube arrangement, the heat transfer fluid is circulated into and out of the evacuated portion of the collector, removing heat from the metal absorber plate attached to the tube.

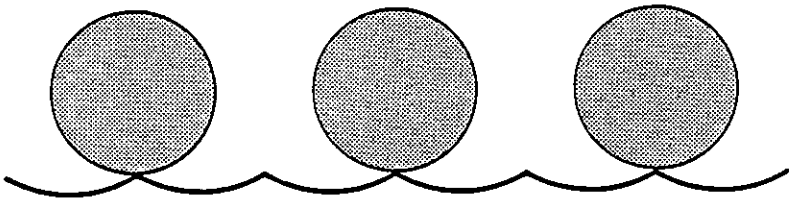
  The Philips collector incorporates a metal fin attached to a heat pipe. This arrangement necessitates only one glass-to-metal seal through the vacuum jacket.

Evacuated tubular collectors have been designed and constructed in a range of sizes with tubes ranging in diameter from 30 mm to 300 mm, and in lengths from 1 metre to 8 metres. Currently available collectors fall in the 50 mm to 100 mm diameter range with tubes of 1 metre to 2.5 metres in length.

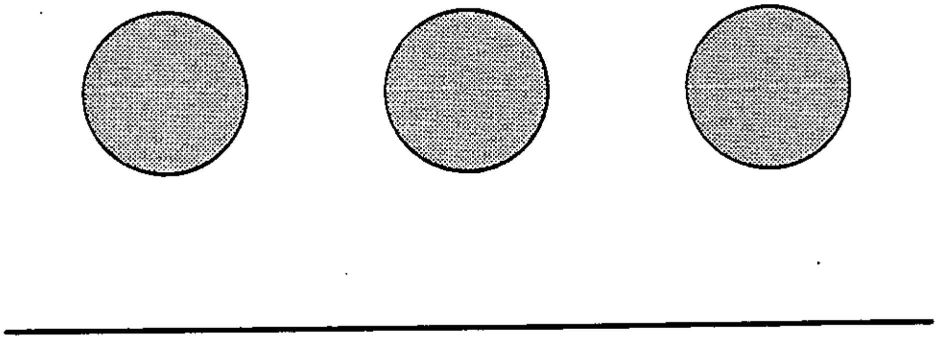
Extensive development work has been undertaken over the past few years to improve the performance and durability of evacuated tubular collectors. Major work has been undertaken in the areas of the types of glass used in the manufacture of these type of collectors, the glass-to-metal seals and the selective surfacing of absorber plates.

At the present time, evacuated tubes represent the major cost component of an evacuated tubular collector array. For this reason alternatives to closely spacing the collector tubes in a close packed array are often used. In these cases reflectors are utilized. Several different reflector configurations are illustrated in Figure 2.2.13.

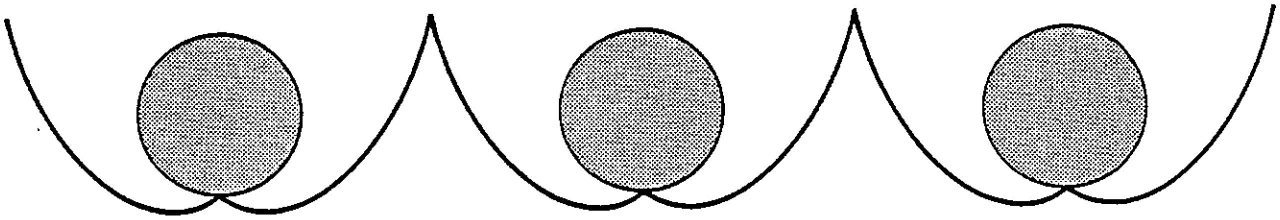
When a ripple reflector is utilized, the reduction of collector tubes is between 25 to 30 percent for a collector of equal aperture area. With a compound parabolic concentrator, tube spacings are even greater, however, a performance penalty is incurred due to the greater reliance on the reflector.



Ripple Reflector



Flat Diffuse Reflector



External Compound Parabolic Concentrator

Figure 2.2.13 VARIOUS REFLECTOR CONFIGURATIONS

3. DESIGN GUIDELINES

3.1. Design Considerations

The design considerations for evacuated tubular collector based solar heating systems are dealt with under three headings. These headings reflect the typical design process through which a project goes from the initial conception stage to the start of construction. These sections are entitled:

- Concept/Schematic Design
- Design Development
- Detailed Design

In the Concept/Schematic Design stage, basic rule of thumb sizing and costing of the system is carried out to assess the feasibility of the project.

In the Design Development stage, the sizing of components is refined and the system performance more carefully assessed.

The Detailed Design stage of the process entails the optimization of the various system components in order to gain the maximum system performance for the overall lowest cost.

In keeping with the philosophy of this document, only those concepts which are peculiar to evacuated tubular collector based systems are dealt with in detail.

3.1.1. Concept/Schematic Design

During the Concept/Schematic Design it is necessary that the first approximations of the major system parameters be set. What is required, at this stage, are rules of thumb, suitable for estimating the collector array size and the annual energy contribution to the load being considered.

Estimates accurate to within plus or minus twenty percent are considered acceptable at this stage. The annual energy contribution of an evacuated tubular collector array can be considered to range between 1.0 and 3.0 GJ/m^2 of collector aperture area.

Because of the extreme variations in space heating and cooling loads, rules of thumb for these types of systems are not presented.

In order to estimate the annual energy contribution from an evacuated tubular collector array in a specific application and in a specific location, Tables 3.1.1 and 3.1.2 are utilized.

Table 3.1.1 lists the base contribution values for an evacuated tubular collector based solar heating system designed for industrial process heating and domestic hot water heating.

The base case systems share two common assumptions:

- the collector system is designed to operate at a temperature difference of 40°C between the collector and ambient air temperature.

- the annual radiation is, nominally, 5 GJ/m^2.

In addition to the general assumptions, a group of assumptions has been made for each type of system.

Industrial Process Heat

- The energy demand matches the available solar radiation.
- No storage system is incorporated into the solar energy system.
- No dumping of collected energy is required at any period during the year.
- Energy losses from piping and heat exchangers equal fifteen percent of the collected energy.

Domestic Hot Water

- The energy demand matches the available solar radiation.
- The storage for one day's use is incorporated into the solar energy system.
- No dumping of collected energy is required at any period during the year.
- Energy losses in the system equal twenty percent of the collected energy.

Table 3.1.2 lists correction factors for climatic conditions and load temperatures encountered at the particular site under evaluation.

In order to determine a rough approximation of the energy contribution from an average collector array under specific conditions, determine the performance value for the appropriate load type from Table 3.1.1 and multiply by the appropriate factor from Table 3.1.2.

3.1.2. Design Development

Through the Design Development phase of the project, refinements of the first estimates presented in Section 3.1.1 are necessary. The more precise data required is presented here in the form of efficiency curves for the commonly available collector types.

Figures 3.1.1 to 3.1.5 give the characteristic curves for the five commercially available collectors discussed in the document. Included is the characteristic equation and incident angle modifier factor for each collector for use as a model in a computer simulation program.

Numerous computer simulation programs such as the University of Wisconsin's TRNSYS or WATSUN from the University of Waterloo, are available for the sizing and optimization of solar energy systems. Because the optical and thermal performance of evacuated collectors are different among types and different from flat plate collectors, simplified methods such as F-Chart should not be used.

SYSTEM TYPE	PERFORMANCE RANGE ($GJ/m^2/yr$)	ASSUMPTIONS
1. INDUSTRIAL PROCESS HEAT	1·8 – 2·2	ΔT = 40°C ANNUAL INSOLATION: $5GJ/m^2/yr$ 15% TRANSPORT LOSSES NO STORAGE
2. DOMESTIC HOT WATER	1·7 – 2·1	ΔT = 40°C ANNUAL INSOLATION: $5GJ/m^2/yr$ 20% TRANSPORT AND STORAGE LOSSES

Table 3.1.1 SOLAR ENERGY DELIVERED TO THE LOAD FOR EVACUATED TUBULAR COLLECTOR MODULES – BASE CASE SYSTEMS

COLLECTOR TO AMBIENT ΔT (°C)	INSOLATION (GJ/m^2/yr)				
	3	4	5	6	7
30	·53	·79	1·05	1·31	1·58
40	·50	·75	1·00	1·25	1·50
50	·48	·71	·95	1·19	1·43
60	·45	·68	·90	1·13	1·35
70	·43	·64	·85	1·06	1·28

Table 3.1.2 COLLECTOR TO AMBIENT ΔT vs INSOLATION
- MODIFIER FACTORS

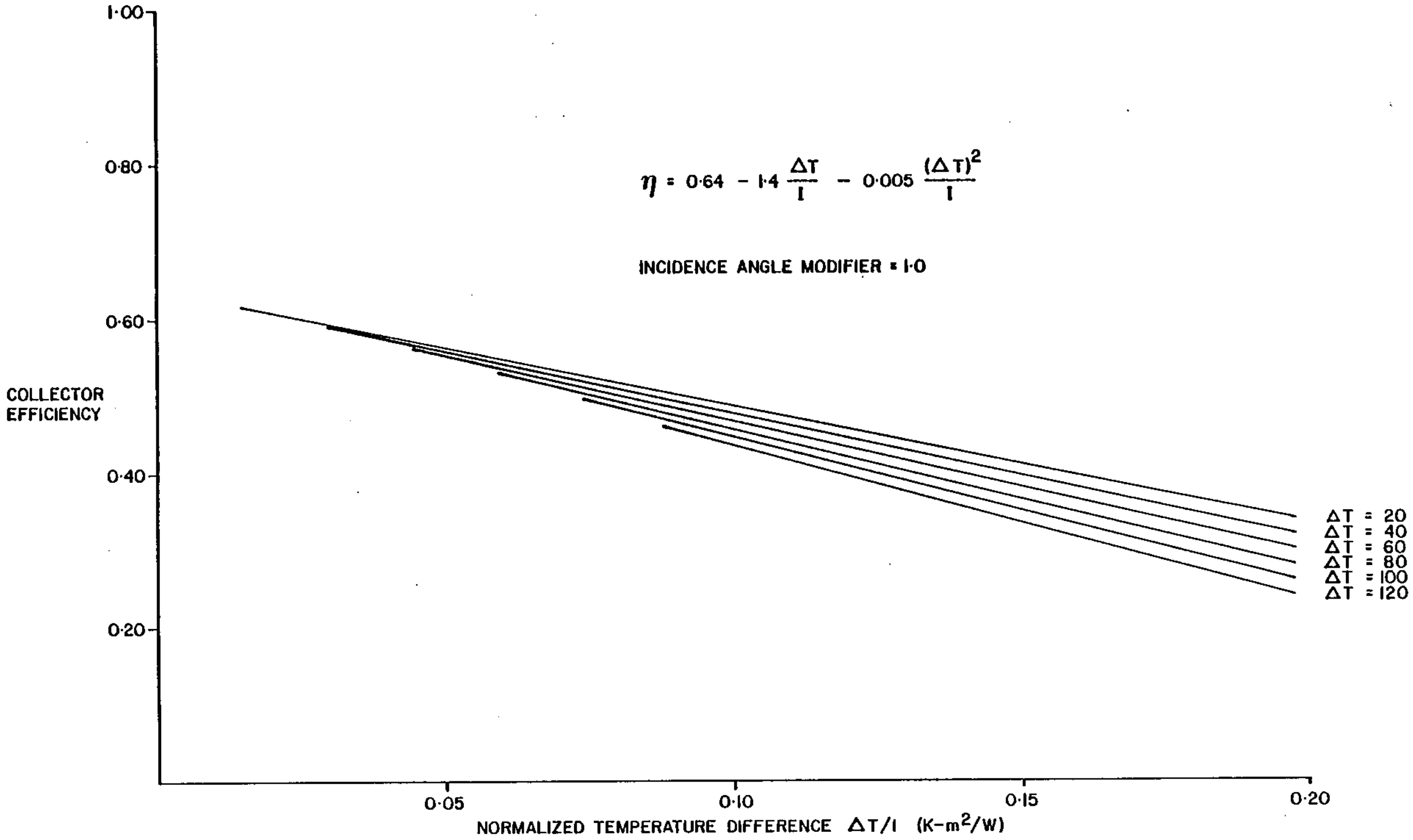


Figure 3.1.1 COLLECTOR EFFICIENCY: CORTEC COLLECTOR MODULE

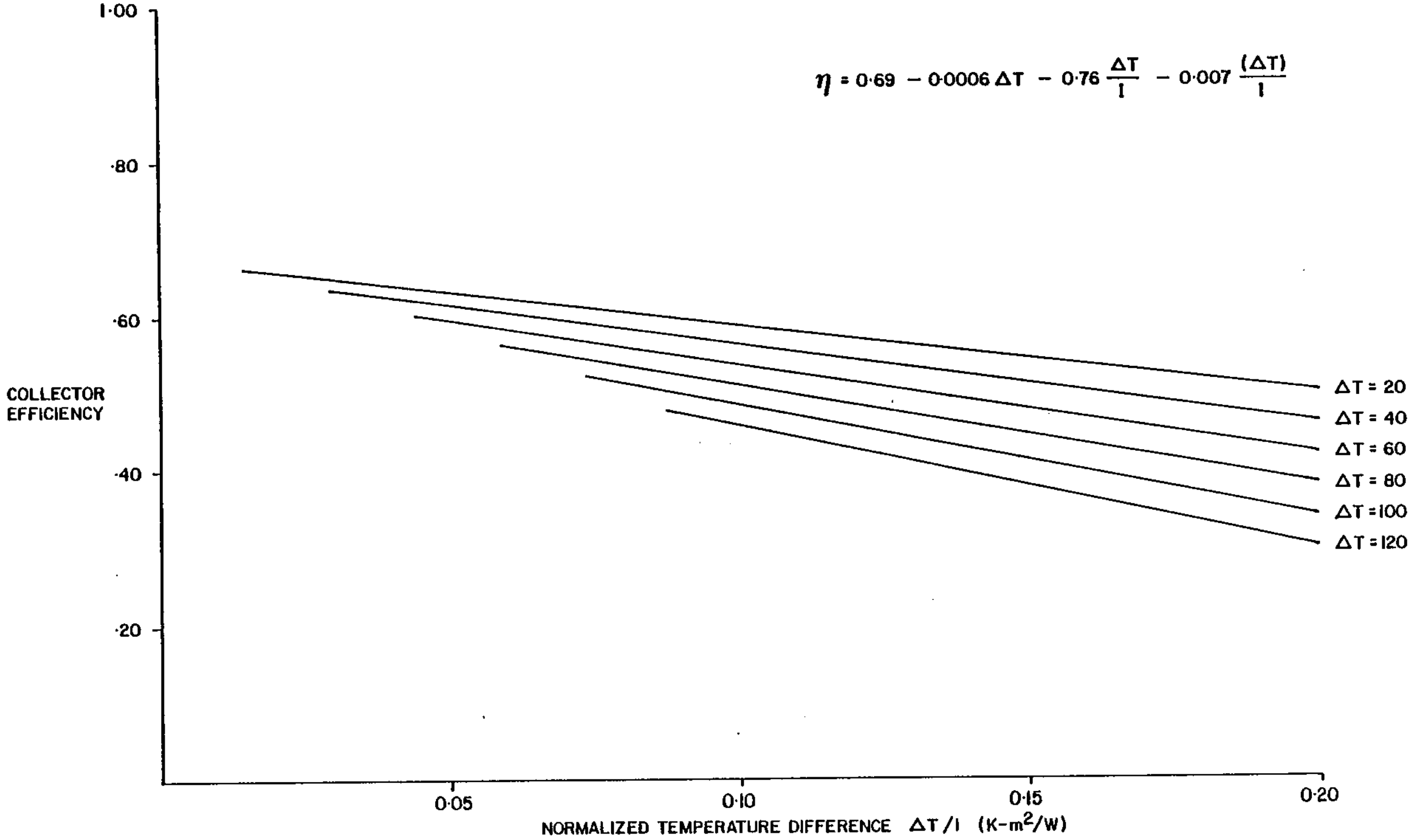


Figure 3.1.2 COLLECTOR EFFICIENCY: PHILIPS VTR 261 COLLECTOR MODULE
(19 tube close packed module, no reflector)

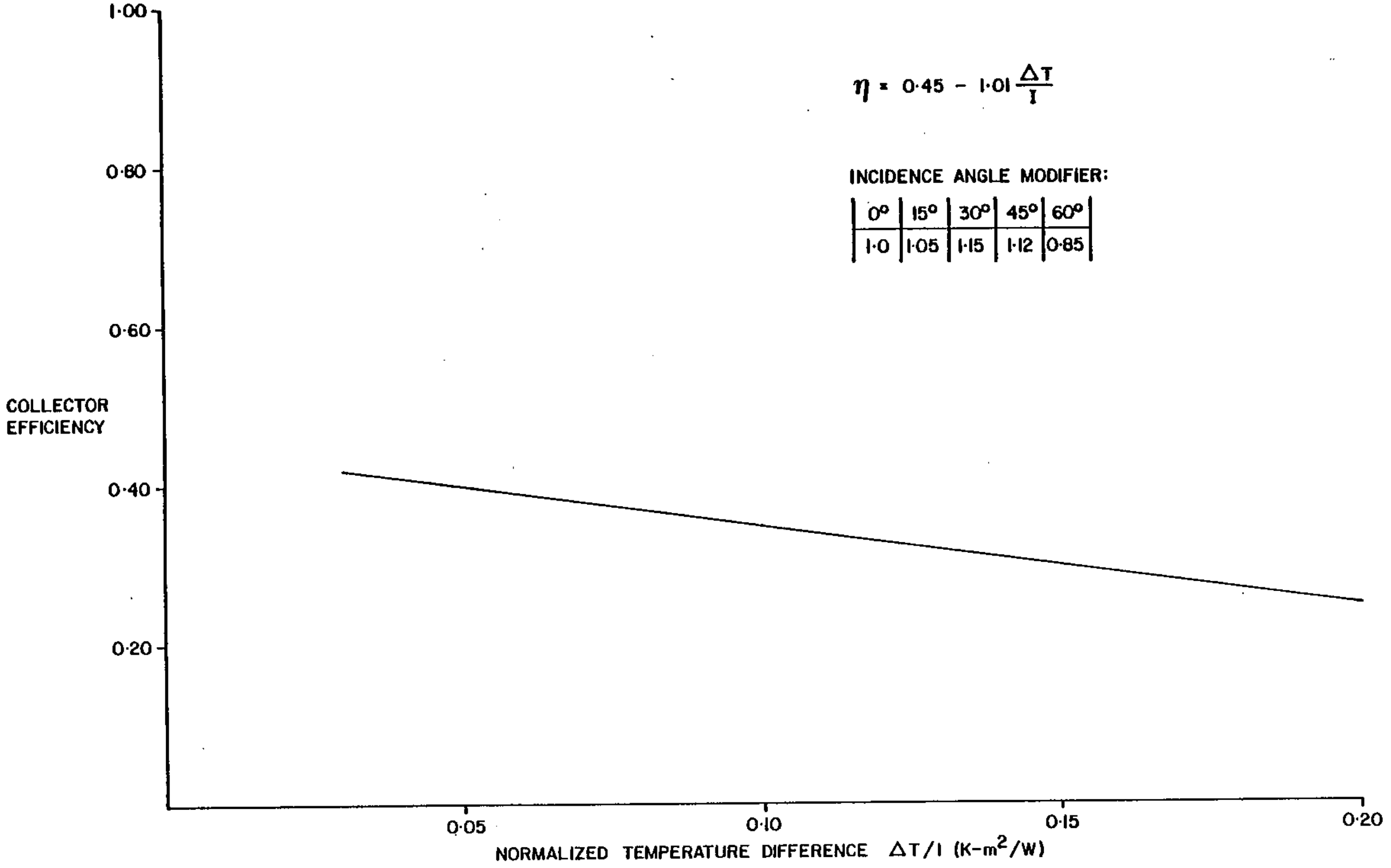
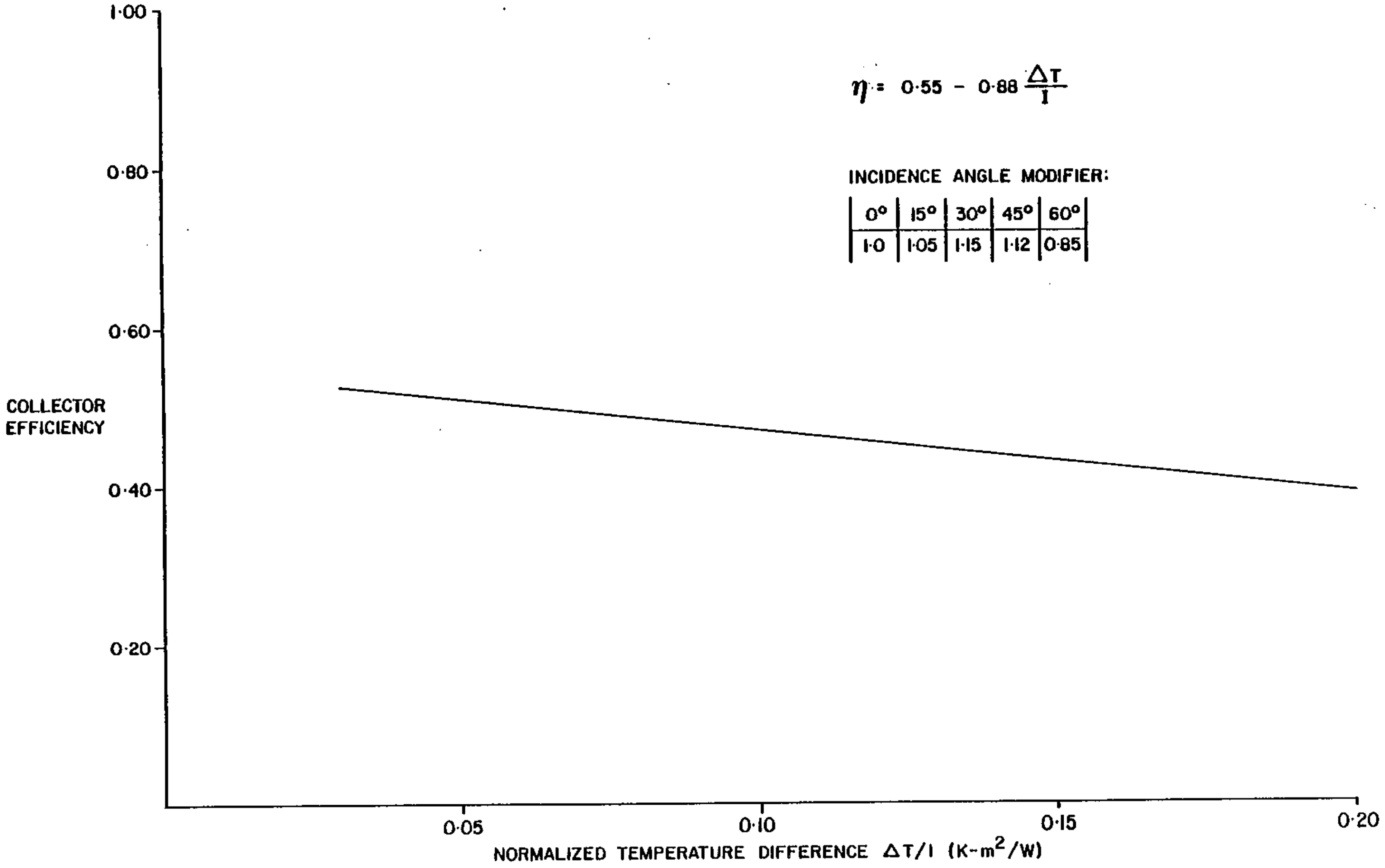


Figure 3.1.3 COLLECTOR EFFICIENCY: SOLARTECH COLLECTOR MODULE



$$\eta = 0.55 - 0.88 \frac{\Delta T}{I}$$

INCIDENCE ANGLE MODIFIER:

0°	15°	30°	45°	60°
1·0	1·05	1·15	1·12	0·85

Figure 3.1.4 COLLECTOR EFFICIENCY: SUNMASTER TRS–81 COLLECTOR MODULE

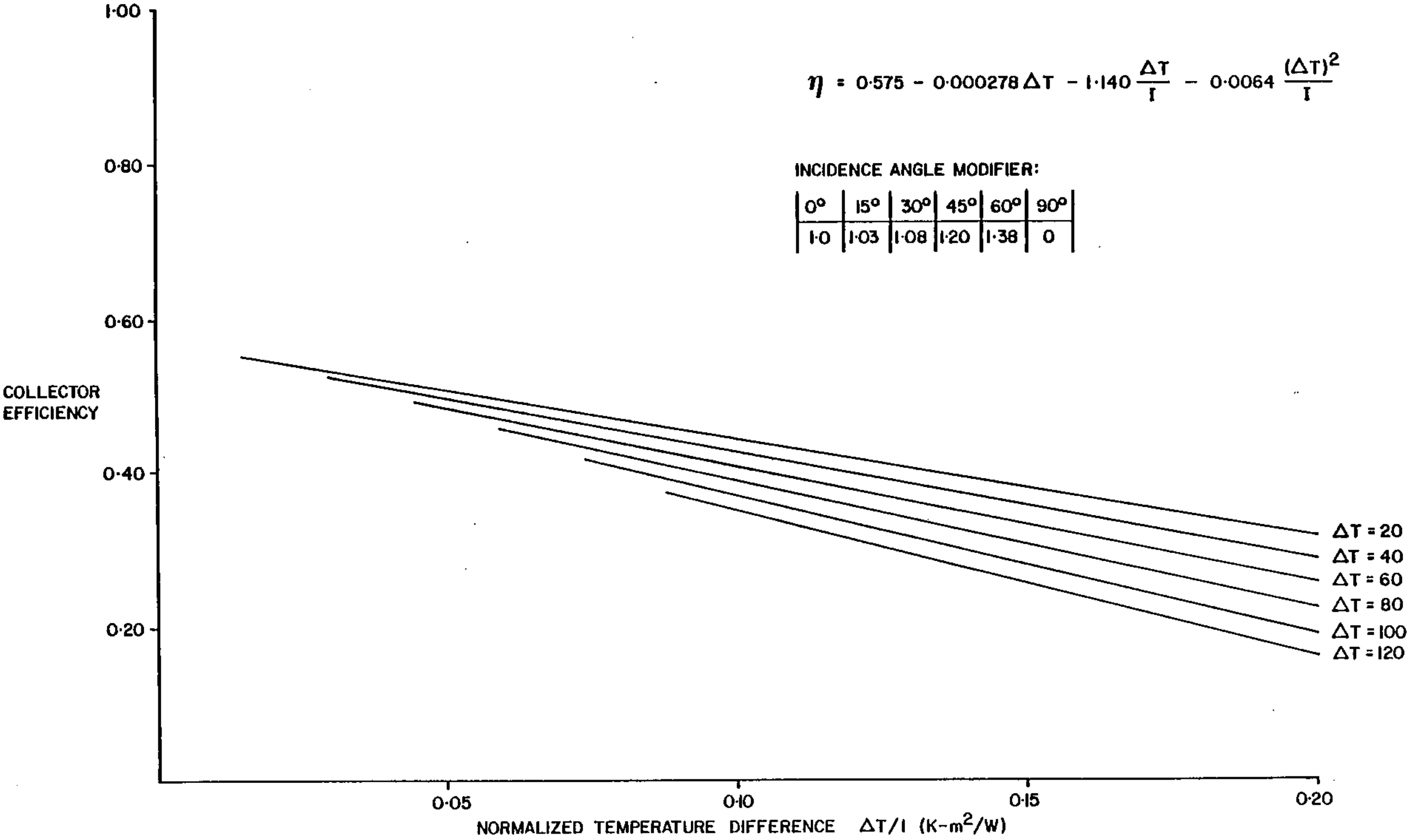


Figure 3.1.5 COLLECTOR MODULE EFFICIENCY:
SYDNEY UNIVERSITY EVACUATED COLLECTOR WITH U-TUBE MANIFOLD

3.1.3. Detailed Design

During the detailed design phase, the various system parameters are optimized.

The numerous components of a solar heating system are sensitive to the type of collector used. The differences between the sensitivities of components to evacuated tubular collectors as opposed to flat plate collectors is dealt with here. The components discussed are:

- Storage
- Heat exchangers
- Collector working fluids
- Pumps
- Piping system
- Pipe insulation
- Control systems.

The most important difference to be considered when comparing evacuated tubular collectors and flat plate collectors is their respective sensitivities to operating temperatures. Evacuated tubular collectors, because of their relative insensitivity to their operating temperature, allow other system components to be smaller and operate less effectively without a major penalty in overall system performance.

Storage

Storage parameters to be considered include:

- the storage medium
- the quantity of storage
- the degree of stratification
- the storage location in the system (load side vs. collector side)
- level of insulation.

The storage medium for an evacuated tubular collector based system requires no different considerations than those for a single glazed selective flat plate collector based system.

The quantity of storage required, as with flat plate systems, varies greatly with the application.

For space heating applications, storage volumes for evacuated tubular collectors can be tolerated with an equivalent single glazed selective flat plate collector based system. When ambient temperatures are low, the efficiency of an evacuated tubular collector is less affected by the higher average collector inlet temperature that results from smaller storage volumes and hence higher storage temperatures. Thus, storages may be sized for higher temperatures with little performance reduction.

Because of the lesser dependence of the performance on the collector temperature with evacuated tubular collectors when compared with flat plate collectors, the location of the storage is less critical. Collector side storage, before the heat exchanger, is preferred with single glazed selective flat plate collector based systems which circulate water through the collectors because of the resulting lower collector fluid inlet temperatures. With evacuated tubular collectors this consideration is far less critical resulting in greater design flexibility.

Where the use of higher temperature storage is employed, the optimum insulation level will be higher.

Heat Exchangers

The heat exchanger effectiveness for a collector side heat exchanger greatly affects the temperature of the fluid entering the collectors. With most evacuated tubular collectors this factor is of less importance in the consideration of the collector efficiency.

Collector Working Fluids

The choice of a collector working fluid for an evacuated tubular collector array involves many of the same considerations as with a single glazed selective flat plate collector array. Several particular concerns, however, must be addressed. The 250°C or greater stagnation temperatures of most evacuated tubular collectors are substantially higher than those encountered with single glazed selective flat plate collectors. For this reason the high temperature characteristics of the fluid are important.

Where working fluids such as oils are used with evacuated tubular collectors, special precautions must be taken because of the high temperatures encountered.

With the higher temperatures generally encountered, corrosion in the system can be enhanced. When selecting the working fluid, care should be given to assessing the corrosion inhibiting properties of the fluid.

In situations where evacuated tubular collectors carry large inventories of working fluid, several items should be considered including:

- the high start-up capacity
- the possible use of an accumulator tank
- the high cost of antifreeze solution and corrosion inhibitors.

Some evacuated collector types can be drained back, simplifying working fluid selection.

Pumps

Because of the higher temperatures encountered in evacuated tubular collector based solar systems, pumps, particularly those located in the collector loop, are often subjected to higher temperatures than those of a flat plate collector based system. Care must be exercised in the selection of materials for glands, seals and rotors. As well, with the higher temperatures, the potential for corrosion is enhanced.

Because of the relatively high fluid working temperatures, attention must be paid to the net positive suction head available to the pump because of the increased chance of cavitation at elevated temperatures.

Piping System

As discussed earlier, the amount of piping required in an evacuated tubular collector based system is less than that for the equivalent flat plate collector based system. Pipe sizes are also generally smaller.

The piping system, including such items as the pipe, fittings and valves, may all be subjected to higher temperatures in an evacuated tubular collector based system. Plastic components are generally not acceptable.

For copper piping systems the standard 50/50 tin and lead solder will not withstand the potential temperatures. As a minimum, 95/5 tin/antimony solder is required. The brazing of the connections may be desirable, and will be the only acceptable alternative if brass fittings are to be used because of the incompatibility of brass with 95/5 solder.

Dielectric insolation is more important at elevated temperatures.

Expansion couplings are required to work through greater distances and hence their placement and integrity are of greater importance.

As a general rule, the thermal capacity of the entire piping system should be minimized in order to reduce start-up losses. This suggests the use of copper rather than iron piping systems.

Pipe Insulation

The most important consideration when selecting pipe insulation is its ability to withstand the elevated temperatures likely to be encountered. The insulation near the collector array will be subjected to temperatures close to the stagnation temperatures of the collectors.

For exterior insulation a non-water absorbing, ultra-violet resistant insulation is required.

The insulation of interior piping is important, not only from the standpoint of thermal losses, but from the standpoint of safety. Piping temperatures far in excess of those that can cause serious burns can be encountered. All piping and fittings that can be accidentally touched must be protected to ensure the safety of persons in the area.

Control Systems

The control system for an evacuated tubular collector based system will be similar to that for a single glazed selective flat plate collector based system designed to serve the same load. Several points, however, should be considered.

Because the collection efficiency of evacuated tubular collectors is less affected by temperature than with single glazed selective flat plate collectors, less sensitivity in the control system may be acceptable with the resultant decreased costs.

Because of the very low heat loss from the collectors, the system, in some cases, may be controlled by either ambient light levels or by a time clock rather than the traditional differential controller. For the same reason, the freeze protection of an evacuated tubular collector array may, in some instances, be accomplished by the recirculation of fluid through the collector array.

When selecting a control system, sensors capable of withstanding the temperatures to be encountered both during operation and during periods of stagnation must be specified. The stagnation temperatures of evacuated tubular collector based systems can be significantly higher than those for single glazed selective flat plate collector based systems. It is generally recommended that high quality stable sensors, such as platinum RTDs or glass encapsulated thermisters, be employed in the area of the collector array.

3.2. Collector Mounting and System Construction

The construction of evacuated tubular collector based solar heating systems presents no unique problems when compared with other types of solar heating systems. However, as with all systems, the quality of the end product is largely dependent on the accuracy and completeness of the specifications. Seemingly unimportant derivations from the original design concept due to incomplete or misleading specifications may cause serious degradation of the performance of the system.

The various options available for mounting evacuated tubular collector arrays and the specific factors that must be considered because of the use of evacuated tubular collectors are discussed below.

The use of evacuated tubular collectors permits a significantly greater degree of flexibility in the mounting of the collector array than do flat plate collectors. The installation flexibility varies, however, with the different types of evacuated tubular collectors.

Many types of evacuated tubular collectors can be oriented in any direction. This feature allows the collector modules to be placed on slopes, particularly existing roofs, that would be unsuitable for the installation of flat plate collectors. Figures 3.2.1 and 3.2.2 illustrate several options to conventional collector installation configurations that can be considered. Direction arrows are appropriate for locations in the northern hemisphere.

Evacuated tubular collectors can be mounted using the same types of support structures that would be used for flat plate collectors. The size of the support structure for evacuated tubular collectors is smaller due to the smaller required collector array area. Evacuated tubular collectors, as supplied by most manufacturers, are assembled modules of approximately eight to fifteen collector tubes complete with header assembly, reflector and mounting frame.

Wind loading considerations for evacuated tubular collector arrays equipped with reflectors are similar to those for flat plate collectors. For arrays without reflectors, the wind loading on the array is somewhat reduced allowing for a possible reduction in the strength of the support structure.

Snow accumulation can present a problem with reflector equipped evacuated tubular collector arrays. Because the heat loss from evacuated tubular collectors is not sufficient to melt snow in cold weather, the snow that collects between the tubes and the reflector does not slide out. Snow retention is not a significant problem on evacuated tubular collector arrays which do not employ reflectors. Without reflectors, some collectors can absorb a significant amount of energy reflected from snow behind the collectors.

In spite of their appearance, evacuated tubular collectors are extremely rugged. The tubes are designed to withstand the impact of 30 mm or greater hailstones at 100 km per hour and, placed horizontally, will withstand being walked on.

Collectors should be mounted so that required roof maintenance, snow removal, and so forth may be performed.

3.3. Operation and Maintenance

3.3.1. General Operating Monitoring Considerations

The prime purpose of operational monitoring is to detect a decrease in the performance of the solar system. This is done by regularly comparing certain indicators, such as temperatures, pressures and pump run times with those specified in the design and commissioning process. A change in these indicators outside of the design range means that the system has an operational problem. Identifying operational problems or system breakdowns as soon as possible is important in reducing damage to the system, and will also maximize the energy output of the solar system. Early detection of problems will also increase the life of the system, and keep operating and maintenance costs to a minimum.

Daily Inspections

Items that should be checked visually on a daily basis are those that would indicate a system malfunction of an immediate nature. These are typically:

- system pressures
- pump operation in relation to weather and control modes
- system temperatures in relation to control modes
- status of system alarms
- evidence of leaks or pressure relief valve activation.

Monthly Checks

Monthly checks will primarily entail a more detailed examination of items that are checked daily. Recording this information will provide a historical record of the system's performance. Verification of control operation in relation to system design modes, the weather, and system temperatures would be an example of a possible monthly check.

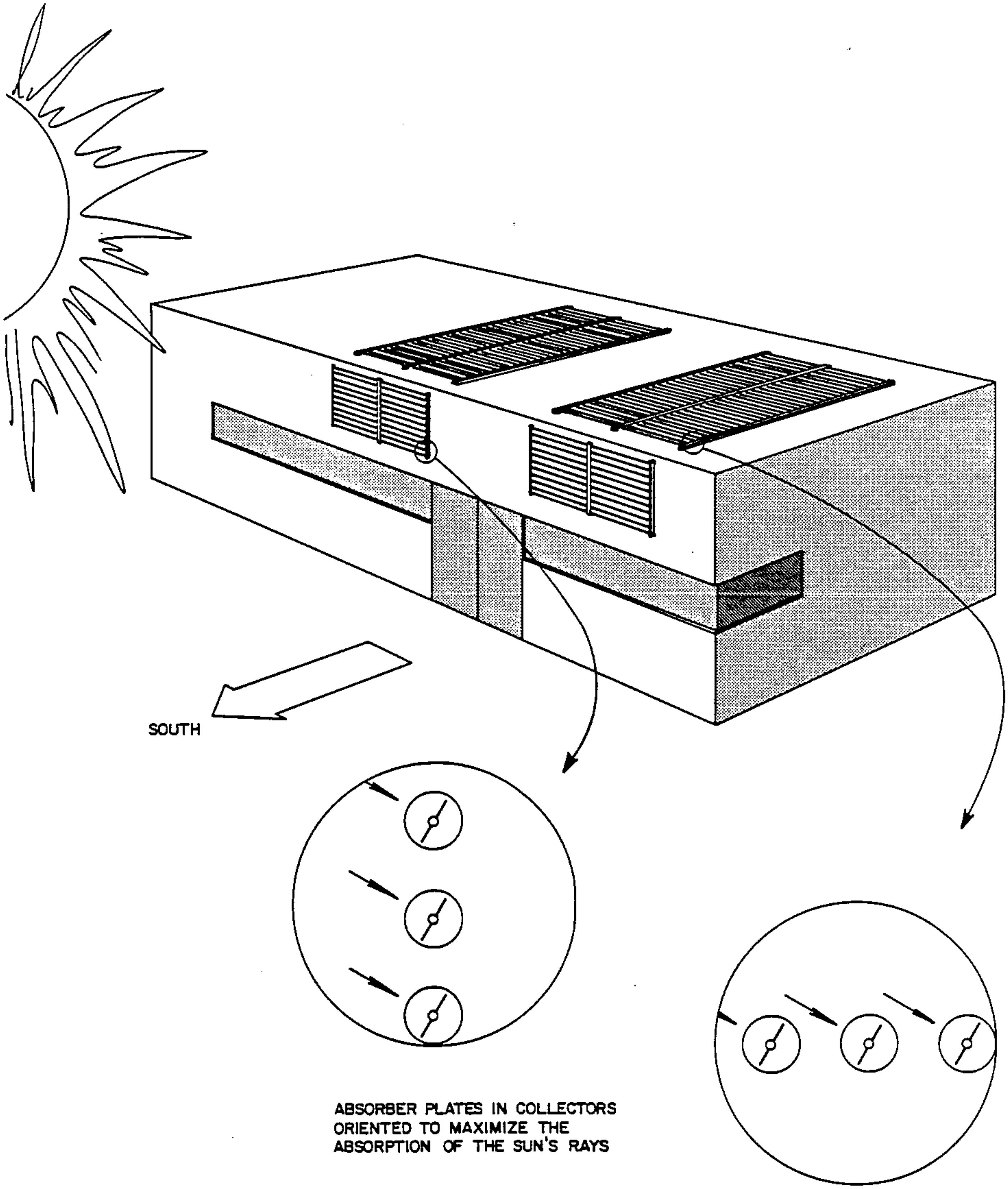


Figure 3.2.1 WALL AND FLAT-MOUNTED COLLECTOR MODULES

Semi-Annual Checks

Each spring and fall, a detailed examination of the system should be performed. Many of the tests required in the start-up and commissioning phase will be repeated. Some typical semi-annual checks and tests include:

- operation of individual collectors
- fluid quality checks
- control system checks for:
    - security of sensor mountings
    - calibration of sensors
- check of the condition of filters and strainers
- testing of valves to ensure proper functioning
- examination of fluid level in the expansion tank
- heat exchanger effectiveness test.

3.3.2. Maintenance of Evacuated Tubular Collector Arrays

Maintenance checks which are of particular importance in an evacuated tubular collector array are:

- checks for vacuum loss
- checks of heat transfer fluid.

Although evacuated tubular collectors of the designs currently available have a remarkably good durability record, it is important that the tubes be checked periodically for vacuum loss. A collector with a degraded vacuum will have a hot outer surface relative to the collectors in the array. Numerous methods can be employed for checking tube temperatures from simply touching each collector to scanning the array with thermographic equipment.

The heat transfer fluid should be checked periodically for signs of degradation. Glycol based fluids can degrade under high temperatures causing the fluid to become acidic. The pH should be checked to ensure that the fluid is essentially neutral and the reserve alkalinity should be checked to see whether the addition of inhibitors is necessary.

For glycol based heat transfer fluids, the concentration should be checked to ensure an adequate level of freeze protection is available.

Some evacuated tubular collector types use a metering orifice to control the flow through individual collector tubes. The Solartech collector sold in Canada is of this type. The Solartech collector employs the same evacuated tubular envelope as the Sunmaster collector, but different flow control methods are employed. Orafice metering systems may, with time, scale, causing restricted flow through some individual tubes.

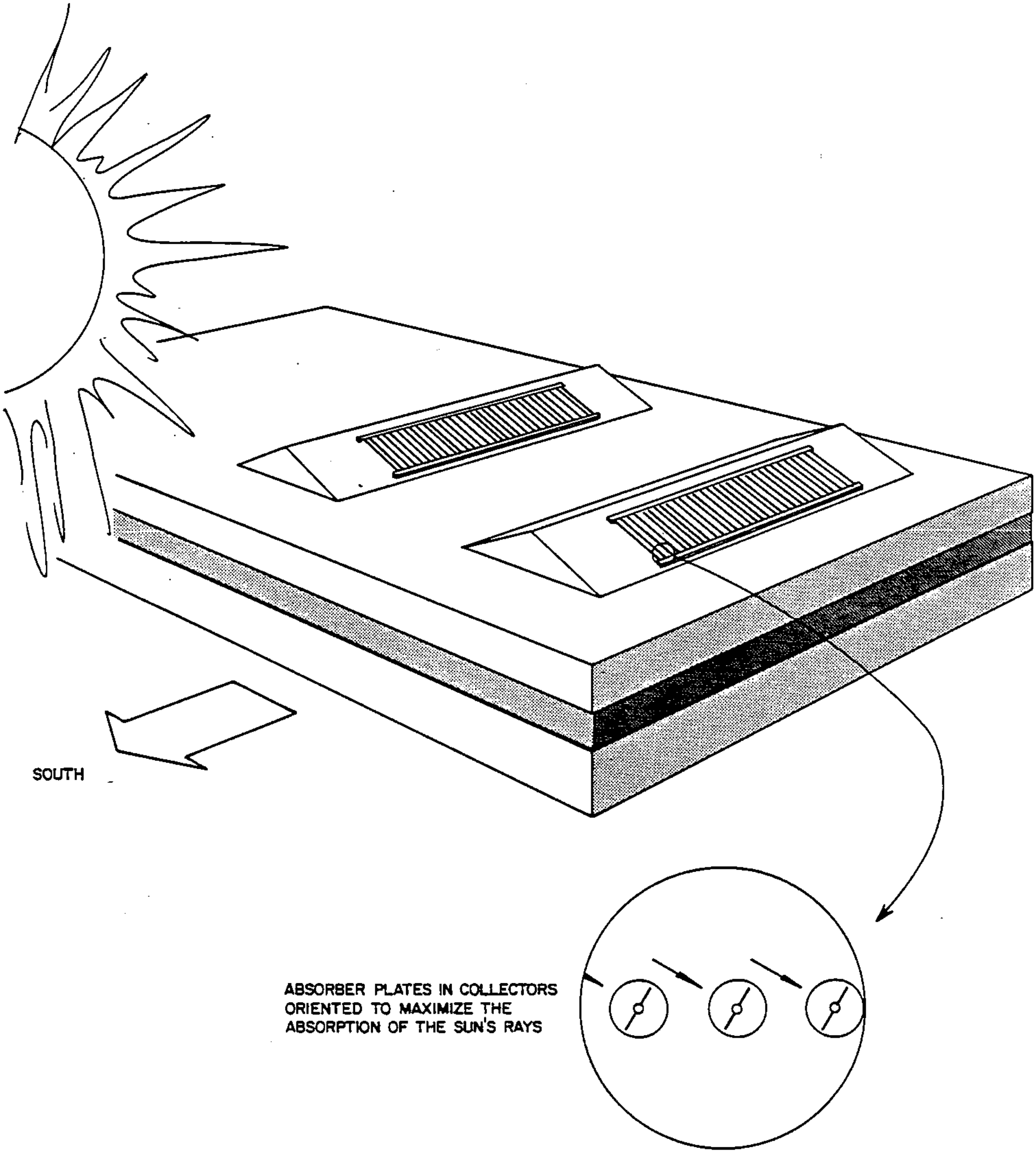


Figure 3.2.2 COLLECTOR MODULES MOUNTED ON AN EAST FACING SLOPE

APPENDIX A
A GENERAL APPROACH TO DESIGN, INSTALLATION AND FOLLOW UP FOR SOLAR HEATING SYSTEMS

Feasibility Study Considerations

Much of the success of a solar heating system rests with the initial engineering feasibility study. A number of items must be addressed during the feasibility study stage of a solar system project. These include obtaining satisfactory answers to the following questions:

- Is the load under consideration a good application for a solar heating system?
- Can the solar heating system be easily and cost-effectively integrated with existing energy systems in the case of a retrofit?
- Is the required space available for the collector array, thermal storage and other other system components?
- If the collector array is to be mounted on an existing roof, is the roof structure adequate to carry loads imposed by the collector array without significant modifications?
- Can piping be installed in such a way that the required slopes are available, particularly in the case of drainback systems?
- After the system has been installed, will adequately qualified maintenance staff be available on-site, or for routine site visits, to operate and repair the system?

A yes answer to all of these questions should indicate that the load being assessed for application of a solar heating system is likely a good one. A no answer to any of the questions is a reason for re-evaluation of the feasibility of the project.

One of the areas most often neglected in the feasibility study phase of a solar project is the accurate assessment of the total load, and, particularly, the load profiles. Many systems have been carefully designed based on totally erroneous load profile estimates. Often, because details of load profiles were not necessary to the operation of the existing energy systems, the system owner or operator had very little knowledge of the details of these load profiles. It is imperative that accurate load profiles be developed before proceeding with the solar heating system design.

The improper sizing of a system not only results in wasted money but can lead to serious system operating problems. Oversized systems with inadequate storage have resulted in overheating problems which have led to system failures and safety hazards.

It is also important to investigate whether the load profile in an existing plant can be modified to more closely match the available solar energy without adversely affecting the plant's operation. These changes, if acceptable, must be determined at the outset, and the appropriate solar system design considerations made.

Other changes anticipated in the plant's operation must also be assessed at the time of the feasibility study. For example, the addition of heat recovery equipment in an existing plant will seriously affect the operation of a solar heating system. In some cases it will preclude the use of solar heating, and in others, radically change the required design approach.

Adequate space for the location of the components of a solar heating system is an absolute necessity. Numerous systems have been installed with little consideration for the future maintenance of components. Typically, components are arranged such that substantial effort is required to access items needing relatively frequent attention, such as pumps and heating coils. Even when space is available, logical placement of components for ease of maintenance must be considered.

The roof mounting of a solar collector array requires a detailed assessment of the existing roof structure. Additional structural costs have been the cause of many solar heating systems experiencing major cost overruns. While solar collector arrays are becoming far less complex with new innovative designs for collector manifolding and mounting, a sound structural foundation is still a primary concern.

When a solar system is contemplated for a particular application, the consideration of the availability of operating personnel is important. This is particularly a concern when the solar system will be the most complex system in the building or where it will be the only sophisticated mechanical system.

Because solar systems usually have an automatically activated backup system, the assessment of the solar system's operational status is not always easy. With conventional space heating or water heating systems, a failure is usually noted by the users or building occupants and quickly reported. With a solar system where the backup activation is automatic, the users or building occupants will not, in most cases, be aware of a solar system failure. In these cases it must be left to experienced and qualified operational personnel to continually monitor the status of the system.

If the required personnel are not available, the installation of the system may be very unwise.

System Installation

Most problems associated with the installation of a solar heating system stem from poor workmanship. Very few parts of a solar heating system are substantially different than those found in conventional HVAC or other mechanical systems. The mounting of solar collectors does present some unique problems, and the constant thermal cycling requires special consideration, but most solar system installation problems are not in these areas.

One of the most common problems encountered during the inspection of solar systems is the poor installation of piping. Pipe hangers are often inadequate and too widely spaced. For a drainback or draindown system, this can prove disasterous.

An area often neglected in the installation of solar heating systems is the insulation of piping, both inside and outside. Numerous types of pipe insulating materials have been used on solar heating systems, some with very limited success, particularly in outdoor applications.

Insulating materials suitable for outdoor application must be weatherproof, protected against water absorption and resistant to ultraviolet radiation deterioration. When used near a collector array, it must be capable of withstanding not only extreme outdoor low temperatures but also the high stagnation temperatures of the collector array. Insulating materials such as closed cells urethane foams and foamed glass have been found suitable for this application.

The power wiring of a solar heating system is generally well done and subject to inspection by the local electric utility. Control wiring is often poorly installed. Because the proper operation of the control system for a solar heating system is difficult to assess, extra care is required to ensure the durability of this part of the installation. Components and wiring must be protected from mechanical damage.

Proper labelling of system controls is essential to ensure that the system is properly operated. Improper setting of controls during a period of cold weather can cause a very expensive freeze of a solar heating system.

System Commissioning

Many solar heating systems employing relatively sound designs have never operated as expected. In many cases this is due to a failure to properly commission the system at the outset. The commissioning of a solar heating system is one of the least understood and most often neglected processes in the entire solar design and construction industry. Fortunately, this problem is beginning to be recognized and an increasing effort is being made to ensure that a solar heating system is actually operating as designed before it is signed off as complete.

The proper commissioning of a solar heating system not only ensures the system is initially operating as designed, but permits the establishment of bench marks to which system operating parameters can be compared over the long term and, hence, ensure the proper operation of the system.

System Maintenance

Once a solar heating system has been designed, constructed and commissioned, it must then be properly maintained. Emphasis must be placed on the complete documentation of the system and the preparation of operating manuals.

Manuals are essential to the successful operation of any mechanical system. They must clearly explain the operation of the system, contain the necessary operational checklists, and detail troubleshooting procedures should a fault be found or suspected. The requirements are essentially the same as required for any other complex mechanical system.

APPENDIX B
DESCRIPTION OF THE IEA TASK VI PROGRAM AND THE PARTICIPATING INSTALLATIONS

The objectives of Task VI is to further the understanding of the performance of evacuated collectors in solar heating, cooling and hot water systems, and to study, document and compare the performance characteristics of such collectors in different systems and climates.

Each of the ten participants in this task is responsible for the operation and analysis of at least one evacuated collector solar heating and/or cooling installation. The installations include five cooling applications, two space heating applications, three district heating systems, two industrial process heat applications and a simulated load test facility.

Participants in this task and their installations are:

Australia - Sydney University Solar Heating and Cooling System
Canada - Edmonton Mountain Spring Bottle Washing Facility
Commission of European Communities - Ispra Solar Heated and Cooled Laboratory
Federal Republic of Germany - Solarhaus Freiburg
Japan - Sanyo Osaka Solar House
Netherlands - Eindhoven Technological University Solar House
Sweden - Knivsta District Heating System, Sodertorn District Heating System
Switzerland - Solarcad District Heating System, Hallau Industrial Process Heat Facility
United Kingdom - Bracknell Solar Test Facility with Simulated Loads
United States - Colorado State University Solar House I

The exchange of information within the task has been greatly enhanced by the adoption of a mandatory common reporting structure. The structure is based on the International Energy Agency Solar Heating and Cooling (IEA SHAC) program performance reporting format which has been modified and made more specific and prescriptive to ensure a high level of communication. Performance comparisons can be made that would be difficult or impractical for non-coordinated projects. Thus, participants have better access to and gain more information from each Task VI installation than they would from other installations in their national program.

The task includes a variety of installations covering important evacuated collector applications, a comprehensive use of available evacuated collectors, the use of the same collectors in several installations and some duplication in end uses. Cooperation in the task provides a means of reducing duplication in each participant's national program and a reference point for future evacuated collector systems research, development and commercialization activities.

DESCRIPTION OF PARTICIPATING SYSTEMS

AUSTRALIA

Sydney University Solar Heating and Cooling System
Department of Mechanical Engineering
University of Sydney
Sydney, Australia

Four offices located on the top floor of the Mechanical Engineering Building are cooled in summer using a heat driven absorption cooling cycle. Solar energy is also used for space heating in winter. The total floor area of the air-conditioned space is 52 metres squared.

The cooling/heating system attempts to maintain office room temperatures between 21°C and 25°C. As the four air-conditioned offices are located on top of a large five story building which is generally not air-conditioned, the load is relatively high and remains fairly constant compared to the size of the offices. Daily loads fluctuate between 120 to 150 MJ/day. During summer, the constant daily loads are significantly increased by solar gains through a large glass area along the western side of the building.

CANADA

Mountain Springs Bottle Washing Facility
Edmonton, Alberta

The 281 m^2 solar system, installed on a bottling plant, was designed to assist in maintaining the temperature of a caustic soda solution used for the washing of reusable empty soft drink bottles.

The load is comprised of two components. Firstly, sensible heat required to heat the pop bottles for washing and sterilization purposes. Secondly, the heat required to overcome standby losses from the washing unit. The temperature of the caustic soda solution used for washing and sterilization is maintained between 60°C and 70°C using a gas-fired heater as an auxiliary source. The actual gas consumption from 1 May 1982 to 31 December 1983 for the washing process was 4055 GJ. The load for the same period was 2420 GJ.

COMMISSION OF EUROPEAN COMMUNITIES

Ispra Solar Heated and Cooled Laboratory
Italy

The Solar Laboratory was built for the study of active solar heating and cooling systems. It is a small office building with a ground surface of 160 metres squared. The solar cooling system is used for the air-conditioning of the building during the summer months. The heating is done with a separate solar heating system.

During wintertime the indoor temperature is kept at 20°C. This requires about 240 MJ/day for 160 days. There is no DHW load in the building. The cooling season includes about 130 days with an average load of about 80 MJ/day. In the cooling season, the room temperature during the heat of the day is allowed to rise above 20°C. The cooling load is decreased by lessening the difference between the indoor and outdoor temperature.

FEDERAL REPUBLIC OF GERMANY

Solarhaus Freiburg

The solar house has a conditioned living area of 652 metres squared. The three story apartment building has approximately twenty-five permanent occupants in the twelve apartments. Solar energy is used for space heating and hot water.

The indoor winter design conditions vary with each individual apartment, thus, only the actual average daily heating loads are known. They ranged from 1341 MJ/day in 1980 to 1213 MJ/day in 1981. The average daily heating load has been reduced to 960 MJ/day (based on 214 days of heating period) due to a reduction of the ventilation rate to approximately 0.5 air cycles per hour. There is no summer cooling. The average daily energy for the warm water supply remained in the same order of magnitude as in previous years (185 to 190 MJ/day), corresponding to a daily hot water consumption of 1300 litres. Special energy saving designs include improved thermal insulation, triple-glazed windows, a ventilation system and a micro-computer operated control system.

THE NETHERLANDS

Eindhoven Technological University Solar House

The solar house at the Eindhoven University of Technology, a rather spacious detached house, is situated in the outskirts of Eindhoven, some four kilometres NNE of the city centre.

The load consists of the domestic hot water system (13 GJ/year) and the heating system of the house (83 GJ/year). The heated floor area amounts to 220 metres squared, the volume is 810 metres cubed. The area of double glazed windows is 40 metres squared (theoretical heat transmission coefficient is 3.2 W/m^2K). The total outside area is about 313 metres squared including the roof area. Both roof and walls have a theoretical heat transmission coefficient of 0.4 W/M^2K. Ventilation and infiltration amounts to about 800 m^3/hr.

SWEDEN

Knivsta District Heating Project

Knivsta, Sweden

Knivsta is situated 45 kilometres north of Stockholm, Sweden, and 20 kilometres south of Uppsala. About 60 percent of the buildings are connected to a local heating net fed from a biomass-fired plant. The landscape in the area is rather flat, consisting mainly of wide fields and some small areas of forest.

Three different types of evacuated solar collectors have been mounted on the roof of the district heating plant in Knivsta. The district heat load is always much larger than the energy production from the collectors, so the heat from the collectors is transferred to the return pipe of the district heating systems. There is no storage. The district heating plant is fired with biomass and the heating system has a peak demand of 15 MW.

Hot water is needed for industrial processing and space heating. In the former case (ie. pasteurization, bottle and case washing) the load is 2900 GJ/year ranging between 350 and 430 GJ/month with a peak demand in the autumn; the required temperature is between 90 and 110°C. In the latter case, for the heating season, the load amounts to 640 GJ/month. The heat produced by solar is used for industrial processing in summer, and space heating in winter. The load is divided into different and complicated loops for processing and heating, and thus is considered as a whole. It is possible to direct solar gains to low temperature use.

UNITED KINGDOM
Evacuated Collector System Test Facility
Bracknell, United Kingdom

The solar domestic space and hot water heating system is installed at the laboratories of the Building Services Research and Information Association. The installation is a complete solar system including storages but the loads are imposed by a subsystem which simulates the space heating and hot water requirements of a single family dwelling.

The load on the solar system is simulated by a physical load simulator controlled by a computer, which calculates the required load from measures of the prevailing weather parameters every five minutes. The simulated house is maintained at 20°C provided the outside air temperature is less than 18°C. The house temperature may freely evolve above 18°C to a maximum of 25°C. The space heating load averages 146 MJ/day during the heating season with an annual total of 37 GJ. The domestic hot water load is 90 litres/day at 55°C distributed intermittently over 16 hours.

USA
Colorado State University Solar House I
Fort Collins, Colorado, USA

Solar House I, completed in 1974, is a wood-frame, two-story, three bedroom residential building utilized for offices. The conditioned living area is 249 m^2. Solar energy is used for space heating and space cooling.

The indoor winter design temperature of 21°C produces an average daily load ranging from 235 MJ/day to 305 MJ/day during the heating season. The summer indoor design temperature of 24°C produces an average daily load of about 445 MJ/day. Special energy saving features include a wall heat loss coefficient of 0.30 $W/m^{2\circ}K$, triple-glazed windows and reduced infiltration by use of a vestibule entry. The calculated heat loss coefficient of the building is 390 $W/^\circ K$.

SWEDEN
Sodertorn District Heating Project
Sodertorn, Sweden

The Sodertorn plant is located 20 km south of Stockholm. Seven different solar collector systems are connected directly to the local district heating system and can be compared at the same operating conditions.

The district heating load is always much larger than the energy production from the collectors so all the collector output can be used. The collectors are normally connected to the return pipe of the network where temperature levels around 50-60°C can be used most of the year.

SWITZERLAND
Solarcad Industry Project
Geneva, Switzerland

Two solar systems are connected directly, without intermediate storage, to the district heating network as the minimum heat demand is always much higher than the heat produced by solar. The district heating network supplies space heating and domestic hot water to surrounding buildings.

Three different systems jointly deliver heat to surrounding buildings for space heating and domestic hot water purposes. Separate loads cannot be identified. The test systems are connected to the return branch of one particular network (called Libellules). The load of this branch is characterized by the following: power capacity of the installed gas-fired furnace, 16MW; delivered power ranging from 0.1 to 6 MW/h; average daily load for the heating season 120 GJ/day; average daily load in summer (DHW only), 21 GJ/day. The solar systems usually operate above 80°C. The total district heating system (3 networks) is typically 15 times greater than the figures given.

SWITZERLAND
Solarin Industry Project
Hallau, Switzerland

Nearly 350 m^2 of evacuated collectors are installed on the roof of a food processing factory. They contribute to space heating and process heat. Hot water is stored in 2 tanks (10 m^3+23 m^3). Existing conventional burners provide auxiliary heating.