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Evaluation of Transparent Insulation Materials in Flat Plate Collectors

**Carol Emrich and Roy Coffman
Florida Solar Energy Center
300 State Road 401
Cape Canaveral, FL 32920**

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EVALUATION OF TRANSPARENT INSULATION MATERIALS IN FLAT-PLATE COLLECTORS

Carol Emrich and Roy Coffman

**Florida Solar Energy Center
300 State Road 401
Cape Canaveral, FL 32920**

Sandia Contract AF-2483

ABSTRACT

Polycarbonate rectangular honeycomb and acrylic capillary honeycomb, two types of transparent insulation material, were tested in flat-plate collectors. The honeycomb was inserted between the cover plate and the absorber, leaving a 1-cm air gap above the absorber to decouple radiative and conductive heat-transfer modes. Four 4 by 8 ft. collectors with selective black chrome absorbers were evaluated side by side using ASHRAE Standard 93-1986. They differed in thickness and type of material as follows: 1) no insulation material, 2) 1 in. of polycarbonate, 3) 4-in. of polycarbonate, and 4) 4 in. of acrylic honeycomb. Another set of tests was completed using absorbers coated with moderately selective black paint, and a third set with flat-black paint. A collector containing a selective chrome absorber and 4 in. of acrylic honeycomb achieved the best thermal performance. The amount of improvement in thermal performance was greatest when transparent insulation material was added to collectors with flat-black absorbers, and it decreased as absorber selectivity increased. Since small-cell honeycomb improves thermal performance by suppressing both convective and radiative transfer, combination with selective coatings is partially redundant because they are poor emitters. Also, the unacceptably low melting temperature of these materials preclude them from withstanding even a wet stagnation, thereby rendering this application impractical.

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1.1 INTRODUCTION

Double pane windows have a remarkable quality, not true of other types of insulating materials such as fiber glass, mineral wool, and foamed plastics. They insulate against heat flow without significantly decreasing visibility. They are transparent to the visible portion of the sun's energy, as well as the ultraviolet and near-infrared wavelengths. However, their insulative properties are insufficient for several applications.

Consequently, scientists and engineers have been continually searching for materials with better insulative properties than double pane glass, but the same or greater visibility. This research has resulted in transparent insulation materials (TIMs) now commercially available which approach ten times the insulative value of a typical double-glass unit. However, the fraction of solar radiation transmitted through the material is about the same.¹ These qualities make them ideally suited for use in devices dependent on thermal energy in the form of solar radiation.

Most thermal energy devices need two basic components; a thermal absorber and a transparent cover to minimize heat loss from the absorber to the environment. Efforts to make these devices more efficient have taken two directions; modifications to improve absorption of heat and modifications to decrease loss of heat. Thermal absorption can be increased directly by modifications in design and materials of the collector and indirectly by modifications in design and materials of the cover to increase available solar radiation. Heat is lost from the absorber by convection, conduction and radiation. Design of a method to reduce heat loss from the absorber must address all three to ensure a net decrease. Incorporation of TIMs into thermal energy devices can achieve this objective if appropriately sized.

1.2 PHYSICAL CATEGORIES

Most TIMs currently available can be grouped into four basic types or categories by Platzer². These groupings are based on the physical structure. The four types are illustrated in Figure 1.1.

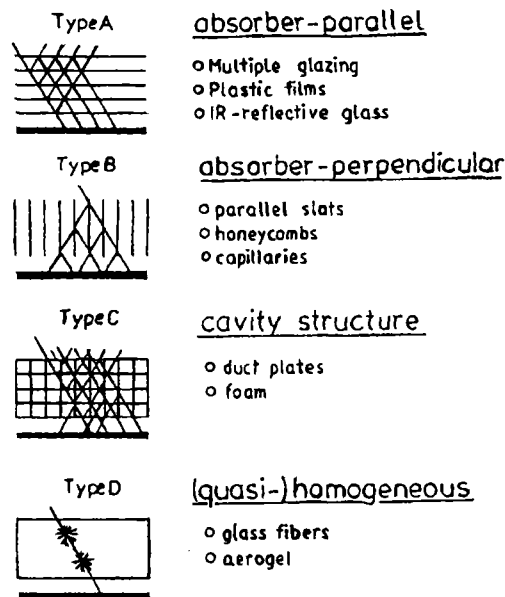


Figure 1.1 Generic types of transparent insulation materials

1.2.1 ABSORBER-PARALLEL TYPE

The first type is the absorber-parallel cover, consisting of one or more glazings, plastic films, panes of glass, or IR reflective glass. These layers may have equal or different optical properties. Unfortunately, high optical reflection losses prohibit the use of a large number of layers. Also, convection between layers must also be avoided. Hollands³ refers to this type of TIM as transparent insulation of the rear-reflecting type (TIRT), because in this arrangement the reflected energy at the parallel surface goes back out and is therefore lost.

1.2.2 ABSORBER PERPENDICULAR TYPE

The second classification includes the absorber perpendicular types, represented by honeycomb or capillaries materials with different cross-sectional geometries. The incoming beam is reflected and transmitted by the walls of the structure much like an optical fiber limiting optical losses to minimal scattering and absorption within the plastic walls. For clear films with low extinction, the transmission properties are nearly independent of the material thickness.

Hollands⁴ refers to this structural arrangement as transparent insulation of the forward-reflecting type (TIFT). The distinct advantage of this type of arrangement is that the solar radiation impinging on the sheet is reflected, and rereflected, by the cell walls in a forward direction. Thus, theoretically if reflections were perfectly specular, and there were no scattering or absorption in the walls, the solar transmission would be 100%.

1.2.3 CAVITY STRUCTURE TYPE

Type 3 is a cavity structure which is a combination of types 1 and 2. Examples of this type of TIM include transparent multiple duct plates or foams with bubble sizes in the order of millimeters. While these structures effectively suppress convection, reflection is the dominate loss mode in this group. Optically, these structures have about the same transmittance as an equivalent multiple film cover. This type of structure can also be modeled by a scattering layer of single bubbles. In both cases there are two parameters. With a multiple film model there is absorption and reflection, and with a scattering model there is absorption and scattering. For large incidence angles, the scattering model is better.

1.2.4 QUASI-HOMOGENEOUS TYPE

The last classification is called quasi-homogeneous and encompasses glass fibers and aerogels. Aerogel is a microporous "silicate foam" with pore diameters in the 10-50 nm range. In this group the major losses are from scattering and absorption. Aerogel scattering is comparable to Rayleigh scattering of solar radiation by gas molecules in the atmosphere. Glass fiber materials, although not as homogeneous, can be analyzed with similar methods.

Hollands⁵ refers to this group as transparent insulation of the continuum type (TICT). His third grouping is based on his description of aerogels as having the length scale of their compartments in the same range as solar radiation wavelengths. This changes the relevant laws of reflection and scattering to those which apply to a material which, as seen by the radiation, is a quasi-continuum.

A large number of different materials and systems have been tested on a laboratory scale in recent years; however, only a limited number are commercially available. Out of these four different categories, this paper will focus on the absorber perpendicular type of transparent insulation.

1.3 MATERIALS

Physical structure accounts for many of the properties of absorber perpendicular transparent insulation; however, the type of material(s) used is also important. The goal is to find a nonfragile, inexpensive transparent material, that can withstand high temperatures and UV exposure, that doesn't degrade with age. The search is still continues.

1.3.1 PLASTICS

The majority of the materials commercially available are made from plastic. Platzer⁶ tested honeycombs made from several base plastics including polymethylmethacrylate (PMMA), polycarbonate (PC), polyethersulfone (PS), polyethylene (PE), and polytetrafluorethylene-derivative (HFL). The materials were distributed by three companies: OKALUX Kapillarglas GmbH (Marktheidenfeld, FRG), AREL Ltd. (Yavne, Israel) and Kaiser Bautechnik (Duisburg, Germany). Thermal and optical properties depend on the base plastic used. One of the primary problems with plastics is their low melting temperature which prevents them from withstanding high stagnation temperatures when used in solar collectors. OKALUX recently came out with a new honeycomb from modified PMMA with the tradename Kamax®, which according to Dengler⁷, is stable to 160°C.

1.3.2 GLASS

For development of TIM-improved, high-temperature flat-plate collectors, a material which is stable for high stagnation temperatures over 300°C is required. Glass is an ideal material for this application. It combines excellent transmittance for the solar spectrum with opacity for thermal radiation and it is stable for temperatures up to 500°C. Table 1.1 includes a comparison plastic and glass for several properties.

Two companies are currently involved in glass capillary research. SCHOTT, Glasswerk in Germany manufactures a glass capillary with a lower limit for the wall thickness of 70 μm , according to Dengler⁸. Using a different production technique developed by the brothers Hans-Joachim and Otto Dietzsch, INFRACONSULT produced a glass capillary honeycomb with a wall thickness of only 30 μm .⁹ Thermal properties and solar transmittance will vary slightly with the geometry of these honeycombs. Unfortunately, neither of these materials could be used in this project because at the

time of TIM procurement they were not commercially available.

Table 1.1. Comparison of plastic and glass capillaries¹⁰

PROPERTIES	PLASTIC	GLASS
specific weight (kg/m ²)	about 3 kg (dens. 8cm)	about 8 kg
thermal conductivity (W/mK)	0.7	1.0
IR absorption	low	high
temperature resistance	up to 160°C	up to 500°C
humidity	change in volumina	stable
UV radiation	unstable	stable
handling	simple	fragile
inflammability	yes	no
durability	5-15 years	stable
aesthetics	poor	regular
recycling	often not possible	yes
ecological risk	yes	no

1.4 APPLICATIONS

Transparent insulation materials have numerous applications. The following includes a summary of some of the major applications reported in the literature.

1.4.1 BUILDINGS

Direct-gain passive heating of buildings in cold climates requires a south-facing window. Heat loss through the standard double-glass unit is a serious drawback. Replacing the window with a transparent insulator can dramatically decrease this loss.

This has been demonstrated in Freiburg, West Germany¹¹. In 1981 a cellular transparent insulating material was attached to the southwest masonry wall of a house that was painted black. The insulated area was covered with glass sheets. A significant fraction of heat, which would normally have been disseminated to the outside air in a conventionally insulated building, was instead transferred into the house. One unexpected consequence of this application was that the house overheated. A control device in the form of a microprocessor regulated roller blind corrected this problem.

Other solutions to the overheating problem have been suggested. Wilson¹² investigated micro-encapsulated liquid crystal devices. These devices switch the amount of direct-hemispherical transmitted radiation in the solar spectral range by values up to 35%, depending on the film thickness and applied voltage. She tested a range of material combinations, including polyvinyl butyryl, a two-component epoxy resin, a UV-setting optical adhesive for the matrix and three different liquid crystals. The best results were achieved with a combination characterized by excellent matching of the liquid crystal ordinary refractive index to that of the optical adhesive, and a high extraordinary refractive index for the liquid crystal.

The micro-encapsulated or polymer dispersed liquid crystal (PDLC) film is sandwiched between two glass or polymer sheets which are coated with indium tin oxide or another transparent conductor so that an electric field can be applied. The switch is accomplished by applying a voltage across the liquid crystals. This causes the molecules to orient in the field direction, resulting in index matching between the droplets and the matrix. Thus, the transmittance of light propagating parallel to the applied field is increased. When the voltage is switched off, the liquid crystal molecules reorient randomly unmatching the indexes of refraction and leading to scattering at the droplet surfaces. This in turn decreases the solar radiation transmitted through the cover glass and prevents overheating.

Wilson¹³ also investigated a thermotropic switching device for shading TI elements to prevent overheating. The word "thermotropic" is intended to describe a property that changes with temperature. In this case, the property is the direct-hemispherical visual or solar transmittance, which is high at typical room and outdoor air temperatures, and decreases markedly once a critical temperature has been exceeded. The thermotropic polymer layer she proposed consisted of two polymer components that can be operated in the temperature range between -20 and 130°C. At temperatures below the critical temperature, the two components are bound at a molecular level by hydrogen bonds, forming a homogeneous mixture which is transparent to light. Above the critical temperature, these bonds break and light scattering domains form with two different component refractive indices. This transition from clear to cloudy occurs over a temperature range of about 40 degrees, with the rate of change being greatest between 50 and 60°C. The results of her initial simulations of their effect on standard buildings are sufficiently positive to justify taking the next step of testing the suggested approaches in architectural dimensions.

Liersch's¹⁴ method was much simpler. He suggested opening an air gap and leading a natural convection air stream away from the facade. During the summer shutters would be opened causing a temperature boundary layer to develop close to the absorber so convective heat flow to the wall is stopped. Optimal values for the gap width were between 4 and 5 cm. The optimal values of the absorber back surface emissivity range from 0.1 to 0.25. This ventilated TI wall system enables closed TIM modules to be used without any dust or condensation problems. Bakker¹⁵ suggested other methods of avoiding moisture and pollution problems, including altering size and quantity of air gaps, and filtering in- and out-going air.

Hartwig¹⁶ experimented with shading a prototype facade with a specially developed lamella sheet. Temperature and radiation measurements were started in December 1992. Absorber temperature reached 68°C unshaded and 44°C on the lamella sheet shaded surface. The energy gain with TI was

reduced 45% with the lamella sheet shaded surface compared to the unshaded wall. A TI-wall with an open roller blind and $50 \text{ W/m}^2\text{K}$ irradiation had no losses. A TI-wall with a lamella sheet needs $70 \text{ W/m}^2\text{K}$ to show no losses. However, even in January (in Switzerland) an average effective U-value of $-0.21 \text{ W/m}^2\text{K}$ was reached with the lamella sheet. Improvements are possible with thinner lamella sheet materials, less support structure, lower angles, and narrower lamellas.

In 1983, the German Ministry for Research and Technology started a TI research program. The program led to fruitful cooperation between different research institutes and provided financial support for cooperation with companies interested in producing and marketing TI systems. The activities involving testing and demonstrating TI applications have increased significantly in recent years. About 3000 m^2 of transparently insulated walls have been installed in more than 15 demonstration projects in which the Fraunhofer Institute for Solar Energy Systems is involved. A selection of these projects is given in Table 1.2.

Several computer models have been developed to determine the effects of transparently insulated walls on building energy requirements. Sick¹⁷ developed a simplified model of the optical portion of a TI wall, that is both fast and reasonably accurate. Using this simplified model, the multi-zone component of the simulation program TRNSYS has been extended to account for transparent or translucent massive or massless layers in the envelop of the building. This extension is based on version 12.2 (1988) of TRNSYS. Jankovic¹⁸ also developed a TI module for TRNSYS which includes thermal resistance, as well as optical transmittance.

Other programs include Liersch's¹⁹ TI wall system characterization subroutine for the SIMUHAUS building simulation program, and Platzer's²⁰ simple monthly calculation procedure for transparently insulated houses, for predicting heat gains and average room temperatures.

Table 1.2 TI-projects with participation of the Fraunhofer-Institute for Solar Energy Systems²¹
(ISE contribution: P=planning, C=construction, M=measurements, A=advice, S=simulation, D=data analysis)

LOCATION	YEAR	TIM	TYPE	AREA(m ²)	ISE	STATUS
Merzhausen	1983	capillary	passive wall	12	P C M D	operating
Ardon (CH)	1988	aerogel	passive wall	120	P M D	operating
Munchen-Grasweg	1988	honeycomb	passive wall	40	P A M D	operating
Sauter-Freiburg	1988	honeycomb	passive wall	31	P A	finished
FR-Sonnenackerweg	1989	honeycomb	passive wall	120	P A M D	operating
Dusseldorf-Hellerhof	1989	honeycomb	passive wall	4x22	P A	operating
Glasgow	1990	honeycomb	passive wall	1000	A	operating
Tiengen (Bollin)	1990	honeycomb	passive wall	70	A M D	operating
Tiengen (Novakov)	1991	aerogel	passive wall	70	A M D	operating
Shanghai	1991	honeycomb	passive wall	40	P A D	operating
Hamburg	1991	honeycomb	collector wall	10	A S	operating
Windberg	1991	capillary	passive wall	150	A S	operating
Dusseldorf	1992	honeycomb	daylighting	1500	A	operating
Freiburg-Christaweg	1992	capillary	passive wall	80	P S C M D	operating
DLR Koln-Porz	1992	capillary	passive wall, daylighting	900	A S	operating
Leipzig	1993	capillary	passive wall	330	P M A S D	construction
Weimar-Hopfgarten	1993	capillary	convective wall	50	A D	planned
Dresden (Umwelthaus)	1993	capillary	forced air wall	33	A D	construction

Wood²² used TRNSYS to address the economics of the energy benefits provided by using a transparent insulation wall in one room of the Bourneville demonstration house in Birmingham, UK. She concluded that transparent insulation at the demonstration house is cost-effective. The payback period for TI, compared to three other typical types of walls for that climate, was between 12.65 and 13.22 years. However, since the average homeowner does not live in a house that long, they would not profit from the energy savings provided by the transparent insulation.

1.4.2 FLAT PLATE COLLECTORS

Transparent insulation has also been used experimentally in flat plate collectors. Some of the earliest work was reported by Hollands²³ in 1965. He conducted a theoretical study on the performance of a flat-plate collector in which a selectively transmitting glass honeycomb panel was mounted between the absorbing flat plate and the outer glass cover. Although no solar collector of the above mentioned honeycomb type was built at that time, preliminary calculations led Hollands to conclude that further research in this direction could lead to an economic flat-plate collector capable of high efficiencies in the 200 to 300°F temperature range.

These increased efficiencies would be accomplished by suppression of natural convection losses and reduction of radiation heat losses from the absorber, while minimizing heat losses by conduction through the honeycomb walls. Optimization is a complicated process in this application. The materials used for transparent insulation should have the property of being transparent to solar radiation and opaque to long-wave radiation. The more material present (i.e. the thicker the walls of the honeycomb cells), the less heat lost due to reradiation from the absorber. However, thicker cell walls decrease solar transmittance and increase heat loss by conduction through the honeycomb sheet..

The cell diameter must be small enough to prevent initiation of convective currents due to the instability of hot air near the absorber surface topped by cooler air below the cover glass. For this reason cell diameters are kept in the range of 12 mm or smaller²⁴. Decreasing cell diameter also increases heat loss by conduction, decreases solar transmittance, and decreases radiative heat losses from the absorber by increasing honeycomb mass. In addition, smaller cell diameters tend to increase the price of the honeycomb, due to increased manufacturing costs.

Hollands^{25, 26} recommends using large-celled honeycomb sheets in combination with selectively coated

absorbers. The objective is to reduce convective losses with the honeycomb material and radiative losses with the selective absorber. Two advantages of large-cell honeycombs, because of their lower material content, are higher solar transmission and lower cost. As with small-celled honeycombs, an air gap of about 10-12 mm between the absorber and the bottom surface of the honeycomb is necessary to decouple conductive and radiative fields.

The appropriate aspect ratio (cell length to cell diameter ratio) is dependent on the application. Buchberg.²⁷ developed a design tool for determining the ideal aspect ratio. He plotted cell length against cell diameter and superimposed temperature difference lines (absorber temperature minus ambient air temperature), creating a window or design region for choosing cylindrical glass capillaries for use in solar collectors, as shown in Figure 1.2.

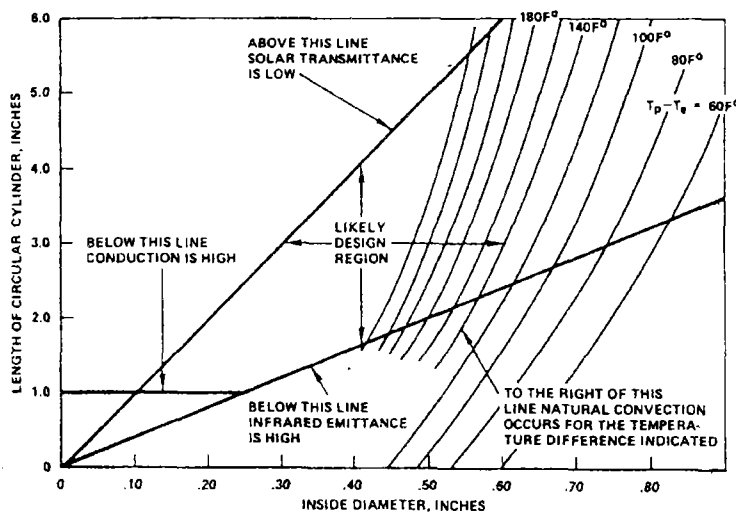


Figure 1.2 Likely designs of cylindrical glass honeycombs.

The likely design region is bounded on the top left side by length-diameter ratio above which solar transmittance is unacceptably low. The bottom-right boundary line is the length-diameter ratio below which infrared emittance is unacceptably high. The right boundary lines are temperature-difference lines to the right of which natural convection occurs for the temperature difference indicated. The

horizontal line at cylinder length equal to one inch forms the lower boundary below which heat loss by conduction is unacceptably high. This type of design tool could be modified for different geometries and material types.

Karlsson²⁸ developed a very long ground based (LGB) flat plate collector. It was connected to the district heating network which requires operating temperatures between 60 and 90°C. The developed collector was equipped with a double glazing composed of a low-iron glass and a flat Teflon film. The performance of this glazing is compared with double Teflon films, V-corrugated films of Teflon, tedlar and mylar, and also AREL honeycomb. The analysis showed that most of the structured materials performed better than the flat Teflon film, but from an economic point of view it is difficult to compete with the high transmitting Teflon film.

Digel²⁹ built a transparently insulated flat plate collector, in which air passes through the capillary tubes causing them to function as heat exchangers. The air inlet is between the cover glass and the TI on one side and the outlet is between the TI and the absorber on the other side. In 1982, polycarbonate TI was used in the first test collector, but was damaged due to non-flow conditions. In 1986, a new module with glass capillaries was tested according to ASHRAE Standard 93-77 (1978). The glass capillary sheet was made from commercially available glass capillary tubes with a length of 180 mm, diameter of 1.7 mm and a ratio of wall thickness to diameter of about 1:28. Reading from his graph, a thermal efficiency of 50% at zero reduced temperature difference (where $T_i = T_A$), decreasing to <30% at 0.06 m²K/W was achieved.

A bifacially irradiated solar flat plate collector was developed by Goetzberger³⁰. Both sides of the absorber were covered with transparent insulation material and both sides were irradiated. The bottom side of the absorber was irradiated using semi-cylindrical mirrors. The constructed prototypes achieved better efficiencies than any other non-concentrating collector, including evacuated tube

collectors. The optical efficiency was measured at temperatures near ambient at 0.72 and the average temperature dependent U-value was determined as $U(\Delta T) = (0.95 + 0.0076\Delta T/K) \text{ W/m}^2\text{K}$. For comparison, the characteristics of a selective flat plate collector are optical efficiency of 0.8 and $U(\Delta T) = 3.8 + 0.01\Delta T/K \text{ W/m}^2\text{K}$ and for an evacuated tube collector, optical efficiency of 0.85 and $U(\Delta T) = 1.78 + 0.0127\Delta T/K \text{ W/m}^2\text{K}$.

The type of TIM used in the bifacially irradiated collector was a polycarbonate honeycomb sheet about 50 mm thick. The plastic was only temperature resistant to 130°C so it could not withstand high stagnation temperatures. The collector was developed especially for use during low radiation conditions like winter in Freiburg.

Several other researchers investigated the use of transparent insulation in flat plate collectors with varying results. Rommel³¹ reported efficiencies comparable to that of evacuated tube collectors using 10 cm of polycarbonate honeycomb at an operating temperature of 80°C. Van der Leun³² reported that the addition of 50 mm of honeycomb transparent insulation to the glass cover of a flat plate collector with a spectral selective absorber would allow an area reduction of 18%. Zegers³³ reported an efficiency improvement of 22% with a spectrally selective absorber, a 2 cm air gap and 10 cm of polycarbonate honeycomb compared to a similar collector with single glass cover. Likewise, Hellstrom³⁴ reported gains of 10-15% annually by replacing Teflon film with 30 mm of AREL polycarbonate honeycomb and 20-30% with thicknesses in the 70-100 mm range.

Even with these increased efficiencies, the inability of the plastic TIM to withstand high stagnation temperatures makes them impractical for use in flat plate collectors without some sort of heat protection device. Platzer³⁵ suggested that tilting the honeycomb structures was a cheap way of improving heat resistance as well as solar transmittance. He found that the heat resistance of the honeycomb increases with tilt angle due to reduced radiation transport. For example, heat conduction

is reduced more than 20% at a 45° tilt angle due to the increased IR radiation barrier. These results were based on a theoretical model which did not take scattering into consideration.

Another theoretical model for approximation of angle dependent solar transmittance of honeycomb transparent insulation was developed by Chaudhry³⁶ and used in a computer simulation. He reported that collector efficiencies did not increase with 100 mm of honeycomb insulation over that of a single glazed collector. This was attributed to the decrease in solar transmittance. He did demonstrate an improvement with 50 - 75 mm of transparent insulation. He concluded that simulation results using TI solar collector modules and other related subroutines developed for TRNSYS show that there is not much room for improvement of flat plate collectors when they are selectively coated and operating at moderate temperatures. Furthermore, the stagnation temperature of the absorber can go as high as 250°C and therefore an emergency cooling mechanism has to be used to prevent TI melting. Further development and cost reduction of TIMs could make the application of transparent insulation in solar collectors more promising.

1.4.3 INTEGRATED COLLECTOR STORAGE UNITS

One way to reduce specific system costs for solar domestic hot water systems is to integrate the hot water storage tank and absorber into one unit. The Fraunhofer Institute for Solar Energy Systems developed such a storage collector with an industrial partner, consisting only of a few components³⁷. However, their integrated collector storage (ICS) unit differed from standard units in that it had a layer of transparent insulation just below the low iron safety glass cover. This addition allows the heat losses from the storage tank to the surroundings to be effectively reduced, while still allowing a high total energy transmission value to be reached.

An important criterion for the quality of an ICS unit is the heat loss per square meter aperture area

(U-value). Fischbach reported U-values up to $3 \text{ W/m}^2\text{K}$ with this unit, which are comparable to those of a good flat-plate collector. Based on a water temperature of 45°C and a daily withdrawal of 120 liters from the storage tank, the collector can supply 480 h/m^2 annually. This corresponds to a solar fraction of approximately 45%.

Schmidt³⁸ constructed two ICS prototypes consisting of a tank with an integrated collector which was covered with transparent insulation. The transparent insulation consisted of thin polycarbonate films arranged in a honeycomb structure. During the test period (November 1986 to October 1987), one ICS unit was operated at water-main pressure (4 bar) and 40 liters, corresponding to the hot water consumption of one person, was withdrawn every day. The solar fraction was 58% (68%) with a system efficiency of 28% (36%) (the numbers in parentheses take the surplus energy in summer into account). Schmidt concluded that the yearly solar fraction and efficiency for these prototypes are equal to or better than those of conventional solar DHW systems.

The second prototype was installed to study stagnation during the same period. Damage from freezing of the ICS prototype did not occur, even during stagnation in the coldest winter periods in Freiburg, West Germany. The boiling point was only reached a few times during stagnation, so that, in a pressurized system, the maximum temperature would have been about 105°C . No supplementary device to prevent overheating was necessary even in the stagnation prototype.

Outdoor tests were also conducted in Freiburg during the summer of 1990, and the performance results of transparently insulated ICS units were used for long term predictions. Based on these, Wagner³⁹ reported an annual system efficiency of 0.35 with a yearly solar fraction of 0.51, assuming an absorber surface of 4.2 m^2 .

The Freiburg group⁴⁰ simulated ICS performance with a computer model they developed. Using the

Test Reference Year for Freiburg, variations of parameters resulted in ICS performance prediction of yearly solar fractions of up to two-thirds. The predicted yearly solar fraction and efficiency were dependent on the temporal profile of water withdrawal with both increasing by about 10% when the water is withdrawn immediately after sunset rather than continuously during the day. Unfortunately, this profile does not correspond well with the normal hot water demand of the average household.

Platzer⁴¹ also developed a theoretical model of the honeycomb absorber system for heat transport and solar transmission. The model takes into consideration both volume scattering and surface scattering of the TIMs. Platzer used it in a simulation to optimize honeycomb transparent insulation material combined with a selectively coated ICS unit. According to his simulations, rectangular honeycomb densities of about 20 kg/m³ are recommended. Also the optimum honeycomb wall thickness is about 60 μm (with an aspect ratio of about 14), but the whole range between 40 μm (aspect ratio around 21) and 80 μm (aspect ratio around 11) is acceptable.

Other uses of transparent insulation in unconventional ICS units include radiators colored black and situated in mirror boxes. These TI radiators, as reported by Balk⁴², were part of the building facade facing the sun radiation. In wintertime, the radiators heat the rooms they belong to and in summer, the heat is given to a domestic water boiler. Lastly, Kaushika⁴³ described a ground (concrete/sand) based solar collector storage media in India with transparent insulation that could continuously supply hot water ($\Delta T = 60^\circ\text{C}$) at a solar conversion efficiency of 40%.

1.4.4 SOLAR PONDS

In solar ponds, the biggest heat loss occurs through the top surface by convection and evaporation. Transparent insulation on the solar pond surface reduces these losses and provides an efficient way of collecting and storing solar energy. Jesch⁴⁴ constructed an 8.64 square meter area and 1.2 meter

deep solar pond in Birmingham, UK for experimental purposes, in 1990. The solar pond was monitored for two years. From these data, Javed⁴⁵ developed a simulation model and tested it by comparing its predictions with the measured results. The predicted temperature of the pond water was in good agreement with the measured temperature.

A module for a transparently insulated pond was developed and incorporated into the transient simulation program TRNSYS. Several computer experiments were conducted to determine the effects of different parametric changes in surface area, pond depth, side insulation, and load. Javed found that a circular pond was optimum and that pond size becomes an insignificant factor in determining loading for ponds larger than 1000 m². Increasing pond depth resulted in higher temperatures in the winter months, thus improving performance. Likewise, using 0.5 W/m² conductance insulation, a reduction of 65% in side losses and an increase of 174% in energy storage was realized. Finally, in the case of heat removal from the pond, increasing the load resulted in lower water temperatures and lower heat losses from the pond. Specifically, with a withdrawal rate of 1 liter/hm², 14% of the global radiation was collected at the expense of a 20°C drop in temperature. In summary, according to Javed's computer simulations, the best options for a 1.5 meter deep pond in the UK climate are a fixed load of 20 W/m² and a withdrawal rate of 1 liter/hm².

Rommel⁴⁶ also investigated the use of transparent insulation in solar ponds. He used a transparent cover consisting of 10 cm of PC honeycomb and a glass pane with low iron content. The original design was modified (after leakage and condensation problems) to include a tank with soldered iron sheet walls. Simulation calculations showed that a system with these properties would have an efficiency of 26% for a day with 5000 Wh total insolation, when operated at at 70°C. This is compared to a collector efficiency without storage of 32% for an improved flat plate collector with honeycomb and 35% for an evacuated tubular collector.

1.5 PHYSICAL PROPERTIES

This section will be limited to physical properties of honeycomb and capillary materials in flat plate collectors, specifically solar transmittance and heat flux.

1.5.1 SOLAR TRANSMITTANCE

Transmittance of specular solar rays through a honeycomb structure is high even at large incident angles, provided cell walls are sufficiently thin to minimize absorption. The reason being rays are reflected and rereflected down the cell toward the absorbing surface. In this way transmittance is minimally effected by the thickness of the honeycomb sheet. This property has been modeled in several different ways.

Hollands⁴⁷ derived a simplified formula for transmittance, that assumes no wall reflectance. He started with a ray at an angle of incidence θ , that travels a distance $L/\cos\theta$ (where L is the length of the honeycomb cell) before reaching the absorber surface. A fraction δ/ω (wall thickness/cell width) of that distance is traveled through honeycomb wall material. Therefore, the effective distance the ray travels through the honeycomb wall material is $\delta L/\omega \cos\theta$. The incident ray is diminished by $\tau_H = \exp(-a\delta L/\omega \cos\theta)$, where a is the extinction coefficient of the wall material to solar radiation. While this equation is an oversimplification of the optics involved, it is accurate enough for most applications.

Taking a slightly different approach, Platzer's⁴⁸ developed a two-dimensional model for transmittance:

$$T(\theta) = [1 - \alpha_1(\phi)]^{A \cdot \tan(\theta)} = \exp[A \cdot \tan(\theta) \cdot \ln(1 - \alpha_1(\phi))] \quad (1.1)$$

which assumes that the thickness of the cell walls is much thinner than the cell diameter(D). $A \cdot \tan(\theta)$ is the average number of cell wall interactions for the incoming beam (where A is the aspect

ratio and $A = L/D$, and ϕ is the incidence angle relative to the cell wall normal. In another article Platzer⁴⁹ uses a weighting factor (g) for structures with other than cylindrical cells (i.e., $A \cdot g \cdot \tan(\theta)$). The quantity $A \cdot \ln[1 - \alpha_1(\phi)]$ describes the absorption in the structure. Equation (1.1) could be extended to three dimensions if the factors $A \cdot \tan(\theta)$ and $\alpha_1(\phi)$ were replaced by the corresponding averages over all azimuthal angles.

Since the treatment of scattering is very difficult and films used for honeycombs should be only weakly scattering, Hollands uses the extinction coefficient (a) instead of the absorption coefficient (α) as Platzer did. Hollands distributes 50% of the scattered radiation to the transmittance and 50% to the reflectance based on the assumption of isotropic scattering.

For applications requiring more accuracy, Hollands⁵⁰ developed an explicit set of equations for prediction of honeycomb transmittance. This method incorporates specular reflections, absorption and scattering. Polarization effect is not included. Specular variations are incorporated using solar-averaged values of the input specular radiation properties.

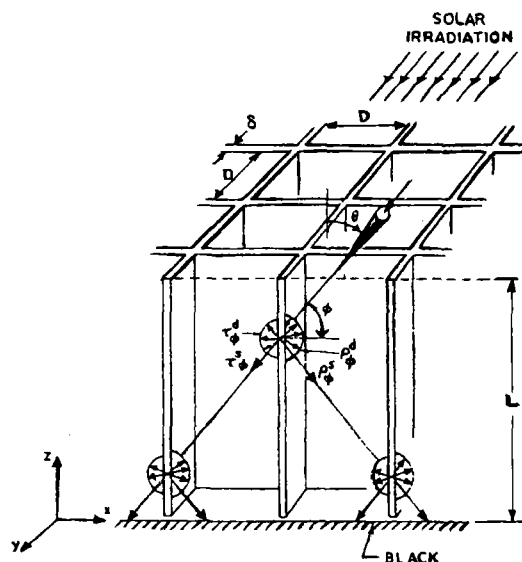


Figure 1.3 Sketch of honeycomb delineating model used.

A sketch of the physical model for Hollands' equations is shown in Figure 1.3. The honeycomb is assumed to be square-celled. The collimated solar radiation is assumed to have a direction parallel to the plane of one of the two sets of parallel walls which form the square-celled honeycomb array. Hollands breaks down the model into a diffuse and specular components with perfectly diffuse transmissivity $\tau_d(\phi)$ and reflectance $\rho_d(\phi)$ and perfectly specular transmissivity $\tau_s(\phi)$ and reflectivity $\rho_s(\phi)$. The angle ϕ is related to the angle of incidence θ by the equation $\theta = \pi/2 - \phi$. Total transmissivity and reflectivity is the sum of these two components.

$$\tau(\phi) = \tau_d(\phi) + \tau_s(\phi) \quad (1.2)$$

$$\rho(\phi) = \rho_d(\phi) + \rho_s(\phi) \quad (1.3)$$

The perfectly specular component represents the fraction of incident radiation transmitted directly through the honeycomb sheet without deviating appreciably from its original direction. The sheet absorbance $\alpha(\phi)$ is related to the reflectivity and transmissivity as shown in the following equation.

$$\tau(\phi) + \rho(\phi) + \alpha(\phi) = 1 \quad (1.4)$$

Wall thickness is assumed to be much less than the cell width or cell diameter of the honeycomb. As a result, reflected and transmitted radiation can be treated as if it originated at the central plane of a single sheet, instead of at the interfaces or from various points within the sheet as is the case with scattered radiation.

Hollands assumed that because of the repetitive nature of the square honeycomb on which he bases his model, photons which are directly transmitted at any given point on the cell wall undergo the same history, on the average, as those which are specularly reflected from the same point. The same parallels are made with diffusely reflected photons. Now the side walls can be treated as opaque and only a single cell of the honeycomb sheet need be considered in the analysis. The problem of

radiant transfer through a honeycomb cell can now be restated in a form which is more amenable to available methods of radiant analysis. Figure 1.4 shows schematically the problem so modified.

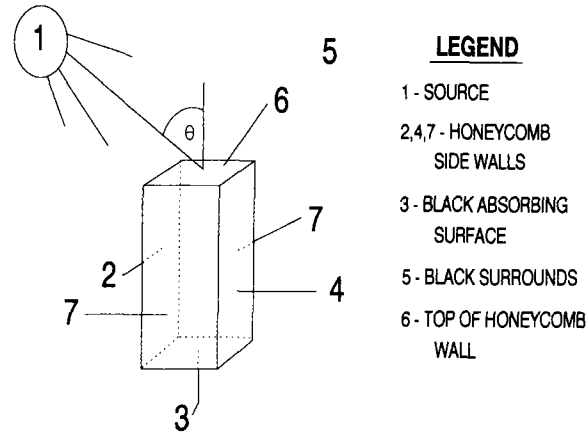


Figure 1.4 Sketch of honeycomb single cell radiant model.

Surface 1 is the black source of radiant energy (all other surfaces are at absolute zero and therefore do not emit). Also surface 1 is so far removed from the other surfaces that its radiant energy incident on surface 6 is unidirectional, making angle-of-incidence θ on 6. Surface 6 is fully transparent and radiation from 1 arrives at surface 3 directly and by reflections off surfaces 2, 4, and 7, which are opaque with specular and diffuse reflectivity components, $\rho_s(\phi)$ and $\rho_d(\phi)$ respectively. The transmittance of the honeycomb cell is the irradiation on 3 divided by the irradiation on 6. The resulting equation is :

$$T_c(\theta) = T_D(\theta) + \frac{\rho_d(\phi)}{\rho_d(\phi) + \alpha(\phi)} \mathcal{F}_{2-3}[1 - T_D(\theta)] \quad (1.5)$$

where:

$$\phi = \pi/2 - \theta \quad (1.6)$$

and

$$T_D(\theta) = F_{1-3}^s / F_{1-6} \quad (1.7)$$

and $\mathcal{F}_{2-3}$ is the fraction of diffuse radiation leaving 2 which arrives at 3 both directly and by all possible specular and diffuse reflections. $T_D(\theta)$ is the fraction of irradiation on 6 which arrives at 3 via specular reflections only. The second term on the right hand side of equation (1.5) represents the fraction which arrives at three via paths which involve at least one diffuse reflection.

Equation (1.5) approximates the solar transmittance that enters the honeycomb cell. The overall transmittance has to include the radiation striking the tops of the cell walls $T_E(\theta)$. The equation for overall transmittance is:

$$T(\theta) = \frac{T_C(\theta) + T_E(\theta) \cdot B}{1 + B} \quad (1.8)$$

where B is the fraction of the cross-section of the honeycomb which is occupied by wall material. Radiation entering the top face of a wall is totally internally reflected at each side wall interface provided $\theta < \theta_c$ where $\theta_c = \sin^{-1}(n^2 - 1)^{1/2}$ and n is the index of refraction of the wall material. If the index of refraction is less than the square root of two then the critical angle is 90 degrees. Therefore, for materials of practical interest, the direct beam component is effectively totally internally reflected, and thereby travels down the wall internally until reaching the bottom face of the wall. Taking into account reflection at the top and bottom faces, governed by interfacial reflectance $r(\theta)$, Hollands arrives at the following equation:

$$T_E(\theta) = (1 - r(\theta))^2 e^{-b(\theta)} + \mathcal{F}_{2-3} \frac{k_s}{k_s + k_a} (1 - e^{-b(\theta)})(1 - r(\theta)) \quad (1.9)$$

where

$$b(\theta) = \frac{(k_s - k_a)L \cdot n}{(n^2 - \sin^2\theta)^{1/2}} \quad (1.10)$$

with L representing the height of the cell, and k_s and k_a the scattering and absorption coefficients respectively. Comparisons with measured values showed that predicted transmittances were very sensitive to uncertainties in specular reflectivity (ρ_s).

Platzer⁵¹ attributes differences between predicted and measured transmittance to surface irregularities or imperfections in real samples of transparent insulation, as well as measurement errors. Table 1.3 lists typical measurement errors. He characterized the imperfections as bulk effects, such as:

- tilted cells
- inhomogeneous cell size
- corrugated cell walls
- dust on cell walls

and surface effects, as follows:

- broken or irregular cell ends
- partially glued or covered cells.

Different samples of the same type show large variation of properties, even when produced in the same batch. For example, in an ideal structure the transmittance for the zero degree incidence angle should be very close to unity. However, due to these irregularities, measured values were smaller and showed a wide scatter, even for small sample thicknesses where the experimental error is small.

Platzer⁵² also points out the dependence of transmittance on azimuth angle with asymmetric transparent insulation. This effect is very small when the incident angle is normal to the TIM sheet and becomes more pronounced as incident angle increases. He explained this as being due to the number of hits for a photon passing through the honeycomb, which is dependent on the azimuth angle.

Table 1.3 Listing of typical measurement errors (PC square-celled honeycomb with L =10 cm)

ORIGIN	$\Delta\tau_n/\tau_n$ (%)	$\Delta\tau_d/\tau_d$ (%)
DETECTOR NOISE AND SOURCE FLUCTUATION	± 2.2	± 1.4
NON-UNIFORM IRRADIANCE	0.0	-1.2
BEAM DIVERGENCE	+1.4	+0.3
SAMPLE BACKREFLECTION	± 1.3	± 1.3
SIDE REFLECTANCE	0.0	-0.4
SPECTRAL	0.0	+0.5
TOTAL MAXIMUM ERROR	-3.5/+4.9	-4.3/+3.5

Zhao⁵³ disagrees with Platzer, reporting that transmittance of structures of vertical polycarbonate honeycomb is dependent only on incident angle. However, he found tilted (45°) polycarbonate honeycomb transmittance to be very anisotropic and dependent on both incidence and azimuth angles.

Jahn⁵⁴ measured the global transmission spectra for polycarbonate capillary structures and found that it reaches 85% at 700 nm and is nearly flat from 500 nm to 1500 nm, varying less than 5%. There are small decreases in transmission at 1380 and 1670 nm and larger decreases at 1670 and 2160 nm. Jahn's measurements started at 400 nm and extended out to 2500 nm.

A comparison of measured results from the Centre Scientifique et Technique du Batiment, Service Materiaux (CSTB) and Fraunhofer-Institut für Solare Energiesysteme, Oltmannsstrasse (FhG) was conducted by Olive⁵⁵. His findings of measurement using PMMA capillary insulation are summarized in Table 1.4. Generally he found good agreement between the two labs, except for thick samples which differed appreciably. Olive also compared diffuse reflectance and transmittance measurements using a set-up with an integrating sphere with a coating that was nearly spectrally flat in the solar region with measurements using solar radiation. These comparisons are included in Table 1.5.

Table 1.4 Measurements at quasi-normal incidence

PANE 1 (mm)	TIM (mm)	PANE 2 (mm)	CSTB ($\pm 2\%$) % τ_n (light)	CSTB ($\pm 2\%$) % τ_n (solar)	FhG ($\pm 3\%$) % τ_n (light)	FhG ($\pm 3\%$) % τ_n (solar)
4	40	4	80.0	72.4	78.2	70.0
4	82	4	76.9	69.4	76.5	65.9
0	38	0	89.9	91.3	-	90.0
0	96	0	88.8	89.7	-	90.0

Table 1.5 Measurements of the diffuse transmittance and reflectance

PANE 1 (mm)	TIM (mm)	PANE 2 (mm)	SOLAR % τ_d	SOLAR % ρ_d	LIGHT % τ_d	LIGHT % ρ_d
4	40	4	54.7	23.2	63.0	19.7
4	82	4	49.7	24.0	60.0	24.0
0	38	0	76.5	10.0	76.0	8.7
0	96	0	72.0	7.9	-	9.1

These comparisons demonstrate the variance between different labs and different light sources. Adamu's⁵⁶ comparison of measured TIMs optical properties, using a 1.2 m diameter integrating spheroid, a 0.4 m diameter integrating sphere, and an illuminated hot box, amplifies this variation. The illuminated hot box consisted of a CM11 pyranometer in front of and behind the sample of transparent insulation. He evaluated OKALUX capillary and AREL honeycomb samples of different thicknesses. He found that transmittance results from the integrating spheroid/sphere were generally higher than those with the illuminated hot box, and at higher incidence angles the integrating spheroid results were higher than those of the integrating sphere. He also reported higher transmittances for the OKALUX samples than for the AREL samples. In addition, reflectance measurements with the light source inside the integrating spheroid were higher than those with an external light source.

Several factors like temperature, sunlight, moisture, biological stresses, and air pollution cause the progressive and irreversible damage of many materials. The effect of aging, specifically accelerated UV exposure, on optical properties of transparent insulation was investigated by Panno⁵⁷. He subjected samples of TIM to an UV cycle of 500 hours at 25°C. Three types of TIM were tested including ISOFLEX AB 40 mm, made of cellulose acetate corrugated sheets arranged in parallel, AREL polycarbonate rectangular honeycomb, and OKALUX polymethylmethacrylate capillary sheets. The direct transmittance of the AREL samples degraded most significantly with accelerated UV exposure as can be seen from the summarized results in Table 1.6. Taking into consideration the instrumental errors, Panno considers a percentage variation greater than 8% significant.

Table 1.6 Average total transmittance measurements (0 - 40° incidence angles)

SAMPLE	UV EXPOSURE	UV EXPOSURE	PERCENTAGE
	0 HOURS	500 HOURS	VARIATION
OKALUX BARE	85	81	5
OKALUX + GLASS	72	69	4
OKALUX + TEFLON	78	76	3
AREL BARE	71	55	22
AREL + GLASS	59	57	3
AREL + TEFLON	68	-	-
ISOFLEX BARE	57	57	0
ISOFLEX + GLASS	47	48	2
ISOFLEX + TEFLON	52	54	4

When comparing different types of TIMs, such as was done in this study, attention should be given to the differences in structure. Most studies compare different thicknesses of a type of TIM; however, cell diameter has more of an effect on transmittance. This was demonstrated in Hollands⁵⁸ article on large-celled (D = 10 mm) honeycomb materials which achieved an impressively high transmittance of 92% at 45° incidence angles.

1.5.2 HEAT FLUX

The situation in a solar collector is an unstable one with a higher temperature at the bottom (absorber) and a cooler temperature at the top (cover glass). This classic stability problem was first treated by Lord Rayleigh⁵⁹. There is a critical Rayleigh Number (Ra_c) at and above which convective currents are initiated. Insertion of a honeycomb structure between the absorber and the cover glass can effectively suppress this convection. Choice of honeycomb geometry is important; because, increasing the aspect ratio (L/D) of the honeycomb increases the magnitude of Rayleigh number at which convective currents are initiated⁶⁰, resulting in a more stable situation.

Large-celled honeycombs, with hydraulic diameters between 10 and 12 mm, can be used to prevent the initiation of these convection currents. The large cells also give the benefit of lower material content. However, radiation suppression in this arrangement must be provided by a selective absorber coating. An alternative approach is the use of small-celled honeycombs, with hydraulic diameters of a few millimeters, which reduce both radiative and convective losses even from a black, nonselective absorber.

The objective in using of transparent insulation as cover materials for flat plat collectors is to reduce front end heat losses with little or no reduction in solar transmission. The choice of honeycomb structure depends on which heat transfer mode is being emphasized. Models to quantify heat flux in these cases have been the topic of numerous articles.

Initially, the standard method for computing heat flux in collectors with transparent insulation was independent mode analysis (IMA), which assumes additive modes of heat transfer. This method may seriously underestimate heat flux because of radiative-conductive coupling when selective surfaces are used. To illustrate this point, Marcus⁶¹ cited a study where the radiation emitted by a highly selective

absorber plate was measured in a vacuum apparatus thereby eliminating heat conduction by the air. As a result, the thermal radiation reaching the cover plate was virtually unchanged when a honeycomb was placed above, but not in direct contact with, the absorber plate. Since emissivity of the honeycomb material used was higher than that of the selective absorber, this result required the honeycomb itself be at a lower temperature than the absorber. In the presence of heat conduction by air, this result would no longer apply, since the discontinuity (or "radiation slip") between the absorber and the honeycomb would be eliminated. The thermal emission by the walls of the honeycomb in close proximity to the absorber, in the latter condition, may largely cancel out the advantage gained by making the absorber plate selective.

This unexpected result was explained on physical grounds by Hollands⁶² in the following way. Walls having an intermediate emissivity value possess a dual capacity lacking those having an emissivity of one or zero. Namely, they can emit (low temperature) radiant heat and, because $(1 - \epsilon)$ is their effective transmissivity (Hollands lumps together wall reflectivity and transmissivity in this term due to honeycomb symmetry), they can also transmit it. Therefore, given an applied temperature difference, honeycomb walls can emit radiant heat from a hot part and, at the same time, transport heat to a cold part. But, if there is no heat conduction, the effect of this dual capability would be of no consequence. The radiative transfer must (in the absence of conduction) begin at the absorber, and because of its low emissivity, a selective surface absorber cannot radiate effectively. It is heat conduction that causes the intermediate emissivity walls to transport the maximum heat; by air in the cells and (to a much less extent) by the plastic in the walls.

A simplified analytic treatment for combined mode heat flux was developed by Marcus⁶³. The physical assumptions included an infinite honeycomb array between two parallel plates separated by a distance L . One cell of the honeycomb was used to represent the whole array. The side walls of the representative cell were considered to be opaque and thermally insulated, with an effective reflectivity

equal to the sum of the transmissivity and reflectivity of the actual honeycomb cell wall. All surfaces were considered to be grey, with the side walls taken to be diffuse emitters and specular reflectors. For the case when the bounding plates are black, the net radiative flux (q_{rad}) at a distance x from the lower plate is given by

$$q_{rad}(x) = \sigma T_1^4 \tau_p(x) - \sigma T_2^4 \tau_p(L-x) - \int_0^L \sigma T^4(x') \frac{d\tau_p(x-x')}{d(x-x')} dx' + \int_x^L \sigma T^4(x') \frac{d\tau_p(x'-x)}{d(x'-x)} dx' \quad (1.11)$$

where $T(0) = T_1$ and $T(L) = T_2$ are the lower and upper bounding plates and the passage transmittance function τ_p depends on the horizontal cross section of the cell and on the effective reflectivity of the side walls.. The conductance of heat flux is given by

$$q_{cond} = -\kappa \frac{\partial T}{\partial x} \quad (1.12)$$

where the effective combined thermal conductivity κ of the honeycomb walls and the air contained in the cells is assumed to be independent of temperature. Marcus also assumes the temperature field is one dimensional and heat conducted through the honeycomb walls is about 10% of that conducted through air in the cells.

Marcus then substitutes the honeycomb array between the two plates with a gray, non-scattering gas whose thermal equilibrium can also be described by equations (1.11) and (1.12). He justifies the assumption that passage transmittance through the honeycomb system is formally equivalent to the transmittance of the non-scattering gas for the purposes of this derivation. He then generalized the problem further include non-black bounding plates. The end result of the derivation is a total non-dimensional heat flux given by the following equation

$$\Psi = \frac{q_{rad} + q_{cond}}{\sigma T_1^4} \quad (1.13)$$

Platzer⁶⁴ believes that this method underestimates the radiation transport, unless the effective optical thickness of the honeycombs should be calculated from the transmittance function.

In investigating radiative-conductive mode interaction for the design of high temperature flat plate collectors, Marcus⁶⁵ concluded that heat flux could be reduced either by increasing the honeycomb aspect ratio (i.e. increasing the distance between plates) or by decreasing the absorber plate emissivity. However, with a high honeycomb aspect ratio the 2π steradian field is occupied mostly by honeycomb, so that reducing the absorber plate emissivity in this case gives a relatively small decrease in heat flux. Thus if the honeycomb is being used for convection suppression, there may be little advantage in using a selective absorber plate unless the emissivity of the honeycomb material is very low.

Platzer⁶⁶ and Hollands⁶⁷ suggest that an air gap between the honeycomb and the selective absorber is sufficient for conductive decoupling. The basic idea, according to Platzer, is the continuity of the conductive heat transport at the boundary of the material surface. If the honeycomb surface (x_{HC}) facing the absorber is at temperature T_{HC} , the condition continuity is

$$q_{cond}(x=x_{HC}) = h_{conv}(T_A - T_{HC}) \quad (1.14)$$

where h_{conv} is the convective heat transfer coefficient. Physically the radiation heat flux is determined by the absorber temperature T_A and emissivity ϵ_A . Mathematically with T_{HC} substituted for T_A , and effective emissivity ϵ_{eff} has to be introduced to correct the heat flux:

$$q_{rad} = \frac{\sigma(T_A^4 - T_B^4)}{\epsilon_A^{-1} + \epsilon_B^{-1} + 0.75\kappa D} = \frac{\sigma(T_{HC}^4 - T_B^4)}{\epsilon_{eff}^{-1} + \epsilon_B^{-1} + 0.75\kappa D} \quad (1.15)$$

where the subscript B in this case would refer to the cover plate. Since this is only a mathematical trick to express the uncoupled radiation heat flux as a function of T_{HC} , values for ϵ_{eff} larger than 1.0 are possible and useful. Platzer compared calculated and experimental results using 10 cm of honeycomb in a 40 x 40 cm collector inclined at 45°. There was almost perfect agreement without an air gap, but experimental values fell halfway between curves calculated with and without convection when a 2 cm air gap was added. Rommel⁶⁸ suggests the optimum gap width is around 1.5 cm, large enough for decoupling but small enough to prevent initiation of natural convection.

Hollands⁶⁹, recommends using large cell honeycomb transparent insulation in combination with a selective absorber, separated by an air gap, to make up what he refers to as "compound honeycomb". The size of the honeycomb cells and the air gap are kept small enough to suppress convection; however, the decrease in honeycomb mass increases solar transmittance. He developed a sophisticated analytic model for this arrangement, using a coupled heat transfer method, which involves inversion of a 7 x 8 matrix for its solution. A Fortran based computer code was written to implement the algorithms contained in his equations and diskette copies can be obtained by writing to him.

This is by no means an exhaustive review of the literature. The intent was to give an overview of the topic and the state of the technology. For the reader's convenience, an annotated bibliography has been included in Appendix A to provide further information and references on the topic of transparent insulation materials.

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2.1 OVERVIEW

Four 4 x 8 foot flat plate collectors were tested side-by-side according to ASHRAE Standard 93-1986 RA. One collector was used as a control, with no modifications to its structure and no transparent insulation added. The second collector had one inch thick sheet of rectangular polycarbonate TIM added between the cover glass and the absorber. The structure of this collector did not need to be modified to accommodate the TIM. Four inch thick sheets of TIM were installed in the third and fourth collectors, a sheet of acrylic capillary honeycomb in one and a sheet of polycarbonate rectangular honeycomb in the other. Both of these collectors were modified in the same manner to accommodate the TIMs.

A total of twelve tests were performed. This total was comprised of three sets of four side-by-side tests. One set was conducted with all four of the above described collectors containing absorbers coated with selective black chrome, the next set with absorbers coated with moderately selective black paint, and the final set with absorbers coated with flat black paint. The Solar Collector Test Report for each of the four collectors has been integrated into the results section of this paper. The results of all tests performed on each collector, as well as, a description of the collector, collector modifications, and installed transparent insulation are detailed. Specification sheets supplied by the distributor for the two types of transparent insulation tested are included in Appendix B.

2.2 TEST FACILITIES AND PERFORMANCE TEST PROCEDURES

2.2.1 TEST FACILITY

The test equipment and configuration used at the Florida Solar Energy Center were chosen to meet

the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) requirements described in ASHRAE Standard 93-86. This document sets standards of accuracy on the measuring equipment used and details the procedures that should be followed to measure instantaneous collector efficiency accurately and repeatedly.

Test facilities are situated on the property used for the laboratories and offices of the Florida Solar Energy Center at 300 State Road 401, Cape Canaveral, Florida. The site is north of Port Canaveral at the south entrance to Cape Canaveral AFS. Geodetic position is 28° 25' N. Latitude and 80° 36' W. Longitude. The height above sea level is 2.7 meters.

The area available to the Florida Solar Energy Center has allowed the test station to be situated far enough from any structures, objects, trees or parked vehicles that no shadows or reflections are cast onto the collectors during a test. The test site is in an open, grassy area not subject to unusual wind conditions.

The facility has six test stands capable of testing collectors up to 4 feet by 10 feet in size. The stands are designed to track the sun continuously between tilt angles of 0° (horizontal) and 65°, and azimuth angles of $\pm 100^\circ$ from due south for testing normal to the sun. The stands can also be set in any fixed position for testing.

Adequate warning will be received of the approach of severe weather, thereby allowing time to remove any collector being tested from the test facility and to secure the facility. However, in the event of sudden extreme weather, tie-downs are incorporated to adequately secure the collector and facility.

The FSEC test equipment is shown schematically in Figure 1, which depicts only one of the test stands. The other test stands are similarly equipped and are connected two to six in parallel. The

system is operated only with water as the heat transfer fluid.

2.2.2 COLLECTOR TIME CONSTANT DETERMINATION

With the inlet temperature constant within $\pm 1^\circ\text{C}$ of ambient temperature, water is circulated through the collector at the test flow rate until a steady outlet temperature is reached. The collector is then shaded abruptly. The time required for the temperature difference across the collector to drop to 36.8 percent of its initial steady-state value is measured.

2.2.3 THERMAL EFFICIENCY AND EXPLANATION OF EFFICIENCY CURVE

The thermal performance of the collector is determined by obtaining values of instantaneous efficiency for a combination of values of incident insolation, ambient temperature, and inlet fluid temperature. This requires experimentally measuring the rate of incident solar radiation onto the solar collector as well as the rate at which energy is added to the heat transfer fluid as it passes through the collector, all under quasi-steady conditions.

Solar collector efficiency is defined as:

$$\eta = \frac{\text{useful energy removed from the collector}}{\text{solar energy incident on the collector}} \quad (2.1)$$

The useful energy can be measured by determining the heat gain in the fluid circulated through the collector. Then,

$$\eta = \frac{m c_p \Delta T}{I A_g} \quad (2.2)$$

where m is the fluid flow rate in kg/s, c_p is the specific heat of fluid (for water it is 4180 to 4200 J/kg $^\circ\text{C}$), ΔT is the difference between inlet and outlet fluid temperatures in $^\circ\text{C}$, I is the incident solar

radiation measured in the aperture plane of the collector in W/m^2 , and A is the gross area of the collector in m^2 .

Procedures recommended by ASHRAE require the measurement of average values of I and Δt during several separate intervals of testing. Instantaneous values of I and Δt should be steady during each test period. A flow rate of about 0.02 kg/s-m^2 should be maintained, and this flow rate should be steady within ± 1 percent during each test. At least four tests are run at each of four or more fluid inlet temperatures for a total of at least 16 separate tests. The duration of each test is the collector time constant or five minutes, whichever is larger.

The test data are presented in tabular form and as an efficiency curve. The efficiency curve is based on the following equation.

$$\eta = F_R(\tau\alpha)_e - F_R U_L (T_i - T_a) / I \quad (2.3)$$

where η is the collector efficiency, F_R is the heat removal factor, $(\tau\alpha)_e$ is the effective transmissivity-absorptivity product, U_L is the overall heat loss coefficient, T_i is the transfer fluid temperature at the collector inlet, T_a is the ambient air temperature, and I is the instantaneous level of solar radiation.

The standard form of the equation of a straight line is:

$$Y = a + bX \quad (2.4)$$

where a is the Y axis intercept and b is the slope.

From these two equations it can be seen that a straight line should result if a plot of efficiency versus the quantity $(T_i - T_a)/I$ is made and if the slope and intercept functions can be assumed constant. It then becomes apparent that the slope of the line is a function of the overall heat loss coefficient and the Y axis intercept is a function of the transmissivity of the cover plate(s) and the absorptivity of the absorber plate(s). In reality, however, U_L is not constant under the test conditions since it varies with the temperature of the collector and the ambient weather conditions. Therefore a second order curve

is used to describe the thermal performance of the collector. That is:

$$Y = a + bX + cX^2 \quad (2.5)$$

The intercept is still related to $(\tau\alpha)$, and the slope at any point on the curve is proportional to the heat loss rate for that value of $(T_i - T_a)/I$.

The efficiency curve does not give absolute values for the overall heat loss coefficient and $(\tau\alpha)_e$, since both are multiplied by the factor F_R . However, the plot does indicate relative values for these two quantities that can be used for comparing collectors. Determination of the absolute values of $(\tau\alpha)_e$ and U_L would require additional measurements beyond the tests performed.

The X quantity, $(T_i - T_a)/I$, can be determined from measurements made during testing. The collector efficiency can be calculated from the following equation:

$$\eta = \frac{m c_p \int \Delta T dt}{A \int I dt} \quad (2.6)$$

where m is the mass flow rate of the transfer fluid, c_p is the specific heat of the transfer fluid, $\int \Delta T dt$ is the integrated (total) temperature rise across the collector, A is the gross frontal area of the collector, and $\int I dt$ is the integrated (total) solar radiation received by the collector during the test.

The data are collected during a series of test runs. Each point, represented as a plus sign of the efficiency plot, is the result of a test run, the exact length of the run being determined by the collector time constant. The line drawn on the plot is a second order least squares curve fit of the data.

2.2.4 INCIDENT ANGLE MODIFIER DETERMINATION

Four separate efficiency values are determined in general accordance with the method described in Section 2.2.3. For each "data" point, the inlet temperature of the transfer fluid is controlled to within

$\pm 1^{\circ}\text{C}$ ($\pm 1.8^{\circ}\text{F}$) of the ambient air temperature. The collector is oriented so that the average incident angles between it and the solar radiation for the four test conditions are respectively approximately 0, 30, 45, and 60 degrees. The foregoing values are appropriate for conventional flat-plate collectors. At least one angle should be greater than the acceptance angle for concentrating collectors.

2.2.5 COMPUTER PRINTOUT KEY

TEST	Number assigned to the data for a particular test
DATE	Date on which the test was performed
SOLAR TIME	Solar time at the start and finish of the test
TA	Ambient air temperature ($^{\circ}\text{C}$ or $^{\circ}\text{F}$)
TI	Temperature of the transfer fluid at the collector inlet ($^{\circ}\text{C}$ or $^{\circ}\text{F}$)
TE	Temperature of the transfer fluid at the collector exit ($^{\circ}\text{C}$ or $^{\circ}\text{F}$)
FLOW	Volumetric flow rate of the transfer fluid (liters/minute or gallons/minute)
AVE IN or SOL	Average instantaneous insolation (W/m^2 or $\text{Btu}/\text{hr}\cdot\text{ft}^2$)
TOTAL IN	Total (integrated) insolation in the plane of the collector during the test period (J/m^2 or Btu/ft^2)
DEL T	Total (integrated) temperature rise across the collector during the test period ($^{\circ}\text{C}$ minutes or $^{\circ}\text{F}$ minutes)
EFFIC or EFF	Calculated collector efficiency for test period (percent)
$(\text{TI}-\text{TA})/I$	Value calculated for the abscissa of the efficiency graph. I = average instantaneous insolation. ($^{\circ}\text{C} - \text{m}^2/\text{W}$ or $^{\circ}\text{F} - \text{hr}\cdot\text{ft}^2/\text{Btu}$)
TILT or TLT	Angle which the collector was tilted from the horizontal (degrees)
AZIM	Collector azimuth angle (degrees from due south; east positive)
INCI or I/A	Angle between the incoming radiation and a normal to collector surface (degrees)
MASS	Mass flow rate of the transfer fluid (kilograms/second or pounds mass/minute)

SPEC HEAT Specific heat of the transfer fluid (J/kg - °C or Btu/pound mass - °F)

IN P Gage pressure at the collector inlet (kiloNewtons/m² or pounds/square inch)

WIND Wind speed (meters/second or miles/hour)

WIND DIR Wind direction (degrees east from north)

DIF IN Diffuse instantaneous insolation (W/m² or Btu/hr-ft²)

% DIFF INSOL or % DIF Percent of the incoming radiation that was diffuse

TI-TA Temperature difference between the inlet fluid temperature and ambient air (°C or °F)

IAM Incident angle modifier

Note: Dashes indicate that no data was taken on the indicated parameter during that test.

3.1 TEST RESULTS ON SOLAR COLLECTOR WITH NO TIM

The SDCRW(4x8) collector was modified as described in section 1.3 to contain no transparent insulation material (TIM). The collector was then tested in accordance with FSEC Test Methods and Minimum Standards for Certifying Solar Collectors, FSEC 77-5-R80. The tests performed were:

Thermal Performance Test

Incident Angle Modifier Test

Internal temperatures during some of the tests were recorded from the installed thermocouples. Data are also included from the inadvertent wet stagnation that took place after the other testing was completed.

3.1.1 COLLECTOR IDENTIFICATION

Manufacturer and Address: Solar Development Inc.

3607-A Prospect Ave.

Riviera Beach, FL 33404

Collector Model Number: SD7CRW(4x8) with no transparent insulation added

3.1.2 COLLECTOR CONSTRUCTION BEFORE MODIFICATION

Overall dimensions*: Length: 2.444 m (8.02 ft)

Width: 1.189 m (3.90 ft)

Depth: 0.098 m (0.32 ft)

Overall front area*: (length x width) = 2.903 m² (31.25 ft²)

Enclosure: Material: Aluminum frame, aluminum back

 Surface finish: Painted aluminum

 Fasteners: Stainless steel screws and aluminum rivets

Holes and cutouts: Frame has holes and gaskets for each end of both headers

Glazing: Number of cover plates: One

 Material: Tempered low iron glass

 Thickness: 0.32 cm (0.125 in)

 Length: 2.441 m (8.01 ft)

 Width: 1.167 m (3.83 ft)

 Surface characteristics: Smooth on outside, textured on inside

 Glazing seal: EPDM rubber

Transparent frontal dimensions*: Area: 2.743 m² (29.53 ft²)

Absorber: Flow pattern: Parallel

 Number of tubes: Ten

 Spacing between tubes: 11.2 cm (4.4 in)

 Material: Copper tubes welded to copper fins

 Length: 2.283 m (7.49 ft)

 Width: 1.119 m (3.67 ft)

 Area: 2.554 m² (27.49 ft²)

 Plate thickness: 0.046 cm (0.018 in)

 Tube diameter (OD): 1.6 cm (0.63 in)

 Header diameter (OD): 2.9 cm (1.13 in)

 Flow tube to header connection: Brazed

 Air spacing, glazing to absorber: approx. 3.2 cm (1.3 in)

Side insulation: Type: Foil faced polyisocyanurate

 Thickness: 2.5 cm (1.0 in)

Back insulation: Type: Foil faced polyisocyanurate

 Thickness: 4.4 cm (1.8 in)

Caulking, sealant, and/or gasket types(s): EPDM gaskets

Heat transfer fluid: Material: Water

 Density: 977.81 kg/m³ at 70°C (61.01 lb/ft³ at 160°F)

 Specific heat: 4189.6 J/kg°C at 70°C (1.001 Btu/lb°F at 160°F)

Collector weight*: 48.5 kg (107.0 lbs)

Collector fluid capacity*: 3.8 liters (1.0 gallons)

* Information provided by manufacturer; not verified by FSEC.

3.1.3 COLLECTOR MODIFICATIONS

This collector was one of a group of four being tested side by side to investigate the effects on performance of adding transparent insulation material (TIM) between the absorber and the glazing. This particular collector was used as a reference and contained no TIM. Structural modifications were not necessary. To make collectors as similar as possible, nine strips of wood 3/16" thick and 3/8" wide were placed widthwise across the absorber. These strips were the same size and number as in the other collectors. Six type T thermocouples were placed in the collector. Two thermocouples were attached to the absorber, two were placed in the air close the absorber, and two were placed in the air close to the glazing. The thermocouple wires were run along the side insulation and exited the frame through two small holes.

No TIM was placed in this collector since its purpose was as a reference. All the collectors in this series of tests were covered with tarpaulins when in a no water flow condition. This prevented damage to the TIM in one collector and gave all the collectors the same amount of exposure.

Tests were run with three absorbers, each with a different coating. The manufacturer of the collectors shipped the collectors with the selectively coated absorber already installed. They also provided the two other absorbers, one with a moderately selective paint coating and one with a flat black paint coating.

After all modifications were complete the collector was measured. The final dimensions are as follows:

Gross length:	2.46 m (8.06 ft)
Gross width:	1.18 m (3.89 ft)
Gross area:	2.91 m ² (31.33 ft ²)
Transparent length:	2.41 m (7.90 ft)
Transparent width:	1.13 m (3.72 ft)
Transparent area:	2.73 m ² (29.36 ft ²)

* Information provided by manufacturer; not verified by FSEC.

3.1.4 THERMAL PERFORMANCE WITH SELECTIVE ABSORBER

The collector, outfitted with a selective black chrome coated absorber, was tested from 16 November - 16 December 1993 in accordance with ASHRAE procedure 93-1986. Results of the thermal performance tests are presented in graphical and tabular form in both the International System of Units (SI) and English units. The thermal performance equations in S.I. units developed from the empirical data are:

$$\text{first order} \quad \eta = 73.9 - 432 \quad (T_i - T_a)/I$$

$$\text{second order} \quad \eta = 73.7 - 382 \quad (T_i - T_a)/I - 1515 \quad [(T_i - T_a)/I]^2$$

These equations in English units are:

$$\text{first order} \quad \eta = 73.9 - 76 \quad (T_i - T_a)/I$$

$$\text{second order} \quad \eta = 73.7 - 67 \quad (T_i - T_a)/I - 47 \quad [(T_i - T_a)/I]^2$$

TABLE 3.1 THERMAL PERFORMANCE TEST ON NO TIM WITH SELECTIVE ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME START END	TA (C)	TI (C)	TE (C)	FLOW AVE IN L/MIN W/M ²	TOTAL IN J/M ²	TE-TI (C)	DEL T C-MIN	EFFIC %	(TI-TA)/I (C-M ²)/W
1	11/16/93	11:21 11:25	27.1	59.2	67.1	3.22 1012.1	303624.	7.88	39.4	58.9	0.0317
2	11/16/93	11:26 11:30	27.1	59.2	67.1	3.21 1013.1	303921.	7.91	39.6	59.0	0.0316
4	11/16/93	11:36 11:40	27.3	59.2	67.2	3.19 1015.2	304565.	8.00	40.0	59.0	0.0314
5	11/16/93	11:41 11:45	27.3	59.2	67.3	3.17 1016.3	304899.	8.04	40.2	59.1	0.0314
9	11/16/93	12:29 12:34	27.3	49.6	58.3	3.16 1015.1	304541.	8.62	43.1	63.3	0.0220
10	11/16/93	12:34 12:39	27.2	49.6	58.2	3.15 1013.2	303950.	8.60	43.0	63.2	0.0221
11	11/16/93	12:39 12:44	27.1	49.6	58.1	3.17 1012.3	303701.	8.52	42.6	62.9	0.0222
12	11/16/93	12:44 12:49	27.0	49.6	58.2	3.16 1012.9	303872.	8.55	42.8	63.0	0.0223
13	11/16/93	12:49 12:54	27.2	49.7	58.2	3.17 1012.3	303697.	8.55	42.8	63.1	0.0222
16	11/16/93	13:04 13:09	27.2	49.7	58.2	3.17 1010.3	303082.	8.52	42.6	63.1	0.0222
17	11/16/93	14:28 14:33	26.9	40.0	48.5	3.23 965.0	289492.	8.56	42.8	67.8	0.0136
18	11/16/93	14:33 14:38	26.8	40.0	48.5	3.22 962.0	288603.	8.51	42.6	67.6	0.0137
19	11/16/93	14:38 14:43	26.8	39.9	48.4	3.21 953.9	286166.	8.48	42.4	67.7	0.0138
20	11/16/93	14:43 14:48	26.8	39.9	48.4	3.20 945.9	283769.	8.46	42.3	67.9	0.0139
29	11/17/93	13:41 13:46	27.7	28.3	37.5	3.27 970.1	291020.	9.17	45.9	73.5	0.0007
30	11/17/93	13:46 13:51	27.6	28.3	37.4	3.26 964.3	289296.	9.13	45.6	73.4	0.0008
35	11/18/93	13:58 14:02	26.5	26.9	35.7	3.31 941.0	282289.	8.84	44.2	74.0	0.0004
36	11/18/93	14:03 14:07	26.2	26.9	35.7	3.31 937.7	281319.	8.80	44.0	73.9	0.0007
37	11/18/93	14:08 14:12	26.2	26.9	35.7	3.31 935.7	280716.	8.80	44.0	74.1	0.0007
41	11/18/93	14:53 14:58	26.2	39.8	47.3	3.31 851.0	255302.	7.50	37.5	69.2	0.0160
42	11/18/93	14:58 15:03	26.3	39.8	47.2	3.31 839.7	251914.	7.40	37.0	69.2	0.0160
43	11/18/93	15:03 15:08	26.1	39.8	47.1	3.31 830.4	249135.	7.32	36.6	69.2	0.0165
48	12/07/93	9:10 9:14	17.7	17.1	26.1	3.21 938.5	281544.	8.93	44.7	73.1	-0.0006
49	12/07/93	9:15 9:19	17.9	17.2	26.2	3.21 944.6	283366.	9.102	45.1	73.4	-0.0007
50	12/07/93	9:20 9:24	18.0	17.2	26.3	3.21 951.9	285563.	9.08	45.4	73.3	-0.0008
54	12/07/93	10:31 10:36	20.2	39.9	48.7	3.29 1017.0	305107.	8.80	44.0	67.5	0.0194
55	12/07/93	10:36 10:41	20.1	39.9	48.7	3.29 1019.9	305984.	8.82	44.1	67.5	0.0194
56	12/07/93	10:41 10:46	20.3	39.9	48.7	3.29 1020.9	306261.	8.84	44.2	67.6	0.0192
58	12/07/93	12:57 13:01	21.6	58.1	66.1	3.24 1028.1	308433.	8.00	40.0	59.4	0.0355
59	12/07/93	13:02 13:06	21.6	58.1	66.1	3.24 1025.8	307749.	7.97	39.9	59.3	0.0356
60	12/07/93	13:07 13:11	21.5	58.1	66.1	3.24 1023.0	306897.	7.95	39.8	59.3	0.0358
61	12/07/93	13:12 13:16	21.5	58.2	66.1	3.24 1021.3	306399.	7.93	39.7	59.2	0.0358

TABLE 3.1 THERMAL PERFORMANCE TEST ON NO TIM WITH SELECTIVE ABSORBER (SI UNITS CONTINUED)

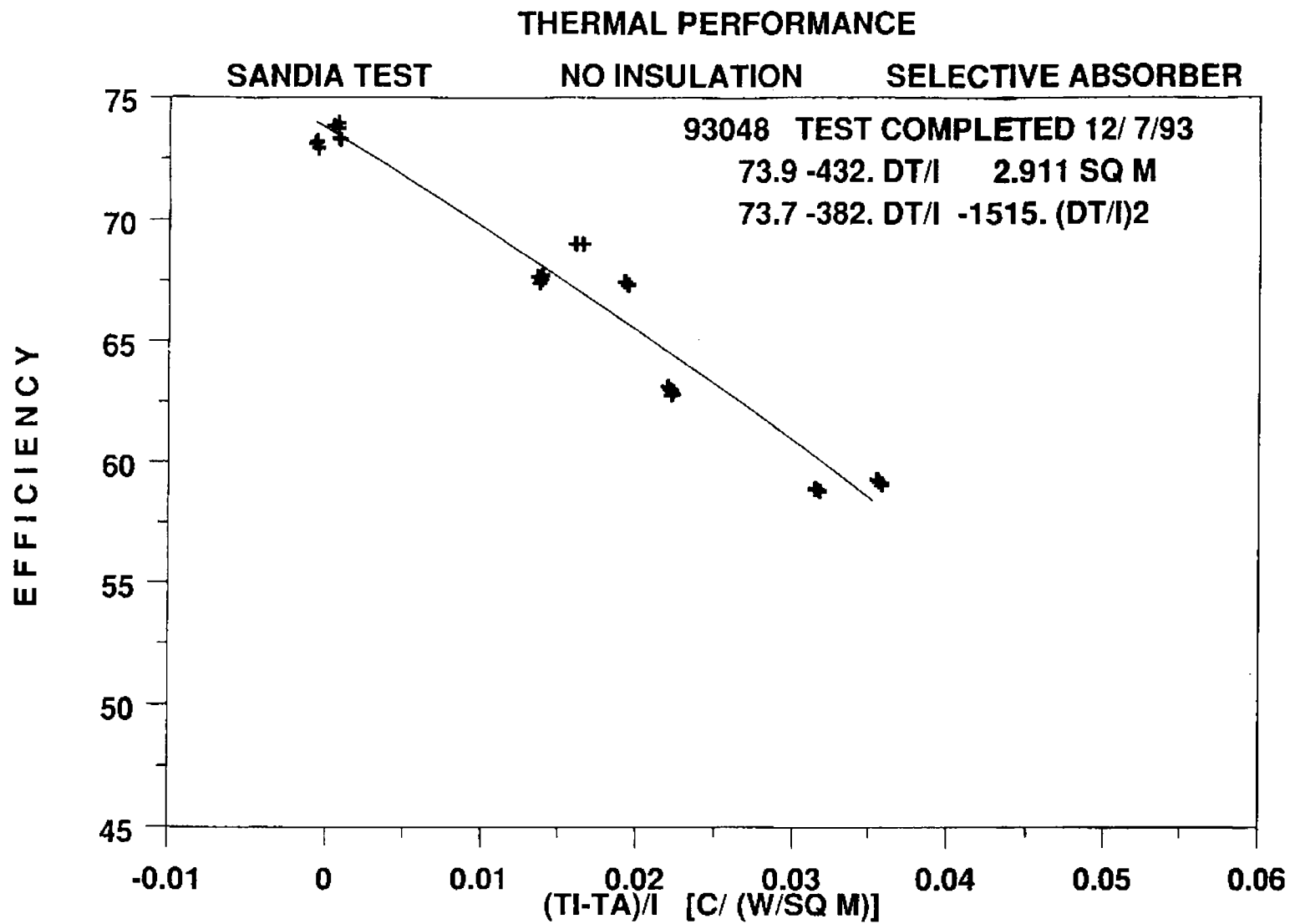
TEST	TILT DEG	AZIM DEG	INCI DEG	MASS KG/SEC	SPEC HEAT J/(KG C)	IN P KN/M ²	WIND M/S	WIND DIR	DIF IN W/M ²	% DIFF INSOL	TI-TA (C)
1	49.	11.	0.	0.0527	4185.7	62.6	2.4	99.	129.3	12.8	32.1
2	48.	10.	0.	0.0525	4185.7	62.8	2.8	97.	127.4	12.6	32.1
4	48.	7.	0.	0.0521	4185.7	64.0	2.3	96.	125.4	12.4	31.9
5	48.	5.	0.	0.0519	4185.8	64.8	3.0	107.	123.3	12.1	32.0
9	48.	-10.	0.	0.0519	4181.8	60.3	2.4	103.	124.3	12.2	22.4
10	49.	-12.	0.	0.0518	4181.8	60.3	3.0	94.	127.6	12.6	22.4
11	49.	-13.	0.	0.0520	4181.8	58.7	2.4	98.	128.3	12.7	22.5
12	49.	-15.	0.	0.0519	4181.8	59.7	2.6	100.	127.2	12.6	22.6
13	49.	-16.	0.	0.0520	4181.8	54.9	2.3	96.	126.3	12.5	22.5
16	50.	-21.	0.	0.0521	4181.8	61.1	2.2	103.	125.0	12.4	22.5
17	60.	-42.	0.	0.0532	4179.3	63.4	2.3	107.	117.7	12.2	13.1
18	61.	-43.	0.	0.0532	4179.3	63.1	2.5	108.	116.0	12.1	13.2
19	62.	-44.	0.	0.0531	4179.3	62.1	2.0	98.	116.1	12.2	13.2
20	62.	-45.	0.	0.0529	4179.3	60.9	2.1	102.	115.1	12.2	13.2
29	54.	-31.	0.	0.0541	4177.9	87.6	2.2	173.	169.7	17.5	0.6
30	55.	-32.	0.	0.0541	4177.9	88.8	2.0	178.	165.5	17.2	0.7
35	56.	-35.	0.	0.0549	4178.0	71.1	2.1	114.	185.6	19.7	0.4
36	57.	-36.	0.	0.0549	4178.0	64.6	2.2	107.	188.5	20.1	0.6
37	58.	-37.	0.	0.0549	4178.0	59.0	2.0	110.	187.4	20.0	0.7
41	64.	-47.	0.	0.0547	4179.2	70.3	1.8	100.	179.4	21.1	13.6
42	65.	-47.	0.	0.0547	4179.2	67.1	1.7	106.	179.7	21.4	13.5
43	66.	-48.	0.	0.0547	4179.2	65.5	1.9	90.	178.3	21.5	13.7
48	65.	43.	0.	0.0534	4181.5	79.8	1.3	357.	106.3	11.3	-0.6
49	64.	42.	0.	0.0535	4181.4	77.7	1.3	350.	107.2	11.3	-0.7
50	64.	41.	0.	0.0535	4181.4	79.7	1.7	349.	107.3	11.3	-0.8
54	55.	24.	0.	0.0543	4179.3	84.6	1.5	0.	102.4	10.1	19.7
55	55.	23.	0.	0.0543	4179.3	84.3	1.8	1.	102.7	10.1	19.8
56	54.	22.	0.	0.0544	4179.3	83.4	1.9	358.	103.2	10.1	19.6
58	53.	-17.	0.	0.0531	4185.2	83.4	1.5	5.	93.7	9.1	36.5
59	54.	-19.	0.	0.0531	4185.2	83.9	1.7	4.	94.6	9.2	36.5
60	54.	-20.	0.	0.0530	4185.2	84.3	1.8	7.	95.3	9.3	36.6
61	54.	-21.	0.	0.0530	4185.2	83.6	1.3	5.	96.2	9.4	36.6

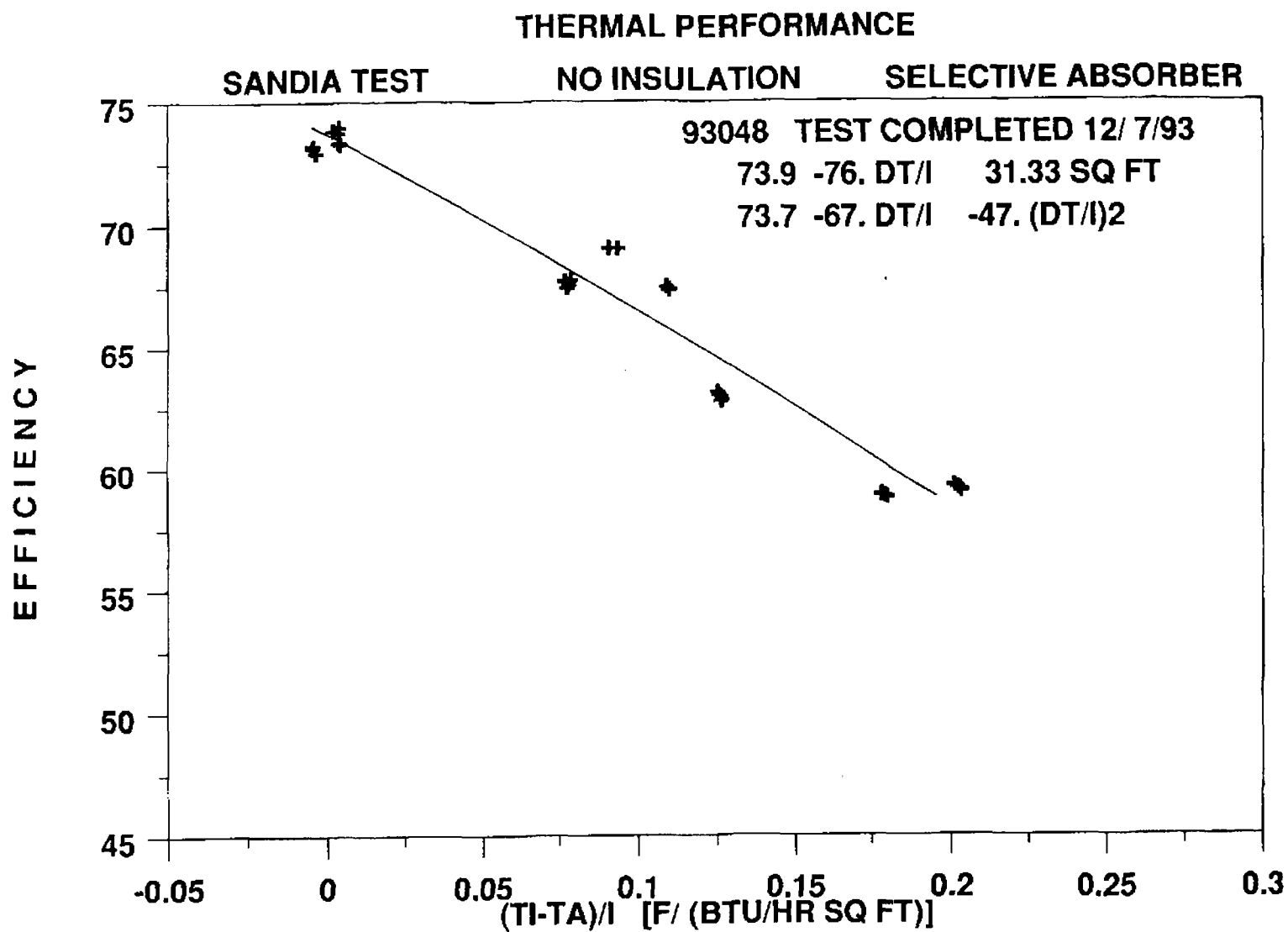
TABLE 3.1A THERMAL PERFORMANCE TEST ON NO TIM WITH SELECTIVE ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME		TA	TI	TE	FLOW	AVE IN	TOTAL IN	TE-TI	DEL T	EFFIC	(TI-TA)/I
		START	END	(F)	(F)	(F)	GPM	B/H-FT ²	BTU/FT ²	(F)	F-MIN	%	(F-H-FT ²)/B
1	11/16/93	11:21	11:25	80.8	138.6	152.7	0.850	321.0	26.8	14.18	70.9	58.9	0.180
2	11/16/93	11:26	11:30	80.9	138.6	152.8	0.848	321.4	26.8	14.24	71.2	59.0	0.180
4	11/16/93	11:36	11:40	81.2	138.6	153.0	0.842	322.0	26.8	14.39	72.0	59.0	0.178
5	11/16/93	11:41	11:45	81.1	138.6	153.1	0.839	322.4	26.9	14.47	72.3	59.1	0.178
9	11/16/93	12:29	12:34	81.1	121.4	136.9	0.834	322.0	26.8	15.51	77.6	63.3	0.125
10	11/16/93	12:34	12:39	81.0	121.3	136.8	0.833	321.4	26.8	15.48	77.4	63.2	0.125
11	11/16/93	12:39	12:44	80.8	121.3	136.7	0.837	321.1	26.8	15.33	76.7	62.9	0.126
12	11/16/93	12:44	12:49	80.7	121.3	136.7	0.834	321.3	26.8	15.40	77.0	63.0	0.127
13	11/16/93	12:49	12:54	80.9	121.4	136.8	0.836	321.1	26.8	15.39	77.0	63.1	0.126
16	11/16/93	13:04	13:09	81.0	121.4	136.7	0.838	320.5	26.7	15.33	76.7	63.1	0.126
17	11/16/93	14:28	14:33	80.4	103.9	119.3	0.852	306.1	25.5	15.42	77.1	67.8	0.077
18	11/16/93	14:33	14:38	80.2	103.9	119.2	0.852	305.2	25.4	15.32	76.6	67.6	0.078
19	11/16/93	14:38	14:43	80.2	103.9	119.1	0.849	302.6	25.2	15.26	76.3	67.7	0.078
20	11/16/93	14:43	14:48	80.2	103.9	119.1	0.846	300.0	25.0	15.23	76.2	67.9	0.079
29	11/17/93	13:41	13:46	81.8	83.0	99.5	0.863	307.7	25.6	16.51	82.5	73.5	0.004
30	11/17/93	13:46	13:51	81.6	83.0	99.4	0.861	305.9	25.5	16.43	82.1	73.4	0.004
35	11/18/93	13:58	14:02	79.7	80.3	96.2	0.874	298.5	24.9	15.91	79.6	74.0	0.002
36	11/18/93	14:03	14:07	79.2	80.3	96.2	0.874	297.5	24.8	15.84	79.2	73.9	0.004
37	11/18/93	14:08	14:12	79.1	80.3	96.2	0.874	296.8	24.7	15.85	79.2	74.1	0.004
41	11/18/93	14:53	14:58	79.2	103.7	117.2	0.875	269.9	22.5	13.50	67.5	69.2	0.091
42	11/18/93	14:58	15:03	79.4	103.7	117.0	0.875	266.4	22.2	13.32	66.6	69.2	0.091
43	11/18/93	15:03	15:08	78.9	103.6	116.8	0.875	263.4	22.0	13.17	65.9	69.2	0.094
48	12/07/93	9:10	9:14	63.8	62.8	78.9	0.848	297.7	24.8	16.08	80.4	73.1	-0.003
49	12/07/93	9:15	9:19	64.2	62.9	79.2	0.849	299.6	25.0	16.24	81.2	73.4	-0.004
50	12/07/93	9:20	9:24	64.4	63.0	79.4	0.849	301.9	25.2	16.35	81.7	73.3	-0.005
54	12/07/93	10:31	10:36	68.3	103.8	119.7	0.870	322.6	26.9	15.85	79.2	67.5	0.110
55	12/07/93	10:36	10:41	68.2	103.9	119.7	0.870	323.5	27.0	15.88	79.4	67.5	0.110
56	12/07/93	10:41	10:46	68.5	103.8	119.7	0.870	323.8	27.0	15.92	79.6	67.6	0.109
58	12/07/93	12:57	13:01	70.9	136.5	150.9	0.857	326.1	27.2	14.41	72.0	59.4	0.201
59	12/07/93	13:02	13:06	70.8	136.6	150.9	0.857	325.4	27.1	14.35	71.8	59.3	0.202
60	12/07/93	13:07	13:11	70.7	136.6	150.9	0.856	324.5	27.0	14.31	71.6	59.3	0.203
61	12/07/93	13:12	13:16	70.8	136.7	150.9	0.856	324.0	27.0	14.28	71.4	59.2	0.203

TABLE 3.1A THERMAL PERFORMANCE TEST ON NO TIM WITH SELECTIVE ABSORBER (ENGLISH UNITS CONTINUED)

TEST	TILT DEG	AZIM DEG	INCI DEG	MASS LBM/MIN	SPEC HEAT BTU/(LBM-F)	IN P PSI	WIND MPH	WIND DIR	DIF IN B/H-FT ²	% DIFF INSOL	TI-TA (F)
1	49.	11.	0.	6.97	1.000	9.1	5.3	99.	41.0	12.8	57.8
2	48.	10.	0.	6.95	1.000	9.1	6.2	97.	40.4	12.6	57.7
4	48.	7.	0.	6.89	1.000	9.3	5.1	96.	39.8	12.4	57.4
5	48.	5.	0.	6.87	1.000	9.4	6.6	107.	39.1	12.1	57.5
9	48.	-10.	0.	6.86	0.999	8.7	5.3	103.	39.4	12.2	40.3
10	49.	-12.	0.	6.85	0.999	8.7	6.6	94.	40.5	12.6	40.3
11	49.	-13.	0.	6.88	0.999	8.5	5.5	98.	40.7	12.7	40.5
12	49.	-15.	0.	6.86	0.999	8.7	5.8	100.	40.4	12.6	40.7
13	49.	-16.	0.	6.88	0.999	8.0	5.2	96.	40.1	12.5	40.5
16	50.	-21.	0.	6.89	0.999	8.9	5.0	103.	39.7	12.4	40.4
17	60.	-42.	0.	7.04	0.998	9.2	5.1	107.	37.3	12.2	23.6
18	61.	-43.	0.	7.04	0.998	9.2	5.7	108.	36.8	12.1	23.7
19	62.	-44.	0.	7.02	0.998	9.0	4.4	98.	36.8	12.2	23.7
20	62.	-45.	0.	6.99	0.998	8.8	4.7	102.	36.5	12.2	23.7
29	54.	-31.	0.	7.16	0.998	12.7	5.0	173.	53.8	17.5	1.2
30	55.	-32.	0.	7.15	0.998	12.9	4.6	178.	52.5	17.2	1.3
35	56.	-35.	0.	7.26	0.998	10.3	4.7	114.	58.9	19.7	0.6
36	57.	-36.	0.	7.26	0.998	9.4	5.0	107.	59.8	20.1	1.1
37	58.	-37.	0.	7.26	0.998	8.6	4.5	110.	59.4	20.0	1.2
41	64.	-47.	0.	7.23	0.998	10.2	3.9	100.	56.9	21.1	24.5
42	65.	-47.	0.	7.23	0.998	9.7	3.7	106.	57.0	21.4	24.3
43	66.	-48.	0.	7.23	0.998	9.5	4.2	90.	56.6	21.5	24.7
48	65.	43.	0.	7.07	0.999	11.6	3.0	357.	33.7	11.3	-1.0
49	64.	42.	0.	7.07	0.999	11.3	2.9	350.	34.0	11.3	-1.3
50	64.	41.	0.	7.07	0.999	11.6	3.8	349.	34.0	11.3	-1.4
54	55.	24.	0.	7.19	0.998	12.3	3.3	0.	32.5	10.1	35.5
55	55.	23.	0.	7.19	0.998	12.2	4.0	1.	32.6	10.1	35.6
56	54.	22.	0.	7.19	0.998	12.1	4.3	358.	32.7	10.1	35.3
58	53.	-17.	0.	7.02	1.000	12.1	3.4	5.	29.7	9.1	65.6
59	54.	-19.	0.	7.02	1.000	12.2	3.9	4.	30.0	9.2	65.7
60	54.	-20.	0.	7.01	1.000	12.2	4.1	7.	30.2	9.3	65.9
61	54.	-21.	0.	7.01	1.000	12.1	3.0	5.	30.5	9.4	65.9





3.1.5 THERMAL PERFORMANCE WITH MODERATELY SELECTIVE ABSORBER

The collector, outfitted with a moderately selective black paint coated absorber, was tested on 25 January 1994 in accordance with ASHRAE procedure 93-1986. Only two different inlet temperatures tests were run for the moderately selective paint absorber. The customary minimum of four points was not taken because the collector was exposed to a period of wet stagnation. This stagnation caused some degradation to the TIM installed in the other collectors. Since only two points were taken only a linear fit could be developed. Results of the thermal performance tests are presented in graphical and tabular form in both the International System of Units (SI) and English units. The thermal performance equations in S.I. units developed from the empirical data are:

$$\text{first order} \quad \eta = 69.9 - 490 \quad (T_i - T_a)/I$$

These equations in English units are:

$$\text{first order} \quad \eta = 69.9 - 86 \quad (T_i - T_a)/I$$

TABLE 3.2 THERMAL PERFORMANCE TEST ON NO TIM WITH MODERATELY SELECTIVE ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME		TA	TI	TE	FLOW AVE IN		TOTAL IN	TE-TI	DEL T	EFFIC	(TI-TA)/I
		START	END	(C)	(C)	(C)	L/MIN	W/M ²	J/M ²	(C)	C-MIN	%	(C-M ²)/W
5	1/25/94	13:31	13:36	23.4	60.0	66.9	3.27	1011.3	303391.	6.85	34.3	52.0	0.0362
6	1/25/94	13:36	13:41	23.1	60.1	66.9	3.26	1009.9	302976.	6.82	34.1	51.8	0.0366
7	1/25/94	13:41	13:46	23.0	60.1	66.9	3.26	1008.7	302617.	6.84	34.2	51.9	0.0368
8	1/25/94	13:46	13:51	23.0	60.1	66.9	3.25	1005.1	301533.	6.85	34.3	52.2	0.0368
10	1/25/94	14:22	14:27	22.8	23.2	32.0	3.26	975.3	292577.	8.74	43.7	69.6	0.0004
11	1/25/94	14:27	14:32	22.9	23.2	31.9	3.25	967.2	290173.	8.71	43.6	69.9	0.0003
13	1/25/94	14:37	14:42	22.7	23.2	31.7	3.25	953.4	286027.	8.55	42.8	69.6	0.0005
16	1/25/94	14:52	14:57	22.7	23.2	31.5	3.25	932.1	279644.	8.39	41.9	69.8	0.0005

TEST	TILT DEG	AZIM DEG	INCI DEG	MASS KG/SEC	SPEC HEAT J/(KG C)	IN P KN/M ²	WIND M/S	WIND DIR	DIF IN W/M ²	% DIFF INSOL	TI-TA (C)
5	53.	-28.	0.	0.0534	4185.9	84.3	1.9	101.	133.6	13.2	36.6
6	53.	-30.	0.	0.0533	4185.9	84.1	2.0	109.	131.2	13.0	37.0
7	54.	-31.	0.	0.0533	4185.9	83.2	1.8	103.	128.4	12.7	37.1
8	54.	-32.	0.	0.0532	4185.9	83.5	2.2	106.	127.2	12.7	37.0
10	59.	-41.	0.	0.0541	4178.8	83.9	1.6	108.	136.3	14.0	0.4
11	60.	-42.	0.	0.0540	4178.8	86.1	1.8	107.	131.5	13.6	0.3
13	61.	-44.	0.	0.0540	4178.8	85.2	2.4	112.	126.3	13.3	0.5
16	64.	-47.	0.	0.0541	4178.9	84.0	2.1	102.	125.4	13.5	0.4

TABLE 3.2A THERMAL PERFORMANCE TEST ON NO TIM WITH MODERATELY SELECTIVE ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME START END	TA (F)	TI (F)	TE (F)	FLOW GPM	AVE IN B/H-FT ²	TOTAL IN BTU/FT ²	TE-TI (F)	DEL T F-MIN	EFFIC %	(TI-TA)/I (F-H-FT ²)/B
5	1/25/94	13:31 13:36	74.1	140.1	152.4	0.863	320.8	26.7	12.33	61.7	52.0	0.206
6	1/25/94	13:36 13:41	73.5	140.1	152.4	0.861	320.4	26.7	12.28	61.4	51.8	0.208
7	1/25/94	13:41 13:46	73.3	140.1	152.4	0.860	320.0	26.7	12.31	61.5	51.9	0.209
8	1/25/94	13:46 13:51	73.5	140.1	152.5	0.860	318.8	26.6	12.33	61.7	52.2	0.209
10	1/25/94	14:22 14:27	73.1	73.8	89.6	0.860	309.4	25.8	15.73	78.7	69.6	0.002
11	1/25/94	14:27 14:32	73.2	73.8	89.5	0.860	306.8	25.6	15.68	78.4	69.9	0.002
13	1/25/94	14:37 14:42	72.8	73.7	89.1	0.860	302.4	25.2	15.40	77.0	69.6	0.003
16	1/25/94	14:52 14:57	72.9	73.7	88.8	0.860	295.7	24.6	15.09	75.5	69.8	0.003

TEST	TILT DEG	AZIM DEG	INCI DEG	MASS LBM/MIN	SPEC HEAT BTU/(LBM-F)	IN P PSI	WIND MPH	WIND DIR	DIF IN B/H-FT ²	% DIFF INSOL	TI-TA (F)
5	53.	-28.	0.	7.07	1.000	12.2	4.3	101.	42.4	13.2	66.0
6	53.	-30.	0.	7.05	1.000	12.2	4.4	109.	41.6	13.0	66.6
7	54.	-31.	0.	7.05	1.000	12.1	3.9	103.	40.7	12.7	66.8
8	54.	-32.	0.	7.04	1.000	12.1	4.9	106.	40.4	12.7	66.7
10	59.	-41.	0.	7.15	0.998	12.2	3.6	108.	43.2	14.0	0.8
11	60.	-42.	0.	7.15	0.998	12.5	4.1	107.	41.7	13.6	0.6
13	61.	-44.	0.	7.15	0.998	12.4	5.3	112.	40.1	13.3	0.9
16	64.	-47.	0.	7.15	0.998	12.2	4.7	102.	39.8	13.5	0.8

THERMAL PERFORMANCE

SANDIA TEST

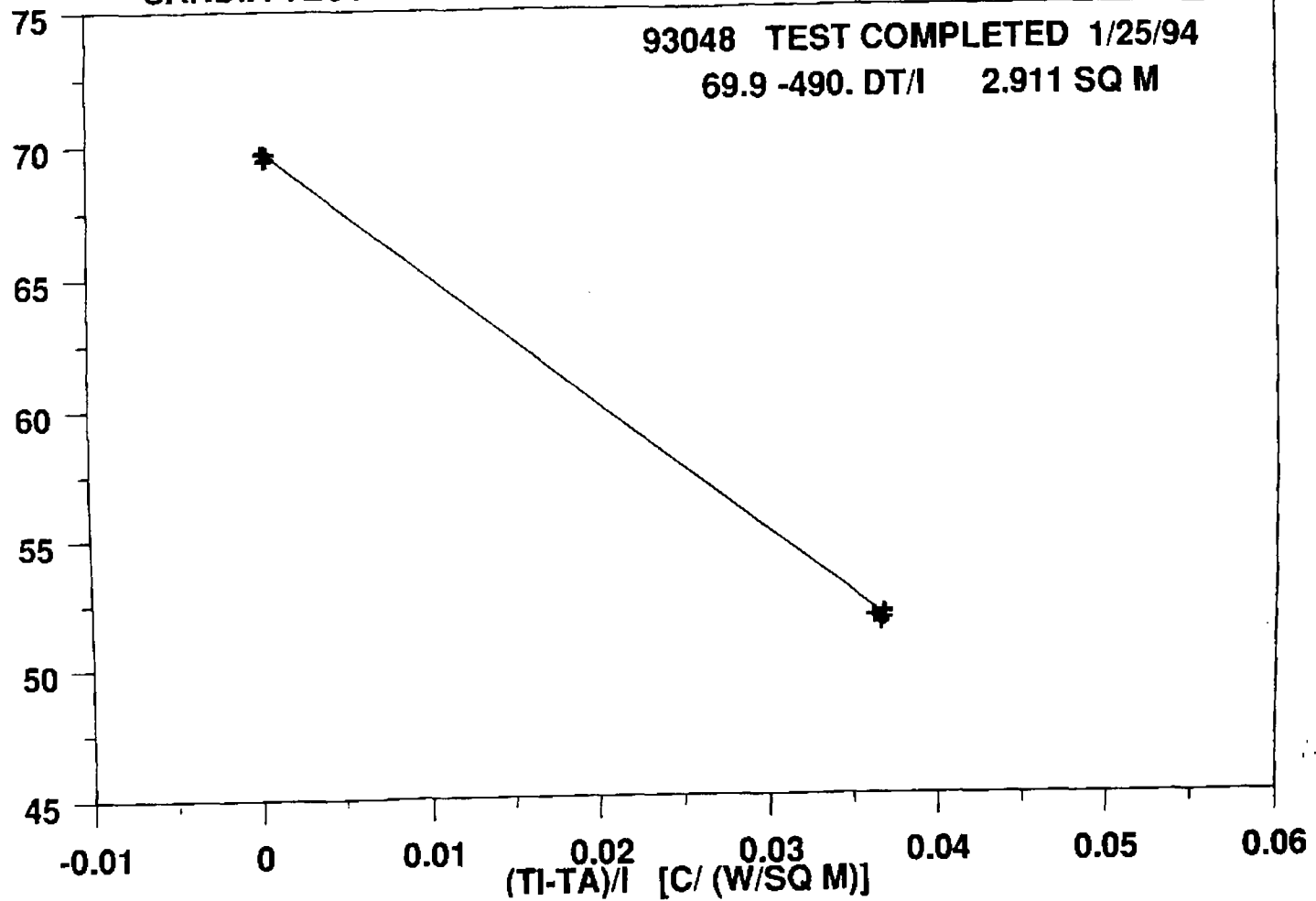
NO INSULATION

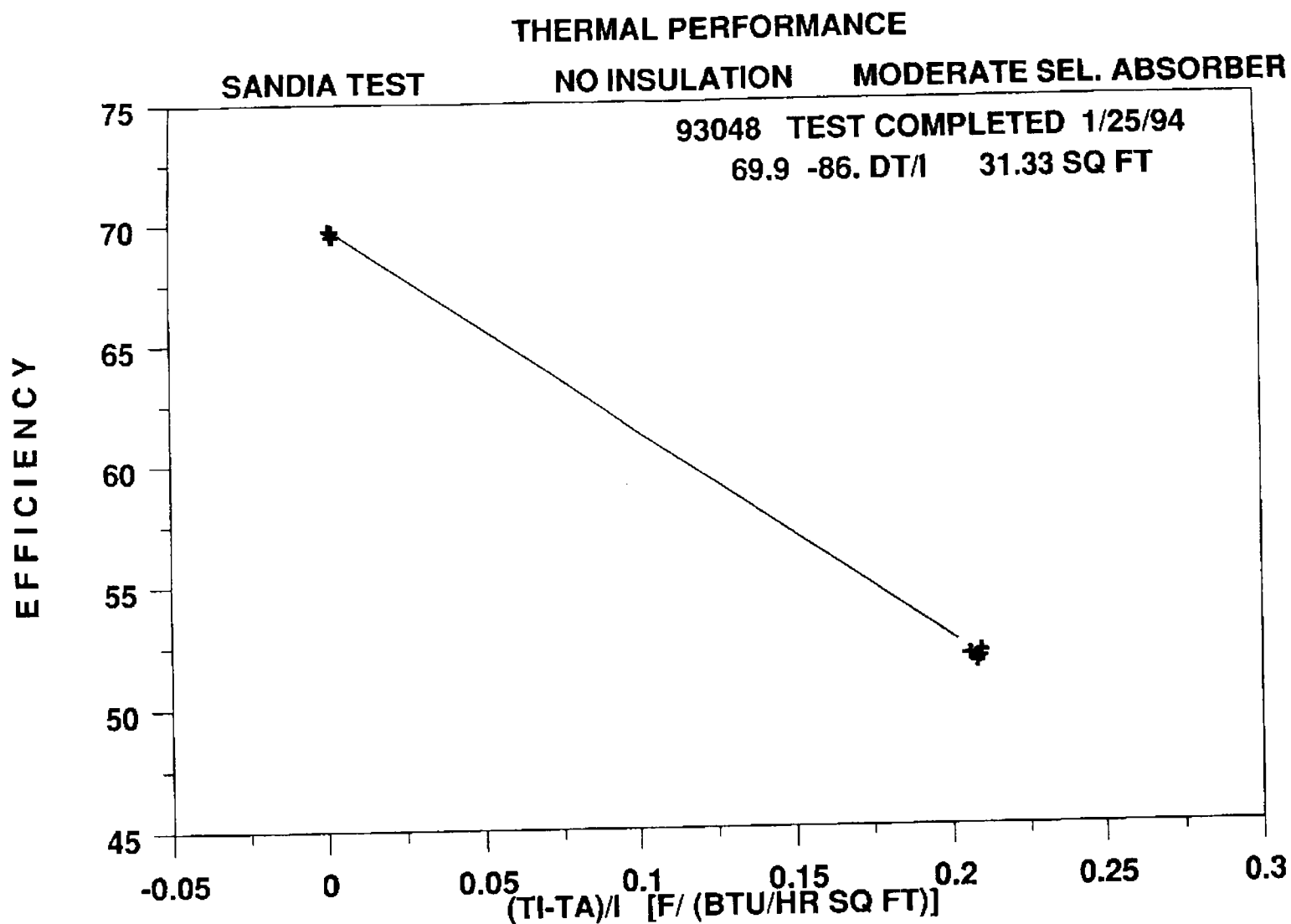
MODERATE SEL. ABSORBER

93048 TEST COMPLETED 1/25/94

69.9 -490. DT/I 2.911 SQ M

EFFICIENCY





3.1.6 THERMAL PERFORMANCE WITH FLAT BLACK PAINT ABSORBER

The collector, outfitted with a flat black paint coated absorber, was tested from 27-28 December 1993 in accordance with ASHRAE procedure 93-1986. Results of the thermal performance tests are presented in graphical and tabular form in both the International System of Units (SI) and English units. The thermal performance equations in S.I. units developed from the empirical data are:

$$\text{first order} \quad \eta = 75.4 - 594 \quad (T_i - T_a)/I$$

$$\text{second order} \quad \eta = 74.6 - 393 \quad (T_i - T_a)/I - 4691 \quad [(T_i - T_a)/I]^2$$

These equations in English units are:

$$\text{first order} \quad \eta = 75.4 - 105 \quad (T_i - T_a)/I$$

$$\text{second order} \quad \eta = 74.6 - 69 \quad (T_i - T_a)/I - 146 \quad [(T_i - T_a)/I]^2$$

TABLE 3.3 THERMAL PERFORMANCE TEST ON NO TIM WITH FLAT BLACK ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME START END	TA (C)	TI (C)	TE (C)	FLOW L/MIN	AVE IN W/M ²	TOTAL IN J/M ²	TE-TI (C)	DEL T C-MIN	EFFIC %	(TI-TA)/I (C-M ²)/W
7	12/27/93	11:11 11:16	14.7	61.8	68.4	3.29	1059.1	317719.	6.59	33.0	48.2	0.0444
8	12/27/93	11:16 11:21	15.0	61.8	68.4	3.29	1058.6	317584.	6.60	33.0	48.2	0.0442
9	12/27/93	11:21 11:26	15.3	61.8	68.5	3.29	1059.2	317751.	6.63	33.2	48.4	0.0439
10	12/27/93	11:26 11:31	15.4	61.8	68.5	3.29	1060.0	317988.	6.67	33.3	48.6	0.0438
12	12/27/93	11:54 11:59	16.0	52.2	59.8	3.27	1056.8	317026.	7.54	37.7	55.1	0.0343
13	12/27/93	11:59 12:04	16.1	52.2	59.8	3.27	1055.6	316671.	7.54	37.7	55.1	0.0342
14	12/27/93	12:04 12:09	16.2	52.3	59.8	3.27	1053.6	316068.	7.54	37.7	55.2	0.0342
15	12/27/93	12:09 12:14	16.5	52.3	59.9	3.27	1053.2	315974.	7.58	37.9	55.5	0.0340
17	12/27/93	12:48 12:52	17.6	39.8	48.5	3.23	1040.2	312073.	8.75	43.8	64.3	0.0213
18	12/27/93	12:53 12:57	17.9	39.8	48.5	3.23	1038.5	311539.	8.75	43.7	64.4	0.0211
20	12/27/93	13:03 13:07	18.2	39.8	48.5	3.23	1030.1	309029.	8.72	43.6	64.7	0.0210
21	12/27/93	13:08 13:12	18.4	39.8	48.5	3.23	1026.9	308067.	8.69	43.5	64.7	0.0208
30	12/28/93	11:37 11:42	21.3	21.3	30.9	3.32	1014.2	304268.	9.60	48.0	75.0	0.0001
31	12/28/93	11:42 11:47	21.5	21.3	30.9	3.29	1011.5	303461.	9.61	48.1	74.7	-0.0002
32	12/28/93	11:47 11:52	21.4	21.3	30.9	3.31	1016.3	304883.	9.58	47.9	74.4	-0.0001
33	12/28/93	11:52 11:57	21.5	21.4	31.0	3.28	1014.6	304370.	9.63	48.2	74.2	-0.0001

TABLE 3.3 THERMAL PERFORMANCE TEST ON NO TIM WITH FLAT BLACK ABSORBER (SI UNITS CONTIUED)

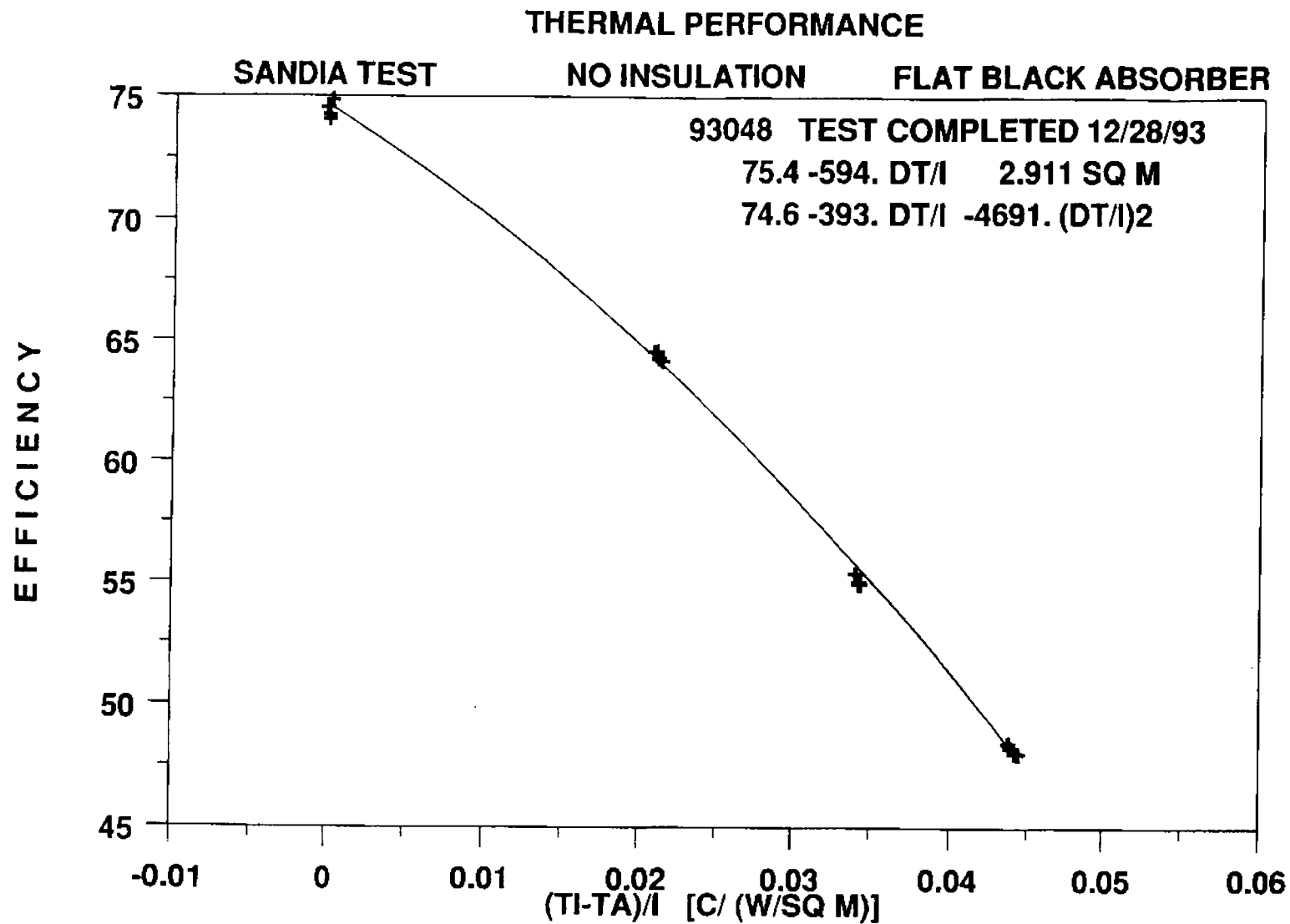
TEST	TILT DEG	AZIM DEG	INCI DEG	MASS KG/SEC	SPEC HEAT J/(KG C)	IN P KN/M ²	WIND M/S	WIND DIR	DIF IN W/M ²	% DIFF INSOL	TI-TA (C)
7	53.	13.	0.	0.0538	4186.7	78.7	1.4	350.	87.8	8.3	47.1
8	53.	12.	0.	0.0538	4186.7	78.6	1.0	351.	87.5	8.3	46.8
9	52.	10.	0.	0.0537	4186.7	79.8	1.1	356.	87.6	8.3	46.5
10	52.	9.	0.	0.0537	4186.8	80.1	1.4	356.	87.9	8.3	46.4
12	52.	1.	0.	0.0537	4182.6	81.7	1.5	346.	90.0	8.5	36.2
13	52.	-1.	0.	0.0537	4182.6	80.8	1.2	348.	90.7	8.6	36.1
14	52.	-2.	0.	0.0537	4182.6	81.9	0.9	347.	90.7	8.6	36.0
15	52.	-3.	0.	0.0537	4182.6	81.3	1.2	353.	90.6	8.6	35.8
17	53.	-15.	0.	0.0533	4179.3	80.6	0.5	348.	87.1	8.4	22.2
18	53.	-16.	0.	0.0533	4179.3	82.9	0.7	337.	88.0	8.5	21.9
20	54.	-19.	0.	0.0533	4179.3	80.3	0.4	335.	86.0	8.4	21.6
21	54.	-20.	0.	0.0532	4179.3	82.1	0.6	344.	83.9	8.2	21.4
30	52.	6.	0.	0.0552	4179.3	81.8	1.2	335.	142.8	14.1	0.1
31	52.	4.	0.	0.0547	4179.3	80.2	0.8	336.	140.7	13.9	-0.2
32	52.	3.	0.	0.0550	4179.3	80.4	0.8	342.	132.7	13.1	-0.1
33	52.	1.	0.	0.0544	4179.3	80.3	0.8	334.	116.7	11.5	-0.1

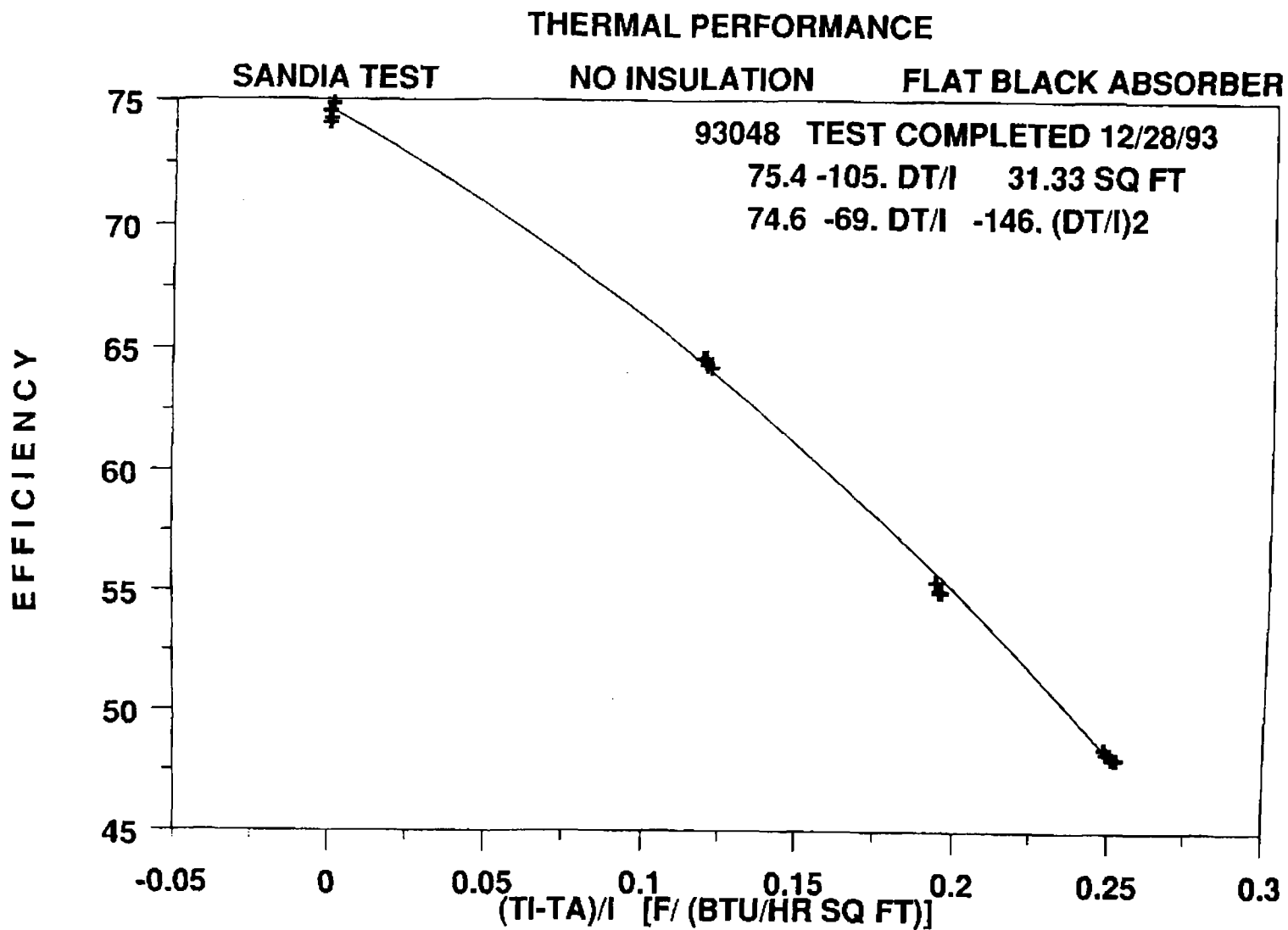
TABLE 3.3A THERMAL PERFORMANCE TEST ON NO TIM WITH FLAT BLACK ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME		TA	TI	TE	FLOW	AVE IN	TOTAL IN	TE-TI	DEL T	EFFIC	(TI-TA)/I
		START	END	(F)	(F)	(F)	GPM	B/H-FT ²	BTU/FT ²	(F)	F-MIN	%	(F-H-FT ²)/B
7	12/27/93	11:11	11:16	58.5	143.2	155.1	0.870	335.9	28.0	11.86	59.3	48.2	0.252
8	12/27/93	11:16	11:21	59.0	143.3	155.2	0.870	335.8	28.0	11.87	59.4	48.2	0.251
9	12/27/93	11:21	11:26	59.6	143.3	155.3	0.869	336.0	28.0	11.94	59.7	48.4	0.249
10	12/27/93	11:26	11:31	59.7	143.3	155.3	0.868	336.2	28.0	12.00	60.0	48.6	0.249
12	12/27/93	11:54	11:59	60.7	126.J	139.6	0.865	335.2	27.9	13.57	67.9	55.1	0.195
13	12/27/93	11:59	12:04	61.1	126.0	139.6	0.864	334.8	27.9	13.56	67.8	55.1	0.194
14	12/27/93	12:04	12:09	61.2	126.1	139.6	0.864	334.2	27.9	13.57	67.8	55.2	0.194
15	12/27/93'	12:09	12:14	61.6	126.1	139.7	0.864	334.1	27.8	13.65	68.3	55.5	0.193
17	12/27/93	12:48	12:52	63.6	103.6	119.4	0.853	330.0	27.5	15.75	78.8	64.3	0.121
18	12/27/93	12:53	12:57	64.2	103.6	119.4	0.853	329.4	27.5	15.75	78.7	64.4	0.120
20	12/27/93	13:03	13:07	64.7	103.6	119.3	0.853	326.8	27.2	15.69	78.4	64.7	0.119
21	12/27/93	13:08	13:12	65.2	103.7	119.3	0.852	325.7	27.1	15.65	78.2	64.7	0.118
30	12/28/93	11:37	11:42	70.3	70.4	87.7	0.878	321.7	26.8	17.27	86.4	75.0	0.000
31	12/28/93	11:42	11:47	70.7	70.4	87.7	0.870	320.9	26.7	17.30	86.5	74.7	-0.001
32	12/28/93	11:47	11:52	70.5	70.4	87.6	0.874	322.4	26.9	17.24	86.2	74.4	0.000
33	12/28/93	11:52	11:57	70.7	70.4	87.8	0.866	321.8	26.8	17.34	86.7	74.2	-0.001

TABLE 3.3A THERMAL PERFORMANCE TEST ON NO TIM WITH FLAT BLACK ABSORBER (ENGLISH UNITS CONTINUED)

TEST	TILT DEG	AZIM DEG	INCI DEG	MASS LBM/MIN	SPEC HEAT BTU/(LBM-F)	IN P PSI	WIND MPH	WIND DIR	DIF IN B/H-FT ²	% DIFF INSOL	TI-TA (F)
7	53.	13.	0.	7.12	1.000	11.4	3.2	350.	27.8	8.3	84.7
8	53.	12.	0.	7.11	1.000	11.4	2.3	351.	27.8	8.3	84.3
9	52.	10.	0.	7.11	1.000	11.6	2.4	356.	27.8	8.3	83.8
10	52.	9.	0.	7.10	1.000	11.6	3.1	356.	27.9	8.3	83.6
12	52.	1.	0.	7.11	0.999	11.8	3.4	346.	28.5	8.5	65.2
13	52.	-1.	0.	7.11	0.999	11.7	2.7	348.	28.8	8.6	65.0
14	52.	-2.	0.	7.10	0.999	11.9	2.1	347.	28.8	8.6	64.8
15	52.	-3.	0.	7.10	0.999	11.8	2.7	353.	28.7	8.6	64.5
17	53.	-15.	0.	7.05	0.998	11.7	1.0	348.	27.6	8.4	40.0
18	53.	-16.	0.	7.05	0.998	12.0	1.6	337.	27.9	8.5	39.4
20	54.	-19.	0.	7.05	0.998	11.6	0.9	335.	27.3	8.4	38.9
21	54.	-20.	0.	7.04	0.998	11.9	1.2	344.	26.6	8.2	38.5
30	52.	6.	0.	7.30	0.998	11.9	2.6	335.	45.3	14.1	0.1
31	52.	4.	0.	7.24	0.998	11.6	1.8	336.	44.6	13.9	-0.3
32	52.	3.	0.	7.27	0.998	11.7	1.7	342.	42.1	13.1	-0.1
33	52.	1.	0.	7.20	0.998	11.6	1.7	334.	37.0	11.5	-0.3





3.1.7 INCIDENT ANGLE MODIFIER TEST

The collector, outfitted with a selective black chrome coated absorber, was tested from 15-18 November 1993 in accordance with the ASHRAE procedure to determine the longitudinal incident angle modifier (IAM). The definition of longitudinal IAM for this report will be incident angles where the collector's azimuth is tracking the sun while its elevation is made higher or lower than the sun's altitude, assuming the collector is mounted with its long axis parallel to the ground. A graph of the longitudinal IAM along with the data in tabular form follows. The longitudinal incident angle modifier equation was determined to be:

$$K_{\tau\alpha} = 1.0 - 0.20 (1/\cos \theta - 1)$$

The collector, outfitted with a selective black chrome coated absorber, was tested from 15 November - 16 December 1993 in accordance with the ASHRAE procedure to determine the transverse incident angle modifier (IAM). The definition of transverse IAM for this report will be incident angles where the collector's elevation is tracking the sun while its azimuth is made further right or left than the sun's azimuth assuming the collector is mounted with its long axis parallel to the ground. A graph of the transverse IAM along with the data in tabular form follows. The transverse incident angle modifier equation was determined to be:

$$K_{\tau\alpha} = 1.0 - 0.23 (1/\cos \theta - 1)$$

The collector, outfitted with a flat black paint coated absorber, was tested on 28 December 1993 in accordance with the ASHRAE procedure to determine the transverse incident angle modifier (IAM). The definition of transverse IAM for this report will be incident angles where the collector's elevation is tracking the sun while its azimuth is made further right or left than the sun's azimuth assuming the collector is mounted with its long axis parallel to the ground. A graph of the transverse IAM along with the data in tabular form follows. The transverse incident angle modifier equation was

determined to be:

$$K\tau\alpha = 1.0 - 0.21 (1/\cos \theta - 1)$$

Incident angle modifier tests were not performed on all collector-absorber configurations since results did not change significantly from one configuration to the next.

TABLE 3.4 LONGITUDINAL INCIDENT ANGLE MODIFIER TEST ON NO TIM WITH SELECTIVE ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM
		START END	(C)	(C)	(C)	(C)	(C)	L/M	KG/SEC	DEG	DEG	DEG	W/M²	DIF	M/S	DEG	%
1	11/15/93	11:45 11:49	27.4	29.2	32.4	3.13	1.9	3.3	0.0547	12.	4.	60.	446.	7.	2.0	119.	55.1
3	11/15/93	11:55 11:59	27.3	29.3	32.4	3.11	2.0	3.3	0.0549	12.	1.	60.	444.	7.	2.1	121.	55.2
7	11/15/93	12:29 12:34	27.8	29.3	34.4	5.14	1.5	3.3	0.0542	3.	-10.	45.	642.	11.	1.8	153.	62.3
8	11/15/93	12:34 12:39	27.8	29.3	34.4	5.12	1.5	3.3	0.0541	3.	-12.	45.	639.	11.	1.9	148.	62.2
9	11/15/93	13:03 13:07	27.9	29.3	38.2	8.91	1.4	3.3	0.0545	35.	-20.	15.	964.	21.	1.6	136.	72.3
10	11/15/93	13:08 13:12	27.8	29.3	38.2	8.89	1.5	3.3	0.0544	35.	-22.	15.	964.	21.	2.2	116.	72.0
14	11/18/93	10:06 10:11	26.9	26.9	31.0	4.05	0.0	3.3	0.0546	5.	32.	60.	510.	23.	1.0	330.	62.4
15	11/18/93	10:11 10:16	26.8	26.9	31.0	4.07	0.1	3.3	0.0547	5.	31.	60.	512.	23.	0.9	331.	62.4
17	11/18/93	10:46 10:51	27.5	28.0	34.0	5.93	0.5	3.3	0.0550	6.	22.	45.	693.	15.	0.7	339.	67.6
18	11/18/93	10:51 10:56	27.6	28.0	34.1	6.10	0.4	3.3	0.0550	6.	20.	45.	711.	16.	0.7	351.	67.7
21	11/18/93	11:27 11:31	27.9	28.0	36.0	7.98	0.1	3.3	0.0542	19.	10.	30.	853.	12.	0.7	350.	72.8
22	11/18/93	11:32 11:36	28.1	28.0	36.0	7.99	0.0	3.3	0.0542	19.	8.	30.	855.	12.	1.0	357.	72.7
23	11/18/93	11:37 11:41	28.1	28.1	36.1	7.99	0.0	3.3	0.0541	18.	6.	30.	857.	13.	0.9	353.	72.4
29	11/18/93	12:42 12:46	26.9	28.3	37.1	8.75	1.4	3.3	0.0543	34.	-14.	15.	939.	19.	2.3	100.	72.6
32	11/18/93	12:57 13:01	27.0	28.3	37.0	8.70	1.4	3.3	0.0544	35.	-18.	15.	939.	18.	2.1	94.	72.5
34	11/17/93	13:36 13:41	28.0	28.3	37.6	9.22	0.3	3.3	0.0541	54.	-29.	0.	975.	17.	1.5	---	73.5
35	11/17/93	13:51 13:56	27.6	28.3	37.4	9.10	0.7	3.3	0.0539	55.	-33.	0.	962.	17.	2.3	---	73.2
38	11/18/93	14:03 14:07	26.2	26.9	35.7	8.80	0.6	3.3	0.0549	57.	-36.	0.	938.	20.	2.2	---	73.9
39	11/18/93	14:08 14:12	26.2	26.9	35.7	8.80	0.7	3.3	0.0549	58.	-37.	0.	936.	20.	2.0	---	74.1

TABLE 3.4A LONGITUDINAL INCIDENT ANGLE MODIFIER TEST ON NO TIM WITH SELECTIVE ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM	
		START END	(F)	(F)	(F)	(F)	(F)	GPM	LB/MIN	DEG	DEG	DEG	B/FT²	DIF	MPH	DEG	%	
1	11/15/93	11:45 11:49	81.2	84.6	90.3	5.64	3.4	0.871	7.23	12.	4.	60.	141.	7.	4.5	119.	55.1	0.773
3	11/15/93	11:55 11:59	81.2	84.7	90.3	5.61	3.6	0.874	7.26	12.	1.	60.	141.	7.	4.6	121.	55.2	0.775
7	11/15/93	12:29 12:34	82.1	84.7	94.0	9.25	2.7	0.863	7.17	3.	-10.	45.	204.	11.	4.0	153.	62.3	0.860
8	11/15/93	12:34 12:39	82.0	84.7	94.0	9.22	2.7	0.861	7.15	3.	-12.	45.	203.	11.	4.4	148.	62.2	0.859
9	11/15/93	13:03 13:07	82.3	84.8	100.8	16.04	2.5	0.869	7.21	35.	-20.	15.	306.	21.	3.7	136.	72.3	0.992
10	11/15/93	13:08 13:12	82.1	84.8	100.8	15.99	2.7	0.867	7.19	35.	-22.	15.	306.	21.	4.8	116.	72.0	0.988
14	11/18/93	10:06 10:11	80.4	80.4	87.7	7.30	0.1	0.869	7.22	5.	32.	60.	162.	23.	2.3	330.	62.4	0.849
15	11/18/93	10:11 10:16	80.3	80.4	87.7	7.32	0.1	0.871	7.24	5.	31.	60.	162.	23.	2.0	331.	62.4	0.849
17	11/18/93	10:46 10:51	81.6	82.4	93.1	10.68	0.9	0.876	7.28	6.	22.	45.	220.	15.	1.5	339.	67.6	0.924
18	11/18/93	10:51 10:56	81.7	82.4	93.4	10.97	0.8	0.876	7.27	6.	20.	45.	226.	16.	1.6	351.	67.7	0.924
21	11/18/93	11:27 11:31	82.3	82.4	96.8	14.36	0.2	0.864	7.17	19.	10.	30.	271.	12.	1.7	350.	72.8	0.991
22	11/18/93	11:32 11:36	82.5	82.4	96.8	14.39	-0.1	0.863	7.17	19.	8.	30.	271.	12.	2.2	357.	72.7	0.989
23	11/18/93	11:37 11:41	82.5	82.5	96.9	14.39	0.0	0.862	7.16	18.	6.	30.	272.	13.	2.1	353.	72.4	0.985
29	11/18/93	12:42 12:46	80.4	83.0	98.7	15.75	2.5	0.865	7.18	34.	-14.	15.	298.	19.	5.1	100.	72.6	0.996
32	11/18/93	12:57 13:01	80.5	83.0	98.7	15.67	2.5	0.868	7.20	35.	-18.	15.	298.	18.	4.6	94.	72.5	0.994
34	11/17/93	13:36 13:41	82.4	83.0	99.6	16.60	0.6	0.863	7.16	54.	-29.	0.	309.	17.	3.4	---	73.5	1.002
35	11/17/93	13:51 13:56	81.6	83.0	99.3	16.39	1.3	0.859	7.13	55.	-33.	0.	305.	17.	5.1	---	73.2	1.000
38	11/18/93	14:03 14:07	79.2	80.3	96.2	15.84	1.1	0.874	7.26	57.	-36.	0.	297.	20.	5.0	---	73.9	1.009
39	11/18/93	14:08 14:12	79.1	80.3	96.2	15.85	1.2	0.874	7.26	58.	-37.	0.	297.	20.	4.5	---	74.1	1.012

LONGITUDINAL INCIDENT ANGLE MODIFIER

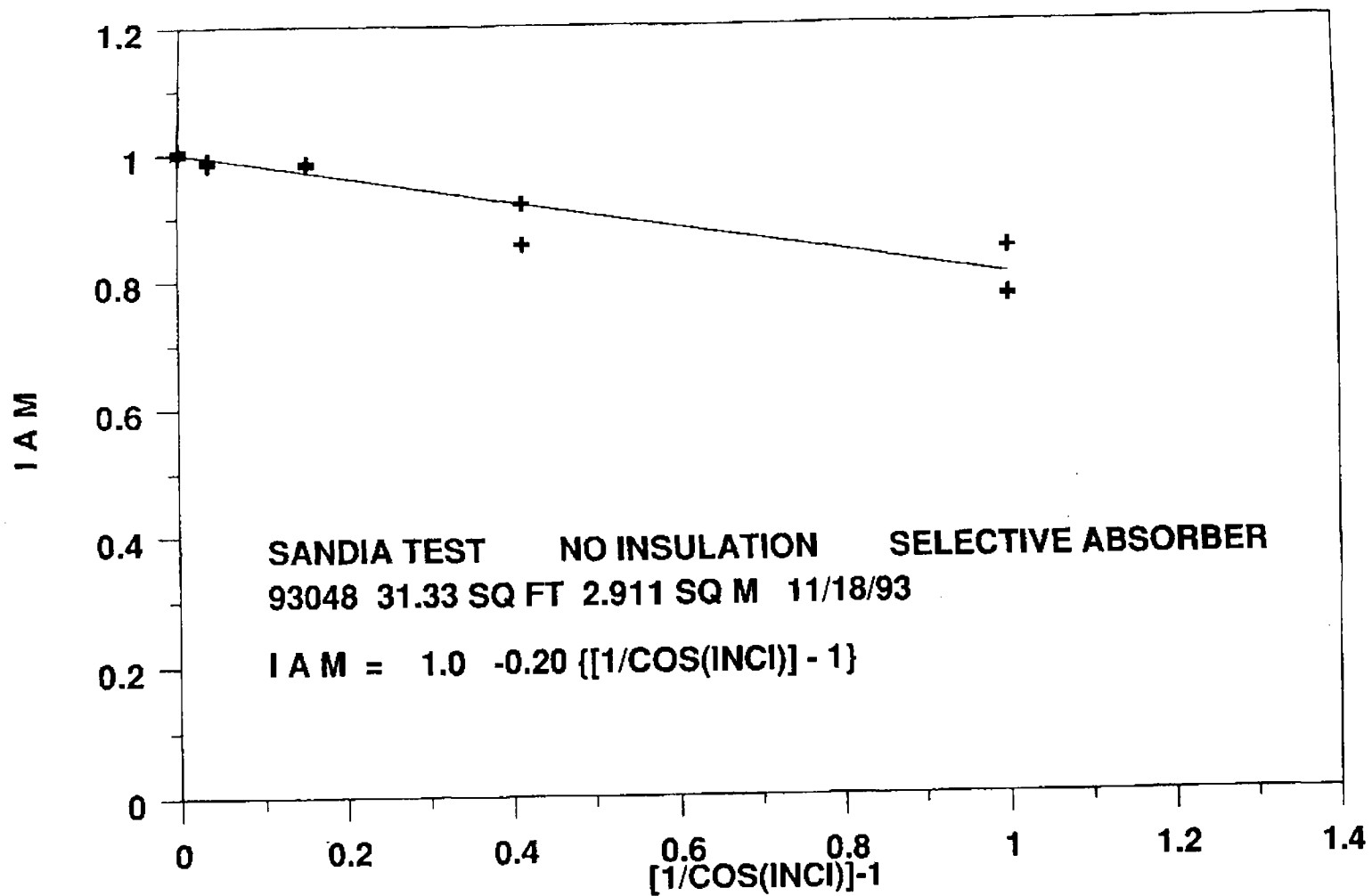


TABLE 3.5 TRANSVERSE INCIDENT ANGLE MODIFIER TEST ON NO TIM WITH SELECTIVE ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM
		START END	(C)	(C)	(C)	(C)	(C)	L/M	KG/SEC	DEG	DEG	DEG	W/M ²	DIF	M/S	DEG %	
1	11/15/93	11:08 11:13	27.4	29.2	34.2	5.01	1.8	3.2	0.0538	1.	15.	50.	636.	17.	1.9	127. 60.8	0.866
3	11/15/93	11:18 11:23	27.1	29.2	34.3	5.05	2.2	3.2	0.0536	1.	12.	50.	639.	19.	2.3	117. 60.7	0.868
7	12/15/93	10:54 10:59	15.5	15.8	21.7	5.89	0.3	3.3	0.0543	9.	18.	45.	738.	14.	3.4	283. 62.3	0.873
8	12/15/93	10:59 11:04	15.6	15.8	21.8	5.95	0.2	3.2	0.0537	9.	16.	45.	738.	14.	3.2	284. 62.3	0.872
13	12/15/93	13:30 13:35	18.5	19.0	26.3	7.34	0.5	3.3	0.0555	26.	-26.	30.	860.	11.	3.4	285. 68.0	0.954
14	12/15/93	13:35 13:40	18.5	19.0	26.3	7.32	0.5	3.3	0.0553	27.	-27.	30.	857.	10.	3.3	282. 67.8	0.952
18	12/15/93	15:12 15:17	17.5	18.3	21.2	2.94	0.8	3.3	0.0556	10.	-47.	60.	421.	11.	3.0	297. 55.8	0.791
19	12/15/93	15:17 15:22	17.5	18.3	21.1	2.87	0.8	3.3	0.0556	11.	-48.	60.	411.	10.	3.4	292. 55.7	0.790
26	12/16/93	13:13 13:17	14.8	14.6	23.2	8.66	-0.3	3.3	0.0543	40.	-21.	15.	968.	14.	1.7	332. 69.9	0.976
27	12/16/93	13:18 13:22	14.9	14.6	23.2	8.67	-0.3	3.3	0.0541	40.	-23.	15.	963.	14.	1.9	321. 70.0	0.977
38	11/18/93	14:03 14:07	26.2	26.9	35.7	8.80	0.6	3.3	0.0549	57.	-36.	0.	938.	20.	2.2	--- 73.9	1.037
39	11/18/93	14:08 14:12	26.2	26.9	35.7	8.80	0.7	3.3	0.0549	58.	-37.	0.	936.	20.	2.0	--- 74.1	1.041

TABLE 3.5A TRANSVERSE INCIDENT ANGLE MODIFIER TEST ON NO TIM WITH SELECTIVE ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM
		START END	(F)	(F)	(F)	(F)	(F)	GPM	LB/MN	DEG	DEG	DEG	B/FT ²	DIF	MPH	DEG %	
1	11/15/93	11:08 11:13	81.4	84.6	93.6	9.02	3.3	0.857	7.12	1.	15.	50.	202.	17.	4.3	127. 60.8	0.866
3	11/15/93	11:18 11:23	80.7	84.6	93.7	9.08	3.9	0.853	7.08	1.	12.	50.	203.	19.	5.1	117. 60.7	0.868
7	12/15/93	10:54 10:59	59.9	60.4	71.0	10.59	0.5	0.862	7.18	9.	18.	45.	234.	14.	7.5	283. 62.3	0.873
8	12/15/93	10:59 11:04	60.1	60.4	71.2	10.70	0.3	0.852	7.11	9.	16.	45.	234.	14.	7.2	284. 62.3	0.872
13	12/15/93	13:30 13:35	65.3	66.1	79.4	13.21	0.8	0.881	7.34	26.	-26.	30.	273.	11.	7.5	285. 68.0	0.954
14	12/15/93	13:35 13:40	65.3	66.2	79.3	13.17	0.8	0.878	7.32	27.	-27.	30.	272.	10.	7.3	282. 67.8	0.952
18	12/15/93	15:12 15:17	63.5	64.9	70.2	5.29	1.4	0.882	7.35	10.	-47.	60.	133.	11.	6.7	297. 55.8	0.791
19	12/15/93	15:17 15:22	63.4	64.9	70.0	5.16	1.4	0.883	7.36	11.	-48.	60.	130.	10.	7.5	292. 55.7	0.790
26	12/16/93	13:13 13:17	58.7	58.2	73.8	15.59	-0.5	0.862	7.19	40.	-21.	15.	307.	14.	3.8	332. 69.9	0.976
27	12/16/93	13:18 13:22	58.8	58.2	73.8	15.60	-0.6	0.859	7.16	40.	-23.	15.	305.	14.	4.2	321. 70.0	0.977
38	11/18/93	14:03 14:07	79.2	80.3	96.2	15.84	1.1	0.874	7.26	57.	-36.	0.	297.	20.	5.0	--- 73.9	1.037
39	11/18/93	14:08 14:12	79.1	80.3	96.2	15.85	1.2	0.874	7.26	58.	-37.	0.	297.	20.	4.5	--- 74.1	1.041

TRANSVERSE INCIDENT ANGLE MODIFIER

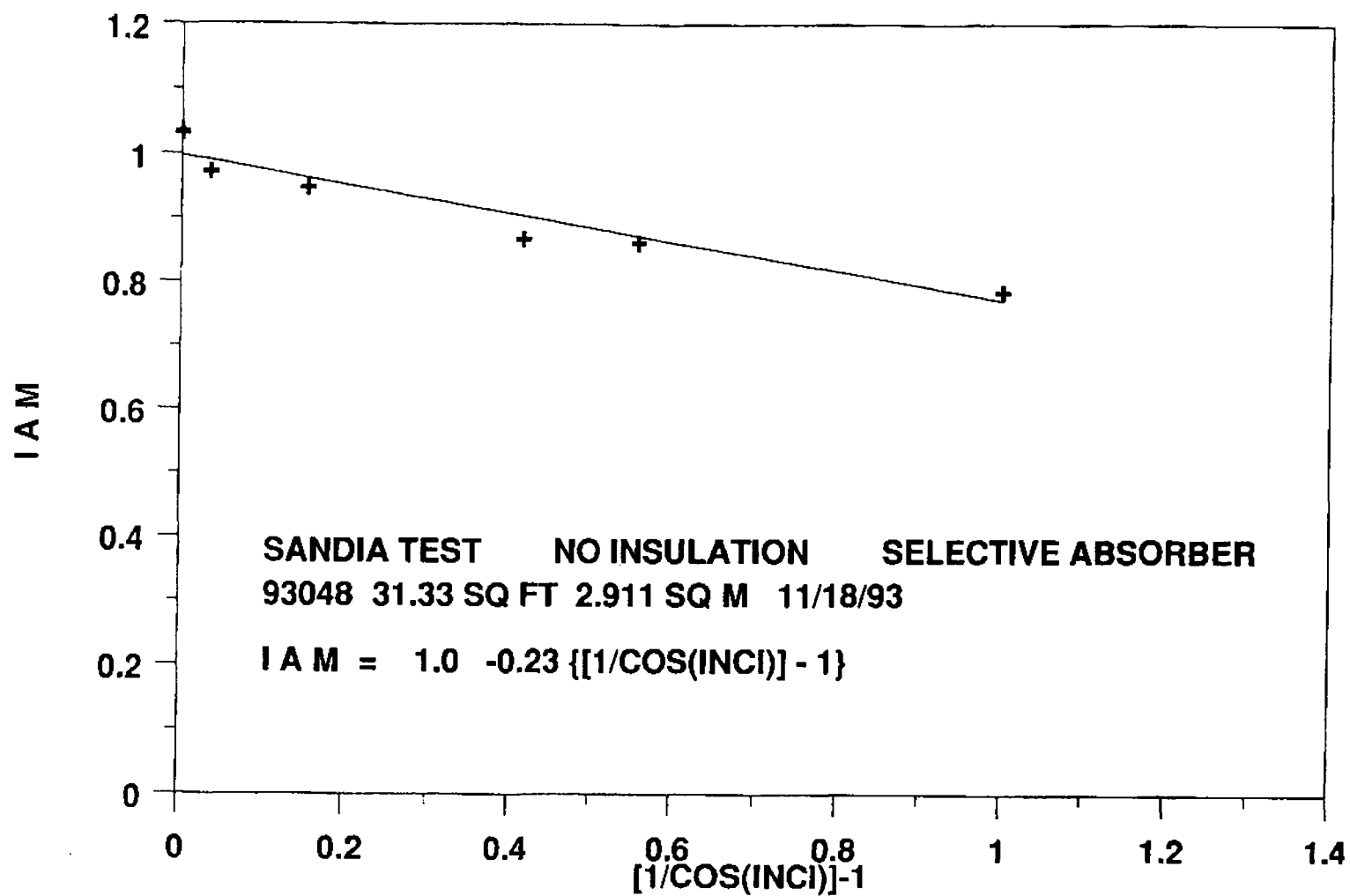


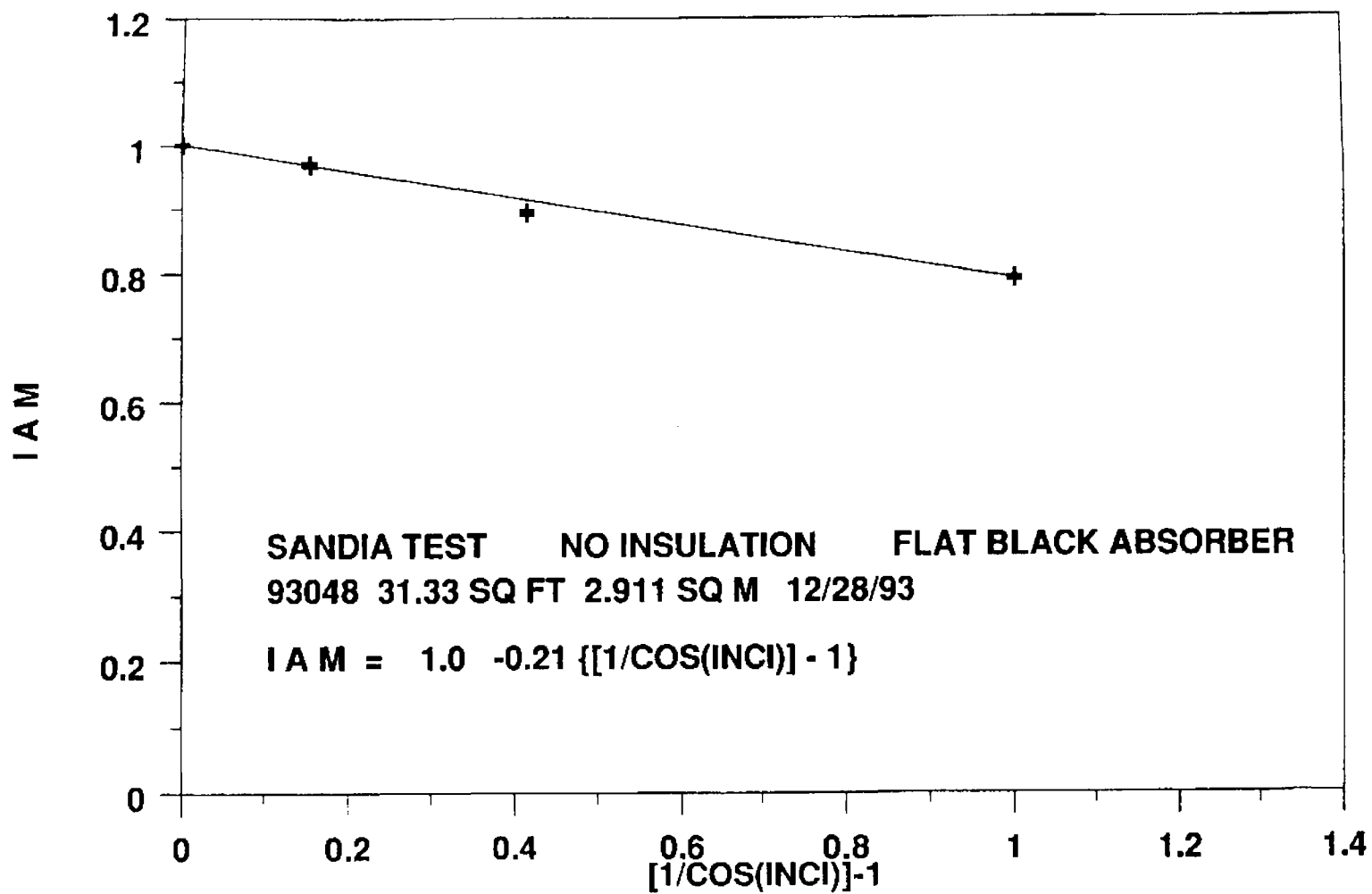
TABLE 3.6 TRANSVERSE INCIDENT ANGLE MODIFIER TEST ON NO TIM WITH FLAT BLACK ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM
		START END	(C)	(C)	(C)	(C)	(C)	L/M	KG/SEC	DEG	DEG	DEG	W/M ²	DIF	M/S	DEG %	
2	12/28/93	12:57 13:01	22.6	22.3	30.2	7.92	-0.3	3.3	0.0547	54.	-17.	30.	858.	11.	1.0	155. 72.6	0.978
3	12/28/93	13:02 13:06	22.6	22.3	30.1	7.82	-0.3	3.3	0.0544	54.	-19.	30.	846.	10.	1.2	166. 72.2	0.973
13	12/28/93	13:57 14:02	22.4	22.3	27.8	5.55	-0.2	3.3	0.0556	59.	-32.	45.	668.	11.	1.1	165. 66.4	0.896
14	12/28/93	14:02 14:07	22.3	22.3	27.9	5.65	0.0	3.3	0.0555	60.	-34.	45.	674.	13.	1.4	180. 66.8	0.903
16	12/28/93	14:24 14:29	22.5	22.3	25.6	3.37	-0.2	3.4	0.0557	63.	-38.	60.	457.	11.	1.2	160. 59.0	0.794
17	12/28/93	14:29 14:34	22.3	22.2	25.5	3.26	0.0	3.4	0.0559	63.	-39.	60.	442.	8.	1.1	157. 59.1	0.799
20	12/28/93	11:42 11:47	21.5	21.3	30.9	9.61	-0.2	3.3	0.0547	52.	4.	0.	1012.	14.	0.8	335. 74.7	1.008
21	12/28/93	11:47 11:52	21.4	21.3	30.9	9.58	-0.1	3.3	0.0550	52.	3.	0.	1016.	13.	0.8	336. 74.4	1.005

TABLE 3.6A TRANSVERSE INCIDENT ANGLE MODIFIER TEST ON NO TIM WITH FLAT BLACK ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM
		START END	(F)	(F)	(F)	(F)	(F)	GPM	LB/MN	DEG	DEG	DEG	B/FT ²	DIF	MPH	DEG %	
2	12/28/93	12:57 13:01	72.7	72.2	86.4	14.26	-0.5	0.870	7.24	54.	-17.	30.	272.	11.	2.2	155. 72.6	0.978
3	12/28/93	13:02 13:06	72.7	72.2	86.3	14.07	-0.5	0.865	7.20	54.	-19.	30.	268.	10.	2.7	166. 72.2	0.973
13	12/28/93	13:57 14:02	72.3	72.1	82.1	10.00	-0.3	0.884	7.36	59.	-32.	45.	212.	11.	2.5	165. 66.4	0.896
14	12/28/93	14:02 14:07	72.2	72.1	82.3	10.17	0.0	0.883	7.35	60.	-34.	45.	214.	13.	3.1	180. 66.8	0.903
16	12/28/93	14:24 14:29	72.5	72.1	78.2	6.06	-0.4	0.886	7.37	63.	-38.	60.	145.	11.	2.8	160. 59.0	0.794
17	12/28/93	14:29 14:34	72.1	72.0	77.9	5.86	0.0	0.887	7.39	63.	-39.	60.	140.	8.	2.4	157. 59.1	0.799
20	12/28/93	11:42 11:47	70.7	70.4	87.7	17.30	-0.3	0.870	7.24	52.	4.	0.	321.	14.	1.8	335. 74.7	1.008
21	12/28/93	11:47 11:52	70.5	70.4	87.6	17.24	-0.1	0.874	7.27	52.	3.	0.	322.	13.	1.7	336. 74.4	1.005

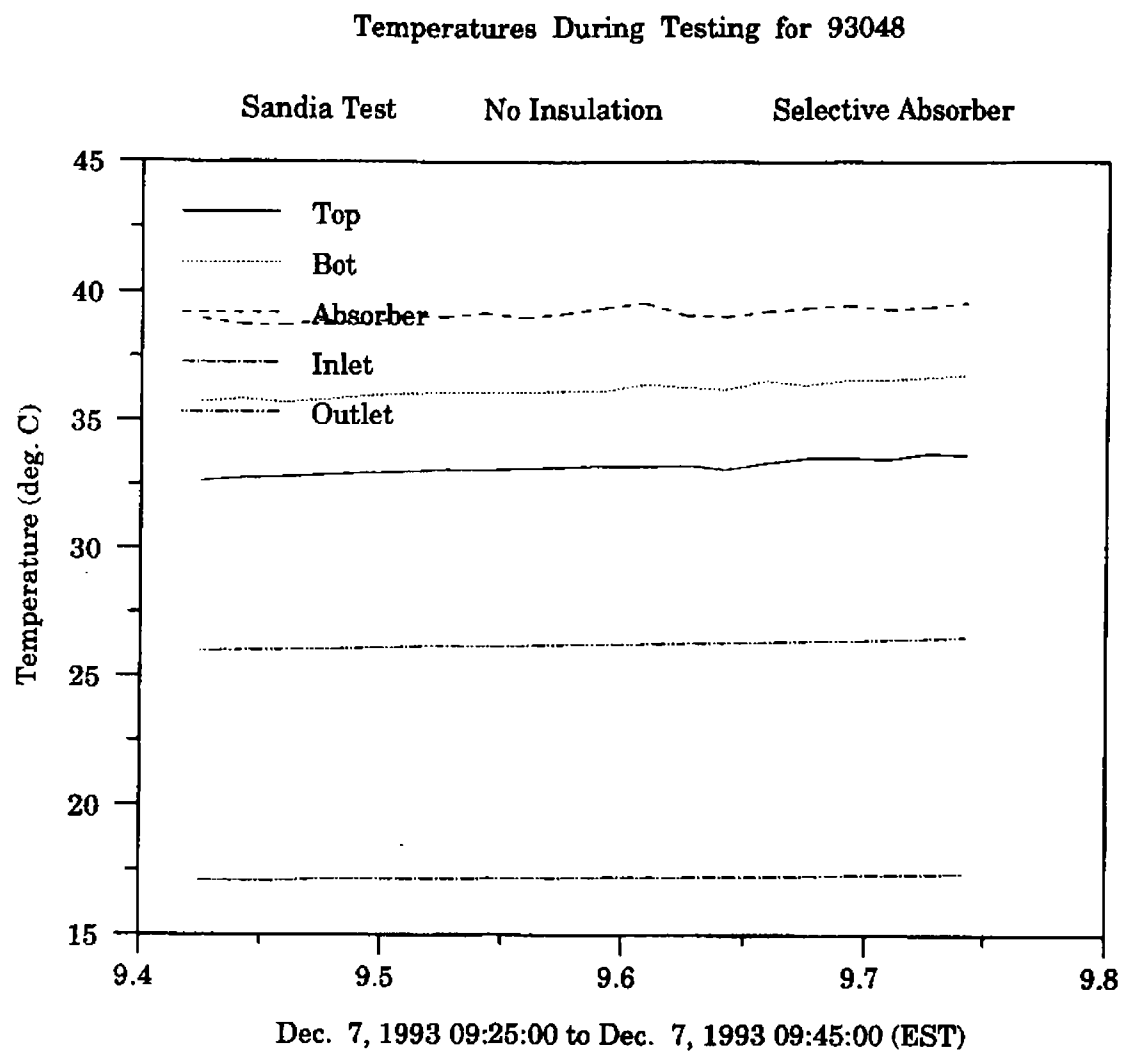
TRANSVERSE INCIDENT ANGLE MODIFIER



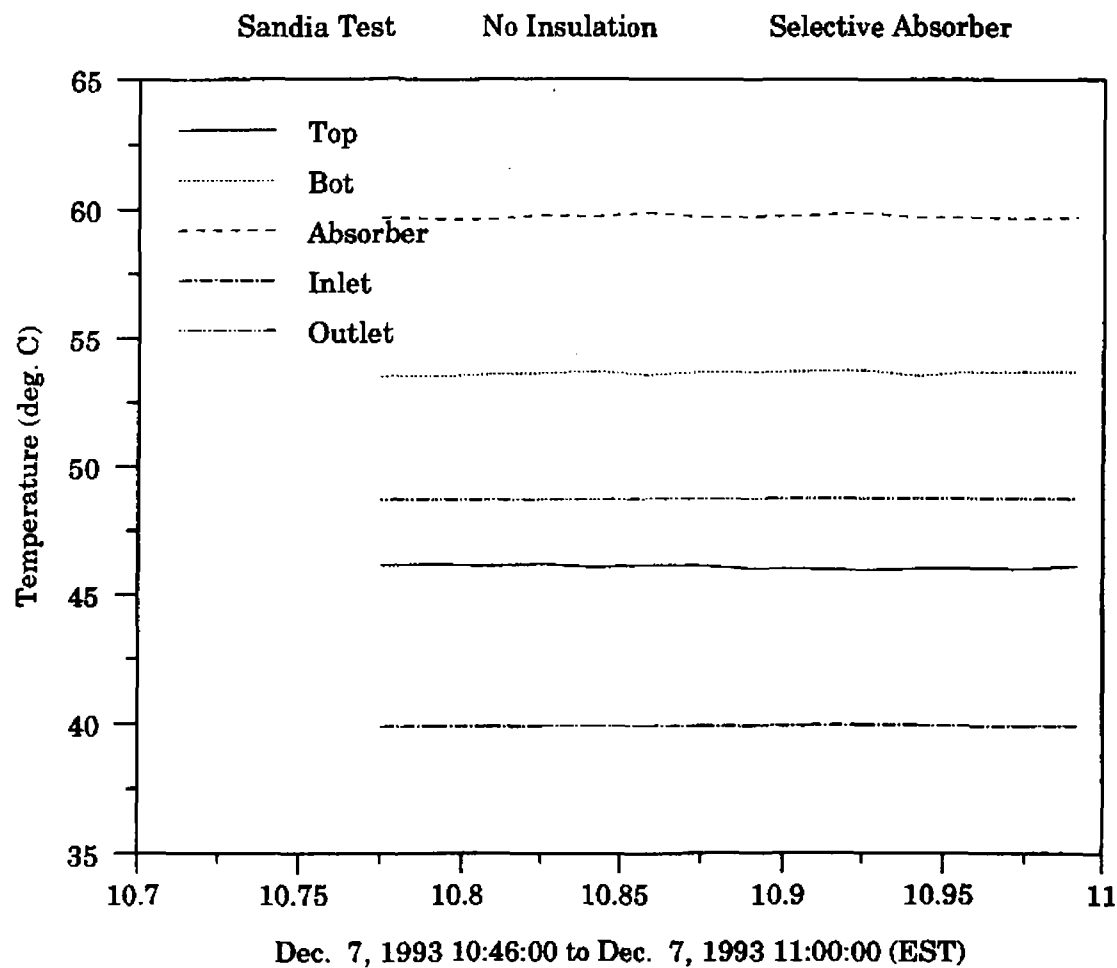
3.1.8 THERMOCOUPLE DATA

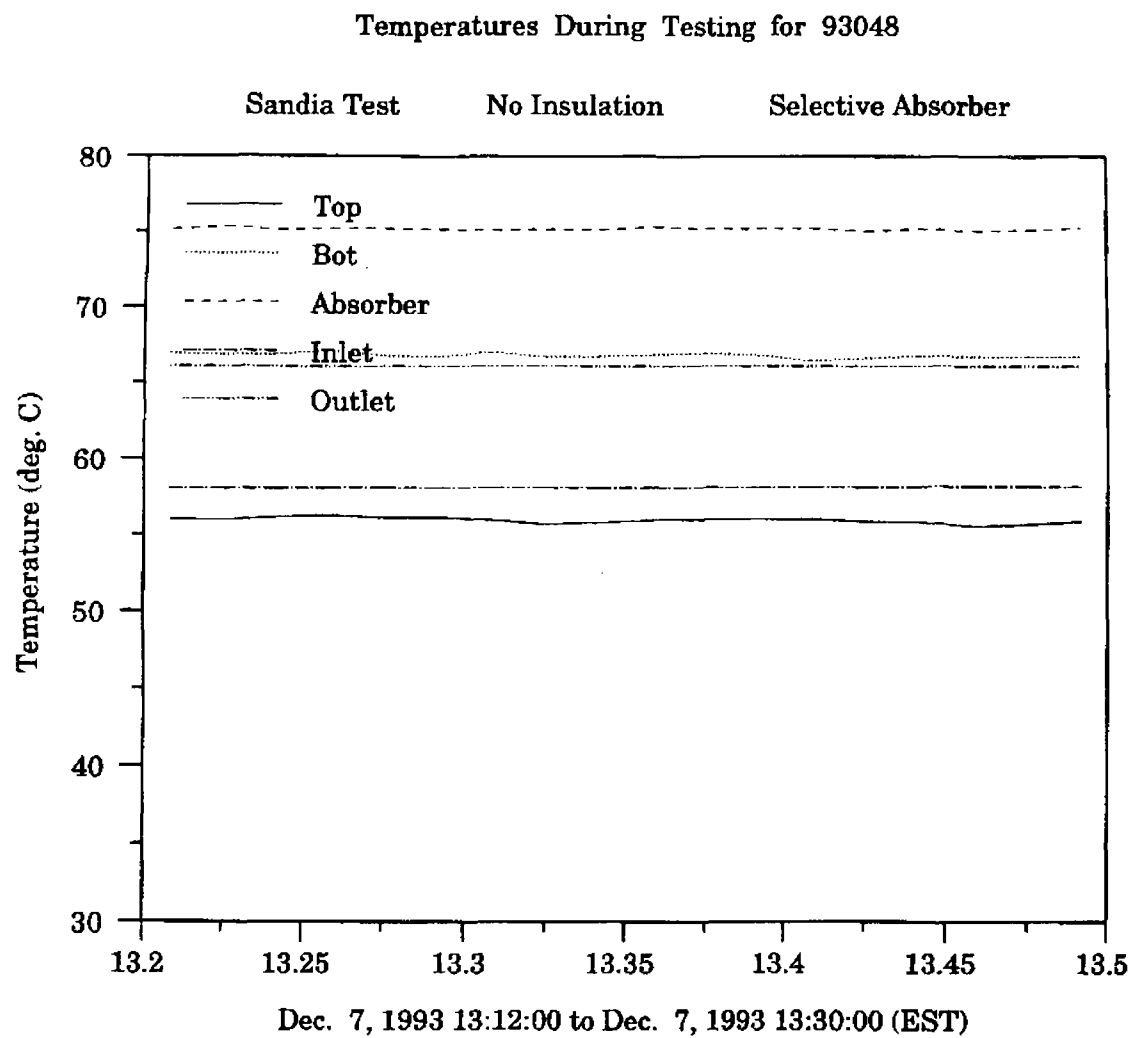
Type T thermocouples were installed inside prior to testing in order to gain insight into the temperatures internal to the collector. A total of six thermocouples were installed. Two of these were epoxied directly to the absorber. Two more were placed in air just under the level where the TIM would sit. The final two thermocouples were placed at a level corresponding the top of the TIM. One set of thermocouples (top, bottom, absorber) were placed in the half of the collector nearest the inlet. The other set of thermocouples were placed in the half of the collector nearest the outlet. Special care was taken to keep direct sunlight from heating the bimetal junctions and the wires leading to them. Temperature data were recorded every thirty seconds during some of the performance and IAM tests.

The graphs which follow give the averaged top, bottom, and absorber thermocouple temperatures along with the inlet and outlet fluid temperatures. During some periods only one of the top and one of the bottom temperatures was available. These periods are noted on the graphs by their lack of absorber temperature data. The first seven graphs present data from actual performance testing periods used in the final data reduction. The next graph shows the transients associated with removing the tarpaulins which covered the collector when not in use. This produces a sharp transition from no solar input to almost full sun. The data for the last graph were taken during a period of no solar input. Conducted at normal testing fluid flow rates, this graph demonstrates the absorber to ambient heat loss characteristics.

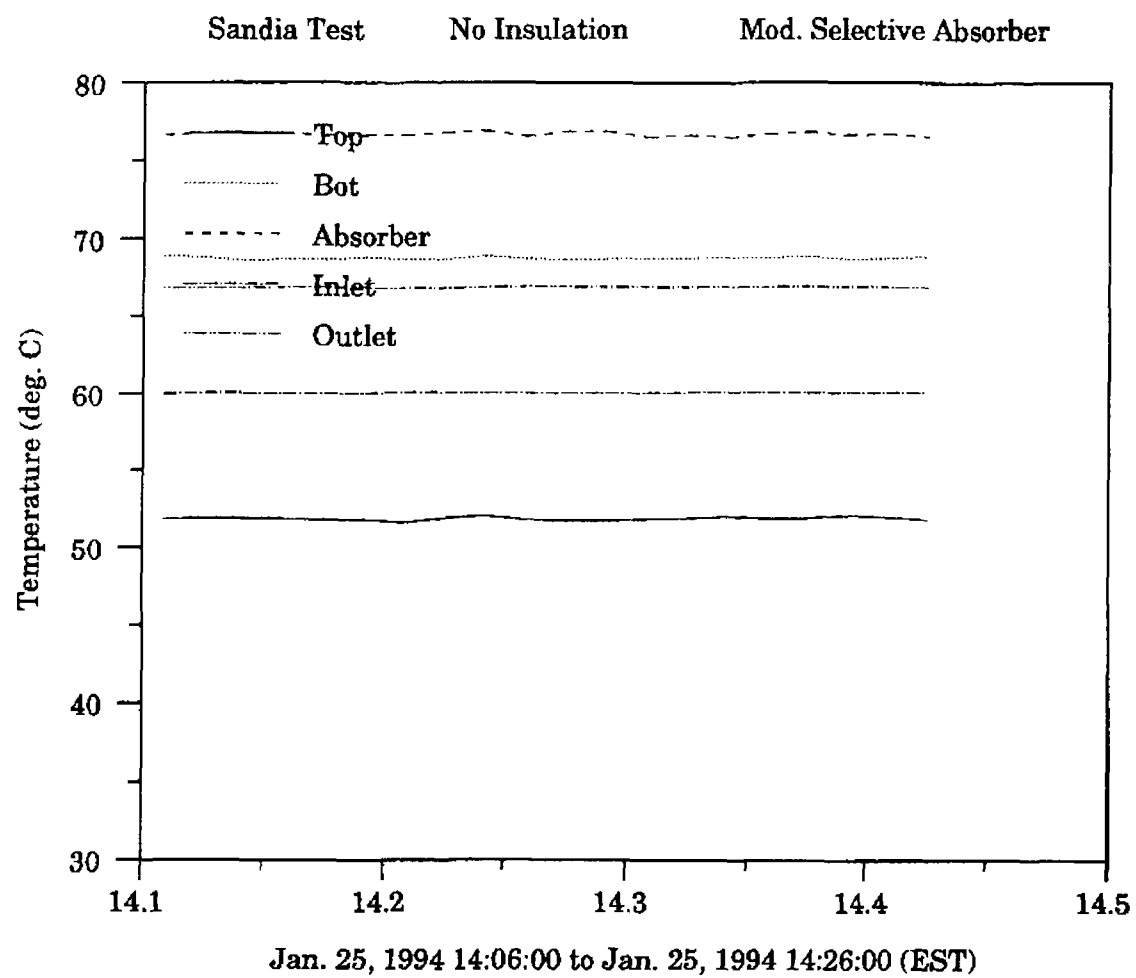


Temperatures During Testing for 93048

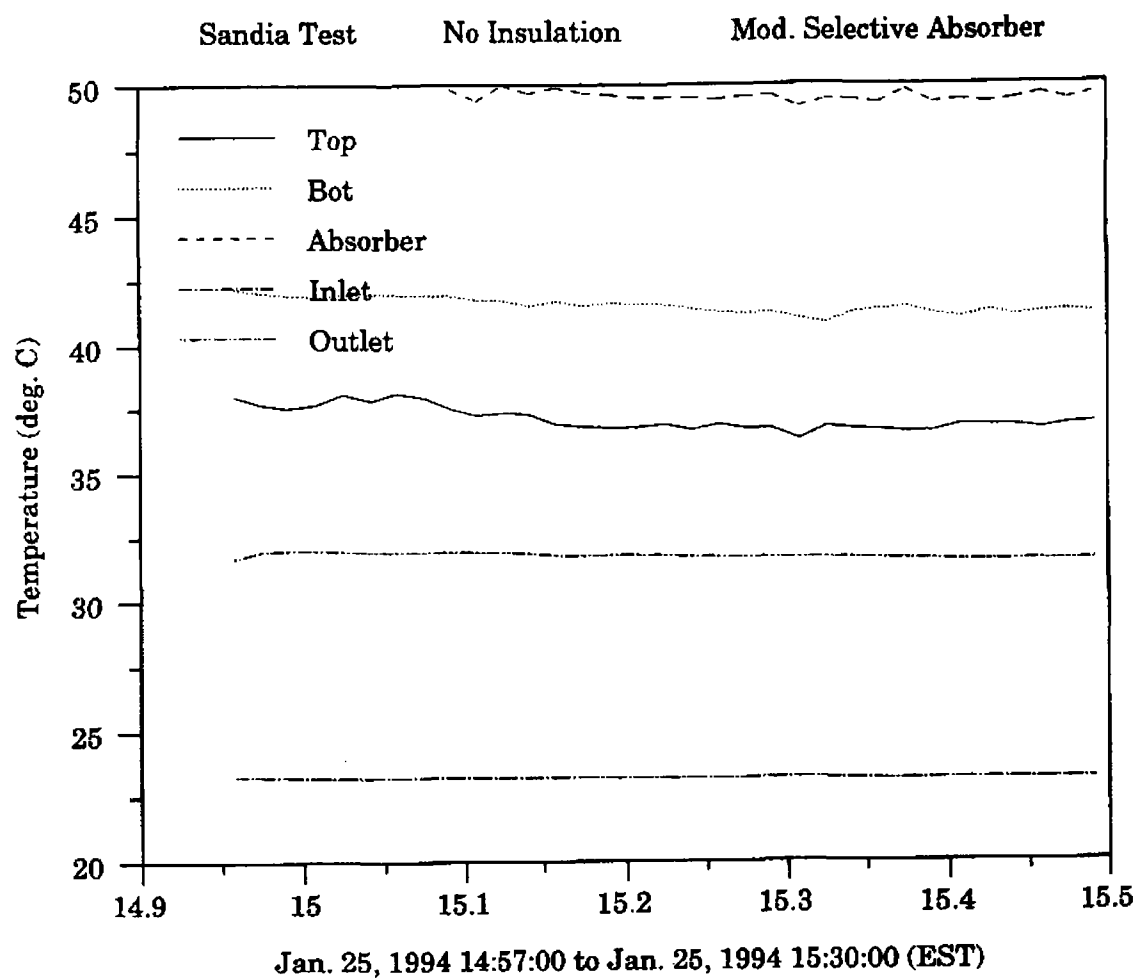




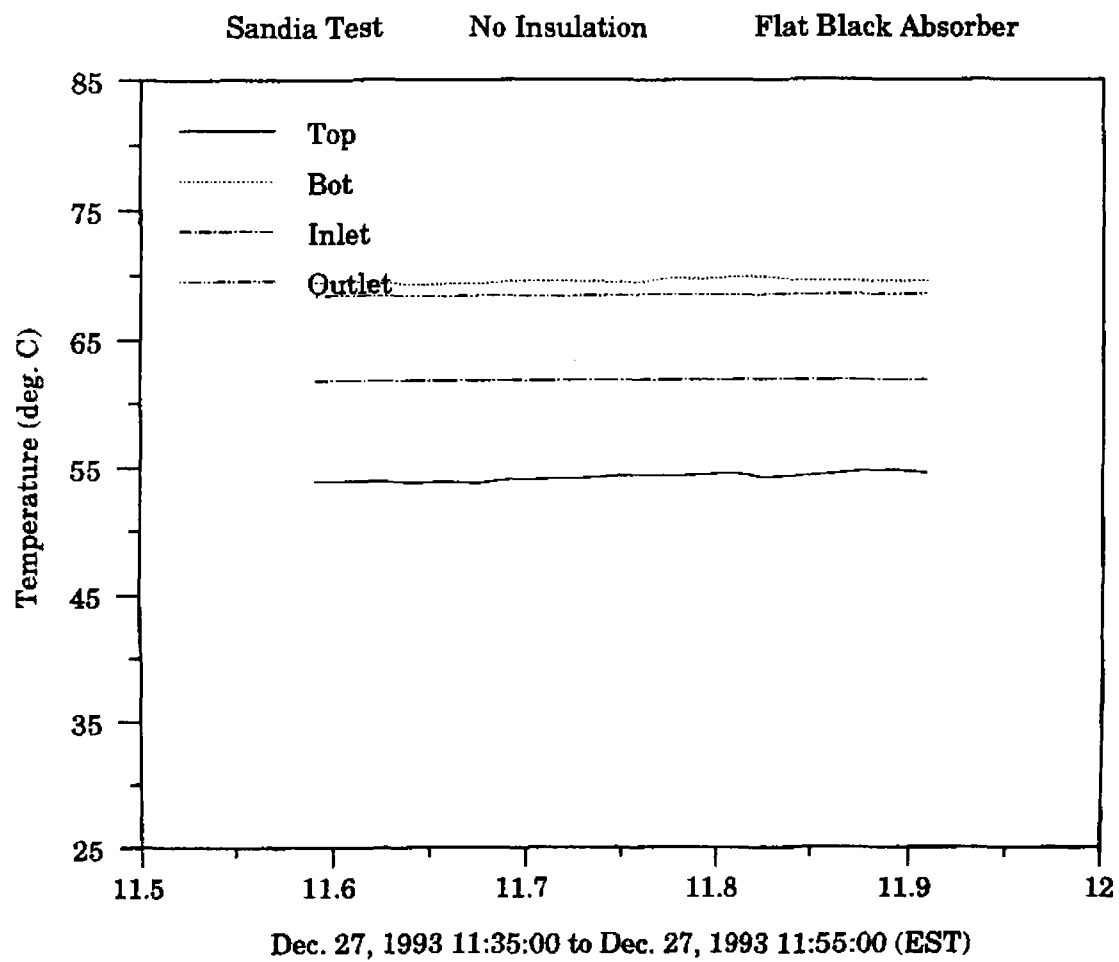
Temperatures During Testing for 93048



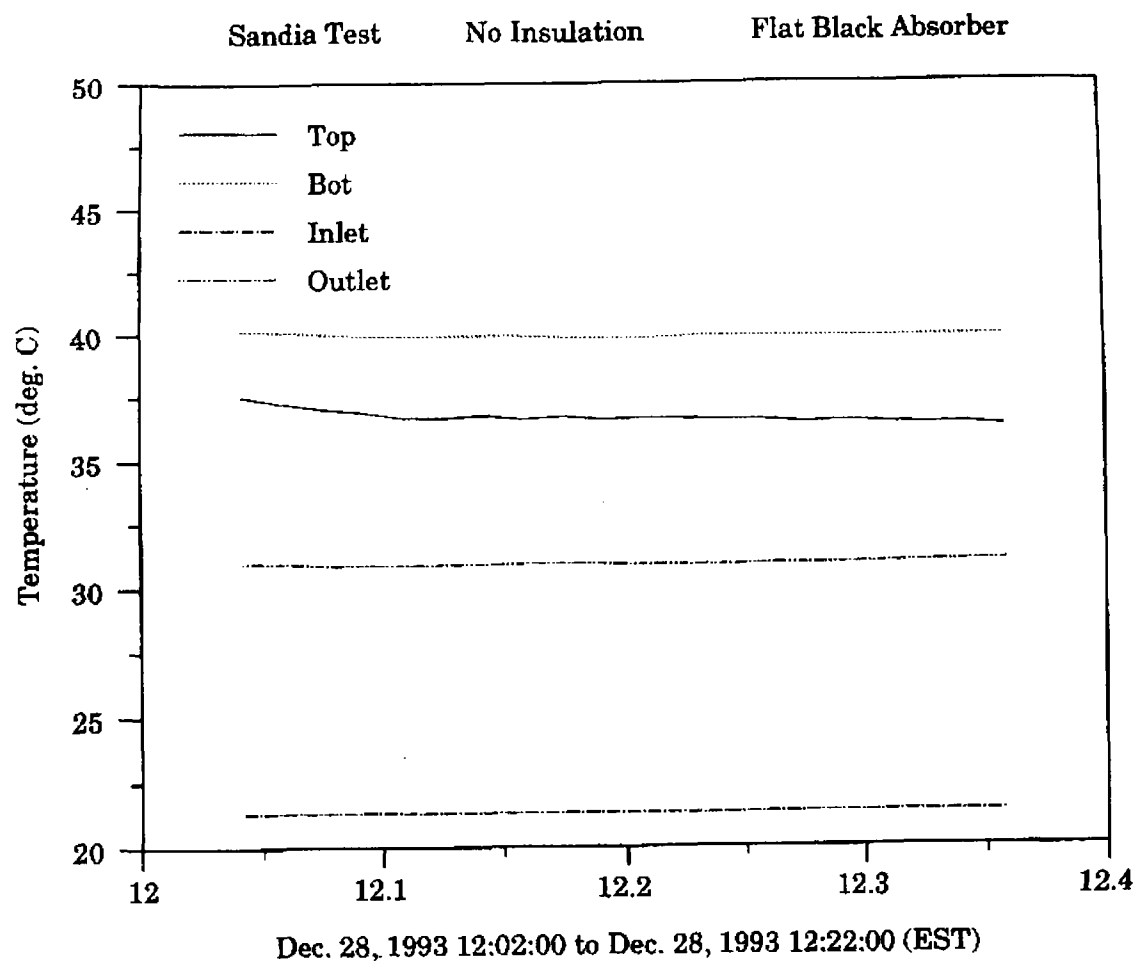
Temperatures During Testing for 93048



Temperatures During Testing for 93048



Temperatures During Testing for 93048

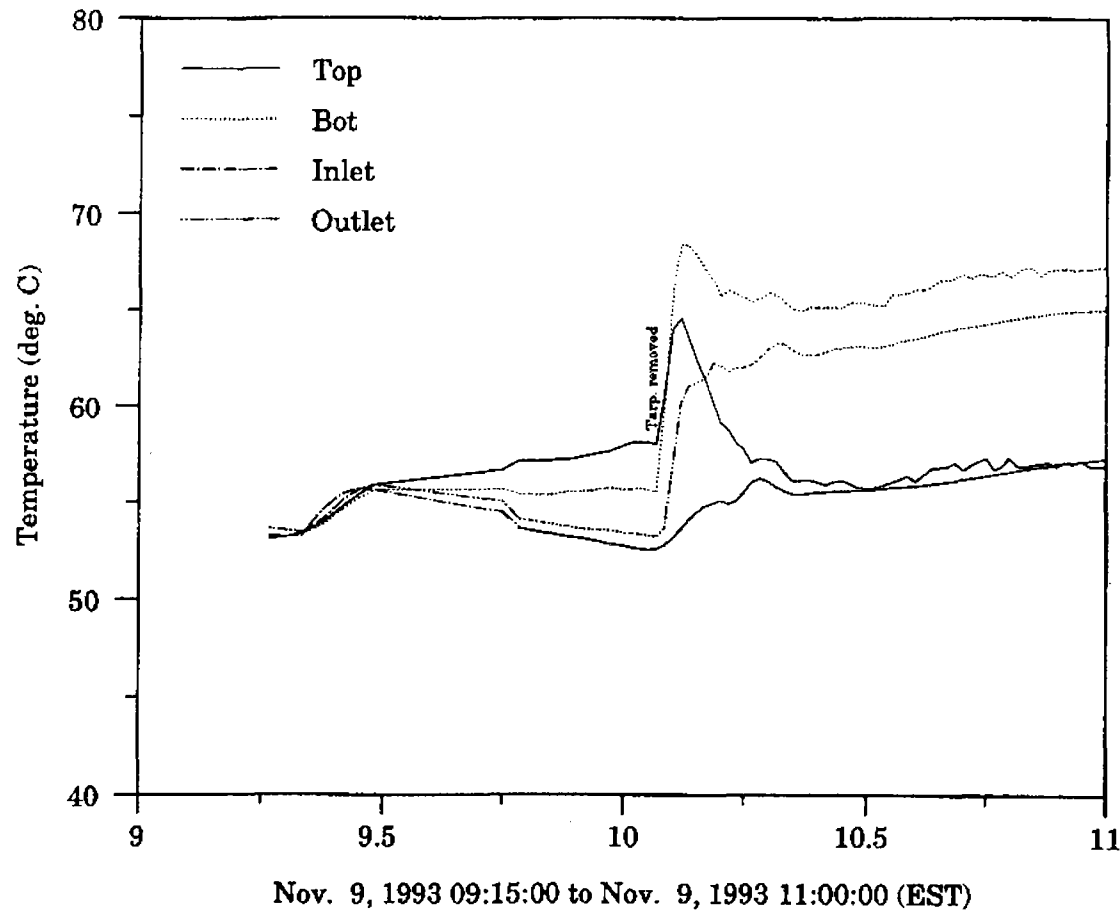


Temperatures During Collector Uncovering for 93048

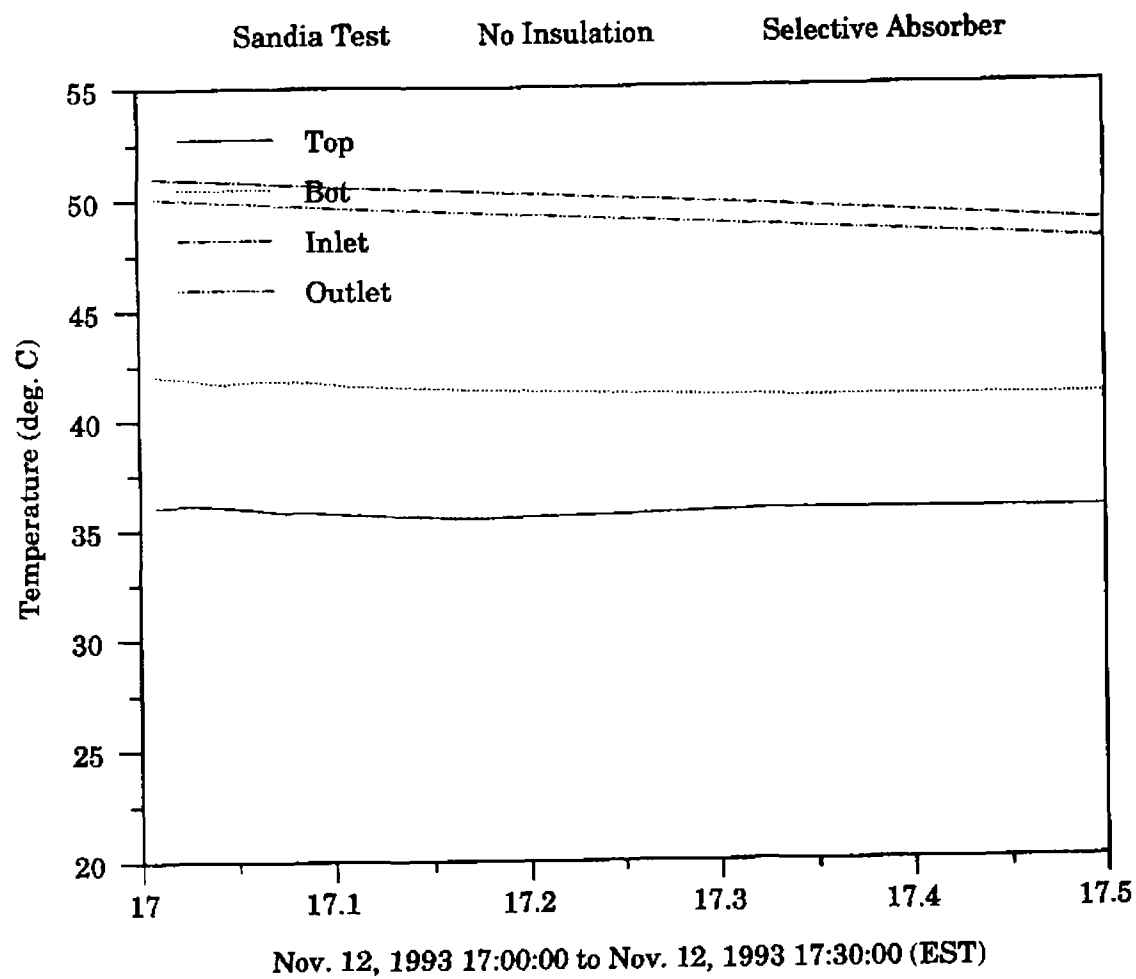
Sandia Test

No Insulation

Selective Absorber



Temperatures During No Solar Input for 93048



3.1.9 COLLECTOR STAGNATION

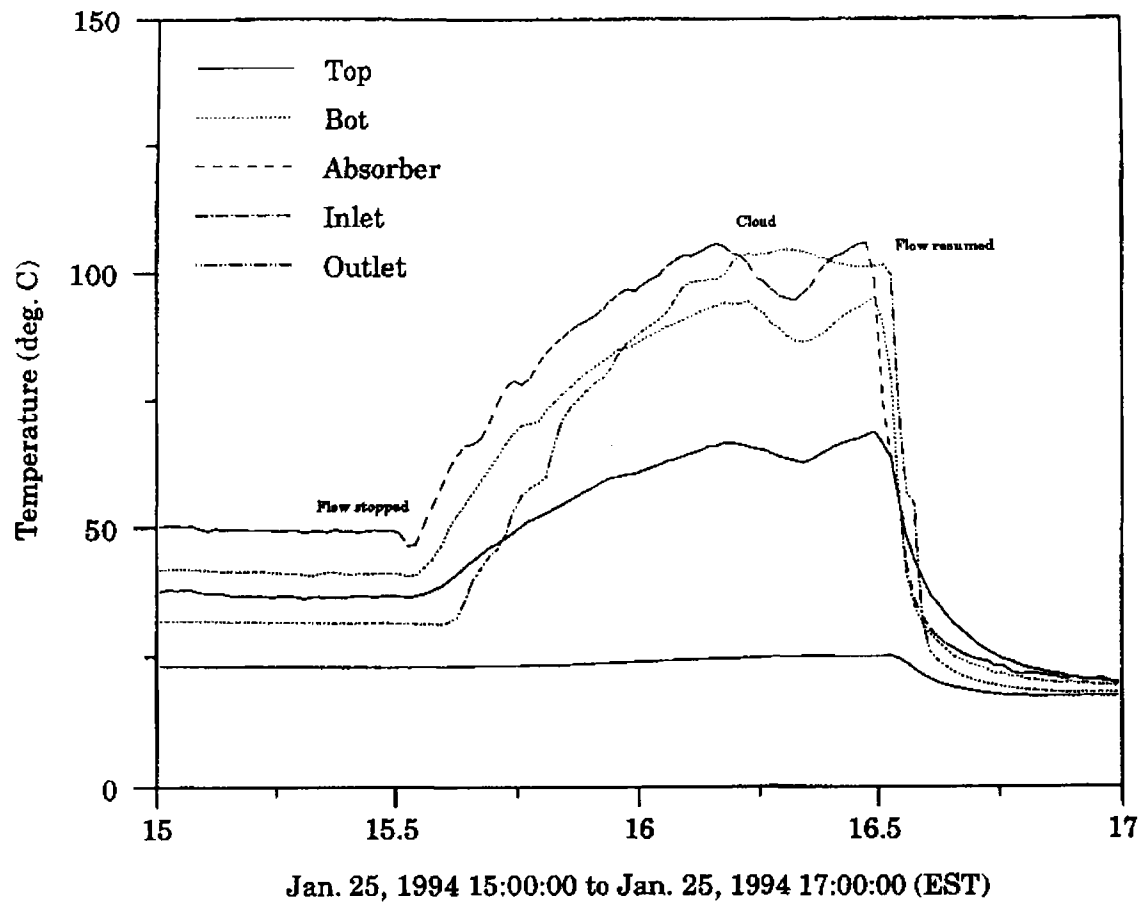
On 25 January 1994 the collectors in this series of tests were inadvertently left uncovered and facing the sun during a no fluid flow period. This constituted a wet stagnation. Although the flow was resumed about an hour later the internal temperatures had already exceeded the point where damage to some of the TIM takes place. The temperature data for this collector during that period is provided on the following page. The damage to the TIM effectively ended the comparison test. A performance test run later showed that this collector with no TIM collectors showed no change in performance.

Wet Stagnation Temperatures for 93048

Sandia Test

No Insulation

Mod. Selective Absorber



3.2 TEST RESULTS ON SOLAR COLLECTOR WITH 1" RECTANGULAR TIM

The SDCRW(4x8) collector was modified as described in section 1.3 to contain 1" rectangular transparent insulation material (TIM). The collector was then tested in accordance with FSEC Test Methods and Minimum Standards for Certifying Solar Collectors, FSEC 77-5-R80. The tests performed were:

Thermal Performance Test

Incident Angle Modifier Test

Internal temperatures during some of the tests were recorded from the installed thermocouples. Data are also included from the inadvertent wet stagnation that took place after the other testing was completed.

3.2.1 COLLECTOR IDENTIFICATION

Manufacturer and Address: Solar Development Inc.

3607-A Prospect Ave.

Riviera Beach, FL 33404

Collector Model Number: SD7CRW(4x8) with 1" rectangular transparent insulation added

3.2.2 COLLECTOR CONSTRUCTION BEFORE MODIFICATION

Overall dimensions*: Length: 2.444 m (8.02 ft)

Width: 1.189 m (3.90 ft)

Depth: 0.098 m (0.32 ft)

Overall front area*: (length x width) = 2.903 m² (31.25 ft²)

Enclosure: Material: Aluminum frame, aluminum back

Surface finish: Painted aluminum

Fasteners: Stainless steel screws and aluminum rivets

Holes and cutouts: Frame has holes and gaskets for each end of both headers

Glazing: Number of cover plates: One

Material: Tempered low iron glass

Thickness: 0.32 cm (0.125 in)

Length: 2.441 m (8.01 ft)

Width: 1.167 m (3.83 ft)

Surface: Smooth on outside, textured on inside

Glazing seal: EPDM rubber

Transparent frontal dimensions*: Area: 2.743 m² (29.53 ft²)

Absorber: Flow pattern: Parallel

Number of tubes: Ten

Spacing between tubes: 11.2 cm (4.4 in)

Material: Copper tubes welded to copper fins

Length: 2.283 m (7.49 ft)

Width: 1.119 m (3.67 ft)

Area: 2.554 m² (27.49 ft²)

Plate thickness: 0.046 cm (0.018 in)

Tube diameter (OD): 1.6 cm (0.63 in)

Header diameter (OD): 2.9 cm (1.13 in)

Flow tube to header connection: Brazed

Air spacing, glazing to absorber: approx. 3.2 cm (1.3 in)

Side insulation: Type: Foil faced polyisocyanurate

Thickness: 2.5 cm (1.0 in)

Back insulation: Type: Foil faced polyisocyanurate

Thickness: 4.4 cm (1.8 in)

Caulking, sealant, and/or gasket types(s): EPDM gaskets

Heat transfer fluid: Material: Water

Density: 977.81 kg/m³ at 70°C (61.01 lb/ft³ at 160°F)

Specific heat: 4189.6 J/kg°C at 70°C (1.001 Btu/lb°F at 160°F)

Collector weight:* 48.5 kg (107.0 lbs)

Collector fluid capacity*: 3.8 liters (1.0 gallons)

* Information provided by manufacturer; not verified by FSEC.

3.2.3 COLLECTOR MODIFICATIONS

This collector was one of a group of four being tested side by side to investigate the effects on performance of adding transparent insulation material (TIM) between the absorber and the glazing. This particular collector was modified to contain one-inch thick TIM. Structural modifications were not necessary. Silicon sealant was used in place of the EPDM gasket for this collector in order to make the glazing contact the top of the TIM. To support the TIM off of the absorber, nine strips of wood 3/16" thick and 3/8" wide were placed widthwise across the absorber. These strips were the same size and number as in the other collectors. Six type T thermocouple were placed in the collector. Two thermocouples were attached to the absorber, two were placed in air just below the TIM, and two were placed on top of the TIM. The thermocouple wires were run along the side insulation and exited the frame through two small holes.

The TIM used in this collector was purchased from JND Sterling, Inc. of Atlanta, Georgia. This TIM has a honeycomb like structure with rectangular cells. The following properties were measured:

Thickness: 2.49 cm (0.98 in.)

Cell shape:	Rectangular (almost square)
Cell size (per side):	0.28 cm (0.11 in.)
Intercell wall thickness:	0.005 cm (0.002 in.)
Material:*	Polycarbonate

All the collectors in this series of tests were covered with tarpaulins when in a no water flow condition. This prevented damage to the TIM in one collector and gave all the collectors the same amount of exposure.

Tests were run with three absorbers, each with a different coating. The manufacturer of the collectors shipped the collectors with the selectively coated absorber already installed. They also provided the two other absorbers, one with a moderately selective paint coating and one with a flat black paint coating.

After all modifications were complete the collector was measured. The final dimensions are as follows:

Gross length:	2.46 m (8.06 ft)
Gross width:	1.19 m (3.91 ft)
Gross area:	2.93 m ² (31.49 ft ²)
Transparent length:	2.41 m (7.90 ft)
Transparent width:	1.14 m (3.74 ft)
Transparent area:	2.74 m ² (29.53 ft ²)

* Information provided by manufacturer; not verified by FSEC.

3.2.4 THERMAL PERFORMANCE WITH SELECTIVE ABSORBER

The collector, outfitted with a selective black chrome coated absorber, was tested from 16 November - 16 December 1993 in accordance with ASHRAE procedure 93-1986. Results of the thermal performance tests are presented in graphical and tabular form in both the International System of Units (SI) and English units. The thermal performance equations in S.I. units developed from the empirical data are:

$$\text{first order} \quad \eta = 67.3 - 263 \quad (T_i - T_a)/I$$

$$\text{second order} \quad \eta = 67.4 - 315 \quad (T_i - T_a)/I + 1629 \quad [(T_i - T_a)/I]^2$$

These equations in English units are:

$$\text{first order} \quad \eta = 67.3 - 46 \quad (T_i - T_a)/I$$

$$\text{second order} \quad \eta = 67.4 - 55 \quad (T_i - T_a)/I + 51 \quad [(T_i - T_a)/I]^2$$

TABLE 3.7 THERMAL PERFORMANCE TEST ON 1" REC WITH SELECTIVE ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	FLOW AVE IN	TOTAL IN	TE-TI	DEL T	EFFIC	(TI-TA)/I
		START END	(C)	(C)	(C)	L/MIN W/M ²	J/M ²	(C)	C-MIN	%	(C-M ²)/W
1	11/16/93	11:21 11:25	27.1	58.2	66.0	3.25 1017.2	305145.	7.79	39.0	58.3	0.0305
2	11/16/93	11:26 11:30	27.1	58.2	66.0	3.24 1017.9	305383.	7.83	39.1	58.3	0.0305
5	11/16/93	11:41 11:45	27.3	58.3	66.2	3.19 1021.5	306452.	7.93	39.7	58.1	0.0303
6	11/16/93	11:46 11:50	27.2	58.2	66.2	3.18 1021.7	306512.	8.01	40.0	58.3	0.0304
9	11/16/93	12:29 12:34	27.3	49.1	57.2	3.30 1019.8	305947.	8.05	40.2	61.2	0.0214
10	11/16/93	12:34 12:39	27.2	49.1	57.1	3.30 1017.8	305347.	8.02	40.1	61.1	0.0215
11	11/16/93	12:39 12:44	27.1	49.1	57.0	3.31 1016.6	304984.	7.95	39.8	60.8	0.0216
14	11/16/93	12:54 12:59	27.2	49.1	57.0	3.32 1015.7	304723.	7.98	39.9	61.3	0.0215
15	11/16/93	12:59 13:04	27.2	49.1	57.0	3.33 1015.2	304558.	7.93	39.7	61.2	0.0215
16	11/16/93	13:04 13:09	27.2	49.1	57.0	3.32 1014.1	304224.	7.93	39.7	61.1	0.0216
21	11/16/93	14:27 14:32	26.9	39.7	47.9	3.20 972.1	291644.	8.19	41.0	63.6	0.0132
22	11/16/93	14:32 14:37	26.8	39.7	47.8	3.20 968.6	290581.	8.15	40.8	63.6	0.0133
23	11/16/93	14:37 14:42	26.8	39.7	47.8	3.19 962.9	288875.	8.14	40.7	63.6	0.0134
24	11/16/93	14:42 14:47	26.8	39.7	47.8	3.18 955.0	286505.	8.09	40.5	63.6	0.0135
32	11/17/93	13:36 13:41	28.0	28.3	36.7	3.29 979.2	293746.	8.42	42.1	67.0	0.0003
33	11/17/93	13:41 13:46	27.7	28.3	36.7	3.29 974.0	292195.	8.37	41.9	67.0	0.0006
39	11/18/93	13:58 14:02	26.5	26.8	35.0	3.27 946.8	284043.	8.15	40.8	66.6	0.0004
41	11/18/93	14:08 14:12	26.2	26.8	34.9	3.27 941.0	282297.	8.10	40.5	66.7	0.0007
43	11/18/93	14:18 14:22	26.4	26.9	34.7	3.28 916.7	275013.	7.86	39.3	66.6	0.0005
45	11/18/93	14:53 14:59	26.2	39.4	46.4	3.30 861.8	258538.	7.01	35.1	63.3	0.0153
46	11/18/93	14:58 15:03	26.3	39.4	46.3	3.30 850.3	255092.	6.92	34.6	63.3	0.0153
47	11/18/93	15:03 15:08	26.1	39.3	46.2	3.30 841.3	252396.	6.88	34.4	63.6	0.0158
52	12/07/93	09:10 09:14	17.7	17.3	25.6	3.26 948.4	284531.	8.33	41.6	68.2	-0.0004
53	12/07/93	09:15 09:19	17.9	17.4	25.8	3.27 954.8	286446.	8.40	42.0	68.3	-0.0005
54	12/07/93	09:20 09:24	18.0	17.4	25.9	3.26 963.4	289013.	8.46	42.3	68.1	-0.0006
59	12/07/93	10:36 10:41	20.1	39.4	47.7	3.34 1040.3	312099.	8.30	41.5	62.9	0.0186
60	12/07/93	10:41 10:46	20.3	39.4	47.8	3.34 1043.0	312914.	8.33	41.7	63.0	0.0184
61	12/07/93	10:46 10:51	20.4	39.5	47.8	3.35 1046.2	313852.	8.35	41.8	63.0	0.0183
62	12/07/93	12:57 13:01	21.6	56.9	64.9	3.35 1049.8	314947.	7.98	39.9	59.6	0.0337
63	12/07/93	13:02 13:06	21.6	57.0	64.9	3.35 1047.0	314102.	7.94	39.7	59.5	0.0338
64	12/07/93	13:07 13:11	21.5	57.0	64.9	3.35 1042.8	312852.	7.90	39.5	59.4	0.0340
66	12/07/93	13:17 13:21	21.5	57.0	64.9	3.35 1036.4	310914.	7.87	39.4	59.5	0.0343

TABLE 3.7 THERMAL PERFORMANCE TEST ON 1" REC WITH SELECTIVE ABSORBER (SI UNITS CONTINUED)

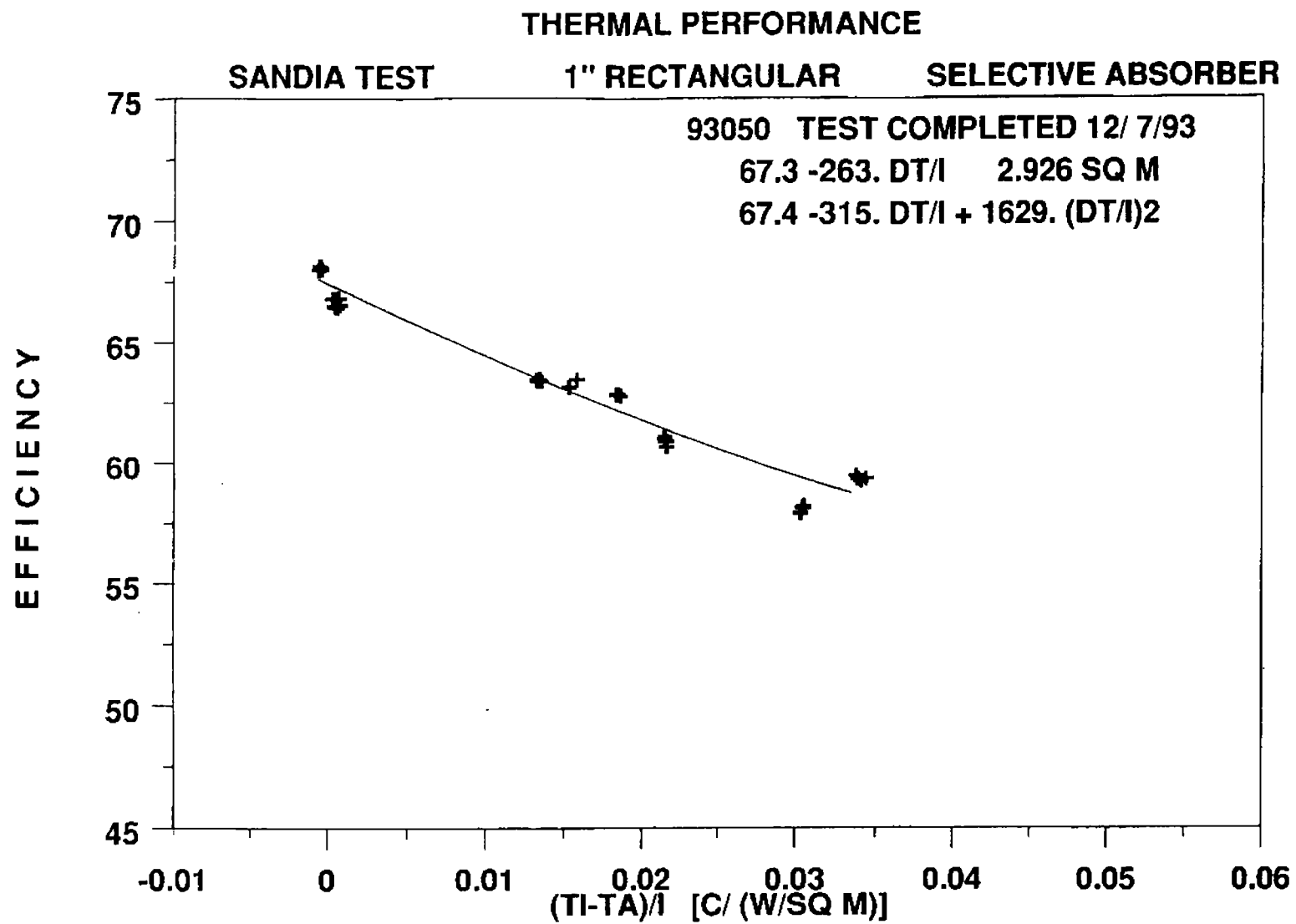
TEST	TILT DEG	AZIM DEG	INCI DEG	MASS KG/SEC	SPEC HEAT J/(KG C)	IN P KN/M ²	WIND M/S	WIND DIR	DIF IN W/M ²	% DIFF INSOL	TI-TA (C)
1	49.	11.	0.	0.0532	4185.2	62.6	2.4	99.	134.3	13.2	31.1
2	48.	10.	0.	0.0530	4185.2	62.8	2.8	97.	132.3	13.0	31.0
5	48.	5.	0.	0.0523	4185.2	64.8	3.0	107.	128.5	12.6	31.0
6	48.	4.	0.	0.0520	4185.2	63.7	2.5	106.	129.2	12.6	31.1
9	48.	-10.	0.	0.0543	4181.6	60.3	2.4	103.	129.0	12.6	21.9
10	49.	-12.	0.	0.0542	4181.5	60.3	3.0	94.	132.3	13.0	21.9
11	49.	-13.	0.	0.0544	4181.5	58.7	2.4	98.	132.6	13.0	22.0
14	50.	-18.	0.	0.0545	4181.5	46.4	2.3	104.	129.4	12.7	21.8
15	50.	-19.	0.	0.0548	4181.5	60.8	2.4	107.	128.3	12.6	21.9
16	50.	-21.	0.	0.0546	4181.5	61.1	2.2	103.	128.9	12.7	21.9
21	60.	-42.	0.	0.0529	4179.2	63.8	2.2	107.	123.9	12.7	12.8
22	61.	-43.	0.	0.0528	4179.2	62.9	2.4	108.	122.5	12.7	12.8
23	62.	-44.	0.	0.0527	4179.2	62.6	2.0	98.	123.3	12.8	12.9
24	62.	-45.	0.	0.0525	4179.2	61.2	2.2	102.	123.0	12.9	12.9
32	54.	-29.	0.	0.0546	4177.9	87.9	1.5	175.	170.6	17.4	0.3
33	54.	-31.	0.	0.0546	4177.9	87.6	2.2	173.	173.6	17.8	0.6
39	56.	-35.	0.	0.0542	4178.1	71.1	2.1	114.	191.4	20.2	0.3
41	58.	-37.	0.	0.0543	4178.1	59.0	2.0	110.	192.6	20.5	0.7
43	59.	-39.	0.	0.0544	4178.1	49.1	1.9	104.	198.1	21.6	0.5
45	64.	-47.	0.	0.0544	4179.1	70.3	1.8	100.	190.2	22.1	13.1
46	65.	-47.	0.	0.0544	4179.1	67.1	1.7	106.	190.2	22.4	13.0
47	66.	-48.	0.	0.0544	4179.1	65.5	1.9	90.	189.2	22.5	13.3
52	65.	43.	0.	0.0543	4181.6	79.8	1.3	357.	116.2	12.3	-0.4
53	64.	42.	0.	0.0543	4181.5	77.7	1.3	350.	117.5	12.3	-0.5
54	64.	41.	0.	0.0543	4181.5	79.7	1.7	349.	118.8	12.3	-0.6
59	55.	23.	0.	0.0552	4179.2	84.3	1.8	1.	123.1	11.8	19.3
60	54.	22.	0.	0.0552	4179.2	83.4	1.9	358.	125.4	12.0	19.2
61	54.	20.	0.	0.0552	4179.2	83.1	2.1	356.	124.0	11.9	19.1
62	53.	-17.	0.	0.0548	4184.6	83.4	1.5	5.	115.4	11.0	35.3
63	54.	-19.	0.	0.0548	4184.6	83.9	1.7	4.	115.8	11.1	35.4
64	54.	-20.	0.	0.0548	4184.6	84.3	1.8	7.	115.1	11.0	35.5
66	55.	-23.	0.	0.0548	4184.7	84.1	1.9	6.	115.5	11.1	35.5

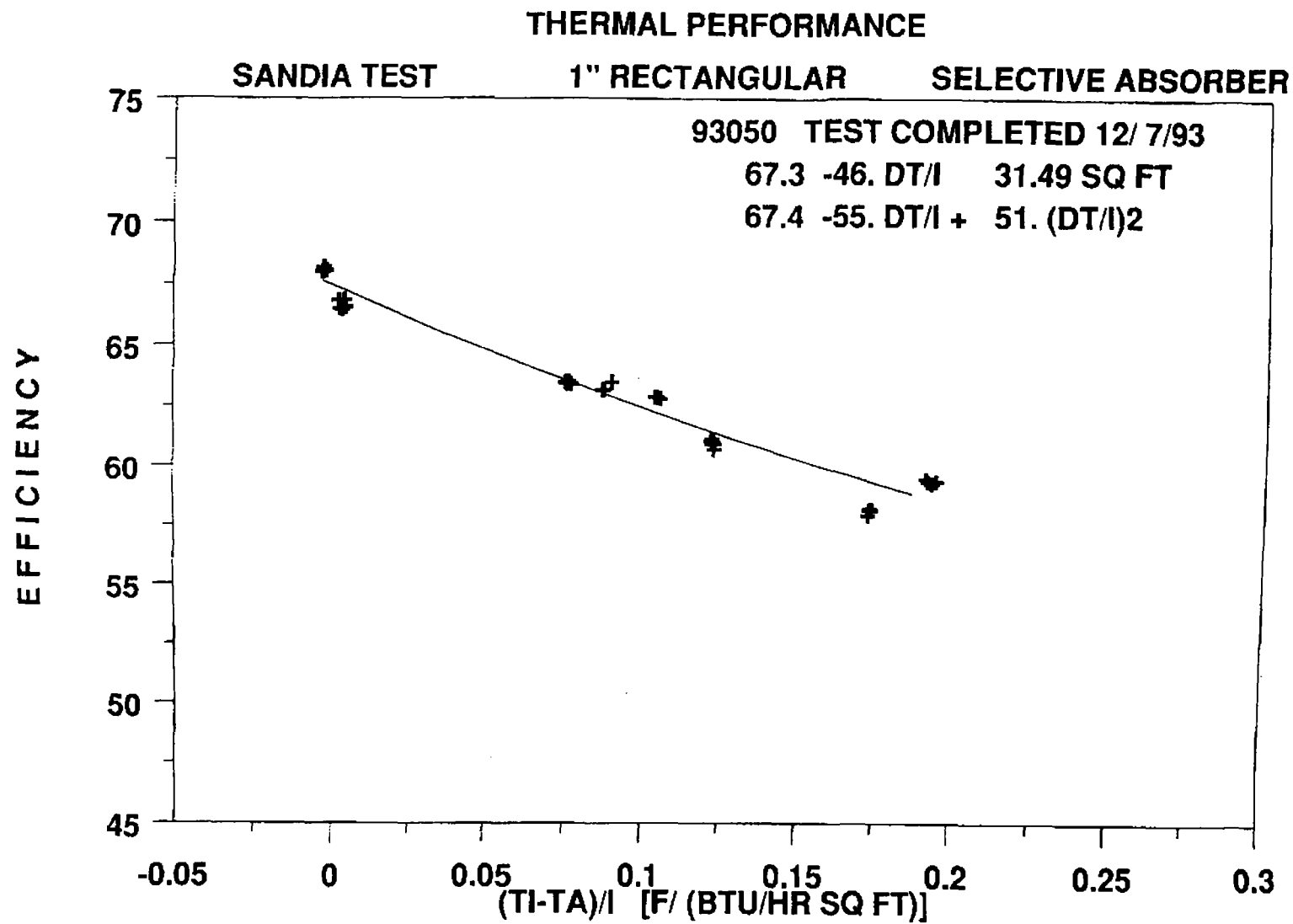
TABLE 3.7A THERMAL PERFORMANCE TEST ON 1" REC WITH SELECTIVE ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME START END	TA (F)	TI (F)	TE (F)	FLOW GPM	AVE IN B/H-FT ²	TOTAL IN BTU/FT ²	TE-TI (F)	DEL T F-MIN	EFFIC %	(TI-TA)/I (F-H-FT ²)/B
1	11/16/93	11:21 11:25	80.8	136.7	150.7	0.859	322.7	26.9	14.02	70.1	58.3	0.173
2	11/16/93	11:26 11:30	80.9	136.7	150.8	0.856	322.9	26.9	14.09	70.4	58.3	0.173
5	11/16/93	11:41 11:45	81.1	136.9	151.1	0.844	324.0	27.0	14.27	71.4	58.1	0.172
6	11/16/93	11:46 11:50	80.9	136.8	151.2	0.839	324.1	27.0	14.42	72.1	58.3	0.173
9	11/16/93	12:29 12:34	81.1	120.4	134.9	0.872	323.5	27.0	14.48	72.4	61.2	0.122
10	11/16/93	12:34 12:39	81.0	120.4	134.8	0.871	322.9	26.9	14.43	72.2	61.1	0.122
11	11/16/93	12:39 12:44	80.8	120.4	134.7	0.874	322.5	26.9	14.32	71.6	60.8	0.123
14	11/16/93	12:54 12:59	81.0	120.3	134.7	0.877	322.2	26.9	14.37	71.8	61.3	0.122
15	11/16/93	12:59 13:04	81.0	120.4	134.6	0.880	322.0	26.8	14.28	71.4	61.2	0.122
16	11/16/93	13:04 13:09	81.0	120.4	134.7	0.878	321.7	26.8	14.28	71.4	61.1	0.123
21	11/16/93	14:27 14:32	80.4	103.4	118.2	0.846	308.4	25.7	14.74	73.7	63.6	0.075
22	11/16/93	14:32 14:37	80.3	103.4	118.1	0.846	307.3	25.6	14.68	73.4	63.6	0.075
23	11/16/93	14:37 14:42	80.2	103.4	118.0	0.843	305.4	25.5	14.65	73.3	63.6	0.076
24	11/16/93	14:42 14:47	80.2	103.4	118.0	0.840	302.9	25.2	14.56	72.8	63.6	0.077
32	11/17/93	13:36 13:41	82.4	83.0	98.1	0.869	310.6	25.9	15.15	75.7	67.0	0.002
33	11/17/93	13:41 13:46	81.8	83.0	98.0	0.869	309.0	25.7	15.07	75.3	67.0	0.004
39	11/18/93	13:58 14:02	79.7	80.3	95.0	0.863	300.3	25.0	14.37	73.4	66.6	0.002
41	11/18/93	14:08 14:12	79.1	80.3	94.9	0.864	298.5	24.9	14.58	72.9	66.7	0.004
43	11/18/93	14:18 14:22	79.5	80.3	94.5	0.866	290.8	24.2	14.14	70.7	66.6	0.003
45	11/18/93	14:53 14:58	79.2	102.8	115.5	0.871	273.4	22.8	12.63	63.1	63.3	0.087
46	11/18/93	14:58 15:03	79.4	102.9	115.3	0.871	269.7	22.5	12.46	62.3	63.3	0.087
47	11/18/93	15:03 15:08	78.9	102.8	115.2	0.871	266.9	22.2	12.39	61.9	63.6	0.090
52	12/07/93	9:10 9:14	63.8	63.1	78.1	0.862	300.9	25.1	14.99	75.0	68.2	-0.002
53	12/07/93	9:15 9:19	64.2	63.2	78.4	0.863	302.9	25.2	15.12	75.6	68.3	-0.003
54	12/07/93	9:20 9:24	64.4	63.3	78.6	0.862	305.6	25.5	15.22	76.1	68.1	-0.003
59	12/07/93	10:36 10:41	68.2	103.0	117.9	0.883	330.0	27.5	14.95	74.7	62.9	0.105
60	12/07/93	10:41 10:46	68.5	103.0	118.0	0.884	330.9	27.6	15.00	75.0	63.0	0.104
61	12/07/93	10:46 10:51	68.6	103.1	118.1	0.884	331.9	27.7	15.03	75.2	63.0	0.104
62	12/07/93	12:57 13:01	70.9	134.5	148.9	0.884	333.0	27.8	14.36	71.8	59.6	0.191
63	12/07/93	13:02 13:06	70.8	134.5	148.8	0.884	332.1	27.7	14.30	71.5	59.5	0.192
64	12/07/93	13:07 13:11	70.7	134.6	148.8	0.884	330.8	27.6	14.23	71.1	59.4	0.193
66	12/07/93	13:17 13:21	70.7	134.7	148.8	0.884	328.8	27.4	14.17	70.8	59.5	0.194

TABLE 3.7A THERMAL PERFORMANCE TEST ON 1" REC WITH SELECTIVE ABSORBER (ENGLISH UNITS CONTINUED)

TEST	TILT DEG	AZIM DEG	INCI DEG	MASS LBM/MIN	SPEC HEAT BTU/(LBM-F)	IN P PSI	WIND MPH	WIND DIR	DIF IN B/H-FT ²	% DIFF INSOL	TI-TA (F)
1	49.	11.	0.7	.04	1.000	9.1	5.3	99.	42.6	13.2	55.9
2	48.	10.	0.	7.02	1.000	9.1	6.2	97.	42.0	13.0	55.8
5	48.	5.	0.	6.92	1.000	9.4	6.6	107.	40.8	12.6	55.8
6	48.	4.	0.	6.88	1.000	9.2	5.7	106.	41.0	12.6	55.9
9	48.	-10.	0.	7.18	0.999	8.7	5.3	103.	40.9	12.6	39.3
10	49.	-12.	0.	7.17	0.999	8.7	6.6	94.	42.0	13.0	39.4
11	49.	-13.	0.	7.20	0.999	8.5	5.5	98.	42.0	13.0	39.5
14	50.	-18.	0.	7.22	0.999	6.7	5.0	104.	41.0	12.7	39.3
15	50.	-19.	0.	7.24	0.999	8.8	5.3	107.	40.7	12.6	39.4
16	50.	-21.	0.	7.23	0.999	8.9	5.0	103.	40.9	12.7	39.4
21	60.	-42.	0.	6.99	0.998	9.2	5.0	107.	39.3	12.7	23.1
22	61.	-43.	0.	6.99	0.998	9.1	5.3	108.	38.9	12.7	23.1
23	62.	-44.	0.	6.97	0.998	9.1	4.5	98.	39.1	12.8	23.2
24	62.	-45.	0.	6.95	0.998	8.9	5.0	120.	39.0	12.9	23.2
32	54.	-29.	0.	7.22	0.998	12.7	3.4	175.	54.1	17.4	0.6
33	54.	-31.	0.	7.22	0.998	12.7	5.0	173.	55.1	17.8	1.1
39	56.	-35.	0.	7.17	0.998	10.3	4.7	114.	60.7	20.2	0.6
41	58.	-37.	0.	7.18	0.998	8.6	4.5	110.	61.1	20.5	1.2
43	59.	-39.	0.	7.20	0.998	7.1	4.3	104.	62.8	21.6	0.8
45	64.	-47.	0.	7.20	0.998	10.2	3.9	100.	60.3	22.1	23.7
46	65.	-47.	0.	7.20	0.998	9.7	3.7	106.	60.3	22.4	23.5
47	66.	-48.	0.	7.20	0.998	9.5	4.2	90.	60.0	22.5	23.9
52	65.	43.	0.	7.19	0.999	11.6	3.0	357.	36.9	12.3	-0.7
53	64.	42.	0.	7.19	0.999	11.3	2.9	350.	37.3	12.3	-0.9
54	64.	41.	0.	7.18	0.999	11.6	3.8	349.	37.7	12.3	-1.1
59	55.	23.	0.	7.30	0.998	12.2	4.0	1.	39.1	11.8	34.7
60	54.	22.	0.	7.30	0.998	12.1	4.3	358.	39.8	12.0	34.5
61	54.	20.	0.	7.31	0.998	12.1	4.7	356.	39.3	11.9	34.4
62	53.	-17.	0.	7.25	0.999	12.1	3.4	5.	36.6	11.0	63.6
63	54.	-19.	0.	7.25	0.999	12.2	3.9	4.	36.7	11.1	63.7
64	54.	-20.	0.	7.25	0.999	12.2	4.1	7.	36.5	11.0	63.9
66	55.	-23.	0.	7.25	0.999	12.2	4.2	6.	36.6	11.1	63.9





3.2.5 THERMAL PERFORMANCE WITH MODERATELY SELECTIVE ABSORBER

The collector, outfitted with a moderately selective black paint coated absorber, was tested on 25 January 1994 in accordance with ASHRAE procedure 93-1986. Only two different inlet temperatures tests were run for the moderately selective paint absorber. The customary minimum of four points was not taken because the collector was exposed to a period of wet stagnation. This stagnation may have caused some degradation to the TIM installed in this collector. Since only two points were taken only a linear fit could be developed. Results of the thermal performance tests are presented in graphical and tabular form in both the International System of Units (SI) and English units. The thermal performance equations in S.I. units developed from the empirical data are:

$$\text{first order} \quad \eta = 67.5 - 300 (T_i - T_a)/I$$

These equations in English units are:

$$\text{first order} \quad \eta = 67.5 - 53 (T_i - T_a)/I$$

TABLE 3.8 THERMAL PERFORMANCE TEST ON 1" REC WITH MODERATELY SELECTIVE ABSORBER (SI UNITS)

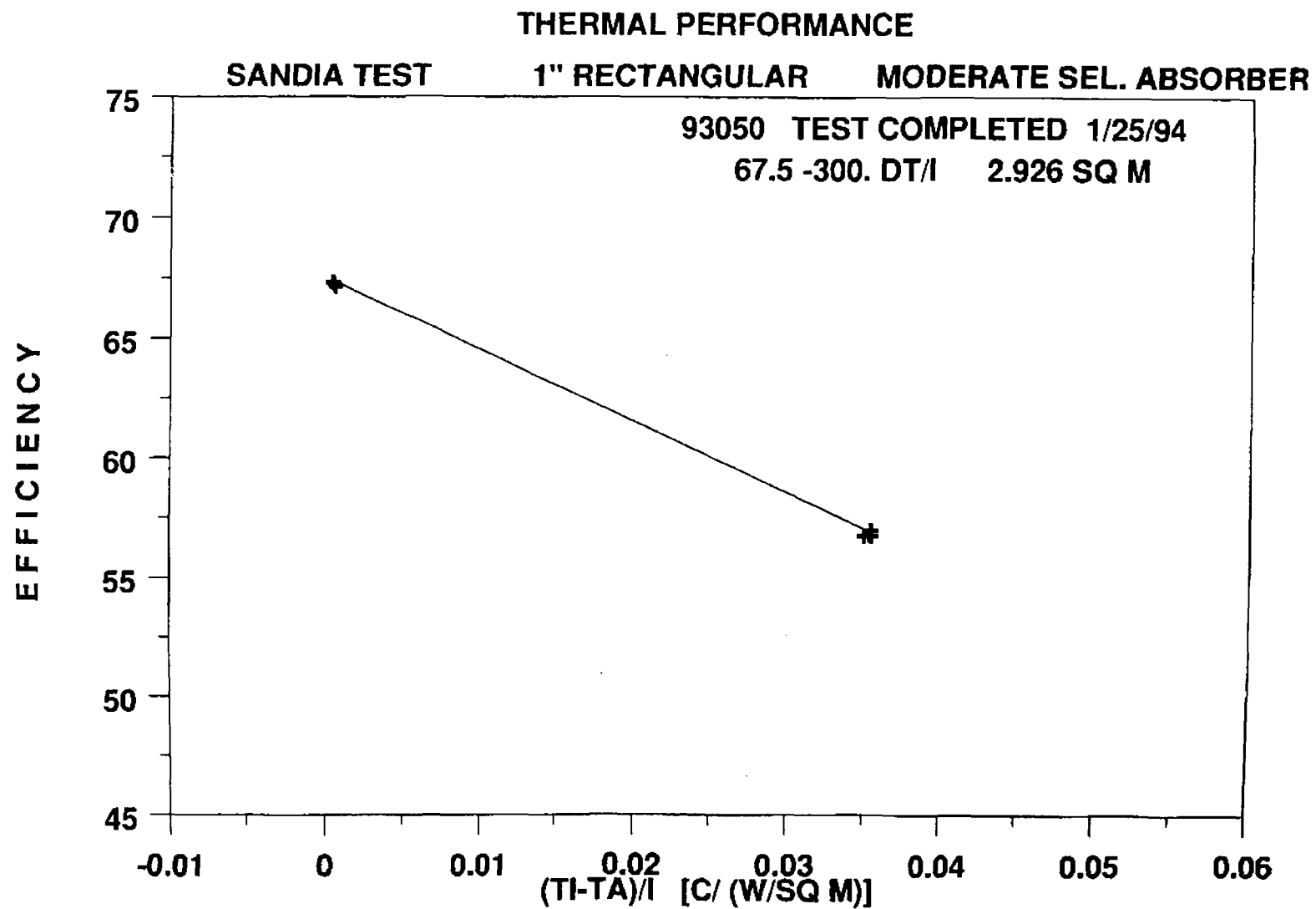
TEST	DATE	SOLAR TIME		TA	TI	TE	FLOW AVE IN		TOTAL IN	TE-TI	DEL T	EFFIC	(TI-TA)/I
		START	END	(C)	(C)	(C)	L/MIN	W/M ²	J/M ²	(C)	C-MIN	%	(C-M ²)/W
1	1/25/94	13:11	13:16	22.7	58.7	66.3	3.26	1021.8	306531.	7.62	38.1	56.9	0.0353
3	1/25/94	13:21	13:26	23.1	58.9	66.5	3.26	1023.7	307096.	7.63	38.2	56.9	0.0349
7	1/25/94	13:41	13:46	23.0	58.9	66.5	3.27	1016.9	305066.	7.60	38.0	57.1	0.0354
8	1/25/94	13:46	13:51	23.0	59.J	66.6	3.24	1015.0	304495.	7.61	38.1	56.9	0.0354
11	1/25/94	14:27	14:32	22.9	23.3	31.8	3.26	979.8	293951.	8.54	42.7	67.5	0.0004
13	1/25/94	14:37	14:42	22.7	23.2	31.6	3.26	965.4	289627.	8.40	42.0	67.4	0.0005
14	1/25/94	14:42	14:47	22.6	23.2	31.5	3.26	962.5	288756.	8.36	41.8	67.3	0.0006
16	1/25/94	14:52	14:57	22.7	23.1	31.4	3.26	945.9	283762.	8.24	41.2	67.5	0.0004

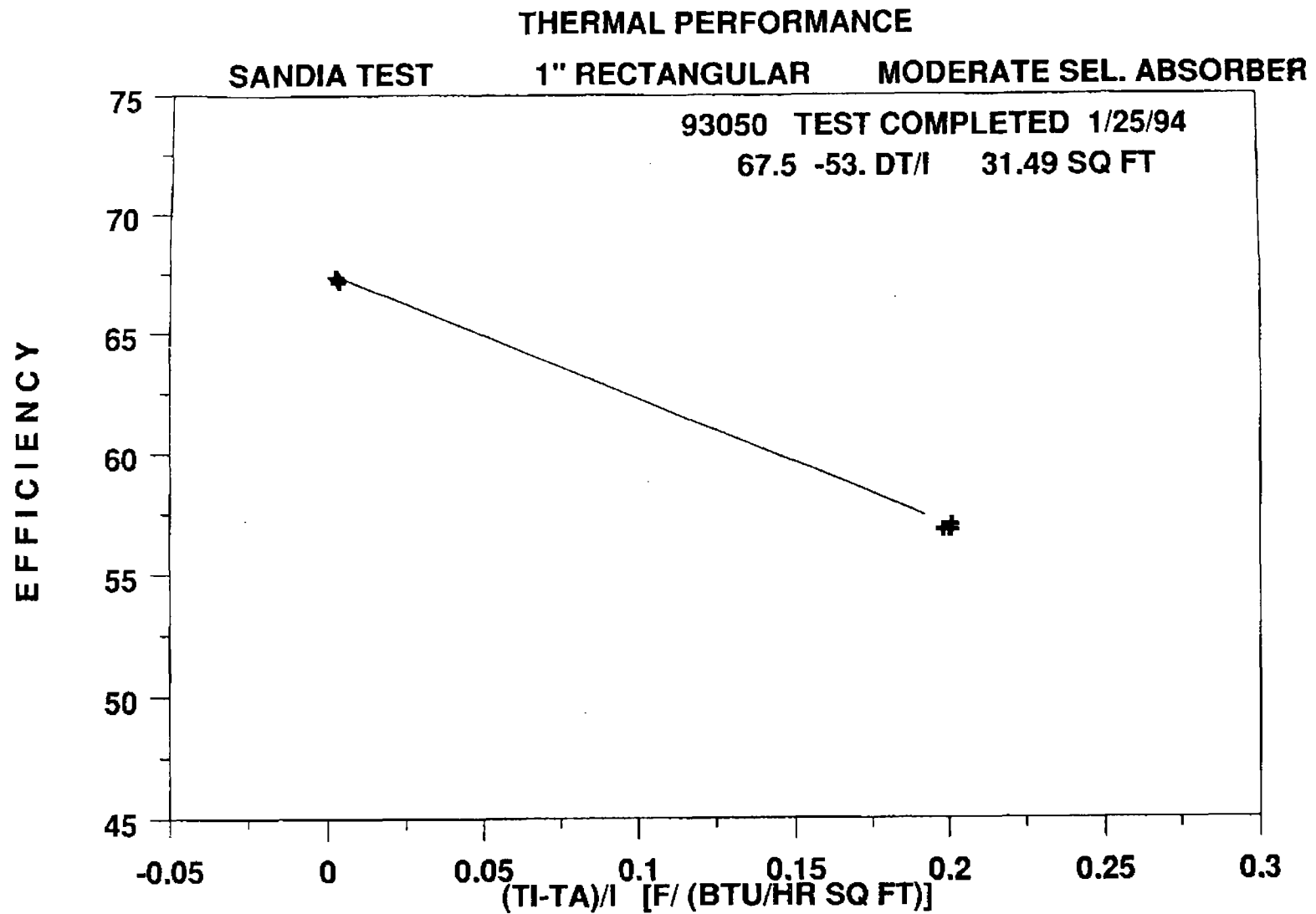
TEST	TILT	AZIM	INCI	MASS	SPEC HEAT	IN P	WIND	WIND	DIF IN	% DIFF	TI-TA
	DEG	DEG	DEG	KG/SEC	J/(KG C)	KN/M ²	M/S	DIR	W/M ²	INSOL	(C)
1	51.	-23.	0.	0.0533	4185.4	84.2	1.8	123.	149.7	14.6	36.0
3	52.	-25.	0.	0.0533	4185.5	84.2	1.7	107.	152.2	14.9	35.8
7	54.	-31.	0.	0.0535	4185.5	83.2	1.8	103.	136.6	13.4	36.0
8	54.	-32.	0.	0.0530	4185.5	83.5	2.2	106.	137.1	13.5	35.9
11	60.	-42.	0.	0.0542	4178.8	86.1	1.8	107.	144.0	14.7	0.4
13	61.	-44.	0.	0.0542	4178.8	85.2	2.4	112.	138.3	14.3	0.5
14	62.	-45.	0.	0.0542	4178.9	84.7	2.0	109.	138.3	14.4	0.5
16	64.	-47.	0.	0.0542	4178.9	84.0	2.1	102.	139.1	14.7	0.4

TABLE 3.8A THERMAL PERFORMANCE TEST ON 1" REC WITH MODERATELY SELECTIVE ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME START END	TA (F)	TI (F)	TE (F)	FLOW GPM	AVE IN B/H-FT ²	TOTAL IN BTU/FT ²	TE-TI (F)	DEL T F-MIN	EFFIC %	(TI-TA)/I (F-H-FT ²)/B
1	1/25/94	13:11 13:16	72.8	137.7	151.4	0.861	324.1	27.0	13.72	68.6	56.9	0.200
3	1/25/94	13:21 13:26	73.6	138.0	151.7	0.861	324.7	27.1	13.74	68.7	56.9	0.198
7	1/25/94	13:41 13:46	73.3	138.1	151.8	0.863	322.6	26.9	13.67	68.4	57.1	0.201
8	1/25/94	13:46 13:51	73.5	138.1	151.9	0.856	322.0	26.8	13.71	68.5	56.9	0.201
11	1/25/94	14:27 14:32	73.2	73.9	89.3	0.862	310.8	25.9	15.37	76.9	67.5	0.002
13	1/25/94	14:37 14:42	72.8	73.8	88.9	0.862	306.2	25.5	15.12	75.6	67.4	0.003
14	1/25/94	14:42 14:47	72.7	73.7	88.8	0.862	305.3	25.4	15.05	75.3	67.3	0.003
16	1/25/94	14:52 14:57	72.9	73.7	88.5	0.862	300.0	25.0	14.83	74.1	67.5	0.003

TEST	TILT DEG	AZIM DEG	INCI DEG	MASS LBM/MIN	SPEC HEAT BTU/(LBM-F)	IN P PSI	WIND MPH	WIND DIR	DIF IN B/H-FT ²	% DIFF INSOL	TI-TA (F)
1	51.	-23.	0.	7.05	1.000	12.2	4.0	123.	47.5	14.6	64.9
3	52.	-25.	0.	7.05	1.000	12.2	3.8	107.	48.3	14.9	64.4
7	54.	-31.	0.	7.07	1.000	12.1	3.9	103.	43.3	13.4	64.8
8	54.	-32.	0.	7.02	1.000	12.1	4.9	106.	43.5	13.5	64.7
11	60.	-42.	0.	7.17	0.998	12.5	4.1	107.	45.7	14.7	0.7
13	61.	-44.	0.	7.17	0.998	12.4	5.3	112.	43.9	14.3	0.9
14	62.	-45.	0.	7.17	0.998	12.3	4.5	109.	43.9	14.4	1.0
16	64.	-47.	0.	7.17	0.998	12.2	4.7	102.	44.1	14.7	0.8





3.2.6 THERMAL PERFORMANCE WITH FLAT BLACK PAINT ABSORBER

The collector, outfitted with a flat black paint coated absorber, was tested from 27-28 December 1993 in accordance with ASHRAE procedure 93-1986. Results of the thermal performance tests are presented in graphical and tabular form in both the International System of Units (SI) and English units. The thermal performance equations in S.I. units developed from the empirical data are:

$$\text{first order} \quad \eta = 71.1 - 354 \quad (T_i - T_a)/I$$

$$\text{second order} \quad \eta = 70.7 - 273 \quad (T_i - T_a)/I - 1996 \quad [(T_i - T_a)/I]^2$$

These equations in English units are:

$$\text{first order} \quad \eta = 71.1 - 62 \quad (T_i - T_a)/I$$

$$\text{second order} \quad \eta = 70.4 - 48 \quad (T_i - T_a)/I - 62 \quad [(T_i - T_a)/I]^2$$

TABLE 3.9 THERMAL PERFORMANCE TEST ON 1" REC WITH FLAT BLACK ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME		TA	TI	TE	FLOW	AVE IN	TOTAL IN	TE-TI	DEL T	EFFIC	(TI-TA)/I
		START	END	(C)	(C)	(C)	L/MIN	W/M ²	J/M ²	(C)	C-MIN	%	(C-M ²)/W
6	12/27/93	11:06	11:11	14.6	60.5	68.3	3.32	1079.5	323845.	7.75	38.8	55.7	0.0425
8	12/27/93	11:16	11:21	15.0	60.6	68.3	3.31	1079.4	323805.	7.76	38.8	55.7	0.0422
9	12/27/93	11:21	11:26	15.3	60.6	68.4	3.31	1080.3	324092.	7.79	39.0	55.9	0.0419
10	12/27/93	11:26	11:31	15.4	60.6	68.4	3.31	1080.7	324205.	7.80	39.0	55.9	0.0418
13	12/27/93	11:59	12:04	16.1	51.4	59.6	3.30	1076.0	322786.	8.26	41.3	59.5	0.0327
14	12/27/93	12:04	12:09	16.2	51.4	59.6	3.30	1073.5	322036.	8.23	41.2	59.4	0.0327
15	12/27/93	12:09	12:14	16.5	51.4	59.7	3.30	1073.4	322013.	8.25	41.3	59.6	0.0326
16	12/27/93	12:14	12:19	16.4	51.4	59.6	3.30	1071.8	321545.	8.25	41.3	59.6	0.0326
17	12/27/93	12:48	12:52	17.6	39.4	48.1	3.30	1058.6	317581.	8.74	43.7	64.3	0.0206
18	12/27/93	12:53	12:57	17.9	39.4	48.1	3.31	1055.5	316663.	8.72	43.6	64.4	0.0204
19	12/27/93	12:58	13:02	18.0	39.4	48.1	3.31	1052.0	315607.	8.72	43.6	64.6	0.0204
20	12/27/93	13:03	13:07	18.2	39.4	48.0	3.31	1047.3	314198.	8.68	43.4	64.6	0.0202
30	12/28/93	11:37	11:42	21.3	21.3	30.8	3.29	1035.0	310488.	9.46	47.3	71.3	0.0001
31	12/28/93	11:42	11:47	21.5	21.3	30.8	3.26	1031.7	309508.	9.45	47.3	70.9	-0.0001
32	12/28/93	11:47	11:52	21.4	21.3	30.7	3.28	1038.3	311482.	9.39	46.9	70.5	-0.0001
33	12/28/93	11:52	11:57	21.5	21.3	30.7	3.26	1035.9	310776.	9.41	47.0	70.3	-0.0002

TABLE 3.9 THERMAL PERFORMANCE TEST ON 1" REC WITH FLAT BLACK ABSORBER (SI UNITS CONTIUED)

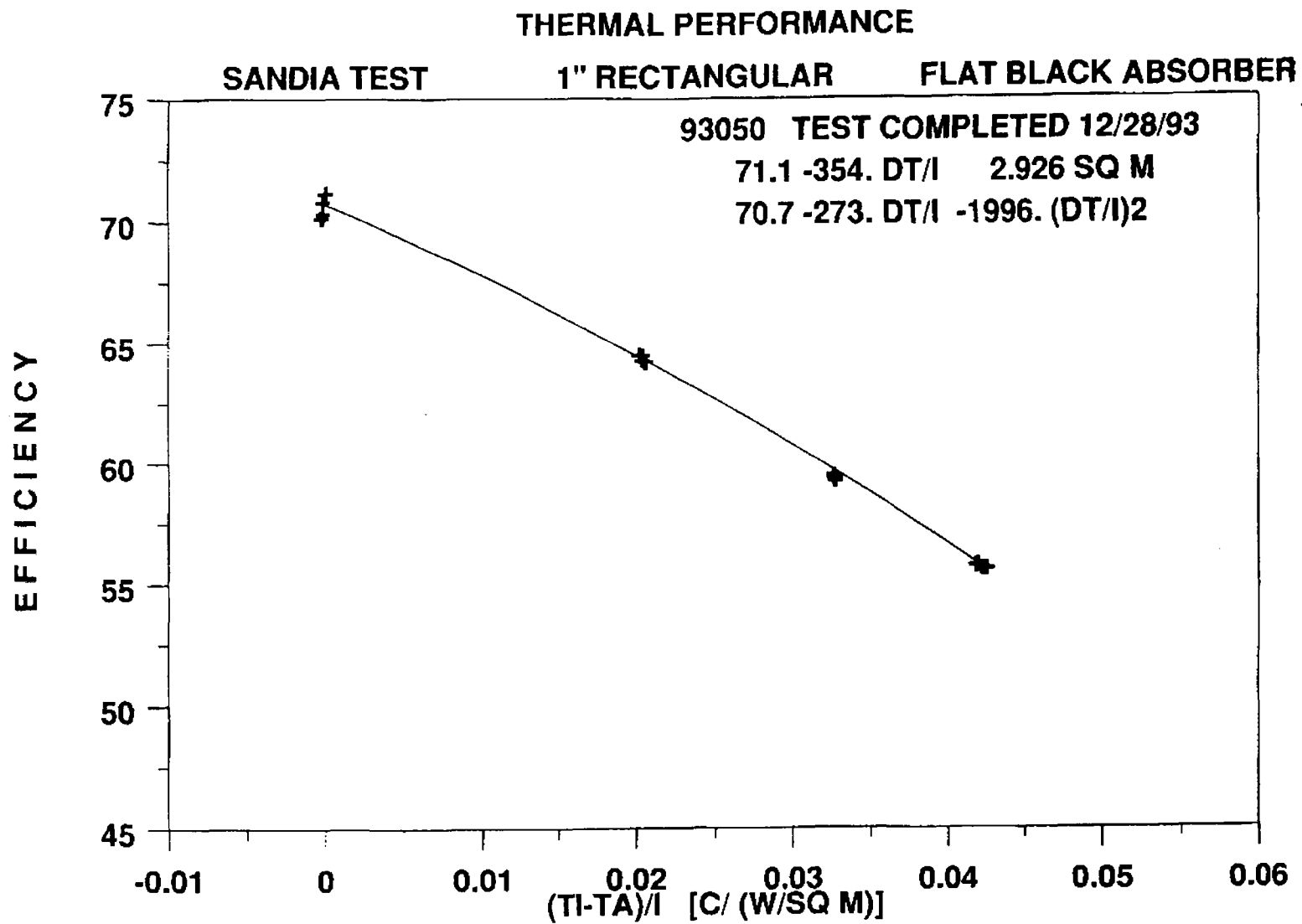
TEST	TILT DEG	AZIM DEG	INCI DEG	MASS KG/SEC	SPEC HEAT J/(KG C)	IN P KN/M ²	WIND M/S	WIND DIR	DIF IN W/M ²	% DIFF INSOL	TI-TA (C)
6	53.	15.	0.	0.0542	4186.3	78.1	1.6	347.	108.2	10.0	45.9
8	53.	12.	0.	0.0542	4186.4	78.6	1.0	351.	108.3	10.0	45.6
9	52.	10.	0.	0.0542	4186.4	79.8	1.1	356.	108.7	10.1	45.3
10	52.	9.	0.	0.0541	4186.4	80.1	1.4	356.	108.6	10.1	45.2
13	52.	-1.	0.	0.0542	4182.4	80.8	1.2	348.	111.1	10.3	35.2
14	52.	-2.	0.	0.0542	4182.4	81.9	0.9	348.	110.6	10.3	35.1
15	52.	-3.	0.	0.0542	4182.4	81.3	1.2	353.	110.7	10.3	34.9
16	52.	-5.	0.	0.0542	4182.4	81.3	1.0	355.	109.9	10.3	35.0
17	53.	-15.	0.	0.0545	4179.2	80.6	0.5	348.	105.4	10.0	21.8
18	53.	-16.	0.	0.0546	4179.2	82.9	0.7	337.	105.1	10.0	21.5
19	54.	-17.	0.	0.0546	4179.2	82.0	0.5	334.	104.5	9.9	21.4
20	54.	-19.	0.	0.0546	4179.2	80.3	0.4	335.	103.3	9.9	21.2
30	52.	6.	0.	0.0546	4179.3	81.8	1.2	335.	163.5	15.8	0.1
31	52.	4.	0.	0.0542	4179.3	80.2	0.8	336.	160.8	15.6	-0.1
32	52.	3.	0.	0.0546	4179.3	80.4	0.8	342.	154.7	14.9	-0.1
33	52.	1.	0.	0.0542	4179.3	80.3	0.8	334.	138.0	13.3	-0.2

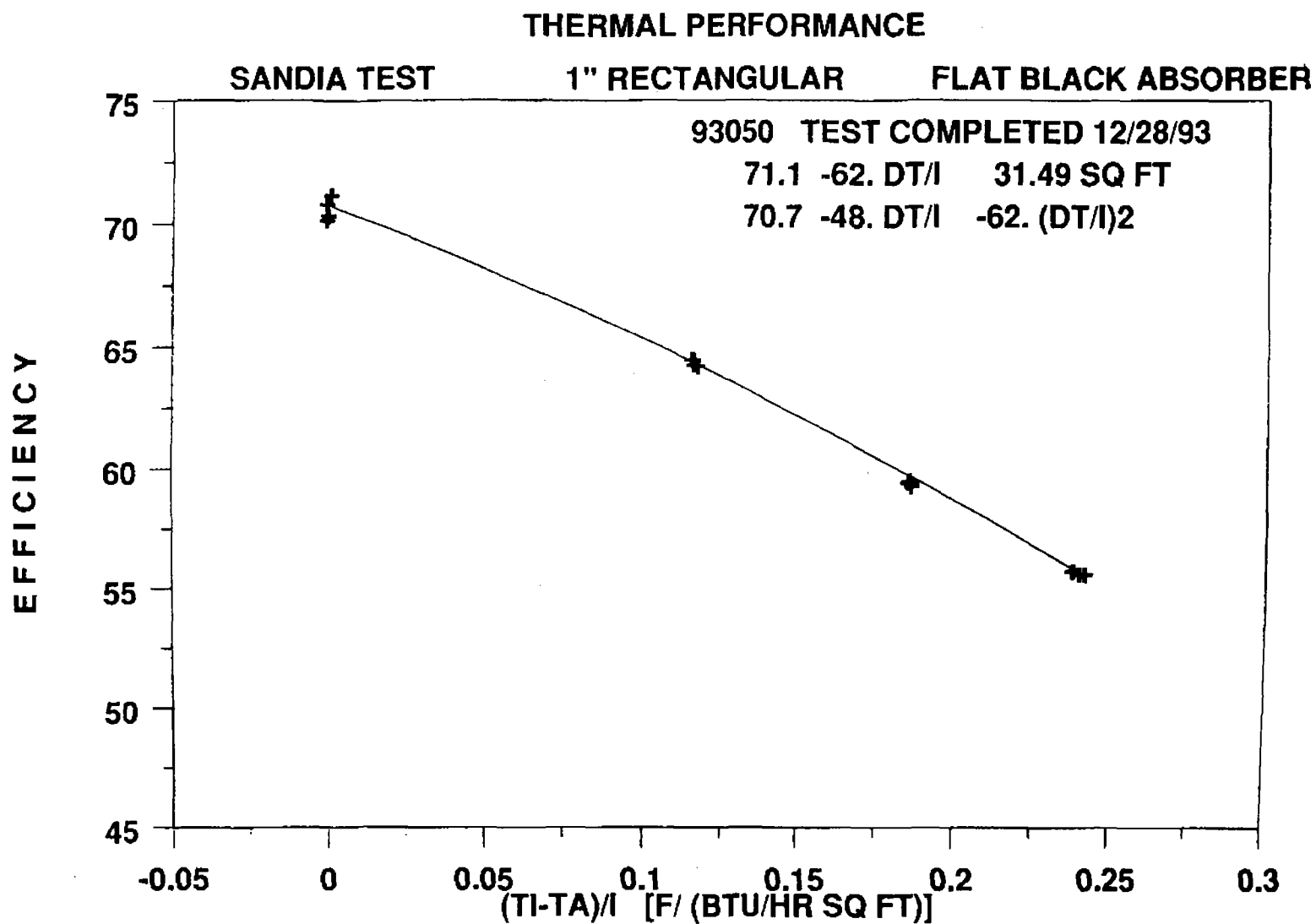
TABLE 3.9A THERMAL PERFORMANCE TEST ON 1" REC WITH FLAT BLACK ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME START END	TA (F)	TI (F)	TE (F)	FLOW GPM	AVE IN B/H-FT ²	TOTAL IN BTU/FT ²	TE-TI (F)	DEL T F-MIN	EFFIC %	(TI-TA)/I (F-H-FT ²)/B
6	12/27/93	11:06 11:11	58.3	141.0	154.9	0.876	342.4	28.5	13.96	69.8	55.7	0.241
8	12/27/93	11:16 11:21	59.0	141.0	155.0	0.876	342.4	28.5	13.97	69.8	55.7	0.239
9	12/27/93	11:21 11:26	59.6	141.0	155.0	0.875	342.7	28.6	14.02	70.1	55.9	0.238
10	12/27/93	11:26 11:31	59.7	141.0	155.1	0.875	342.8	28.6	14.03	70.2	55.9	0.237
13	12/27/93	11:59 12:04	61.1	124.5	139.3	0.872	341.3	28.4	14.87	74.3	59.5	0.186
14	12/27/93	12:04 12:09	61.2	124.5	139.3	0.872	340.5	28.4	14.81	74.1	59.4	0.186
15	12/27/93	12:09 12:14	61.6	124.5	139.4	0.872	340.5	28.4	14.86	74.3	59.6	0.185
16	12/27/93	12:14 12:19	61.5	124.5	139.4	0.872	340.0	28.3	14.85	74.3	59.6	0.185
17	12/27/93	12:48 12:52	63.6	102.9	118.6	0.873	335.8	28.0	15.74	78.7	64.3	0.117
18	12/27/93	12:53 12:57	64.2	102.9	118.6	0.873	334.8	27.9	15.69	78.5	64.4	0.116
19	12/27/93	12:58 13:02	64.3	102.9	118.6	0.873	333.7	27.8	15.69	78.5	64.6	0.115
20	12/27/93	13:03 13:07	64.7	102.8	118.5	0.873	332.2	27.7	15.63	78.1	64.6	0.115
30	12/28/93	11:37 11:42	70.3	70.4	87.4	0.868	328.3	27.4	17.02	85.1	71.3	0.000
31	12/28/93	11:42 11:47	70.7	70.4	87.4	0.862	327.3	27.3	17.02	85.1	70.9	-0.001
32	12/28/93	11:47 11:52	70.5	70.4	87.3	0.867	329.4	27.4	16.90	84.5	70.5	0.000
33	12/28/93	11:52 11:57	70.7	70.4	87.3	0.861	328.6	27.4	16.93	84.7	70.3	-0.001

TABLE 3.9A THERMAL PERFORMANCE TEST ON 1" REC WITH FLAT BLACK ABSORBER (ENGLISH UNITS CONTINUED)

TEST	TILT DEG	AZIM DEG	INCI DEG	MASS LBM/MIN	SPEC HEAT BTU/(LBM-F)	IN P PSI	WIND MPH	WIND DIR	DIF IN B/H-FT ²	% DIFF INSOL	TI-TA (F)
6	53.	15.	0.	7.17	1.000	11.3	3.7	347.	34.3	10.0	82.7
8	53.	12.	0.	7.17	1.000	11.4	2.3	351.	34.3	10.0	82.0
9	52.	10.	0.	7.16	1.000	11.6	2.4	356.	34.5	10.1	81.5
10	52.	9.	0.	7.16	1.000	11.6	3.1	356.	34.5	10.1	81.3
13	52.	-1.	0.	7.17	0.999	11.7	2.7	348.	35.2	10.3	63.4
14	52.	-2.	0.	7.17	0.999	11.9	2.1	348.	35.1	10.3	63.3
15	52.	-3.	0.	7.17	0.999	11.8	2.7	353.	35.1	10.3	62.9
16	52.	-5.	0.	7.17	0.999	11.8	2.3	355.	34.9	10.3	63.0
17	53.	-15.	0.	7.21	0.998	11.7	1.0	348.	33.4	10.0	39.2
18	53.	-16.	0.	7.22	0.998	12.0	1.6	337.	33.3	10.0	38.7
19	54.	-17.	0.	7.22	0.998	11.9	1.1	334.	33.1	9.9	38.5
20	54.	-19.	0.	7.22	0.998	11.6	0.9	335.	32.8	9.9	38.2
30	52.	6.	0.	7.22	0.998	11.9	2.6	335.	51.9	15.8	0.1
31	52.	4.	0.	7.17	0.998	11.6	1.8	336.	51.0	15.6	-0.3
32	52.	3.	0.	7.22	0.998	11.7	1.7	342.	49.1	14.9	-0.1
33	52.	1.	0.	7.17	0.998	11.6	1.7	334.	43.8	13.3	-0.3





3.2.7 INCIDENT ANGLE MODIFIER TEST

The collector, outfitted with a selective black chrome coated absorber, was tested from 15-18 November 1993 in accordance with the ASHRAE procedure to determine the longitudinal incident angle modifier (IAM). The definition of longitudinal IAM for this report will be incident angles where the collector's azimuth is tracking the sun while its elevation is made higher or lower than the sun's altitude, assuming the collector is mounted with its long axis parallel to the ground. A graph of the longitudinal IAM along with the data in tabular form follows. The longitudinal incident angle modifier equation was determined to be:

$$K_{\tau\alpha} = 1.0 - 0.27 (1/\cos \theta - 1)$$

The collector, outfitted with a selective black chrome coated absorber, was tested from 15 November - 16 December 1993 in accordance with the ASHRAE procedure to determine the transverse incident angle modifier (IAM). The definition of transverse IAM for this report will be incident angles where the collector's elevation is tracking the sun while its azimuth is made further right or left than the sun's azimuth assuming the collector is mounted with its long axis parallel to the ground. A graph of the transverse IAM along with the data in tabular form follows. The transverse incident angle modifier equation was determined to be:

$$K_{\tau\alpha} = 1.0 - 0.30 (1/\cos \theta - 1)$$

The collector, outfitted with a flat black paint coated absorber, was tested on 28 December 1993 in accordance with the ASHRAE procedure to determine the transverse incident angle modifier (IAM). The definition of transverse IAM for this report will be incident angles where the collector's elevation is tracking the sun while its azimuth is made further right or left than the sun's azimuth assuming the collector is mounted with its long axis parallel to the ground. A graph of the transverse IAM along with the data in tabular form follows. The transverse incident angle

modifier equation was determined to be:

$$K\tau\alpha = 1.0 - 0.28 (1/\cos \theta - 1)$$

Incident angle modifier tests were not performed on all collector-absorber configurations since results did not change significantly from one configuration to the next.

TABLE 3.10 LONGITUDINAL INCIDENT ANGLE MODIFIER TEST ON 1" REC WITH SELECTIVE ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM
		START END	(C)	(C)	(C)	(C)	(C)	L/M	KG/SEC	DEG	DEG	DEG	W/M ²	DIF	M/S	DEG	%
1	11/15/93	11:45 11:49	27.4	29.2	32.1	2.95	1.8	3.3	0.0546	12.	4.	60.	501.	18.	2.0	119.	45.9 0.717
2	11/15/93	11:50 11:54	27.3	29.2	32.2	2.95	1.9	3.3	0.0546	12.	3.	60.	500.	17.	2.2	116.	46.0 0.720
6	11/15/93	12:24 12:29	27.8	29.2	34.0	4.78	1.4	3.2	0.0538	3.	-8.	45.	677.	16.	1.6	127.	54.3 0.838
7	11/15/93	12:29 12:34	27.8	29.2	34.0	4.78	1.4	3.2	0.0537	3.	-10.	45.	676.	16.	1.8	153.	54.2 0.837
9	11/15/93	13:03 13:07	27.9	29.2	37.5	8.22	1.3	3.3	0.0547	35.	-20.	15.	986.	22.	1.6	136.	65.1 1.000
11	11/15/93	13:13 13:17	27.6	29.2	37.4	8.20	1.7	3.3	0.0545	36.	-23.	15.	983.	23.	2.2	117.	65.0 0.999
14	11/18/93	10:06 10:11	26.9	26.9	30.0	3.07	0.1	3.3	0.0550	5.	32.	60.	483.	19.	1.0	330.	49.9 0.763
15	11/18/93	10:11 10:16	26.8	26.9	30.0	3.09	0.1	3.3	0.0550	5.	31.	60.	486.	19.	0.9	331.	50.0 0.764
16	11/18/93	10:41 10:46	27.4	28.0	32.9	4.88	0.6	3.3	0.0551	7.	23.	45.	681.	14.	0.8	340.	56.5 0.866
17	11/18/93	10:46 10:51	27.5	28.0	32.9	4.91	0.5	3.3	0.0551	6.	22.	45.	684.	14.	0.7	339.	56.5 0.865
21	11/18/93	11:27 11:31	27.9	28.0	34.8	6.85	0.1	3.3	0.0546	19.	10.	30.	855.	12.	0.7	350.	62.4 0.953
22	11/18/93	11:32 11:36	28.1	28.0	34.8	6.86	-0.1	3.3	0.0545	19.	8.	30.	858.	12.	1.0	357.	62.2 0.949
24	11/18/93	11:42 11:46	28.1	28.0	34.9	6.83	0.0	3.3	0.0544	18.	5.	30.	855.	15.	1.0	359.	62.0 0.947
29	11/18/93	12:42 12:46	26.9	28.3	36.0	7.71	1.4	3.3	0.0545	34..	-14.	15.	930.	18.	2.3	100.	64.5 0.991
30	11/18/93	12:47 12:51	26.6	28.3	36.0	7.67	1.7	3.3	0.0544	35..	-15.	15.	926.	18.	2.3	94.	64.4 0.991
34	11/17/93	13:41 13:46	27.7	28.3	36.7	8.37	0.6	3.3	0.0546	54.	-31.	0.	974.	18.	2.2	---	67.0 1.025
35	11/17/93	13:56 14:01	27.6	28.3	36.6	8.32	0.7	3.3	0.0542	6..	-34.	0.	968.	18.	1.8	---	66.5 1.018
38	11/18/93	14:03 14:07	26.2	26.8	35.0	8.10	0.6	3.3	0.0542	57.	-36.	0.	943.	21.	2.2	---	66.5 1.019
39	11/18/93	14:08 14:12	26.2	26.8	34.9	8.10	0.7	3.3	0.0543	58.	-37.	0.	941.	20.	2.0	---	66.7 1.021

TABLE 3.10A LONGITUDINAL INCIDENT ANGLE MODIFIER TEST ON 1" REC WITH SELECTIVE ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME		TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND		EFF	IAM
		START	END	(F)	(F)	(F)	(F)	(F)	GPM	LB/MIN	DEG	DEG	DEG	B/FT ²	DIF	MPH	DEG	%	
1	11/15/93	11:45	11:49	81.2	84.5	89.8	5.32	3.3	0.869	7.22	12.	4.	60.	159.	18.	4.5	119.	45.9	0.717
2	11/15/93	11:50	11:54	81.1	84.6	89.9	5.31	3.4	0.870	7.23	12.	3.	60.	159.	17.	5.0	116.	46.0	0.720
6	11/15/93	12:24	12:29	82.1	84.6	93.2	8.60	2.6	0.858	7.12	3.	-8.	45.	215.	16.	3.6	127.	54.3	0.838
7	11/15/93	12:29	12:34	82.1	84.6	93.2	8.60	2.5	0.855	7.10	3.	-10.	45.	214.	16.	4.0	153.	54.2	0.837
9	11/15/93	13:03	13:07	82.3	84.6	99.4	14.80	2.4	0.871	7.23	35.	-20.	15.	313.	22.	3.7	136.	65.1	1.000
11	11/15/93	13:13	13:17	81.6	84.6	99.4	14.76	3.0	0.869	7.21	36.	-23@	15.	312.	23.	5.0	117.	65.0	0.999
14	11/18/93	10:06	10:11	80.4	80.5	86.0	5.52	0.1	0.875	7.28	5.	32.	60.	153.	19.	2.3	330.	49.9	0.763
15	11/18/93	10:11	10:16	80.3	80.4	86.0	5.57	0.1	0.976	7.28	5.	31.	60.	154.	19.	2.0	331.	50.0	0.764
16	11/18/93	10:41	10:46	81.3	82.4	91.1	8.79	1.1	0.878	7.29	7.	23.	45.	216.	14.	1.9	340.	56.5	0.866
17	11/18/93	10:46	10:51	81.6	82.4	91.2	8.84	0.8	0.878	7.29	6.	22.	45.	217.	14.	1.5	339.	56.5	0.865
21	11/18/93	11:27	11:31	82.3	82.4	94.7	12.33	0.1	0.869	7.22	19.	10.	30.	271.	12.	1.7	350.	62.4	0.953
22	11/18/93	11:32	11:36	82.5	82.4	94.7	12.34	-0.1	0.868	7.21	19.	8.	30.	272.	12.	2.2	357.	62.2	0.949
24	11/18/93	11:42	11:46	82.5	82.4	94.7	12.29	-0.1	0.866	7.19	18.	5.	30.	271.	15.	2.2	359.	62.0	0.947
29	11/18/93	12:42	12:46	80.4	82.9	96.8	13.88	2.5	0.868	7.21	34.	-14.	15.	295.	18.	5.1	100.	64.5	0.991
30	11/18/93	12:47	12:51	79.8	82.9	96.7	13.81	3.1	0.867	7.20	35.	-15.	15.	294.	18.	5.1	94.	64.4	0.991
34	11/17/93	13:41	13:46	81.8	83.0	98.0	15.07	1.1	0.869	7.22	54.	-31.	0.	309.	18.	5.0	---	67.0	1.025
35	11/17/93	13:56	14:01	81.7	82.9	97.9	14.98	1.3	0.863	7.17	56.	-34.	0.	307.	18.	4.0	---	66.5	1.018
38	11/18/93	14:03	14:07	79.2	80.3	94.9	14.59	1.1	0.863	7.17	57.	-36.	0.	299.	21.	5.0	---	66.5	1.019
39	11/18/93	14:08	14:12	79.1	80.3	94.9	14.58	1.2	0.864	7.18	58.	-37.	0.	298.	20.	4.5	---	66.7	1.021

LONGITUDINAL INCIDENT ANGLE MODIFIER

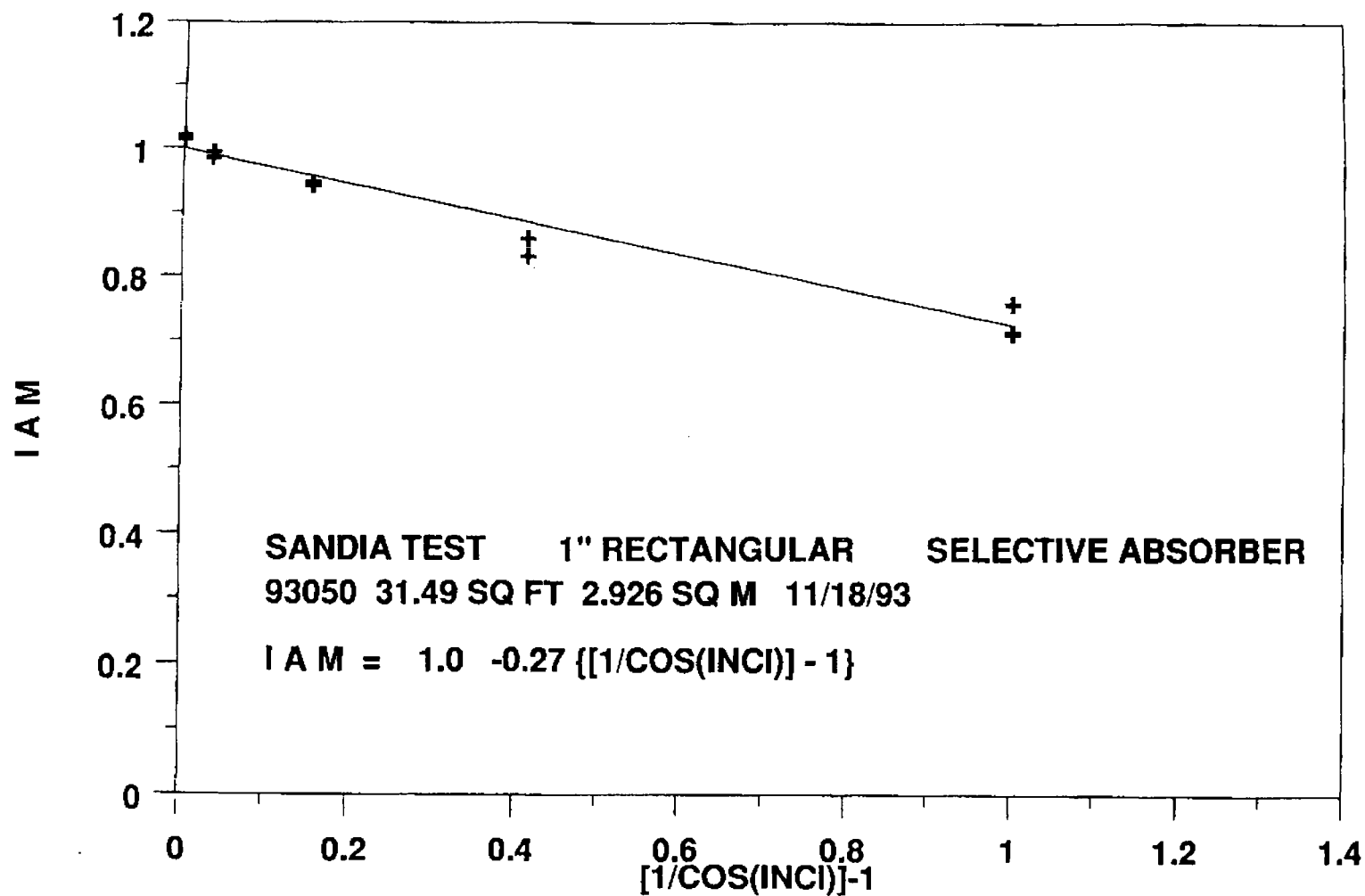


TABLE 3.11 TRANSVERSE INCIDENT ANGLE MODIFIER TEST ON 1" REC WITH SELECTIVE ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM
		START END	(C)	(C)	(C)	(C)	(C)	L/M	KG/SEC	DEG	DEG	DEG	W/M ²	DIF	M/S	DEG %	
2	11/15/93	11:13 11:18	27.3	29.2	33.5	4.37	1.9	3.3	0.0542	1.	14.	50.	645.	20.	2.1	136.	0.807
3	11/15/93	11:18 11:23	27.1	29.2	33.6	4.43	2.1	3.2	0.0537	1.	12.	50.	650.	20.	2.3	117.	0.806
7	12/15/93	10:54 10:59	15.5	15.9	21.2	5.30	0.4	3.3	0.0543	9.	18.	45.	731.	13.	3.4	283.	0.856
8	12/15/93	10:59 11:04	15.6	16.0	21.3	5.35	0.3	3.2	0.0538	9.	16.	45.	732.	13.	3.2	284.	0.855
13	12/15/93	13:30 13:35	18.5	19.0	25.8	6.82	0.5	3.3	0.0546	26.	-26.	30.	855.	10.	3.4	285.	0.944
14	12/15/93	13:35 13:40	18.5	19.0	25.8	6.79	0.5	3.3	0.0544	27.	-27.	30.	851.	10.	3.3	282.	0.942
18	12/15/93	15:12 15:17	17.5	18.4	20.7	2.38	0.8	3.3	0.0553	10.	-47.	60.	399.	6.	3.0	297.	0.723
21	12/16/93	10:28 10:33	12.0	12.0	15.0	3.08	-0.1	3.3	0.0545	4.	25.	60.	509.	14.	2.4	327.	0.715
26	12/16/93	13:13 13:17	14.8	14.7	22.8	8.15	-0.1	3.3	0.0554	40.	-21.	15.	970.	14.	1.7	332.	1.008
28	12/16/93	13:23 13:27	14.9	14.7	22.9	8.22	-0.2	3.3	0.0545	41.	-24.	15.	958.	14.	1.7	327.	1.012
34	11/18/93	14:03 14:07	26.2	26.8	35.0	8.10	0.6	3.3	0.0542	57.	-36.	0.	943.	21.	2.2	---	1.011
35	11/18/93	14:08 14:12	26.2	26.8	34.9	8.10	0.7	3.3	0.0543	58.	-37.	0.	941.	20.	2.0	---	1.014

TABLE 3.11A TRANSVERSE INCIDENT ANGLE MODIFIER TEST ON 1" REC WITH SELECTIVE ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM
		START END	(F)	(F)	(F)	(F)	(F)	GPM	LB/MN	DEG	DEG	DEG	B/FT ²	DIF	MPH	DEG %	
2	11/15/93	11:13 11:18	81.1	84.5	92.4	7.86	3.4	0.863	7.17	1.	14.	50.	205.	20.	4.6	136.	0.807
3	11/15/93	11:18 11:23	80.7	84.5	92.5	7.97	3.8	0.856	7.11	1.	12.	50.	206.	20.	5.1	117.	0.806
7	12/15/93	10:54 10:59	59.9	60.7	70.2	9.53	0.8	0.862	7.19	9.	18.	45.	232.	13.	7.5	283.	0.856
8	12/15/93	10:59 11:04	60.1	60.7	70.4	9.64	0.6	0.853	7.12	9.	16.	45.	232.	13.	7.2	284.	0.855
13	12/15/93	13:30 13:35	65.3	66.2	78.4	12.27	0.9	0.866	7.22	26.	-26.	30.	271.	10.	7.5	285.	0.944
14	12/15/93	13:35 13:40	65.3	66.2	78.4	12.22	0.9	0.864	7.19	27.	-27.	30.	270.	10.	7.3	282.	0.942
18	12/15/93	15:12 15:17	63.5	65.0	69.3	4.28	1.5	0.877	7.31	10.	-47.	60.	127.	6.	6.7	297.	0.723
21	12/16/93	10:28 10:33	53.6	53.5	59.1	5.54	-0.1	0.864	7.21	4.	25.	60.	161.	14.	5.4	327.	0.715
26	12/16/93	13:13 13:17	58.7	58.4	73.1	14.66	-0.3	0.879	7.33	40.	-21.	15.	308.	14.	3.8	332.	1.008
28	12/16/93	13:23 13:27	58.8	58.5	73.3	14.79	-0.3	0.865	7.21	41.	-24.	15.	304.	14.	3.8	327.	1.012
34	11/18/93	14:03 14:07	79.2	80.3	94.9	14.59	1.1	0.863	7.17	57.	-36.	0.	299.	21.	5.0	---	1.011
35	11/18/93	14:08 14:12	79.1	80.3	94.9	14.58	1.2	0.864	7.18	58.	-37.	0.	298.	20.	4.5	---	1.014

TRANSVERSE INCIDENT ANGLE MODIFIER

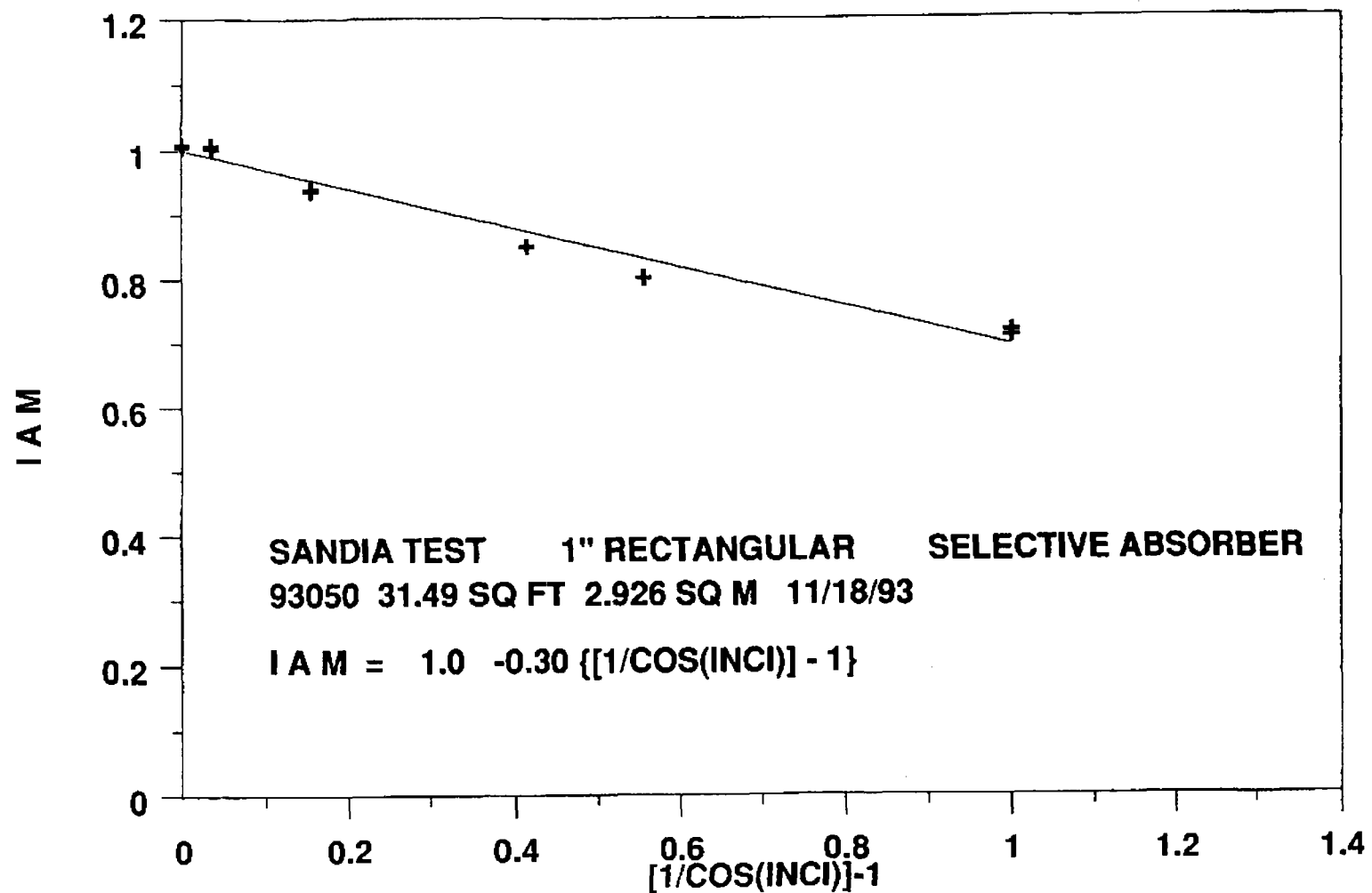


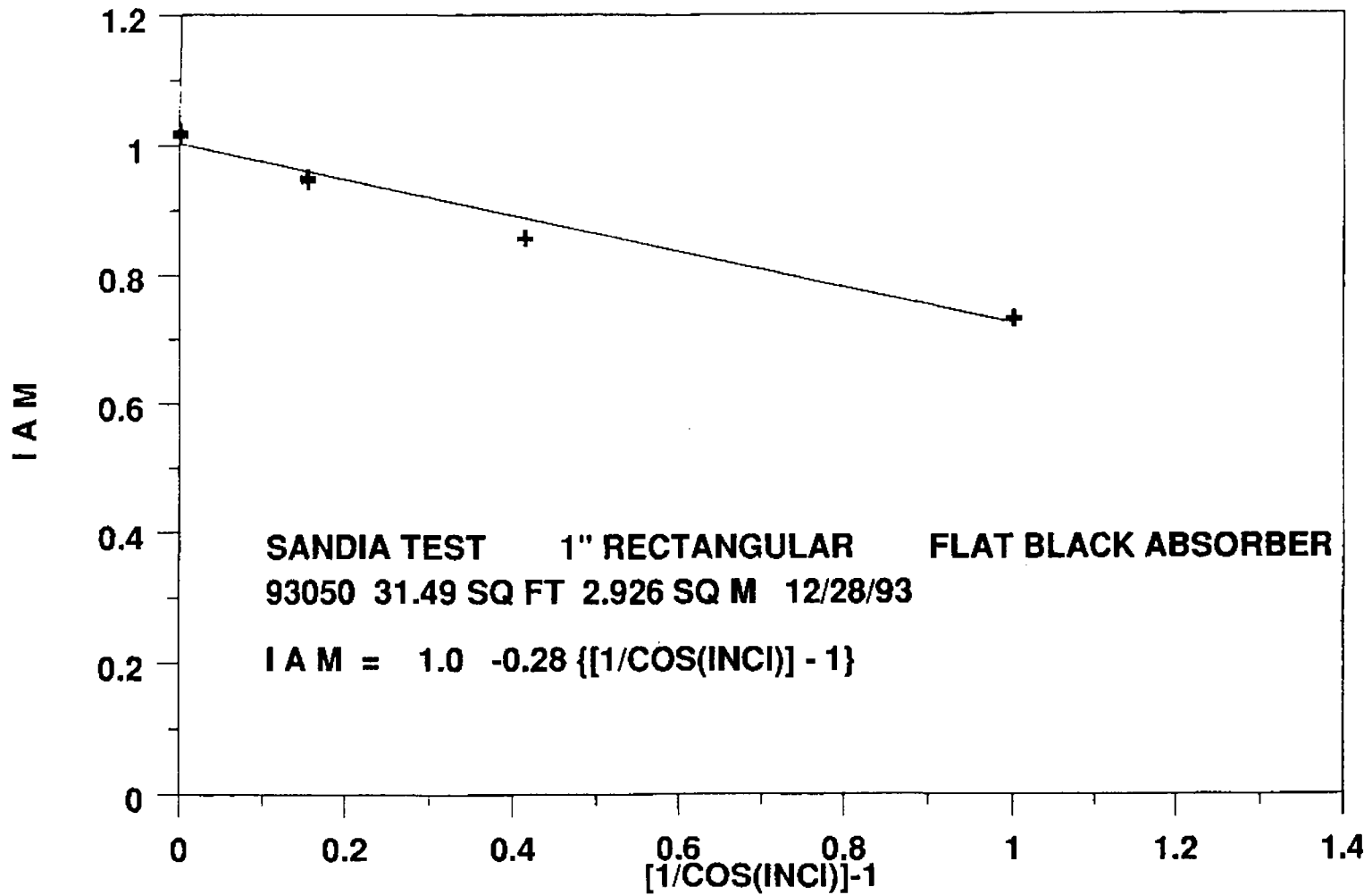
TABLE 3.12 TRANSVERSE INCIDENT ANGLE MODIFIER TEST ON 1" REC WITH FLAT BLACK ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM
		START END	(C)	(C)	(C)	(C)	(C)	L/M	KG/SEC	DEG	DEG	DEG	W/M ²	DIF	M/S	DEG %	
2	12/28/93	12:57 13:01	22.6	22.3	29.6	7.34	-0.3	3.3	0.0545	54.	-17.	30.	865.	12.	1.0	155. 66.1	0.957
3	12/28/93	13:02 13:06	22.6	22.3	29.5	7.23	-0.3	3.3	0.0542	54.	-19.	30.	852.	11.	1.2	166. 65.7	0.950
12	12/28/93	13:52 13:57	22.2	22.3	27.2	4.90	0.0	3.4	0.0563	59.	-31.	45.	661.	10.	0.9	152. 59.5	0.863
14	12/28/93	14:02 14:07	22.3	22.2	27.3	5.05	-0.1	3.3	0.0553	60.	-34.	45.	672.	12.	1.4	180. 59.5	0.861
16	12/28/93	14:24 14:29	22.5	22.2	25.1	2.93	-0.3	3.3	0.0549	63.	-38.	60.	451.	10.	1.2	160. 50.9	0.735
17	12/28/93	14:29 14:34	22.3	22.2	25.0	2.85	-0.1	3.3	0.0550	63.	-39.	60.	440.	7.	1.1	157. 51.0	0.738
20	12/28/93	11:42 11:47	21.5	21.3	30.8	9.45	-0.1	3.3	0.0542	52.	4.	0.	1032.	16.	0.8	335. 70.9	1.027
21	12/28/93	11:47 11:52	21.4	21.3	30.7	9.39	-0.1	3.3	0.0546	52.	3.	0.	1038.	15.	0.8	336. 70.5	1.021

TABLE 3.12A TRANSVERSE INCIDENT ANGLE MODIFIER TEST ON 1" REC WITH FLAT BLACK ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM
		START END	(F)	(F)	(F)	(F)	(F)	GPM	LB/MN	DEG	DEG	DEG	B/FT ²	DIF	MPH	DEG %	
2	12/28/93	12:57 13:01	72.7	72.1	85.3	13.22	-0.6	0.867	7.21	54.	-17.	30.	274.	12.	2.2	155. 66.1	0.957
3	12/28/93	13:02 13:06	72.7	72.1	85.1	13.01	-0.6	0.862	7.17	54.	-19.	30.	270.	11.	2.7	166. 65.7	0.950
12	12/28/93	13:52 13:57	72.0	72.1	80.9	8.81	0.0	0.894	7.45	59.	-31.	45.	210.	10.	2.0	152. 59.5	0.863
14	12/28/93	14:02 14:07	72.2	72.0	81.1	9.09	-0.2	0.879	7.32	60.	-34.	45.	213.	12.	3.1	180. 59.5	0.861
16	12/28/93	14:24 14:29	72.5	72.0	77.3	5.27	-0.5	0.872	7.26	63.	-38.	60.	143.	10.	2.8	160. 50.9	0.735
17	12/28/93	14:29 14:34	72.1	71.9	77.0	5.14	-0.2	0.874	7.27	63.	-39.	60.	140.	7.	2.4	157. 51.0	0.738
20	12/28/93	11:42 11:47	70.7	70.4	87.4	17.02	-0.3	0.862	7.17	52.	4.	0.	327.	16.	1.8	335. 70.9	1.027
21	12/28/93	11:47 11:52	70.5	70.4	87.3	16.90	-0.1	0.867	7.22	52.	3.	0.	329.	15.	1.7	336. 70.5	1.021

TRANSVERSE INCIDENT ANGLE MODIFIER

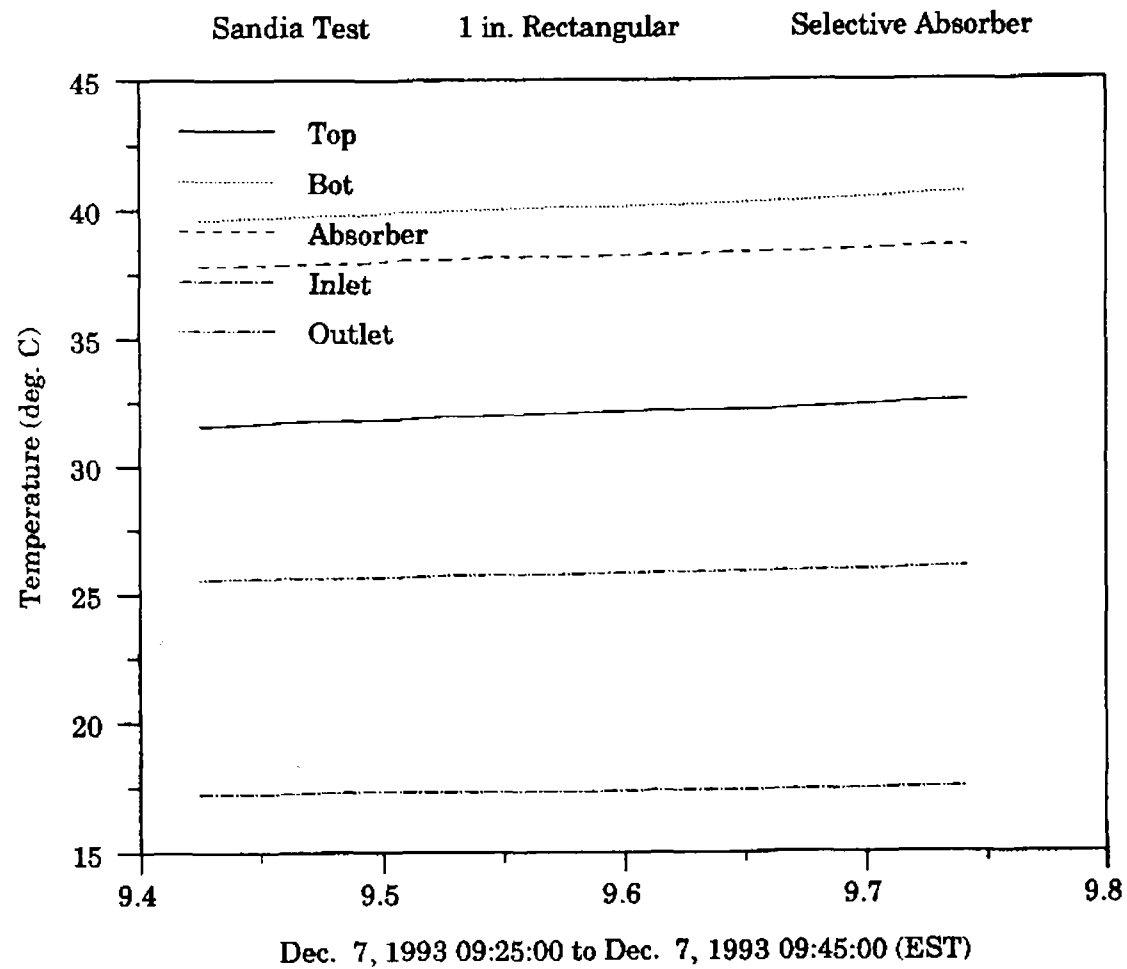


3.2.8 THERMOCOUPLE DATA

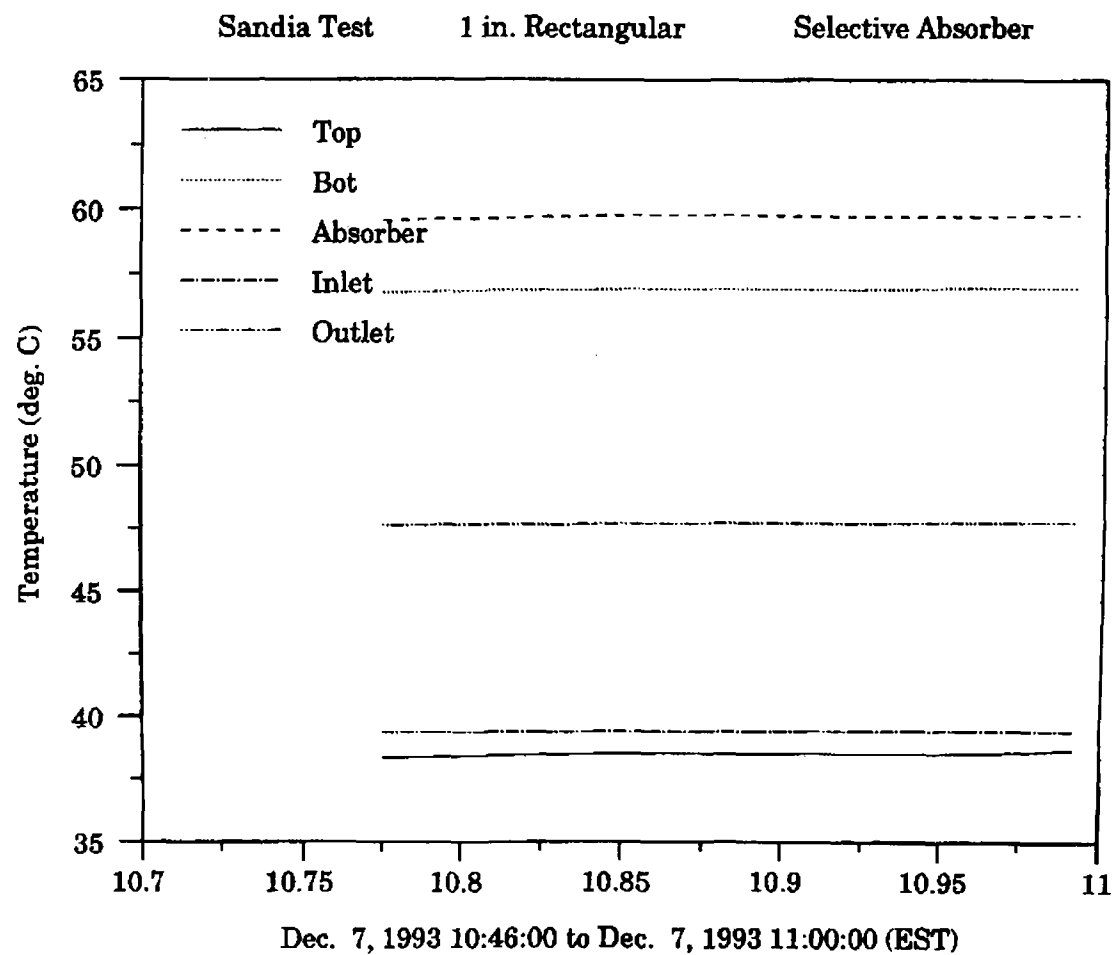
T-type thermocouples were installed inside prior to testing in order to gain insight into the temperatures internal to the collector. A total of six thermocouples were installed. Two of these were epoxied directly to the absorber. Two more were placed in air just under the TIM. The final two thermocouples were placed at the top of the TIM with the tip of the thermocouple sticking downward into a cell of the TIM. One set of thermocouples (top, bottom, absorber) were placed in the half of the collector nearest the inlet. The other set of thermocouples were placed in the half of the collector nearest the outlet. Special care was taken to keep direct sunlight from heating the top and bottom bimetal junctions and the wires leading to them. Temperature data were recorded every thirty seconds during some of the performance and IAM tests.

The graphs which follow give the averaged top, bottom, and absorber thermocouple temperatures along with the inlet and outlet fluid temperatures. During some periods only one of the top and one of the bottom temperatures was available. These periods are noted on the graphs by their lack of absorber temperature data. The first seven graphs present data from actual performance testing periods used in the final data reduction. The next graph shows the transients associated with removing the tarpaulins which covered the collector when not in use. This produces a sharp transition from no solar input to almost full sun. The data for the last graph were taken during a period of no solar input. Conducted at normal testing fluid flow rates, this graph demonstrates the absorber to ambient heat loss characteristics.

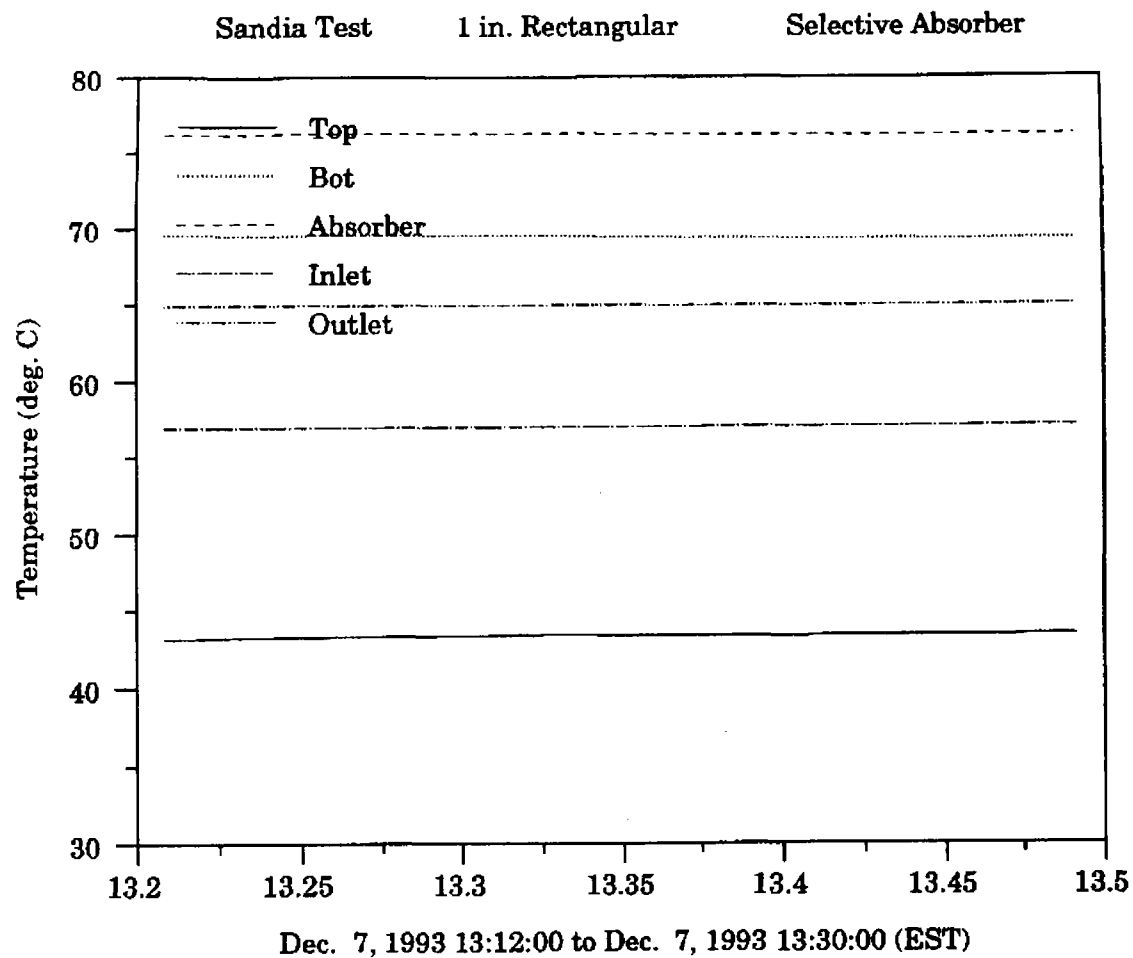
Temperatures During Testing for 93050



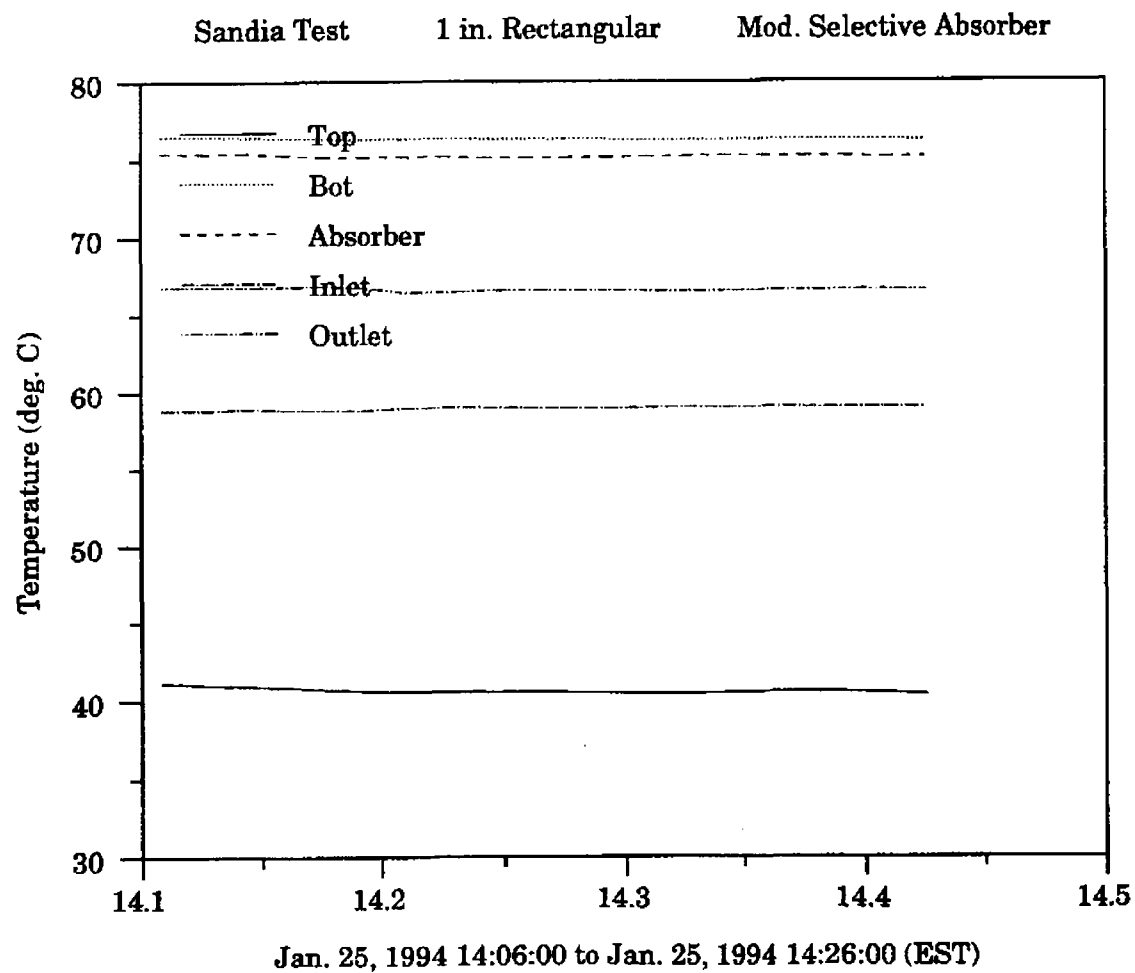
Temperatures During Testing for 93050



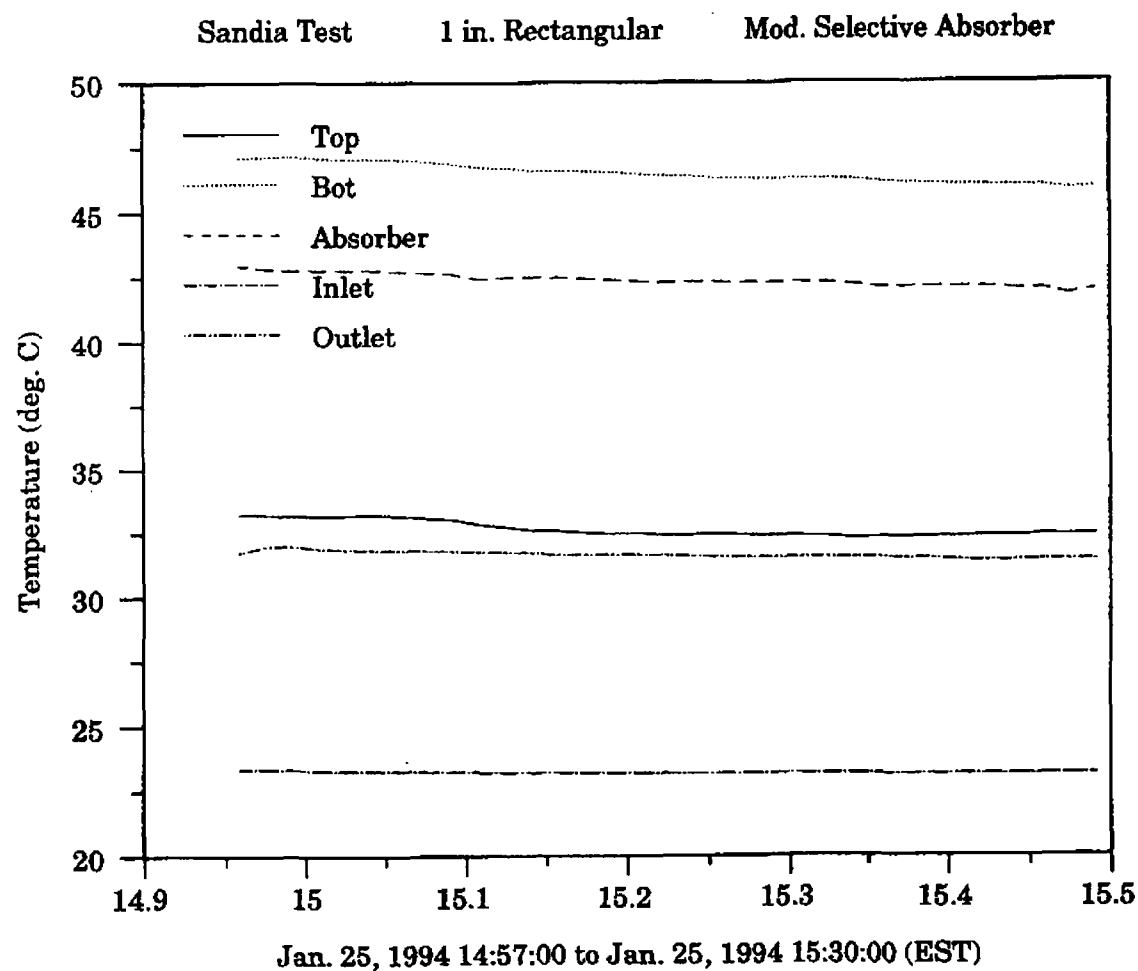
Temperatures During Testing for 93050



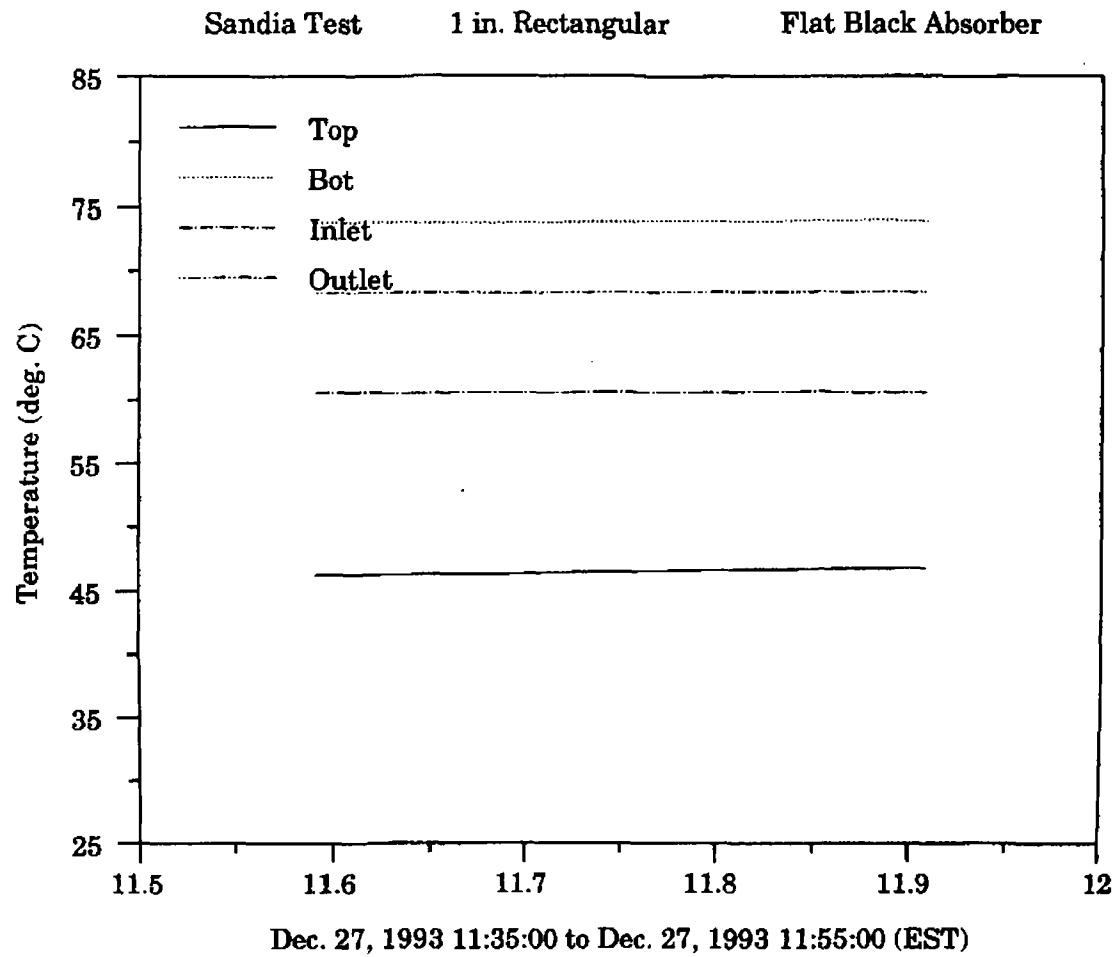
Temperatures During Testing for 93050

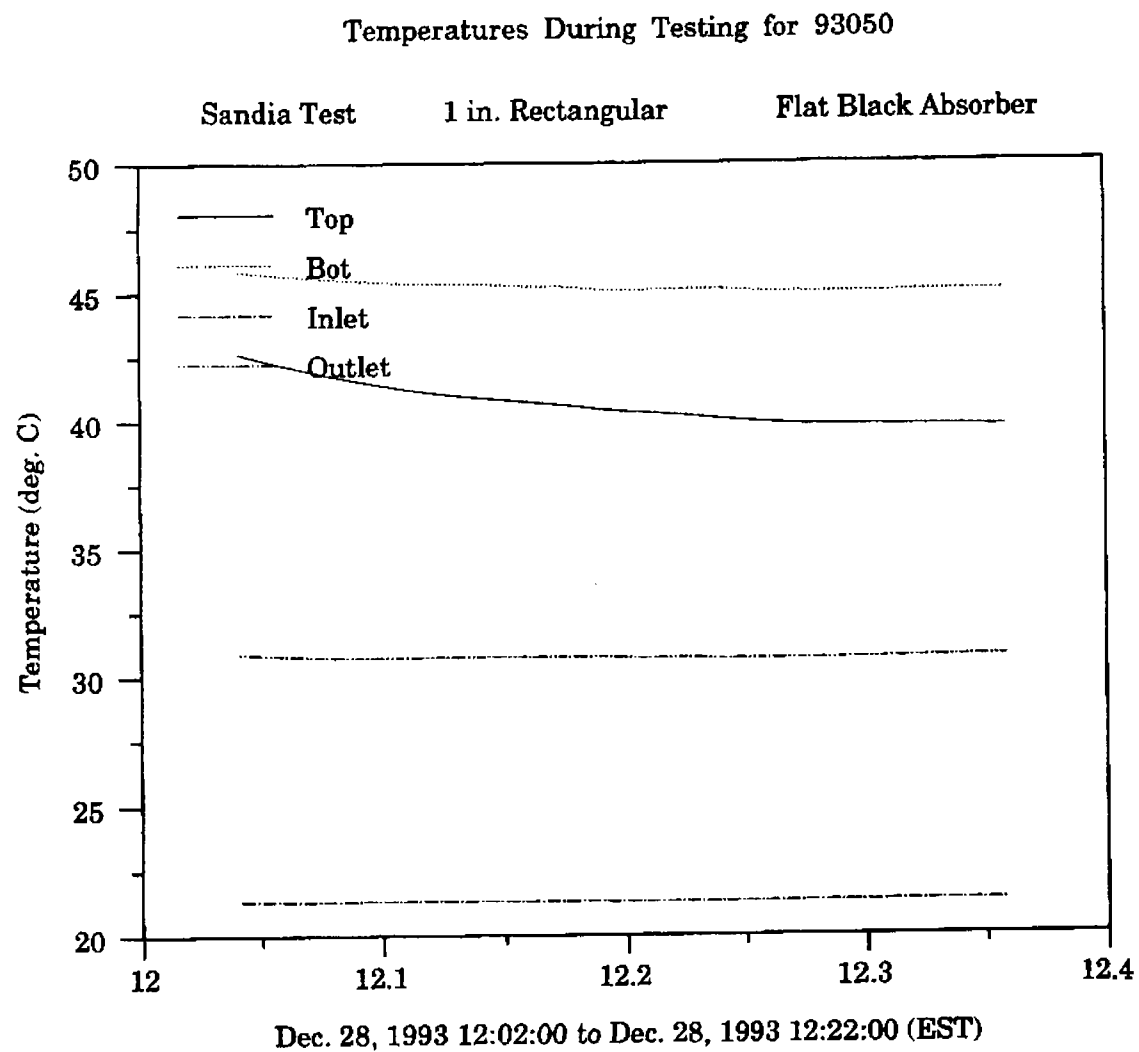


Temperatures During Testing for 93050

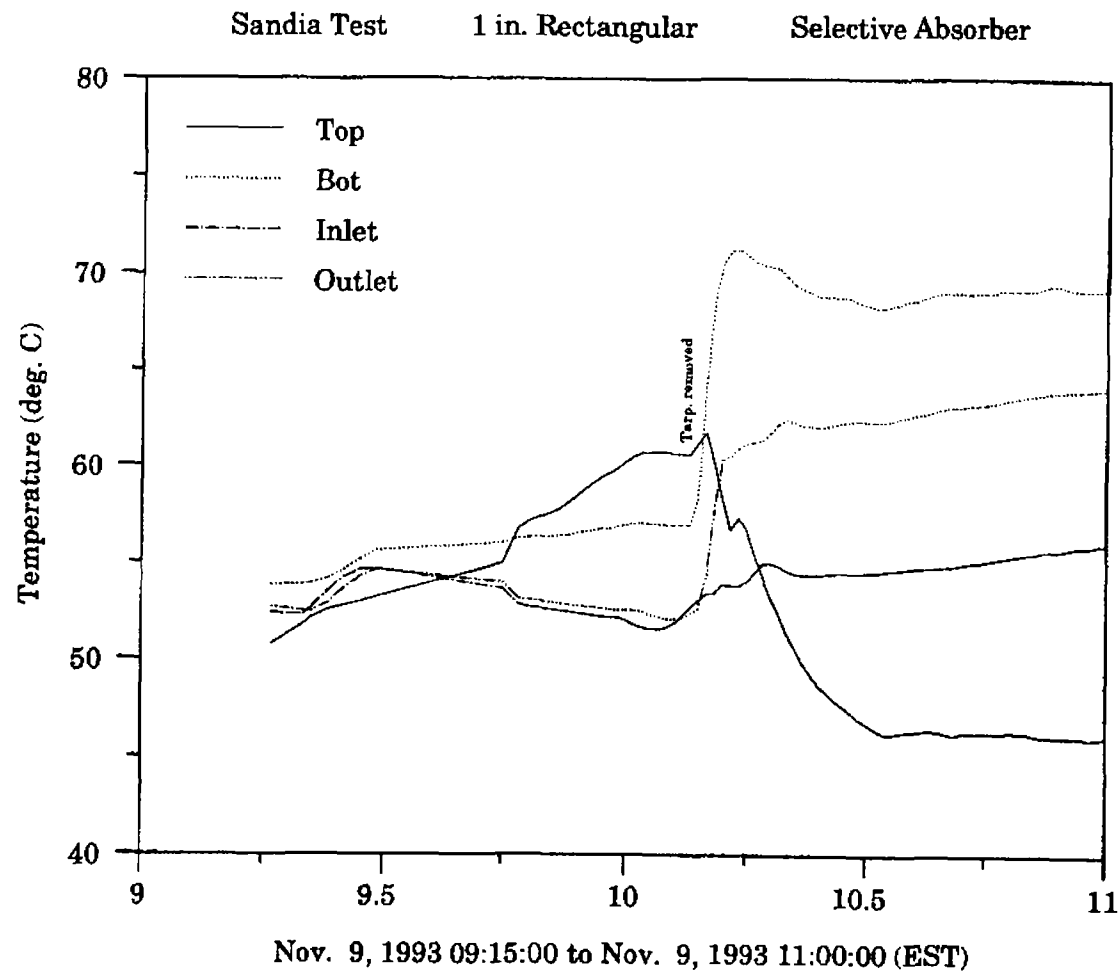


Temperatures During Testing for 93050

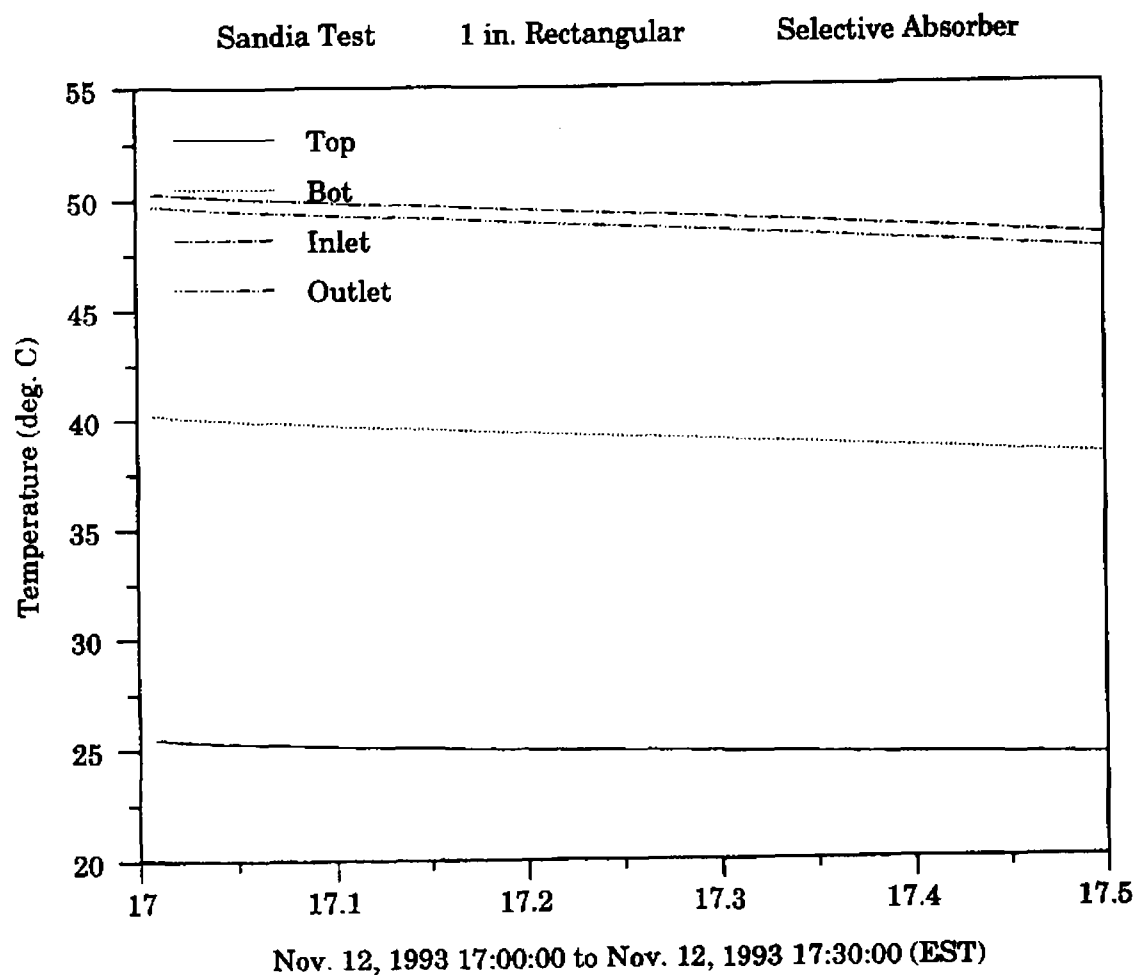




Temperatures During Collector Uncovering for 93050



Temperatures During No Solar Input for 93050

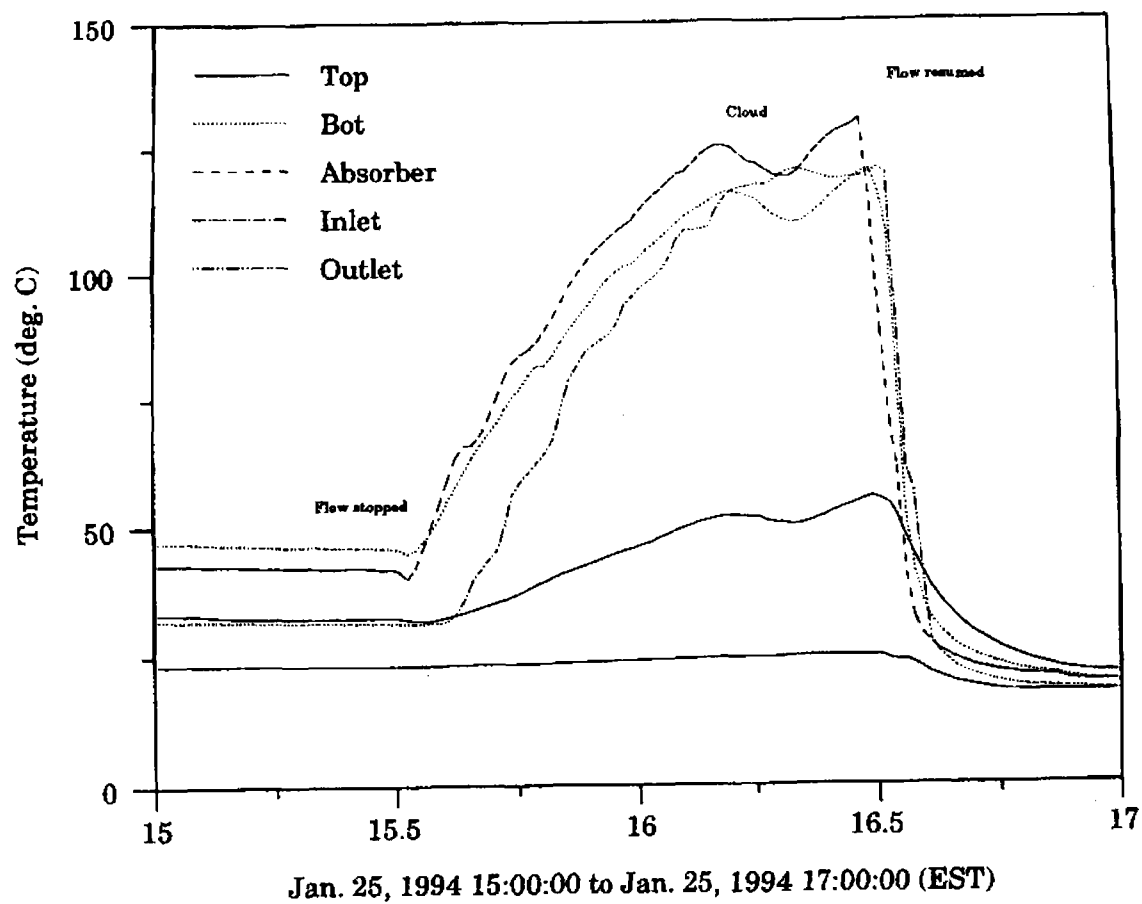


3.2.9 COLLECTOR STAGNATION

On 25 January 1994 the collectors in this series of tests were inadvertently left uncovered and facing the sun during a no fluid flow period. This constituted a wet stagnation. Although the flow was resumed about an hour later the internal temperatures had already exceeded the point where damage to some of the TIM takes place. The temperature data for this collector during that period is provided on the following page. The damage to the TIM effectively ended the comparison test. A performance test run later showed that this collector with 1" rectangular TIM showed no a change in performance.

Wet Stagnation Temperatures for 93050

Sandia Test 1 in. Rectangular Mod. Selective Absorber



3.3 TEST RESULTS ON SOLAR COLLECTOR WITH 4" RECTANGULAR TIM

The SDCRW(4x8) collector was modified as described in section 1.3 to contain 4" rectangular transparent insulation material (TIM). The collector was then tested in accordance with FSEC Test Methods and Minimum Standards for Certifying Solar Collectors, FSEC 77-5-R80. The tests performed were:

Thermal Performance Test

Incident Angle Modifier Test

Internal temperatures during some of the tests were recorded from the installed thermocouples.

Data are also included from the inadvertent wet stagnation that took place after the other testing was completed.

3.3.1 COLLECTOR IDENTIFICATION

Manufacturer and Address: Solar Development Inc.

3607-A Prospect Ave.

Riviera Beach, FL 33404

Collector Model Number: SD7CRW(4x8) with 4" rectangular transparent insulation added

3.3.3 COLLECTOR CONSTRUCTION BEFORE MODIFICATION

Overall dimensions*: Length: 2.444 m (8.02 ft)

Width: 1.189 m (3.90 ft)

Depth: 0.098 m (0.32 ft)

Overall front area*: (length x width) = 2.903 m² (31.25 ft²)

Enclosure: Material: Aluminum frame, aluminum back

Surface finish: Painted aluminum

Fasteners: Stainless steel screws and aluminum rivets

Holes and cutouts: Frame has holes and gaskets for each end of both headers

Glazing: Number of cover plates: One

Material: Tempered low iron glass

Thickness: 0.32 cm (0.125 in)

Length: 2.441 m (8.01 ft)

Width: 1.167 m (3.83 ft)

Surface characteristics: Smooth on outside, textured on inside

Glazing seal: EPDM rubber

Transparent frontal dimensions*: Area: 2.743 m² (29.53 ft²)

Absorber: Flow pattern: Parallel

Number of tubes: Ten

Spacing between tubes: 11.2 cm (4.4 in)

Material: Copper tubes welded to copper fins

Length: 2.283 m (7.49 ft)

Width: 1.119 m (3.67 ft)

Area: 2.554 m² (27.49 ft²)

Plate thickness: 0.046 cm (0.018 in)

Tube diameter (OD): 1.6 cm (0.63 in)

Header diameter (OD): 2.9 cm (1.13 in)

Flow tube to header connection: Brazed

Air spacing, glazing to absorber: approx. 3.2 cm (1.3 in)

Side insulation: Type: Foil faced polyisocyanurate

Thickness: 2.5 cm (1.0 in)

Back insulation: Type: Foil faced polyisocyanurate

Thickness: 4.4 cm (1.8 in)

Caulking, sealant, and/or gasket types(s): EPDM gaskets

Heat transfer fluid: Material: Water

Density: 977.81 kg/m³ at 70°C (61.01 lb/ft³ at 160°F)

Specific heat: 4189.6 J/kg°C at 70°C (1.001 Btu/lb°F at 160°F)

Collector weight*: 48.5 kg (107.0 lbs)

Collector fluid capacity*: 3.8 liters (1.0 gallons)

* Information provided by manufacturer; not verified by FSEC.

3.3.3 COLLECTOR MODIFICATIONS

This collector was one of a group of four being tested side by side to investigate the effects on performance of adding transparent insulation material (TIM) between the absorber and the glazing. This particular collector was modified to contain four-inch thick TIM. Aluminum extender sides were attached to the existing sides of the collector to accommodate the four-inches of TIM. These sides were bent to have a one-inch horizontal lip for the glazing to rest upon like the original collector. The extender side attachments were made to be slightly adjustable so the glazing could be placed in contact with the TIM. One-inch of foil faced polyisocyanurate insulation was placed within the extended sides to make them consistent the rest of the collector. To support the TIM off of the absorber, nine strips of wood 3/16" thick and 3/8" wide were placed widthwise across the absorber. These strips were the same size and number as in the other collectors. Six type T thermocouples were placed in the collector. Two thermocouples were attached to the absorber, two were placed in air just below the TIM, and two were placed on top of the TIM. The thermocouple wires were run along the side insulation and exited the frame through two small holes.

The TIM used in this collector was purchased from JND Sterling, Inc. of Atlanta, Georgia. This TIM has a honeycomb like structure with rectangular cells. The following properties were measured:

Thickness:	10.16 cm (4.00 in.)
Cell shape:	Rectangular (almost square)
Cell size (per side):	0.28 cm (0.11 in.)
Intercell wall thickness:	0.005 cm (0.002 in.)
Material*:	Polycarbonate

All the collectors in this series of tests were covered with tarpaulins when in a no water flow condition. This prevented damage to the TIM in one collector and gave all the collectors the same amount of exposure.

Tests were run with three absorbers, each with a different coating. The manufacturer of the collectors shipped the collectors with the selectively coated absorber already installed. They also provided the two other absorbers, one with a moderately selective paint coating and one with a flat black paint coating.

After all modifications were complete the collector was measured. The final dimensions were as follows:

Gross length:	2.46 m (8.07 ft)
Gross width:	1.19 m (3.90 ft)
Gross area:	2.93 m ² (31.49 ft ²)
Transparent length:	2.41 m (7.91 ft)
Transparent width:	1.14 m (3.73 ft)
Transparent area:	2.74 m ² (29.52 ft ²)

* Information provided by manufacturer; not verified by FSEC.

3.3.4 THERMAL PERFORMANCE WITH SELECTIVE ABSORBER

The collector, outfitted with a selective black chrome coated absorber, was tested from 16 November - 16 December 1993 in accordance with ASHRAE procedure 93-1986. Results of the thermal performance tests are presented in graphical and tabular form in both the International System of Units (SI) and English units. The thermal performance equations in S.I. units developed from the empirical data are:

$$\text{first order} \quad \eta = 67.6 - 245 \quad (T_i - T_a)/I$$

$$\text{second order} \quad \eta = 67.7 - 260 \quad (T_i - T_a)/I + 445 \quad [(T_i - T_a)/I]^2$$

These equations in English units are:

$$\text{first order} \quad \eta = 67.6 - 43 \quad (T_i - T_a)/I$$

$$\text{second order} \quad \eta = 67.7 - 46 \quad (T_i - T_a)/I + 14 \quad [(T_i - T_a)/I]^2$$

TABLE 3.13 THERMAL PERFORMANCE TEST ON 4" REC WITH SELECTIVE ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME		TA	TI	TE	FLOW	AVE IN	TOTAL IN	TE-TI	DEL T	EFFIC	(TI-TA)/
		START	END	(C)	(C)	(C)	J/M ²	W/M ²	L/MIN	(C)	C-MIN	%	(C-M ²)/W
1	11/16/93	11:21	11:25	27.1	59.3	67.0	3.26	1008.0	302394.	7.74	38.7	58.6	0.0319
2	11/16/93	11:26	11:30	27.1	59.3	67.1	3.25	1013.1	303923.	7.81	39.1	58.7	0.0317
4	11/16/93	11:36	11:40	27.3	59.3	67.2	3.22	1014.0	304202.	7.94	39.7	59.1	0.0315
5	11/16/93	11:41	11:45	27.3	59.3	67.3	3.21	1015.3	304582.	7.98	39.9	59.1	0.0315
11	11/16/93	12:39	12:44	27.1	49.7	57.7	3.27	1010.4	303115.	8.06	40.3	61.4	0.0223
12	11/16/93	12:44	12:49	27.0	49.7	57.7	3.27	1011.7	303500.	8.08	40.4	61.3	0.0224
13	11/16/93	12:49	12:54	27.2	49.7	57.8	3.28	1011.4	303409.	8.08	40.4	61.4	0.0223
14	11/16/93	12:54	12:59	27.2	49.6	57.7	3.28	1009.0	302688.	8.06	40.3	61.5	0.0222
15	11/16/93	12:59	13:04	27.2	49.7	57.7	3.29	1010.8	303236.	8.04	40.2	61.5	0.0222
16	11/16/93	13:04	13:09	27.2	49.7	57.7	3.28	1009.6	302875.	8.04	40.2	61.4	0.0223
21	11/16/93	14:27	14:32	26.9	40.0	47.9	3.30	966.8	290048.	7.97	39.8	64.2	0.0135
22	11/16/93	14:32	14:37	26.8	39.9	47.9	3.30	963.8	289144.	7.95	39.8	64.2	0.0136
23	11/16/93	14:37	14:42	26.8	39.9	47.9	3.29	956.6	286976.	7.91	39.6	64.3	0.0138
24	11/16/93	14:42	14:47	26.8	40.0	47.8	3.28	947.9	284380.	7.86	39.3	64.1	0.0139
33	11/17/93	13:41	13:46	27.7	28.3	36.7	3.28	974.1	292231.	8.35	41.7	66.5	0.0006
34	11/17/93	13:46	13:51	27.6	28.3	36.6	3.28	968.8	290644.	8.32	41.6	66.6	0.0007
39	11/18/93	13:58	14:02	26.5	26.8	34.9	3.28	941.9	282582.	8.10	40.5	66.9	0.0004
41	11/18/93	14:08	14:12	26.2	26.8	34.9	3.28	933.9	280173.	8.06	40.3	67.1	0.0007
43	11/18/93	14:18	14:22	26.4	26.9	34.7	3.29	909.9	272966.	7.81	39.1	67.0	0.0005
45	11/18/93	14:53	14:58	26.2	39.8	46.9	3.28	851.9	255567.	7.08	35.4	64.4	0.0160
46	11/18/93	14:58	15:03	26.3	39.8	46.8	3.28	840.3	252101.	6.99	34.9	64.4	0.0161
47	11/18/93	15:03	15:08	26.1	39.8	46.7	3.28	831.1	249327.	6.93	34.7	64.6	0.0165
52	12/07/93	9:10	9:14	17.7	17.1	25.1	3.27	909.3	272788.	8.04	40.2	68.7	-0.0006
53	12/07/93	9:15	9:19	17.9	17.2	25.3	3.27	919.8	275952.	8.13	40.7	68.8	-0.0008
54	12/07/93	9:20	9:24	18.0	17.2	25.4	3.27	928.4	278534.	8.19	41.0	68.7	-0.0008
58	12/07/93	10:31	10:36	20.2	39.9	48.2	3.31	1005.4	301630.	8.26	41.3	64.1	0.0197
59	12/07/93	10:36	10:41	20.1	39.9	48.2	3.31	1008.2	302452.	8.29	41.4	64.1	0.0196
60	12/07/93	10:41	10:46	20.3	39.9	48.2	3.31	1009.1	302726.	8.28	41.4	64.0	0.0195
62	12/07/93	12:57	13:01	21.6	58.1	66.1	3.30	1028.9	308664.	7.98	39.9	59.8	0.0355
63	12/07/93	13:02	13:06	21.6	58.1	66.1	3.30	1026.5	307952.	7.97	39.8	60.0	0.0356
64	12/07/93	13:07	13:11	21.5	58.1	66.1	3.30	1022.2	306663.	7.91	39.6	59.8	0.0358
65	12/07/93	13:12	13:16	21.5	58.2	66.1	3.30	1020.3	306096.	7.90	39.5	59.8	0.0359

TABLE 3.13 THERMAL PERFORMANCE TEST ON 4" REC WITH SELECTIVE ABSORBER (SI UNITS CONTINUED)

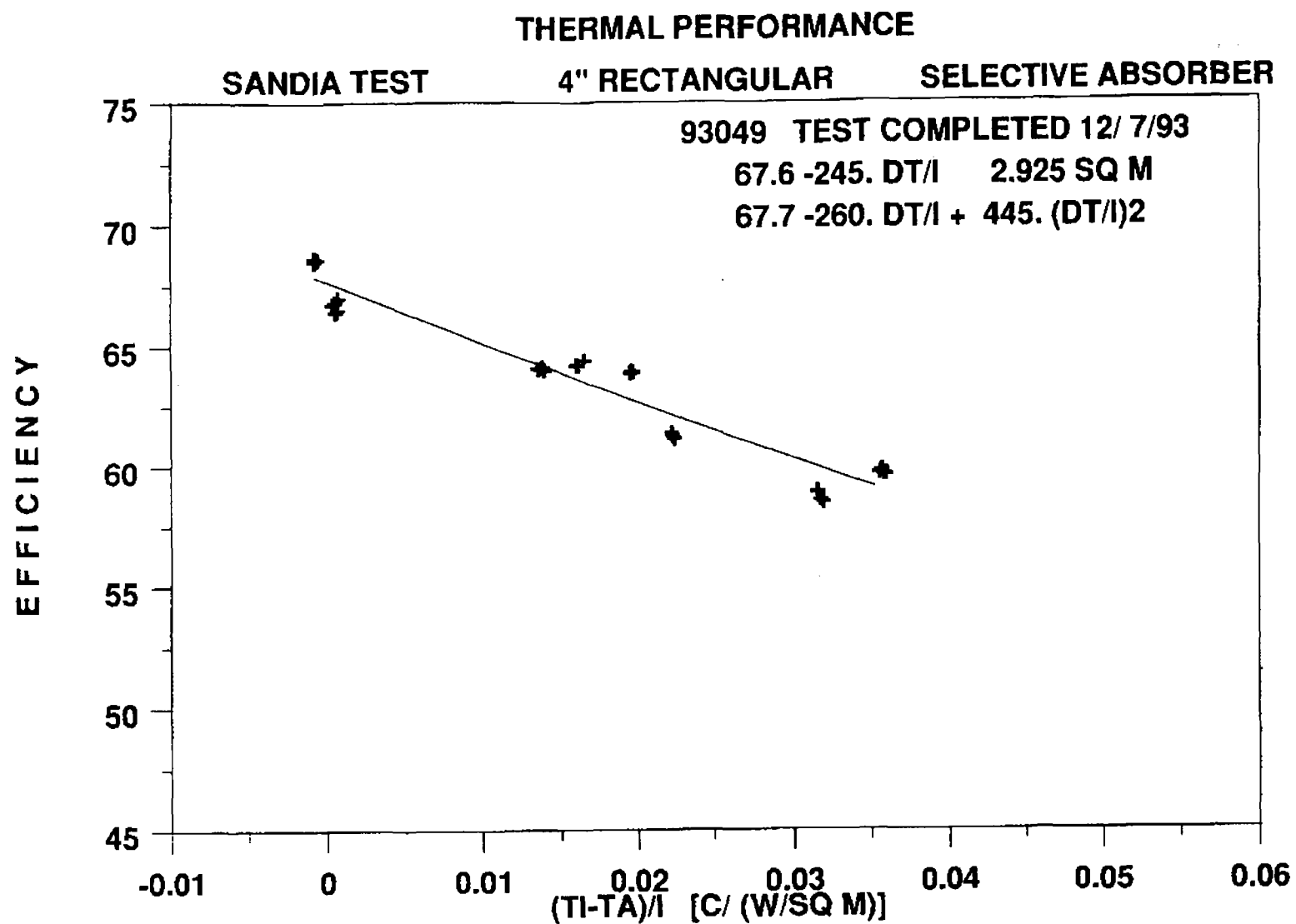
TEST	TILT DEG	AZIM DEG	INCI DEG	MASS KG/SEC	SPEC HEAT J/(KG C)	IN P KN/M ²	WIND M/S	WIND DIR	DIF IN W/M ²	% DIFF INSOL	TI-TA (C)
1	49.	11.	0.	0.0534	4185.7	62.6	2.4	99.	125.2	12.4	32.2
2	48.	10.	0.	0.0532	4185.7	62.8	2.8	97.	127.4	12.6	32.1
4	48.	7.	0.	0.0527	4185.8	64.0	2.3	96.	124.2	12.2	32.0
5	48.	5.	0.	0.0525	4185.8	64.8	3.0	107.	122.3	12.0	32.0
11	49.	-13.	0.	0.0538	4181.7	58.7	2.4	98.	126.3	12.5	22.5
12	49.	-15.	0.	0.0537	4181.7	59.7	2.6	100.	126.0	12.5	22.6
13	49.	-16.	0.	0.0538	4181.8	54.9	2.3	96.	125.3	12.4	22.5
14	50.	-18.	0.	0.0539	4181.7	46.4	2.3	104.	122.6	12.2	22.4
15	50.	-19.	0.	0.0541	4181.7	60.8	2.4	107.	123.9	12.3	22.4
16	50.	-21.	0.	0.0539	4181.7	61.1	2.2	103.	124.4	12.3	22.5
21	60.	-42.	0.	0.0545	4179.3	63.8	2.2	107.	118.6	12.3	13.1
22	61.	-43.	0.	0.0545	4179.3	62.9	2.4	108.	117.7	12.2	13.1
23	62.	-44.	0.	0.0544	4179.3	62.6	2.0	98.	117.0	12.2	13.2
24	62.	-45.	0.	0.0542	4179.3	61.2	2.2	102.	115.9	12.2	13.2
33	54.	-31.	0.	0.0544	4177.9	87.6	2.2	173.	173.7	17.8	0.6
34	55.	-32.	0.	0.0543	4177.9	88.8	2.0	178.	170.0	17.5	0.7
39	56.	-35.	0.	0.0544	4178.1	71.1	2.1	114.	186.6	19.8	0.3
41	58.	-37.	0.	0.0545	4178.1	59.0	2.0	110.	185.6	19.9	0.7
43	59.	-39.	0.	0.0546	4178.1	49.1	1.9	104.	191.3	21.0	0.5
45	64.	-47.	0.	0.0542	4179.2	70.3	1.8	100.	180.3	21.2	13.6
46	65.	-47.	0.	0.0542	4179.2	67.1	1.7	106.	180.3	21.5	13.5
47	66.	-48.	0.	0.0542	4179.2	65.5	1.9	90.	179.0	21.5	13.7
52	65.	43.	0.	0.0544	4181.8	79.8	1.3	357.	77.1	8.5	-0.6
53	64.	42.	0.	0.0544	4181.7	77.7	1.3	350.	82.5	9.0	-0.7
54	64.	41.	0.	0.0544	4181.7	79.7	1.7	349.	83.9	9.0	-0.8
58	55.	24.	0.	0.0546	4179.3	84.6	1.5	0.	90.8	9.0	19.8
59	55.	23.	0.	0.0546	4179.3	84.3	1.8	1.	91.0	9.0	19.8
60	54.	22.	0.	0.0546	4179.3	83.4	1.9	358.	91.5	9.1	19.7
62	53.	-17.	0.	0.0539	4185.2	83.4	1.5	5.	94.5	9.2	36.5
63	54.	-19.	0.	0.0540	4185.2	83.9	1.7	4.	95.3	9.3	36.6
64	54.	-20.	0.	0.0540	4185.2	84.3	1.8	7.	94.5	9.2	36.6
65	54.	-21.	0.	0.0540	4185.2	83.6	1.3	5.	95.2	9.3	36.6

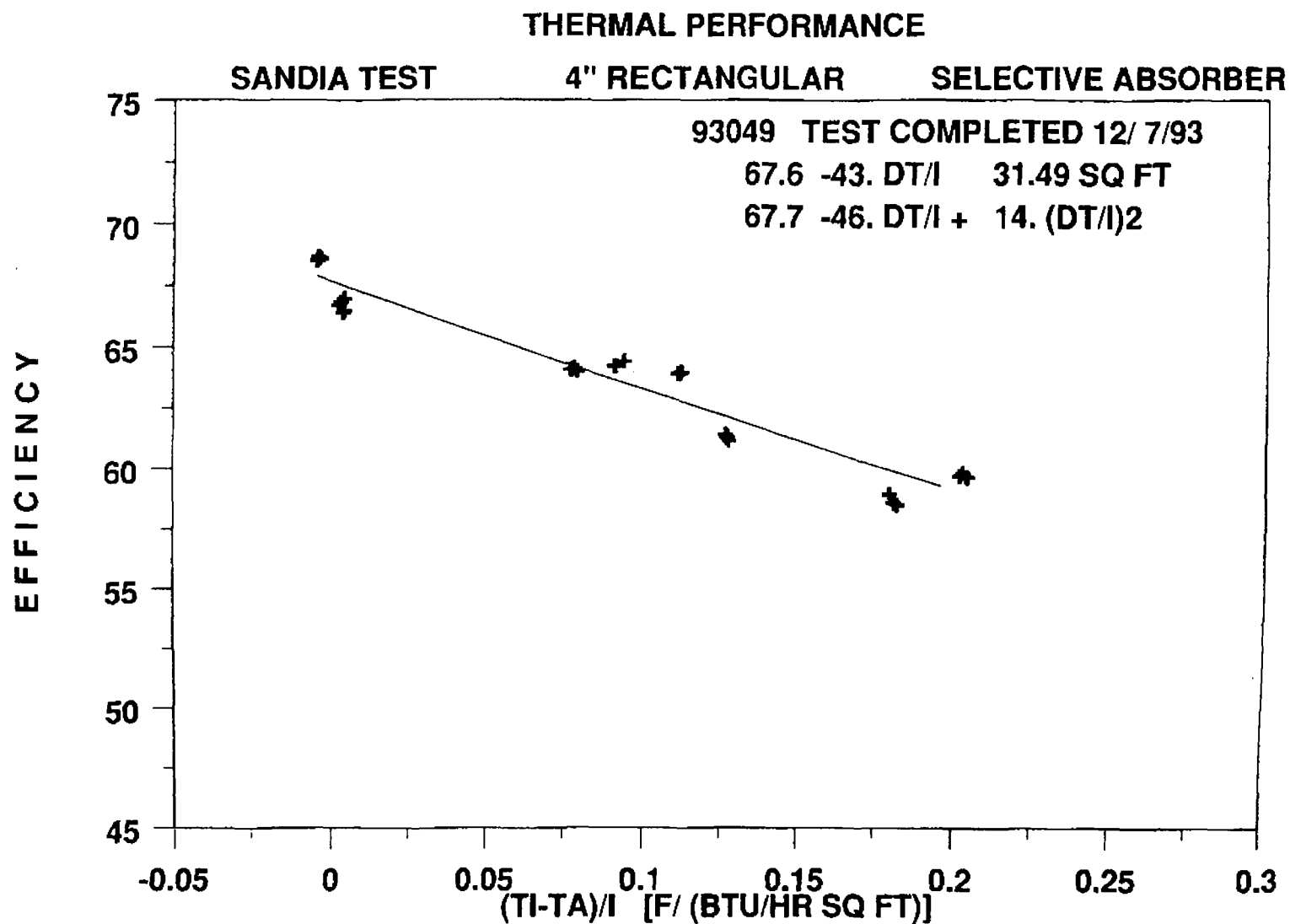
TABLE 3.13A THERMAL PERFORMANCE TEST ON 4" REC WITH SELECTIVE ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME START END	TA (F)	TI (F)	TE (F)	FLOW AVE IN GPM B/H-FT ²	TOTAL IN BTU/FT ²	TE-TI (F)	DEL T F-MIN	EFFIC %	(TI-TA)/I (F-H-FT ²)/B
1	11/16/93	11:21 11:25	80.8	138.7	152.6	0.862 319.7	26.6	13.93	69.7	58.6	0.181
2	11/16/93	11:26 11:30	80.9	138.7	152.8	0.859 321.4	26.8	14.06	70.3	58.7	0.180
4	11/16/93	11:36 11:40	81.2	138.8	153.0	0.851 321.7	26.8	14.29	71.5	59.1	0.179
5	11/16/93	11:41 11:45	81.1	138.7	153.1	0.848 322.1	26.8	14.37	71.8	59.1	0.179
11	11/16/93	12:39 12:44	80.8	121.4	135.9	0.865 320.5	26.7	14.52	72.6	61.4	0.127
12	11/16/93	12:44 12:49	80.7	121.4	135.9	0.863 320.9	26.7	14.54	72.7	61.3	0.127
13	11/16/93	12:49 12:54	80.9	121.4	136.0	0.865 320.8	26.7	14.54	72.7	61.4	0.126
14	11/16/93	12:54 12:59	81.0	121.3	135.8	0.866 320.1	26.7	14.50	72.5	61.5	0.126
15	11/16/93	12:59 13:04	81.0	121.4	135.8	0.869 320.6	26.7	14.46	72.3	61.5	0.126
16	11/16/93	13:04 13:09	81.0	121.4	135.9	0.867 320.3	26.7	14.47	72.3	61.4	0.126
21	11/16/93	14:27 14:32	80.4	103.9	118.3	0.873 306.7	25.6	14.34	71.7	64.2	0.077
22	11/16/93	14:32 14:37	80.3	103.9	118.2	0.872 305.7	25.5	14.31	71.6	64.2	0.077
23	11/16/93	14:37 14:42	80.2	103.9	118.1	0.870 303.4	25.3	14.25	71.2	64.3	0.078
24	11/16/93	14:42 14:47	80.2	103.9	118.1	0.867 300.7	25.1	14.15	70.7	64.1	0.079
33	11/17/93	13:41 13:46	81.8	82.9	98.0	0.866 309.0	25.7	15.03	75.1	66.5	0.004
34	11/17/93	13:46 13:51	81.6	82.9	97.9	0.865 307.3	25.6	14.98	74.9	66.6	0.004
39	11/18/93	13:58 14:02	79.7	80.3	94.9	0.867 298.8	24.9	14.58	72.9	66.9	0.002
41	11/18/93	14:08 14:12	79.1	80.3	94.8	0.868 296.2	24.7	14.50	72.5	67.1	0.004
43	11/18/93	14:18 14:22	79.5	80.4	94.4	0.870 288.6	24.1	14.06	70.3	67.0	0.003
45	11/18/93	14:53 14:58	79.2	103.7	116.5	0.867 270.2	22.5	12.75	63.8	64.4	0.091
46	11/18/93	14:58 15:03	79.4	103.7	116.3	0.867 266.6	22.2	12.57	62.9	64.4	0.091
47	11/18/93	15:03 15:08	78.9	103.6	116.1	0.867 263.6	22.0	12.47	62.4	64.6	0.094
52	12/07/93	9:10 9:14	63.8	62.8	77.3	0.864 288.4	24.0	14.47	72.3	68.7	-0.004
53	12/07/93	9:15 9:19	64.2	62.9	77.6	0.864 291.8	24.3	14.64	73.2	68.8	-0.004
54	12/07/93	9:20 9:24	64.4	63.0	77.8	0.864 294.5	24.5	14.75	73.7	68.7	-0.005
58	12/07/93	10:31 10:36	68.3	103.8	118.7	0.873 318.9	26.6	14.88	74.4	64.1	0.112
59	12/07/93	10:36 10:41	68.2	103.9	118.8	0.874 319.8	26.7	14.92	74.6	64.1	0.111
60	12/07/93	10:41 10:46	68.5	103.9	118.8	0.874 320.1	26.7	14.90	74.5	64.0	0.111
62	12/07/93	12:57 13:01	70.9	136.5	150.9	0.871 326.4	27.2	14.36	71.8	59.8	0.201
63	12/07/93	13:02 13:06	70.8	136.6	150.9	0.871 325.6	27.1	14.35	71.7	60.0	0.202
64	12/07/93	13:07 13:11	70.7	136.6	150.9	0.871 324.3	27.0	14.25	71.2	59.8	0.203
65	12/07/93	13:12 13:16	70.8	136.7	150.9	0.871 323.7	27.0	14.21	71.1	59.8	0.204

TABLE 3.13A THERMAL PERFORMANCE TEST ON 4" REC WITH SELECTIVE ABSORBER (ENGLISH UNITS CONTINUED)

TEST	TILT DEG	AZIM DEG	INCI DEG	MASS LBM/MIN	SPEC HEAT BTU/(LBM-F)	IN P PSI	WIND MPH	WIND DIR	DIF IN B/H-FT ²	% DIFF INSOL	TI-TA (F)
1	49.	11.	0.	7.06	1.000	9.1	5.3	99.	39.7	12.4	57.9
2	48.	10.	0.	7.04	1.000	9.1	6.2	97.	40.4	12.6	57.8
4	48.	7.	0.	6.97	1.000	9.3	5.1	96.	39.4	12.2	57.5
5	48.	5.	0.	6.95	1.000	9.4	6.6	107.	38.8	12.0	57.6
11	49.	-13.	0.	7.12	0.999	8.5	5.5	98.	40.1	12.5	40.6
12	49.	-15.	0.	7.10	0.999	8.7	5.8	100.	40.0	12.5	40.7
13	49.	-16.	0.	7.12	0.999	8.0	5.2	96.	39.8	12.4	40.6
14	50.	-18.	0.	7.13	0.999	6.7	5.0	104.	38.9	12.2	40.3
15	50.	-19.	0.	7.15	0.999	8.8	5.3	107.	39.3	12.3	40.4
16	50.	-21.	0.	7.13	0.999	8.9	5.0	103.	39.4	12.3	40.5
21	60.	-42.	0.	7.21	0.998	9.2	5.0	107.	37.6	12.3	23.6
22	61.	-43.	0.	7.21	0.998	9.1	5.3	108.	37.3	12.2	23.6
23	62.	-44.	0.	7.19	0.998	9.1	4.5	98.	37.1	12.2	23.7
24	62.	-45.	0.	7.16	0.998	8.9	5.0	102.	36.8	12.2	23.7
33	54.	-31.	0.	7.19	0.998	12.7	5.0	173.	55.1	17.8	1.1
34	55.	-32.	0.	7.18	0.998	12.9	4.6	178.	53.9	17.5	1.3
39	56.	-35.	0.	7.20	0.998	10.3	4.7	114.	59.2	19.8	0.6
41	58.	-37.	0.	7.21	0.998	8.6	4.5	110.	58.9	19.9	1.2
43	59.	-39.	0.	7.23	0.998	7.1	4.3	104.	60.7	21.0	0.9
45	64.	-47.	0.	7.17	0.998	10.2	3.9	100.	57.2	21.2	24.5
46	65.	-47.	0.	7.17	0.998	9.7	3.7	106.	57.2	21.5	24.3
47	66.	-48.	0.	7.17	0.998	9.5	4.2	90.	56.8	21.5	24.7
52	65.	43.	0.	7.20	0.999	11.6	3.0	357.	24.5	8.5	-1.0
53	64.	42.	0.	7.20	0.999	11.3	2.9	350.	26.2	9.0	-1.3
54	64.	41.	0.	7.20	0.999	11.6	3.8	349.	26.6	9.0	-1.4
58	55.	24.	0.	7.22	0.998	12.3	3.3	0.	28.8	9.0	35.6
59	55.	23.	0.	7.22	0.998	12.2	4.0	1.	28.9	9.0	35.6
60	54.	22.	0.	7.23	0.998	12.1	4.3	358.	29.0	9.1	35.4
62	53.	-17.	0.	7.14	1.000	12.1	3.4	5.	30.0	9.2	65.7
63	54.	-19.	0.	7.14	1.000	12.2	3.9	4.	30.2	9.3	65.8
64	54.	-20.	0.	7.14	1.000	12.2	4.1	7.	30.0	9.2	65.9
65	54.	-21.	0.	7.14	1.000	12.1	3.0	5.	30.2	9.3	65.9





3.3.5 THERMAL PERFORMANCE WITH MODERATELY SELECTIVE ABSORBER

The collector, outfitted with a moderately selective black paint coated absorber, was tested on 25 January 1994 in accordance with ASHRAE procedure 93-1986. Only two different inlet temperatures tests were run for the moderately selective paint absorber. The customary minimum of four points was not taken because the collector was exposed to a period of wet stagnation. This stagnation may have caused some degradation to the TIM installed in this collector. Since only two points were taken only a linear fit could be developed. Results of the thermal performance tests are presented in graphical and tabular form in both the International System of Units (SI) and English units. The thermal performance equations in S.I. units developed from the empirical data are:

$$\text{first order} \quad \eta = 67.1 - 214 \quad (T_i - T_a)/I$$

These equations in English units are:

$$\text{first order} \quad \eta = 67.1 - 38 \quad (T_i - T_a)/I$$

TABLE 3.14 THERMAL PERFORMANCE TEST ON 4" REC WITH MODERATELY SELECTIVE ABSORBER (SI UNITS)

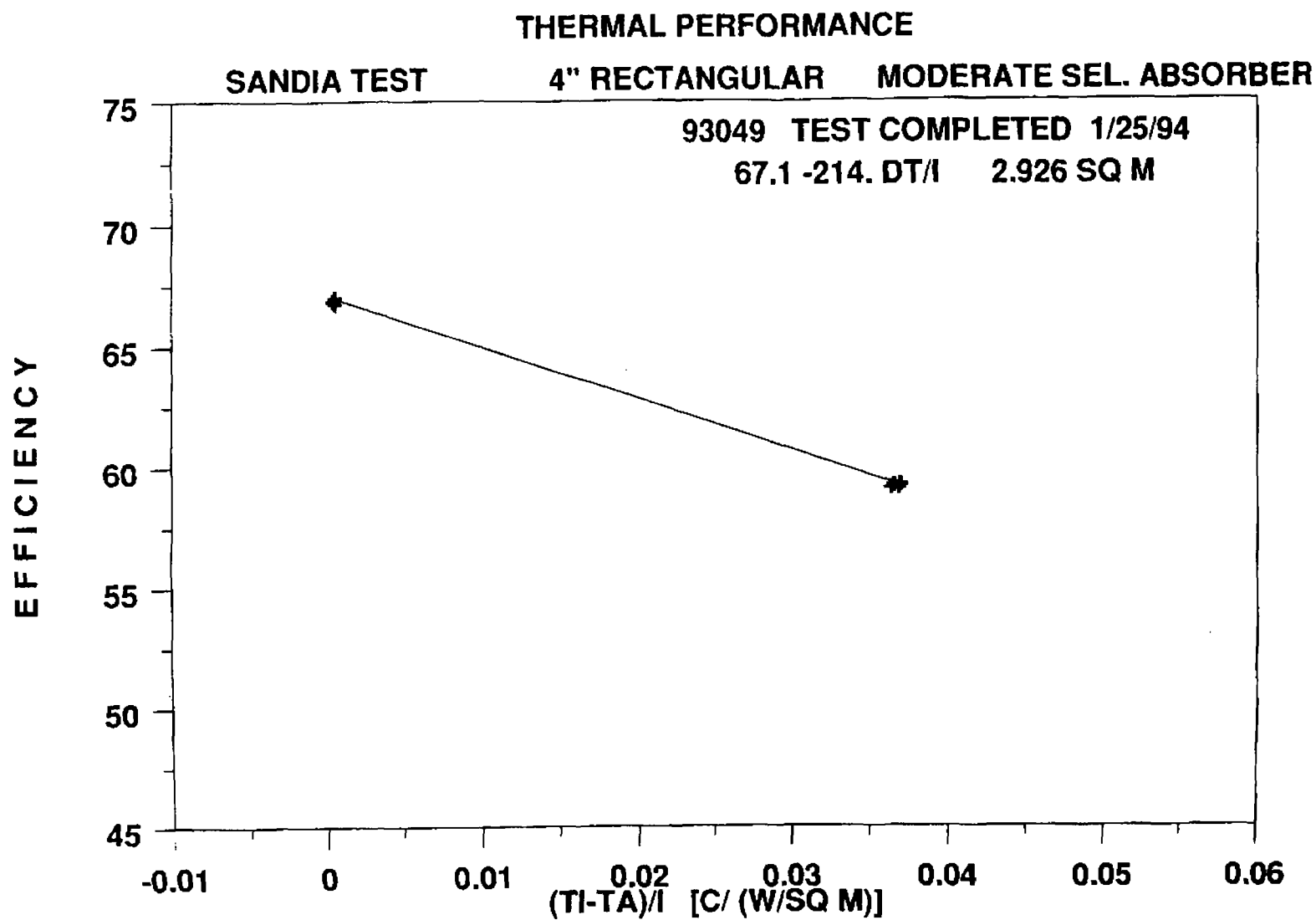
TEST	DATE	SOLAR TIME START END	TA (C)	TI (C)	TE (C)	FLOW AVE IN L/MIN W/M ²	TOTAL IN J/M ²	TE-TI (C)	DEL T C-MIN	EFFIC %	(TI-TA)/I (C-M ²)/W
4	1/25/94	13:26 13:31	23.1	60.0	67.9	3.27 1012.0	303587.	7.86	39.3	59.3	0.0365
5	1/25/94	13:31 13:36	23.4	60.1	67.9	3.27 1012.4	303707.	7.84	39.2	59.2	0.0363
7	1/25/94	13:41 13:46	23.0	60.1	68.0	3.26 1010.0	302995.	7.84	39.2	59.2	0.0368
8	1/25/94	13:46 13:51	23.0	60.1	68.0	3.26 1006.2	301865.	7.83	39.1	59.4	0.0369
10	1/25/94	14:22 14:27	22.8	23.2	31.7	3.25 976.2	292861.	8.48	42.4	67.0	0.0004
13	1/25/94	14:37 14:42	22.7	23.1	31.4	3.25 954.4	286327.	8.30	41.5	67.1	0.0005
14	1/25/94	14:42 14:47	22.6	23.1	31.4	3.25 951.5	285462.	8.25	41.2	66.9	0.0005
16	1/25/94	14:52 14:57	22.7	23.1	31.2	3.26 934.9	280462.	8.11	40.5	67.0	0.0004

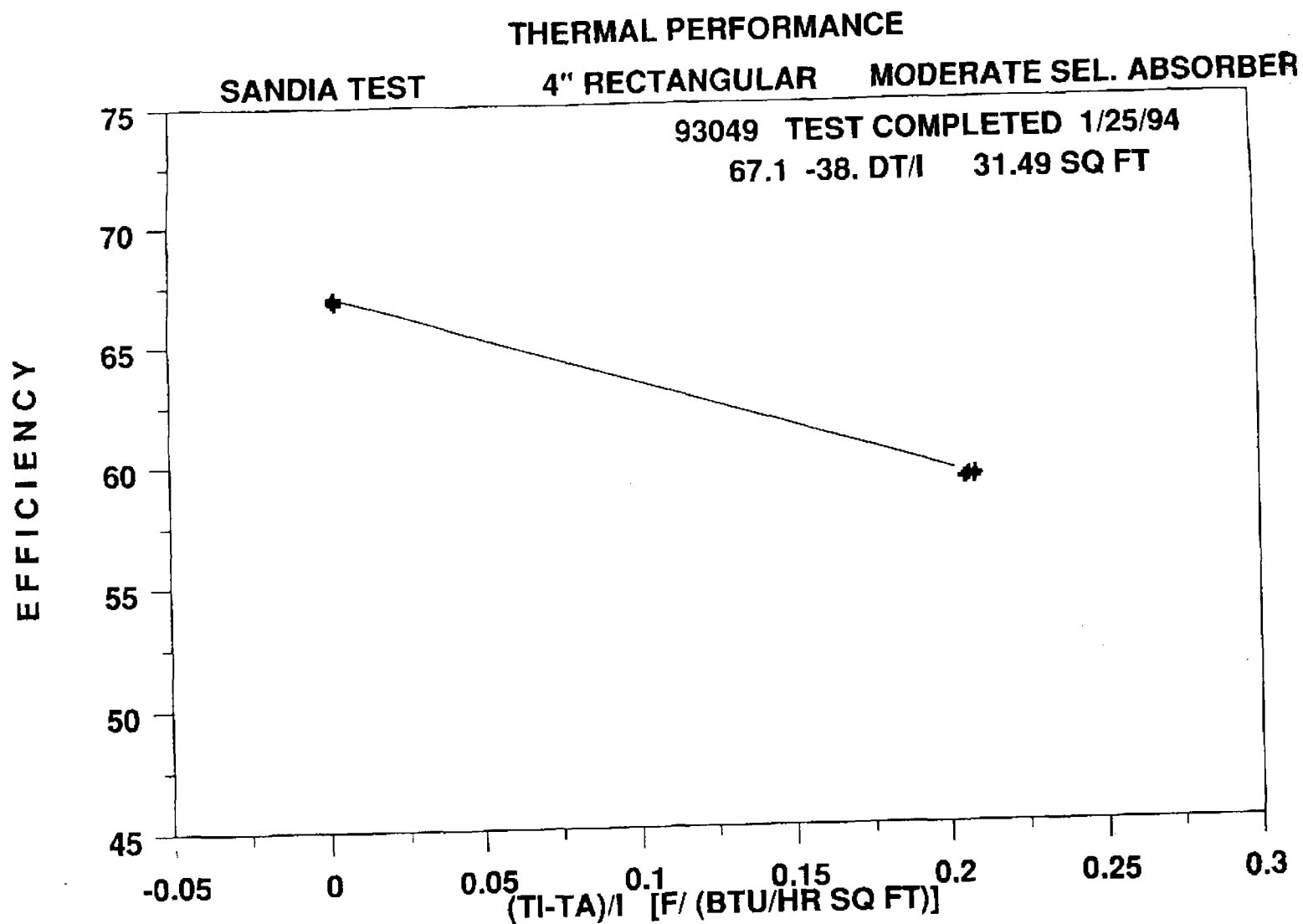
TEST	TILT DEG	AZIM DEG	INCI DEG	MASS KG/SEC	SPEC HEAT J/(KG C)	IN P KN/M ²	WIND M/S	WIND DIR	DIF IN W/M ²	% DIFF INSOL	TI-TA (C)
4	52.	-27.	0.	0.0534	4186.1	84.1	1.9	101.	136.3	13.5	36.9
5	53.	-28.	0.	0.0535	4186.1	84.3	1.9	101.	134.7	13.3	36.7
7	54.	-31.	0.	0.0534	4186.2	83.2	1.8	103.	129.7	12.8	37.1
8	54.	-32.	0.	0.0533	4186.2	83.5	2.2	106.	128.4	12.8	37.1
10	59.	-41.	0.	0.0540	4178.8	83.9	1.6	108.	137.2	14.1	0.4
13	61.	-44.	0.	0.0540	4178.9	85.2	2.4	112.	127.3	13.3	0.5
14	62.	-45.	0.	0.0540	4178.9	84.7	2.0	109.	127.3	13.4	0.5
16	64.	-47.	0.	0.0541	4178.9	84.0	2.1	102.	128.1	13.7	0.4

TABLE 3.14A THERMAL PERFORMANCE TEST ON 4" REC WITH MODERATELY SELECTIVE ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME START END	TA (F)	TI (F)	TE (F)	FLOW GPM	AVE IN B/H-FT ²	TOTAL IN BTU/FT ²	TE-TI (F)	DEL T F-MIN	EFFIC %	(TI-TA)/I (F-H-FT ²)/B
4	1/25/94	13:26 13:31	73.6	140.1	154.2	0.863	321.0	26.8	14.14	70.7	59.3	0.207
5	1/25/94	13:31 13:36	74.1	140.2	154.3	0.864	321.1	26.8	14.10	70.5	59.2	0.206
7	1/25/94	13:41 13:46	73.3	140.2	154.3	0.862	320.4	26.7	14.10	70.5	59.2	0.209
8	1/25/94	13:46 13:51	73.5	140.2	154.3	0.862	319.2	26.6	14.09	70.4	59.4	0.209
10	1/25/94	14:22 14:27	73.1	73.8	89.0	0.859	309.7	25.8	15.27	76.3	67.0	0.002
13	1/25/94	14:37 14:42	72.8	73.7	88.6	0.859	302.8	25.2	14.94	74.7	67.1	0.003
14	1/25/94	14:42 14:47	72.7	73.6	88.5	0.860	301.8	25.2	14.84	74.2	66.9	0.003
16	1/25/94	14:52 14:57	72.9	73.6	88.2	0.860	296.6	24.7	14.59	73.0	67.0	0.002

TEST	TILT DEG	AZIM DEG	INCI DEG	MASS LBM/MIN	SPEC HEAT BTU/(LBM-F)	IN P PSI	WIND MPH	WIND DIR	DIF IN B/H-FT ²	% DIFF INSOL	TI-TA (F)
4	52.	-27.	0.	7.07	1.000	12.2	4.3	101.	43.2	13.5	66.4
5	53.	-28.	0.	7.07	1.000	12.2	4.3	101.	42.7	13.3	66.1
7	54.	-31.	0.	7.06	1.000	12.1	3.9	103.	41.1	12.8	66.9
8	54.	-32.	0.	7.06	1.000	12.1	4.9	106.	40.7	12.8	66.8
10	59.	-41.	0.	7.14	0.998	12.2	3.6	108.	43.5	14.1	0.7
13	61.	-44.	0.	7.15	0.998	12.4	5.3	112.	40.4	13.3	0.8
14	62.	-45.	0.	7.15	0.998	12.3	4.5	109.	40.4	13.4	0.9
16	64.	-47.	0.	7.16	0.998	12.2	4.7	102.	40.6	13.7	0.7





3.3.6 THERMAL PERFORMANCE WITH FLAT BLACK PAINT ABSORBER

The collector, outfitted with a flat black paint coated absorber, was tested from 27-28 December 1993 in accordance with ASHRAE procedure 93-1986. Results of the thermal performance tests are presented in graphical and tabular form in both the International System of Units (SI) and English units. The thermal performance equations in S.I. units developed from the empirical data are:

$$\text{first order} \quad \eta = 69.3 - 265 \quad (T_i - T_a)/I$$

$$\text{second order} \quad \eta = 68.9 - 165 \quad (T_i - T_a)/I - 2339 \quad [(T_i - T_a)/I]^2$$

These equations in English units are:

$$\text{first order} \quad \eta = 69.3 - 47 \quad (T_i - T_a)/I$$

$$\text{second order} \quad \eta = 68.9 - 29 \quad (T_i - T_a)/I - 73 \quad [(T_i - T_a)/I]^2$$

TABLE 3.15 THERMAL PERFORMANCE TEST ON 4" REC WITH FLAT BLACK ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME		TA	TI	TE	FLOW	AVE IN	TOTAL IN	TE-TI	DEL T	EFFIC	(TI-TA)/I
		START	END	(C)	(C)	(C)	L/MIN	W/M ²	J/M ²	(C)	C-MIN	%	(C-M ²)/W
6	12/27/93	11:06	11:11	14.6	61.9	69.7	3.34	1065.7	319707.	7.81	39.1	57.2	0.0443
7	12/27/93	11:11	11:16	14.7	61.8	69.7	3.34	1067.2	320159.	7.84	39.2	57.4	0.0441
9	12/27/93	11:21	11:26	15.3	61.8	69.7	3.34	1069.6	320880.	7.86	39.3	57.4	0.0435
10	12/27/93	11:26	11:31	15.4	61.8	69.7	3.34	1070.4	321130.	7.90	39.5	57.6	0.0434
13	12/27/93	11:59	12:04	16.1	52.2	60.5	3.31	1065.1	319539.	8.25	41.3	60.2	0.0339
14	12/27/93	12:04	12:09	16.2	52.3	60.5	3.31	1061.3	318399.	8.22	41.1	60.1	0.0339
15	12/27/93	12:09	12:14	16.5	52.3	60.5	3.31	1059.9	317981.	8.22	41.1	60.3	0.0338
16	12/27/93	12:14	12:19	16.4	52.3	60.5	3.31	1060.2	318058.	8.22	41.1	60.3	0.0338
18	12/27/93	12:53	12:57	17.9	39.8	48.4	3.33	1043.2	312957.	8.59	42.9	64.7	0.0210
19	12/27/93	12:58	13:02	18.0	39.8	48.4	3.33	1038.4	311510.	8.57	42.9	64.8	0.0210
20	12/27/93	13:03	13:07	18.2	39.8	48.3	3.33	1034.6	310375.	8.52	42.6	64.7	0.0209
21	12/27/93	13:08	13:12	18.4	39.8	48.4	3.33	1031.2	309370.	8.50	42.5	64.8	0.0208
30	12/28/93	11:37	11:42	21.3	21.4	30.2	3.35	1020.7	306202.	8.88	44.4	69.3	0.0001
31	12/28/93	11:42	11:47	21.5	21.3	30.3	3.33	1018.3	305495.	8.91	44.5	69.2	-0.0001
32	12/28/93	11:47	11:52	21.4	21.3	30.3	3.32	1024.8	307437.	8.93	44.6	68.6	0.0000
33	12/28/93	11:52	11:57	21.5	21.4	30.3	3.28	1022.4	306726.	8.97	44.9	68.4	-0.0001

TABLE 3.15 THERMAL PERFORMANCE TEST ON 4" REC WITH FLAT BLACK ABSORBER (SI UNITS CONTIUED)

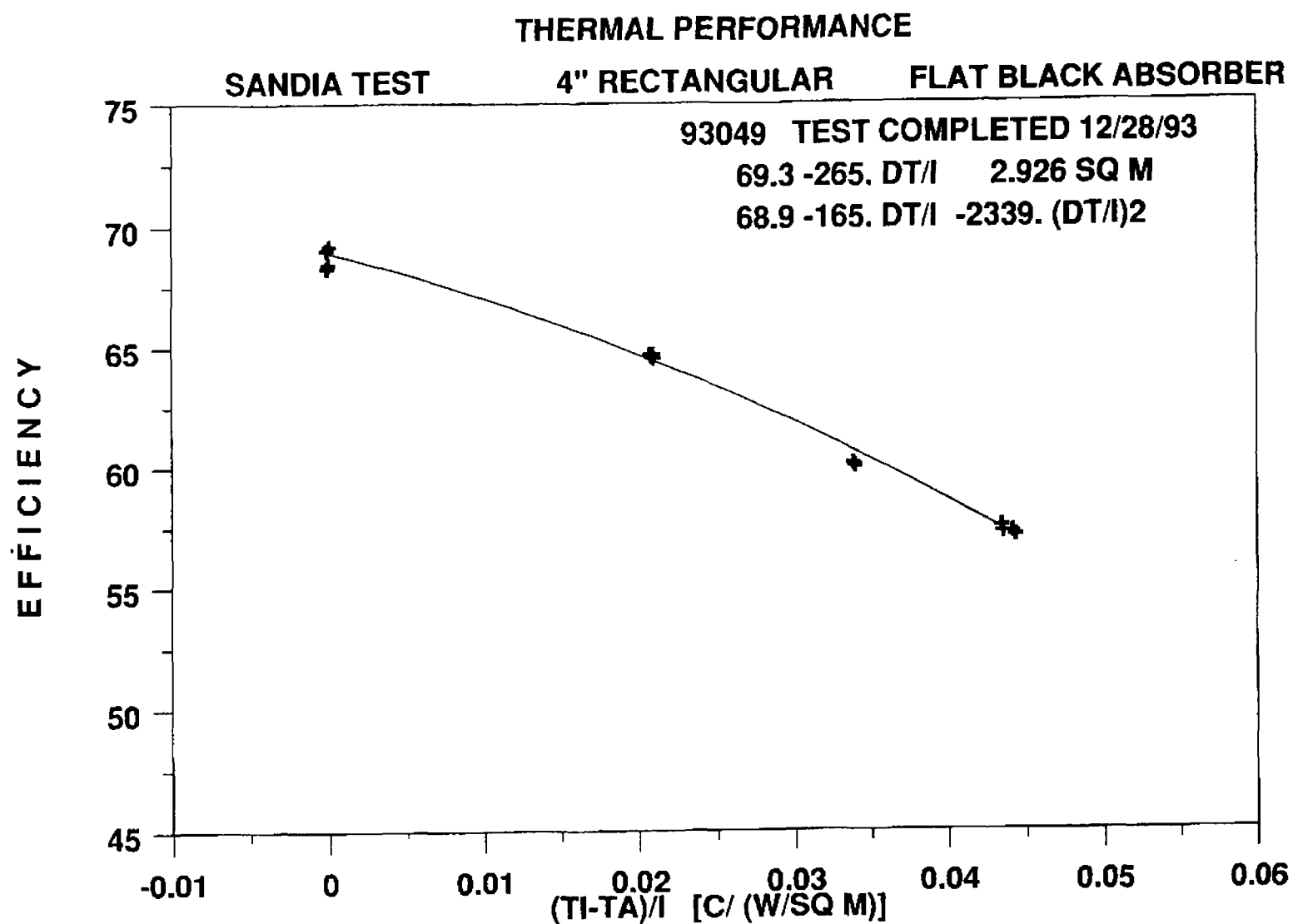
TEST	TILT DEG	AZIM DEG	INCI DEG	MASS KG/SEC	SPEC HEAT J/(KG C)	IN P KN/M ²	WIND M/S	WIND DIR	DIF IN W/M ²	% DIFF INSOL	TI-TA (C)
6	53.	15.	0.	0.0545	4187.1	78.1	1.6	347.	94.4	8.9	47.2
7	53.	13.	0.	0.0545	4187.1	78.7	1.4	350.	95.9	9.0	47.1
9	52.	10.	0.	0.0545	4187.1	79.8	1.1	356.	98.0	9.2	46.5
10	52.	9.	0.	0.0545	4187.1	80.1	1.4	356.	98.4	9.2	46.4
13	52.	-1.	0.	0.0544	4182.7	80.8	1.2	348.	100.2	9.4	36.1
14	52.	-2.	0.	0.0544	4182.7	81.9	0.9	347.	98.4	9.3	36.0
15	52.	-3.	0.	0.0544	4182.7	81.3	1.2	353.	97.3	9.2	35.8
16	52.	-5.	0.	0.0544	4182.7	81.3	1.0	355.	98.3	9.3	35.9
18	53.	-16.	0.	0.0550	4179.3	82.9	0.7	337.	92.8	8.9	21.9
19	54.	-17.	0.	0.0550	4179.3	82.0	0.5	334.	90.8	8.7	21.8
20	54.	-19.	0.	0.0550	4179.3	80.3	0.4	335.	90.5	8.8	21.6
21	54.	-20.	0.	0.0550	4179.3	82.1	0.6	344.	88.2	8.6	21.4
30	52.	6.	0.	0.0557	4179.4	81.8	1.2	335.	149.2	14.6	0.1
31	52.	4.	0.	0.0553	4179.4	80.2	0.8	336.	147.4	14.5	-0.1
32	52.	3.	0.	0.0551	4179.4	80.4	0.8	342.	141.2	13.8	0.0
33	52.	1.	0.	0.0546	4179.4	80.3	0.8	334.	124.5	12.2	-0.1

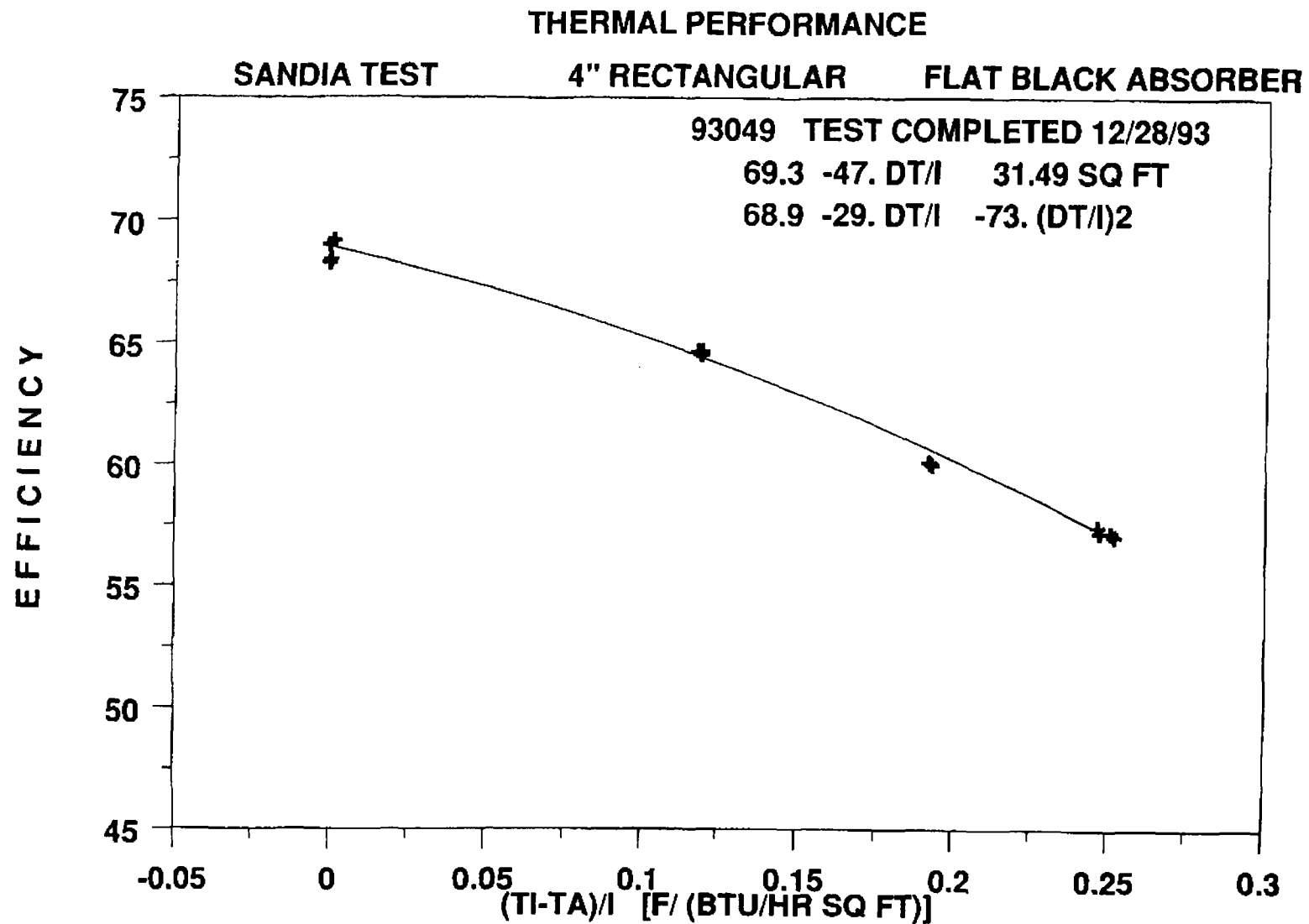
TABLE 3.15A THERMAL PERFORMANCE TEST ON 4" REC WITH FLAT BLACK ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME		TA	TI	TE	FLOW	AVE IN	TOTAL IN	TE-TI	DEL T	EFFIC	(TI-TA)/I
		START	END	(F)	(F)	(F)	GPM	B/H-FT ²	BTU/FT ²	(F)	F-MIN	%	(F-H-FT ²)/B
6	12/27/93	11:06	11:11	58.3	143.3	157.4	0.882	338.0	28.2	14.06	70.3	57.2	0.252
7	12/27/93	11:11	11:16	58.5	143.3	157.4	0.882	338.5	28.2	14.12	70.6	57.4	0.250
9	12/27/93	11:21	11:26	59.6	143.3	157.5	0.882	339.3	28.3	14.15	70.7	57.4	0.247
10	12/27/93	11:26	11:31	59.7	143.3	157.5	0.882	339.6	28.3	14.22	71.1	57.6	0.246
13	12/27/93	11:59	12:04	61.1	126.0	140.9	0.875	337.9	28.2	14.85	74.3	60.2	0.192
14	12/27/93	12:04	12:09	61.2	126.1	140.9	0.875	336.7	28.1	14.79	73.9	60.1	0.193
15	12/27/93	12:09	12:14	61.6	126.1	140.9	0.875	336.2	28.0	14.79	73.9	60.3	0.192
16	12/27/93	12:14	12:19	61.5	126.1	140.9	0.875	336.3	28.0	14.79	73.9	60.3	0.192
18	12/27/93	12:53	12:57	64.2	103.7	119.1	0.880	330.9	27.6	15.46	77.3	64.7	0.119
19	12/27/93	12:58	13:02	64.3	103.6	119.1	0.880	329.4	27.4	15.43	77.1	64.8	0.119
20	12/27/93	13:03	13:07	64.7	103.6	119.0	0.881	328.2	27.3	15.33	76.7	64.7	0.119
21	12/27/93	13:08	13:12	65.2	103.7	119.0	0.881	327.1	27.3	15.31	76.5	64.8	0.118
30	12/28/93	11:37	11:42	70.3	70.4	86.4	0.886	323.8	27.0	15.99	80.0	69.3	0.001
31	12/28/93	11:42	11:47	70.7	70.4	86.5	0.880	323.0	26.9	16.03	80.2	69.2	-0.001
32	12/28/93	11:47	11:52	70.5	70.4	86.5	0.876	325.1	27.1	16.07	80.3	68.6	0.000
33	12/28/93	11:52	11:57	70.7	70.5	86.6	0.868	324.3	27.0	16.15	80.7	68.4	-0.001

TABLE 3.15A THERMAL PERFORMANCE TEST ON 4" REC WITH FLAT BLACK ABSORBER (ENGLISH UNITS CONTINUED)

TEST	TILT DEG	AZIM DEG	INCI DEG	MASS LBM/MIN	SPEC HEAT BTU/(LBM-F)	IN P PSI	WIND MPH	WIND DIR	DIF IN B/H-FT ²	% DIFF INSOL	TI-TA (F)
6	53.	15.	0.	7.21	1.000	11.3	3.7	347.	30.0	8.9	85.0
7	53.	13.	0.	7.21	1.000	11.4	3.2	350.	30.4	9.0	84.8
9	52.	10.	0.	7.22	1.000	11.6	2.4	356.	31.1	9.2	83.8
10	52.	9.	0.	7.21	1.000	11.6	3.1	356.	31.2	9.2	83.6
13	52.	-1.	0.	7.19	0.999	11.7	2.7	348.	31.8	9.4	65.0
14	52.	-2.	0.	7.19	0.999	11.9	2.1	347.	31.2	9.3	64.8
15	52.	-3.	0.	7.19	0.999	11.8	2.7	353.	30.9	9.2	64.5
16	52.	-5.	0.	7.19	0.999	11.8	2.3	355.	31.2	9.3	64.5
18	53.	-16.	0.	7.27	0.998	12.0	1.6	337.	29.4	8.9	39.4
19	54.	-17.	0.	7.27	0.998	11.9	1.1	334.	28.8	8.7	39.3
20	54.	-19.	0.	7.28	0.998	11.6	0.9	335.	28.7	8.8	39.0
21	54.	-20.	0.	7.28	0.998	11.9	1.2	344.	28.0	8.6	38.5
30	52.	6.	0.	7.37	0.998	11.9	2.6	335.	47.3	14.6	0.2
31	52.	4.	0.	7.32	0.998	11.6	1.8	336.	46.8	14.5	-0.2
32	52.	3.	0.	7.29	0.998	11.7	1.7	342.	44.8	13.8	-0.1
33	52.	1.	0.	7.22	0.998	11.6	1.7	334.	39.5	12.2	-0.2





3.3.7 INCIDENT ANGLE MODIFIER TEST

The collector, outfitted with a selective black chrome coated absorber, was tested from 15-18 November 1993 in accordance with the ASHRAE procedure to determine the longitudinal incident angle modifier (IAM). The definition of longitudinal IAM for this report will be incident angles where the collector's azimuth is tracking the sun while its elevation is made higher or lower than the sun's altitude, assuming the collector is mounted with its long axis parallel to the ground. A graph of the longitudinal IAM along with the data in tabular form follows. The longitudinal incident angle modifier equation was determined to be:

$$K_{\tau\alpha} = 1.0 - 0.28 (1/\cos \theta - 1)$$

The collector, outfitted with a selective black chrome coated absorber, was tested from 15 November - 16 December 1993 in accordance with the ASHRAE procedure to determine the transverse incident angle modifier (IAM). The definition of transverse IAM for this report will be incident angles where the collector's elevation is tracking the sun while its azimuth is made further right or left than the sun's azimuth assuming the collector is mounted with its long axis parallel to the ground. A graph of the transverse IAM along with the data in tabular form follows. The transverse incident angle modifier equation was determined to be:

$$K_{\tau\alpha} = 1.0 - 0.34 (1/\cos \theta - 1)$$

The collector, outfitted with a flat black paint coated absorber, was tested on 28 December 1993 in accordance with the ASHRAE procedure to determine the transverse incident angle modifier (IAM). The definition of transverse IAM for this report will be incident angles where the collector's elevation is tracking the sun while its azimuth is made further right or left than the sun's azimuth assuming the collector is mounted with its long axis parallel to the ground. A graph of the transverse IAM along with the data in tabular form follows. The transverse incident angle

modifier equation was determined to be:

$$K\tau\alpha = 1.0 - 0.22 (1/\cos \theta - 1)$$

Incident angle modifier tests were not performed on all collector-absorber configurations since results did not change significantly from one configuration to the next.

TABLE 3.16 LONGITUDINAL INCIDENT ANGLE MODIFIER TEST ON 4" REC WITH SELECTIVE ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM
		START END	(C)	(C)	(C)	(C)	(C)	L/M	KG/SEC	DEG	DEG	DEG	W/M²	DIF	M/S	DEG	%
2	11/15/93	11:50 11:54	27.3	29.3	31.8	2.45	2.0	3.3	0.0551	12.	3.	60.	412.	-1.	2.2	116.	46.9
3	11/15/93	11:55 11:59	27.3	29.3	31.8	2.44	2.0	3.3	0.0553	12.	1.	60.	410.	-1.	2.1	121.	47.0
7	11/15/93	12:29 12:34	27.8	29.3	33.5	4.23	1.5	3.3	0.0544	3.	-10.	45.	614.	7.	1.8	153.	53.5
8	11/15/93	12:34 12:39	27.8	29.3	33.5	4.22	1.5	3.3	0.0544	3.	-12.	45.	612.	7.	1.9	148.	53.6
9	11/15/93	13:03 13:07	27.9	29.3	37.1	7.81	1.4	3.3	0.0548	35.	-20.	15.	958.	20.	1.6	136.	63.8
11	11/15/93	13:13 13:17	27.6	29.3	37.1	7.80	1.8	3.3	0.0547	36.	-23.	15.	952.	20.	2.2	117.	63.9
14	11/18/93	10:06 10:11	26.9	26.9	30.1	3.22	0.0	3.3	0.0549	5.	32.	60.	526.	26.	1.0	330.	48.0
15	11/18/93	10:11 10:16	26.8	26.9	30.1	3.23	0.1	3.3	0.0549	5.	31.	60.	529.	25.	0.9	331.	48.0
16	11/18/93	10:41 10:46	27.4	28.0	32.6	4.63	0.6	3.3	0.0550	7.	23.	45.	690.	15.	0.8	340.	52.8
18	11/18/93	10:51 10:56	27.6	28.0	32.9	4.82	0.4	3.3	0.0550	6.	20.	45.	710.	16.	0.7	351.	53.3
21	11/18/93	11:27 11:31	27.9	28.0	34.9	6.91	0.1	3.3	0.0541	19.	10.	30.	880.	15.	0.7	350.	60.6
22	11/18/93	11:32 11:36	28.1	28.0	34.9	6.90	0.0	3.3	0.0540	19.	8.	30.	882.	15.	1.0	357.	60.4
24	11/18/93	11:42 11:46	28.1	28.1	34.9	6.88	0.0	3.2	0.0539	18.	5.	30.	876.	17.	1.0	359.	60.5
29	11/18/93	12:42 12:46	26.9	28.3	36.2	7.89	1.4	3.2	0.0539	34.	-14.	15.	949.	20.	2.3	100.	64.0
30	11/18/93	12:47 12:51	26.6	28.3	36.2	7.85	1.8	3.2	0.0539	35.	-15.	15.	946.	20.	2.3	94.	63.8
34	11/17/93	13:46 13:51	27.6	28.3	36.6	8.32	0.7	3.3	0.0543	55.	-32.	0.	969.	18.	2.0	---	66.6
35	11/17/93	13:51 13:56	27.6	28.3	36.6	8.29	0.7	3.3	0.0542	55.	-33.	0.	965.	18.	2.3	---	66.4
38	11/18/93	14:03 14:07	26.2	26.8	34.9	8.08	0.6	3.3	0.0544	57.	-36.	0.	938.	20.	2.2	---	67.0
39	11/18/93	14:08 14:12	26.2	26.8	34.9	8.06	0.7	3.3	0.0545	58.	-37.	0.	934.	20.	2.0	---	67.1

TABLE 3.16A LONGITUDINAL INCIDENT ANGLE MODIFIER TEST ON 4" REC WITH SELECTIVE ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM
		START END	(F)	(F)	(F)	(F)	(F)	GPM	LB/MIN	DEG	DEG	DEG	B/FT ²	DIF	MPH	DEG %	
2	11/15/93	11:50 11:54	81.1	84.8	89.2	4.42	3.6	0.878	7.29	12.	3.	60.	131.	-1.	5.0	116.	0.746
3	11/15/93	11:55 11:59	81.2	84.8	89.2	4.40	3.6	0.880	7.31	12.	1.	60.	130.	-1.	4.6	121.	0.747
7	11/15/93	12:29 12:34	82.1	84.8	92.4	7.61	2.7	0.867	7.20	3.	-10.	45.	195.	7.	4.0	153.	0.840
8	11/15/93	12:34 12:39	82.0	84.8	92.4	7.59	2.7	0.867	7.20	3.	-12.	45.	194.	7.	4.4	148.	0.840
9	11/15/93	13:03 13:07	82.3	84.8	98.9	14.05	2.5	0.873	7.25	35.	-20.	15.	304.	20.	3.7	136.	0.995
11	11/15/93	13:13 13:17	81.6	84.8	98.8	14.03	3.2	0.871	7.23	36.	-23.	15.	302.	20.	5.0	117.	0.998
14	11/18/93	10:06 10:11	80.4	80.5	86.3	5.79	0.1	0.873	7.26	5.	32.	60.	167.	26.	2.3	330.	0.744
15	11/18/93	10:11 10:16	80.3	80.4	86.2	5.82	0.1	0.874	7.27	5.	31.	60.	168.	25.	2.0	331.	0.745
16	11/18/93	10:41 10:46	81.3	82.4	90.8	8.34	1.2	0.876	7.28	7.	23.	45.	219.	15.	1.9	340.	0.821
18	11/18/93	10:51 10:56	81.7	82.5	91.1	8.68	0.8	0.875	7.27	6.	20.	45.	225.	16.	1.6	351.	0.829
21	11/18/93	11:27 11:31	82.3	82.5	94.9	12.43	0.2	0.861	7.15	19.	10.	30.	279.	15.	1.7	350.	0.940
22	11/18/93	11:32 11:36	82.5	82.4	94.9	12.43	-0.1	0.861	7.15	19.	8.	30.	280.	15.	2.2	357.	0.936
24	11/18/93	11:42 11:46	82.5	82.5	94.9	12.39	0.0	0.858	7.13	18.	5.	30.	278.	17.	2.2	359.	0.938
29	11/18/93	12:42 12:46	80.4	83.0	97.2	14.20	2.6	0.859	7.13	34.	-14.	15.	301.	20.	5.1	100.	0.998
30	11/18/93	12:47 12:51	79.8	83.0	97.1	14.13	3.2	0.858	7.13	35.	-15.	15.	300.	20.	5.1	94.	0.996
34	11/17/93	13:46 13:51	81.6	82.9	97.9	14.98	1.3	0.865	7.18	55.	-32.	0.	307.	18.	4.6	---	1.036
35	11/17/93	13:51 13:56	81.6	82.9	97.8	14.92	1.3	0.863	7.17	55.	-33.	0.	306.	18.	5.1	---	1.033
38	11/18/93	14:03 14:07	79.2	80.3	94.9	14.54	1.1	0.867	7.20	57.	-36.	0.	297.	20.	5.0	---	1.041
39	11/18/93	14:08 14:12	79.1	80.3	94.8	14.50	1.2	0.868	7.21	58.	-37.	0.	296.	20.	4.5	---	1.043

LONGITUDINAL INCIDENT ANGLE MODIFIER

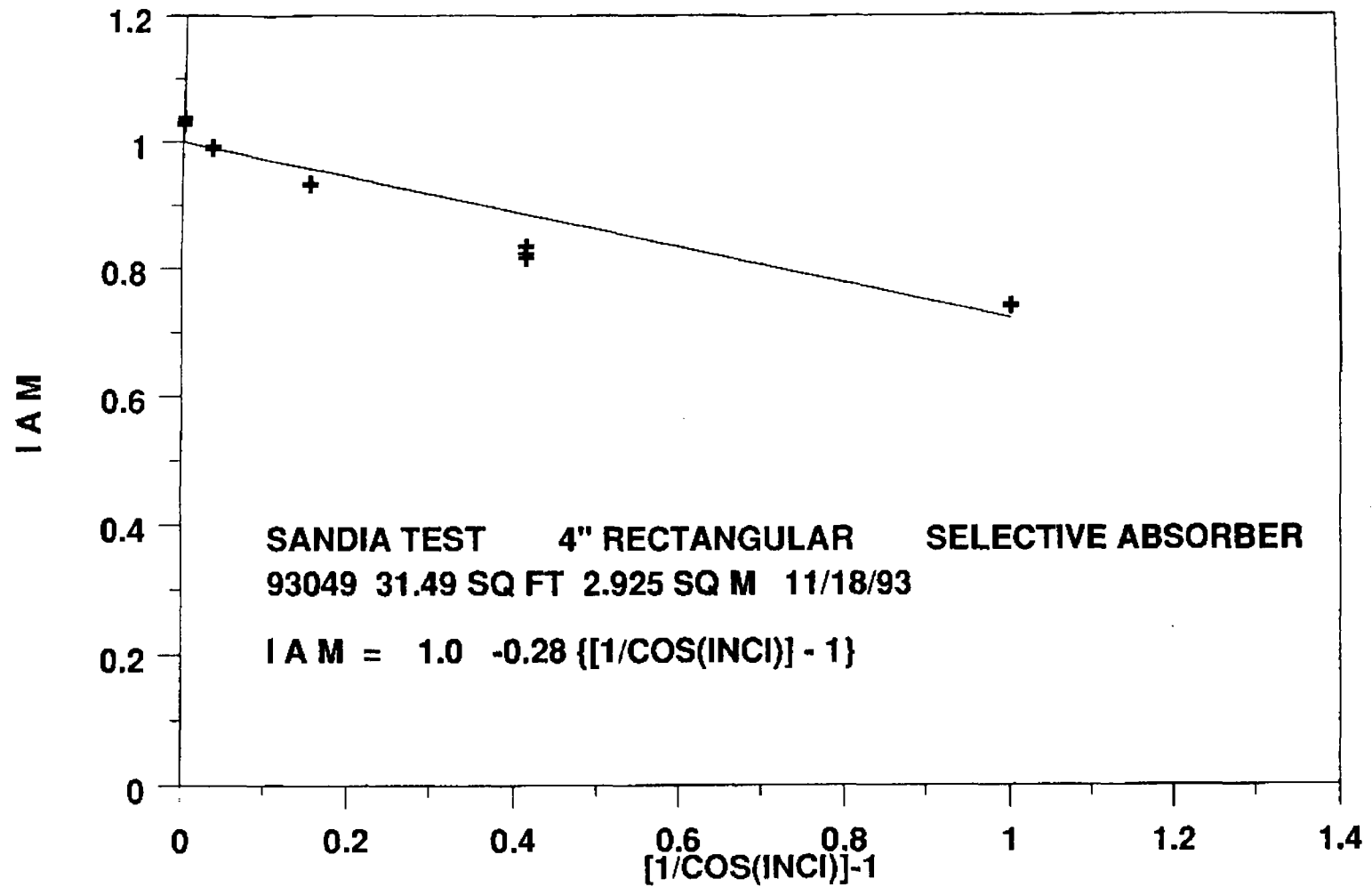


TABLE 3.17 TRANSVERSE INCIDENT ANGLE MODIFIER TEST ON 4" REC WITH SELECTIVE ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM	
		START	END	(C)	(C)	(C)	(C)	L/M	KG/SEC	DEG	DEG	DEG	W/M ²	DIF	M/S	DEG	%	
2	11/15/93	11:13	11:18	27.3	29.3	33.4	4.09	2.0	3.3	0.0547	1.	14.	50.	661.	22.	2.1	136. 48.3	0.773
3	11/15/93	11:18	11:23	27.1	29.3	33.4	4.14	2.3	3.3	0.0544	1.	12.	50.	667.	22.	2.3	117. 48.2	0.773
7	12/15/93	10:54	10:59	15.5	15.8	20.7	4.90	0.3	3.3	0.0544	9.	18.	45.	734.	13.	3.4	283. 52.0	0.821
8	12/15/93	10:59	11:04	15.6	15.8	20.8	4.96	0.2	3.2	0.0539	9.	16.	45.	734.	13.	3.2	284. 52.1	0.822
13	12/15/93	13:30	13:35	18.5	19.0	25.6	6.60	0.5	3.3	0.0547	26.	-26.	30.	875.	12.	3.4	285. 58.9	0.930
14	12/15/93	13:35	13:40	18.5	19.0	25.6	6.59	0.5	3.3	0.0545	27.	-27.	30.	871.	12.	3.3	282. 58.9	0.930
18	12/15/93	15:12	15:17	17.5	18.3	20.6	2.27	0.8	3.3	0.0551	10.	-47.	60.	411.	8.	3.0	297. 43.6	0.694
19	12/15/93	15:17	15:22	17.5	18.3	20.5	2.22	0.8	3.3	0.0552	11.	-48.	60.	400.	7.	3.4	292. 43.8	0.698
26	12/16/93	13:13	13:17	14.8	14.6	22.2	7.67	-0.3	3.3	0.0549	40.	-21.	15.	972.	15.	1.7	332. 62.0	0.975
28	12/16/93	13:23	13:27	14.9	14.6	22.3	7.73	-0.3	3.3	0.0547	41.	-24.	15.	961.	14.	1.7	327. 62.9	0.990
34	11/18/93	14:03	14:07	26.2	26.8	34.9	8.08	0.6	3.3	0.0544	57.	-36.	0.	938.	20.	2.2	--- 67.0	1.057
35	11/18/93	14:08	14:12	26.2	26.8	34.9	8.06	0.7	3.3	0.0545	58.	-37.	0.	934.	20.	2.0	--- 67.1	1.060

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TABLE 3.17A TRANSVERSE INCIDENT ANGLE MODIFIER TEST ON 4" REC WITH SELECTIVE ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR START	TIME END	TA (F)	TI (F)	TE (F)	TE-TI (F)	TI-TA (F)	FLOW GPM	MASS LB/MN	TLT DEG	AZIM DEG	I/A DEG	SOL B/FT ²	% DIF	WIND MPH	EFF DEG	IAM %	
2	11/15/93	11:13	11:18	81.1	84.7	92.1	7.37	3.6	0.871	7.23	1.	14.	50.	210.	22.	4.6	136.	48.3	0.773
3	11/15/93	11:18	11:23	80.7	84.7	92.2	7.45	4.1	0.867	7.20	1.	12.	50.	212.	22.	5.1	117.	48.2	0.773
7	12/15/93	10:54	10:59	59.9	60.4	69.2	8.82	0.5	0.863	7.20	9.	18.	45.	233.	13.	7.5	283.	52.0	0.821
8	12/15/93	10:59	11:04	60.1	60.5	69.4	8.94	0.3	0.855	7.13	9.	16.	45.	233.	13.	7.2	284.	52.1	0.822
13	12/15/93	13:30	13:35	65.3	66.2	78.0	11.88	0.9	0.868	7.23	26.	-26.	30.	277.	12.	7.5	285.	58.9	0.930
14	12/15/93	13:35	13:40	65.3	66.2	78.0	11.85	0.8	0.865	7.21	27.	-27.	30.	276.	12.	7.3	282.	58.9	0.930
18	12/15/93	15:12	15:17	63.5	64.9	69.0	4.09	1.4	0.875	7.29	10.	-47.	60.	130.	8.	6.7	297.	43.6	0.694
19	12/15/93	15:17	15:22	63.4	64.9	68.8	4.00	1.4	0.876	7.30	11.	-48.	60.	127.	7.	7.5	292.	43.8	0.698
26	12/16/93	13:13	13:17	58.7	58.2	72.0	13.81	-0.5	0.870	7.26	40.	-21.	15.	308.	15.	3.8	332.	62.0	0.975
28	12/16/93	13:23	13:27	58.8	58.2	72.1	13.91	-0.5	0.868	7.24	41.	-24.	15.	305.	14.	3.8	327.	62.9	0.990
34	11/18/93	14:03	14:07	79.2	80.3	94.9	14.54	1.1	0.867	7.20	57.	-36.	0.	297.	20.	5.0	---	67.0	1.057
35	11/18/93	14:08	14:12	79.1	80.3	94.8	14.50	1.2	0.868	7.21	58.	-37.	0.	296.	20.	4.5	---	67.1	1.060

TRANSVERSE INCIDENT ANGLE MODIFIER

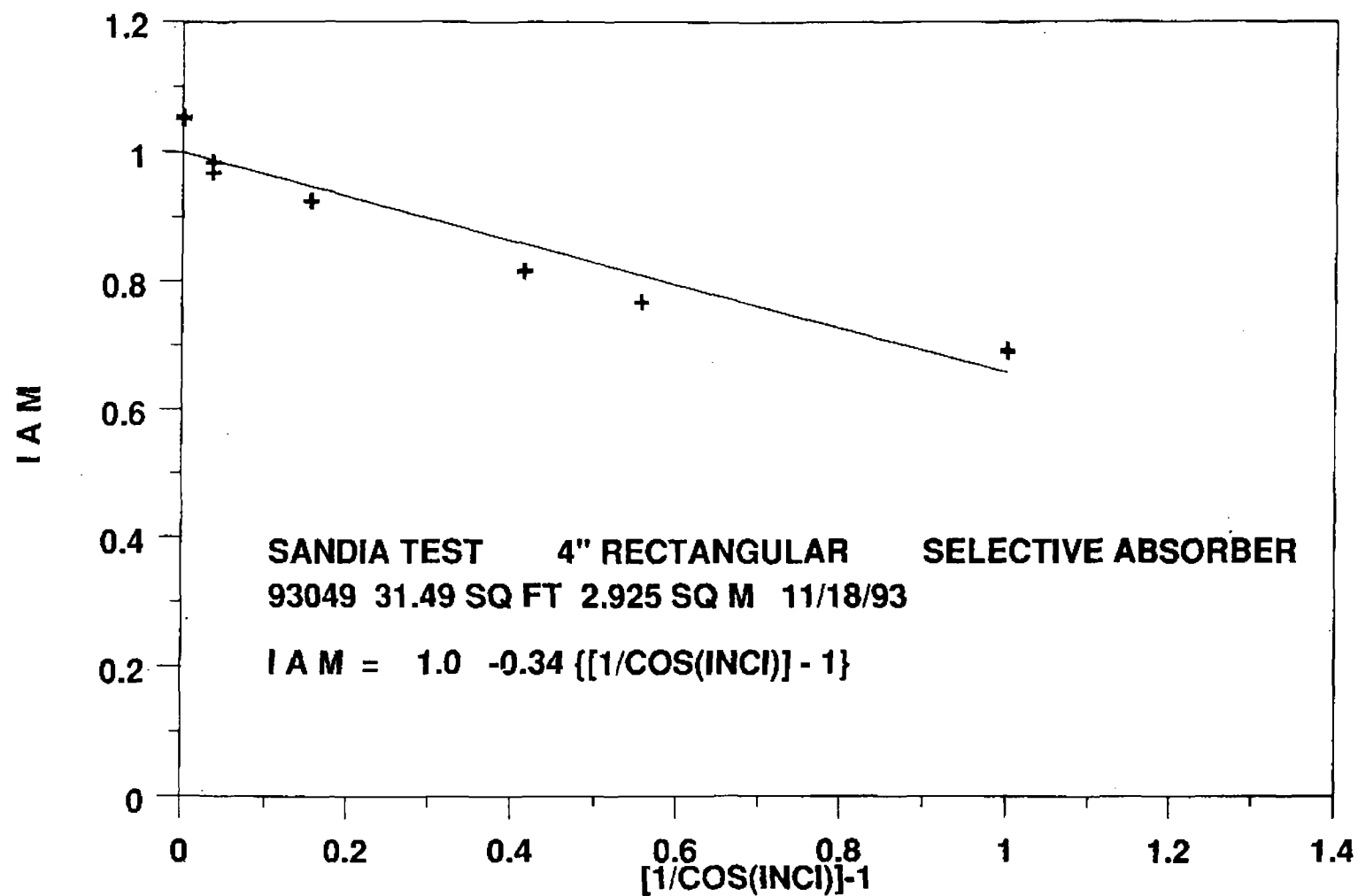


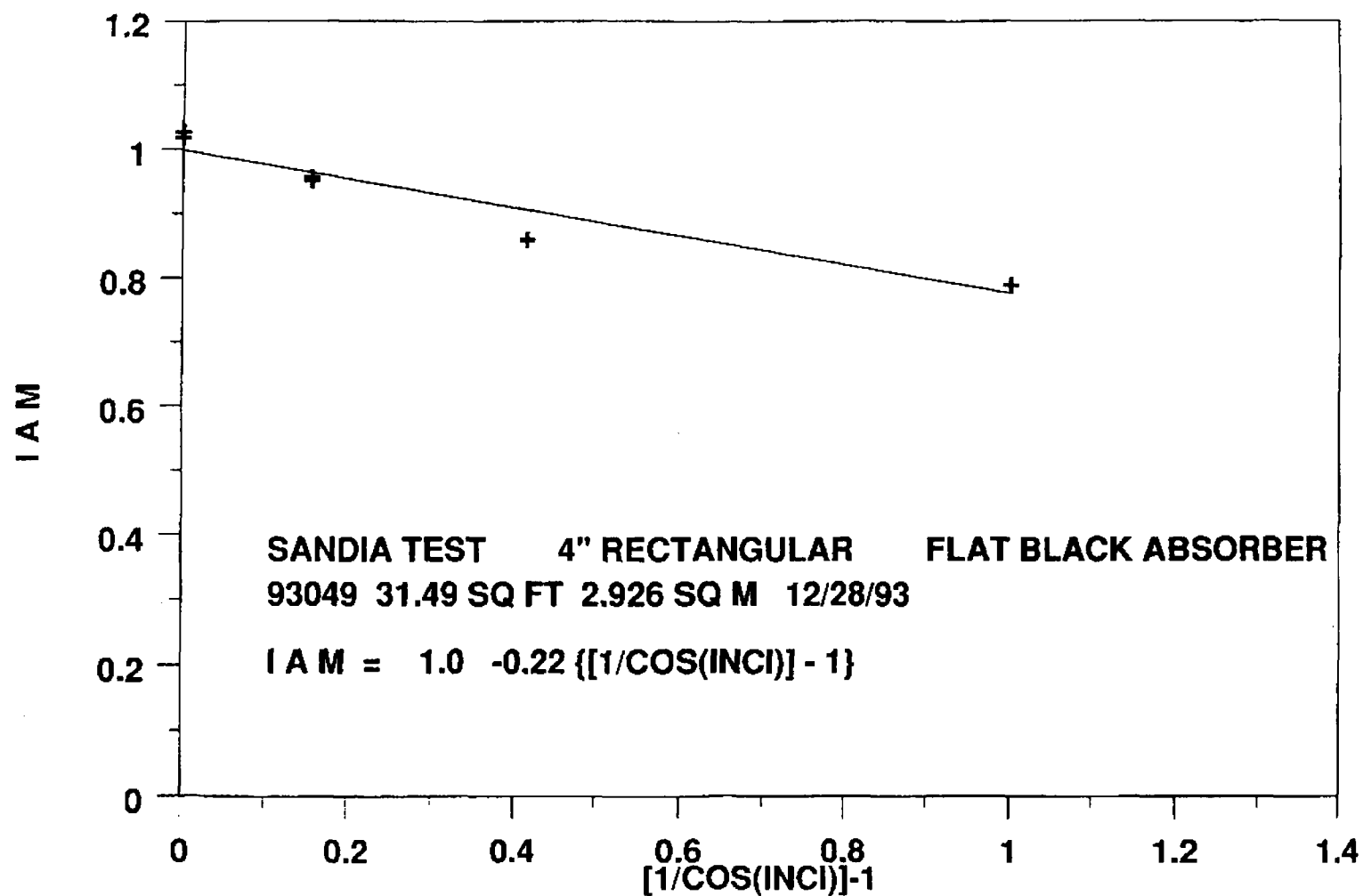
TABLE 3.18 TRANSVERSE INCIDENT ANGLE MODIFIER TEST ON 4" REC WITH FLAT BLACK ABSORBER (SI UNITS)

TEST	DATE	SOLAR	TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND		EFF	IAM
		START	END	(C)	(C)	(C)	(C)	(C)	L/M	KG/SEC	DEG	DEG	DEG	W/M²	DIF	M/S	DEG	%	
2	12/28/93	12:57	13:01	22.6	22.3	29.4	7.03	-0.3	3.3	0.0551	54.	-17.	30.	857.	11.	1.0	155.	64.5	0.962
3	12/28/93	13:02	13:06	22.6	22.4	29.3	6.92	-0.3	3.3	0.0548	54.	-19.	30.	844.	10.	1.2	166.	64.2	0.957
13	12/28/93	13:57	14:02	22.4	22.3	26.8	4.59	-0.2	3.4	0.0562	59.	-32.	45.	635.	7.	1.1	165.	58.0	0.866
14	12/28/93	14:02	14:07	22.3	22.3	26.9	4.65	0.0	3.4	0.0559	60.	-34.	45.	640.	8.	1.4	180.	58.0	0.866
16	12/28/93	14:24	14:29	22.5	22.3	25.2	2.98	-0.2	3.3	0.0556	63.	-38.	60.	428.	5.	1.2	160.	53.3	0.794
17	12/28/93	14:29	14:34	22.3	22.2	25.1	2.82	0.0	3.4	0.0557	63.	-39.	60.	422.	3.	1.1	157.	53.2	0.795
20	12/28/93	11:42	11:47	21.5	21.3	30.3	8.91	-0.1	3.3	0.0553	52.	4.	0.	1018.	14.	0.8	335.	69.2	1.032
21	12/28/93	11:47	11:52	21.4	21.3	30.3	8.92	0.0	3.3	0.0551	52.	3.	0.	1025.	14.	0.8	336.	68.6	1.023

TABLE 3.18A TRANSVERSE INCIDENT ANGLE MODIFIER TEST ON 4" REC WITH FLAT BLACK ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR	TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND		EFF	IAM
		START	END	(F)	(F)	(F)	(F)	(F)	GPM	LB/MN	DEG	DEG	DEG	B/FT ²	DIF	MPH	DEG	%	
2	12/28/93	12:57	13:01	72.7	72.2	84.9	12.65	-0.5	0.876	7.29	54.	-17.	30.	272.	11.	2.2	155.	64.5	0.962
3	12/28/93	13:02	13:06	72.7	72.2	84.7	12.46	-0.5	0.871	7.25	54.	-19.	30.	268.	10.	2.7	166.	64.2	0.957
13	12/28/93	13:57	14:02	72.3	72.1	80.3	8.26	-0.3	0.893	7.43	59.	-32.	45.	201.	7.	2.5	165.	58.0	0.866
14	12/28/93	14:02	14:07	72.2	72.1	80.5	8.37	0.0	0.888	7.39	60.	-34.	45.	203.	B.	3.1	180.	58.0	0.866
16	12/28/93	14:24	14:29	72.5	72.1	77.3	5.17	-0.4	0.883	7.36	63.	-38.	60.	136.	5.	2.8	160.	53.3	0.794
17	12/28/93	14:29	14:34	72.1	72.0	77.1	5.08	0.0	0.885	7.37	63.	-39.	60.	134.	3.	2.4	157.	53.2	0.795
20	12/28/93	11:42	11:47	70.7	70.4	86.5	16.03	-0.2	0.880	7.32	52.	4.	0.	323.	14.	1.8	335.	69.2	1.032
21	12/28/93	11:47	11:52	70.5	70.4	86.5	16.06	-0.1	0.876	7.29	52.	3.	0.	325.	14.	1.7	336.	68.6	1.023

TRANSVERSE INCIDENT ANGLE MODIFIER

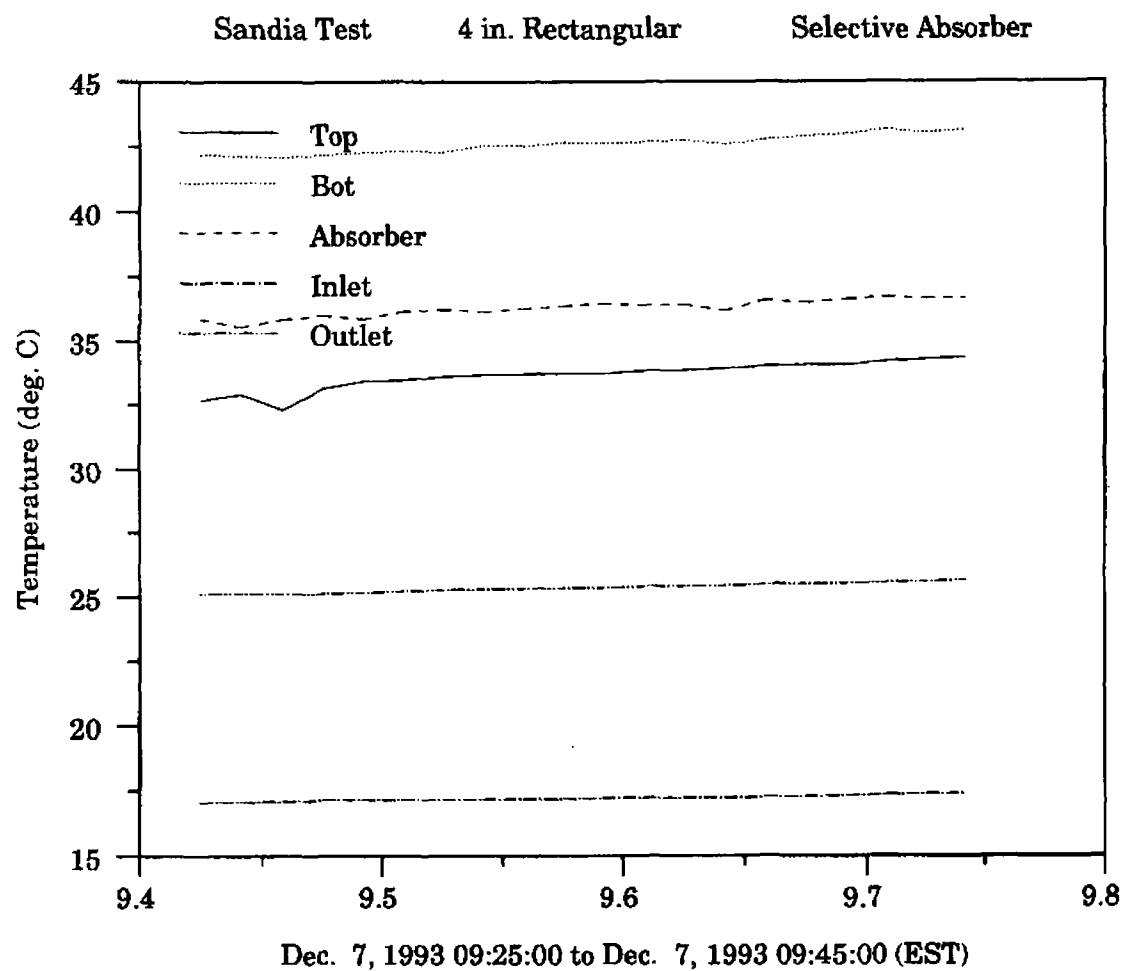


3.3.8 THERMOCOUPLE DATA

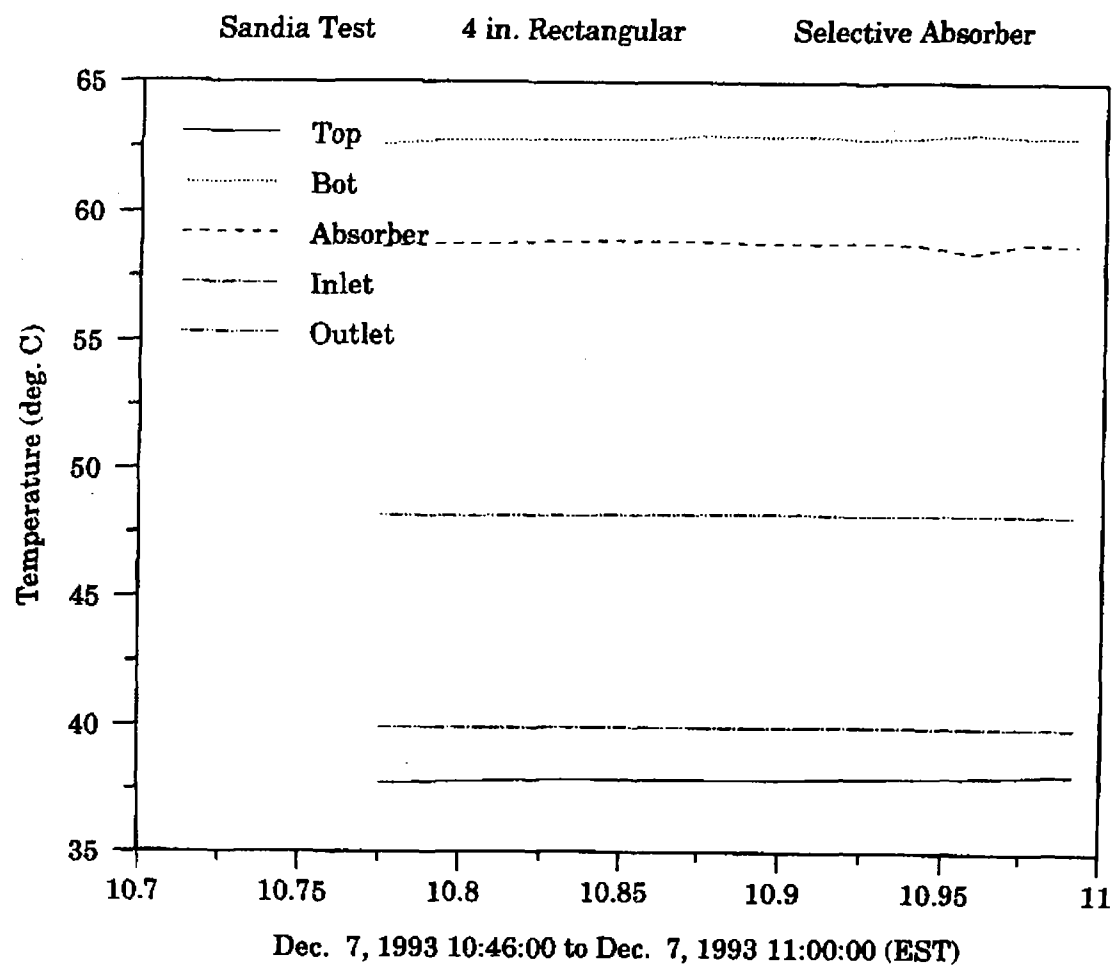
T-type thermocouples were installed inside prior to testing in order to gain insight into the temperatures internal to the collector. A total of six thermocouples were installed. Two of these were epoxied directly to the absorber. Two more were placed in air just under the TIM. The final two thermocouples were placed at the top of the TIM with the tip of the thermocouple sticking downward into a cell of the TIM. One set of thermocouples (top, bottom, absorber) were placed in the half of the collector nearest the inlet. The other set of thermocouples were placed in the half of the collector nearest the outlet. Special care was taken to keep direct sunlight from heating the top and bottom bimetal junctions and the wires leading to them. Temperature data were recorded every thirty seconds during some of the performance and IAM tests.

The graphs which follow give the averaged top, bottom, and absorber thermocouple temperatures along with the inlet and outlet fluid temperatures. During some periods only one of the top and one of the bottom temperatures was available. These periods are noted on the graphs by their lack of absorber temperature data. The first seven graphs present data from actual performance testing periods used in the final data reduction. The next graph shows the transients associated with removing the tarpaulins which covered the collector when not in use. This produces a sharp transition from no solar input to almost full sun. The data for the last graph were taken during a period of no solar input. Conducted at normal testing fluid flow rates, this graph demonstrates the absorber to ambient heat loss characteristics.

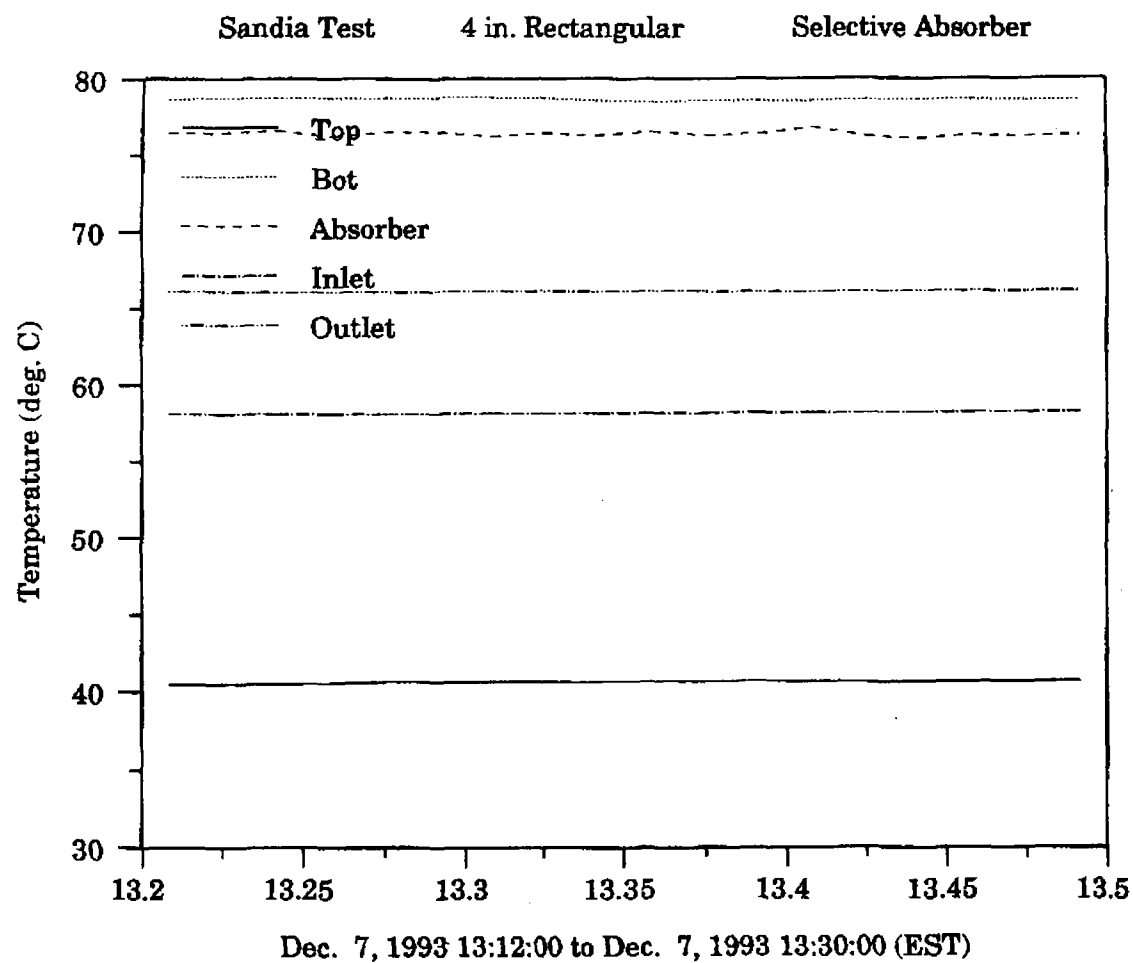
Temperatures During Testing for 93049



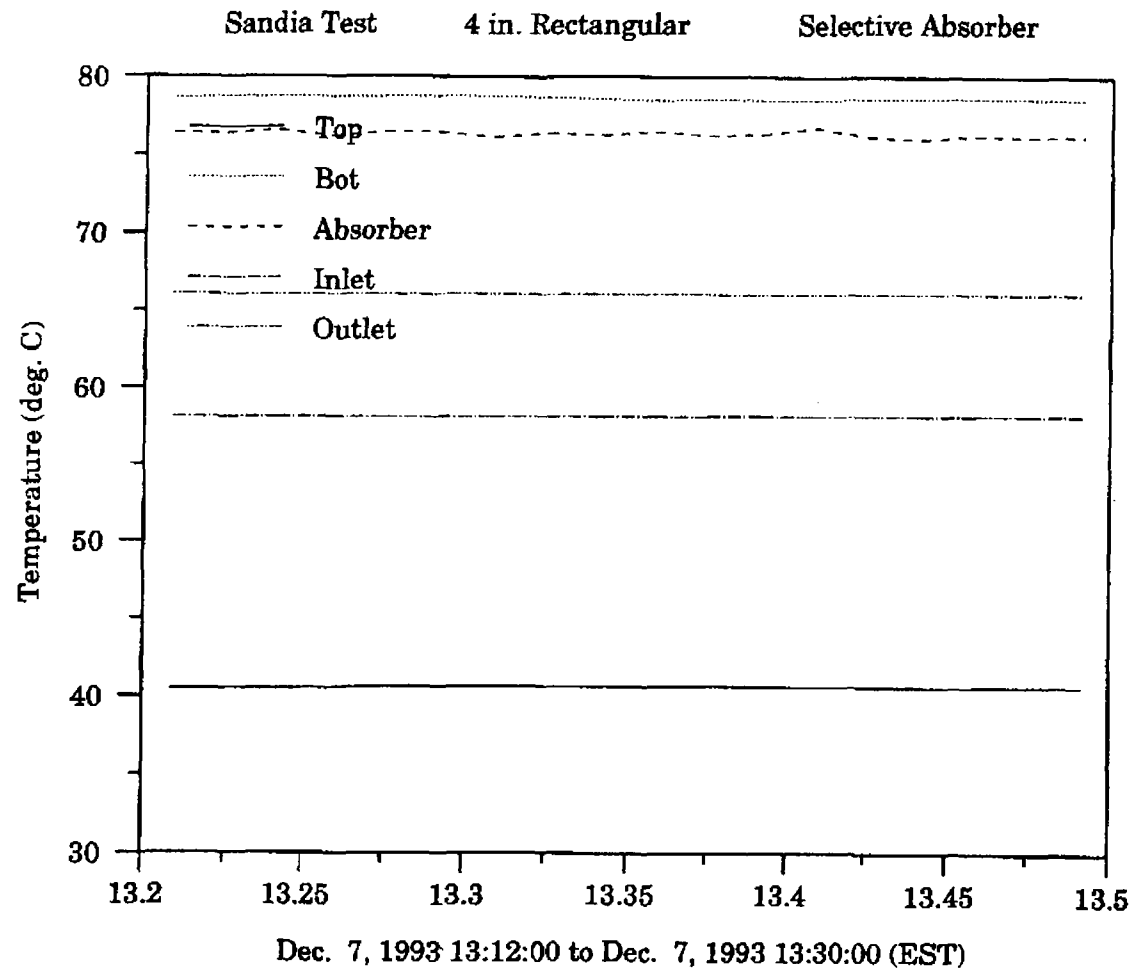
Temperatures During Testing for 93049



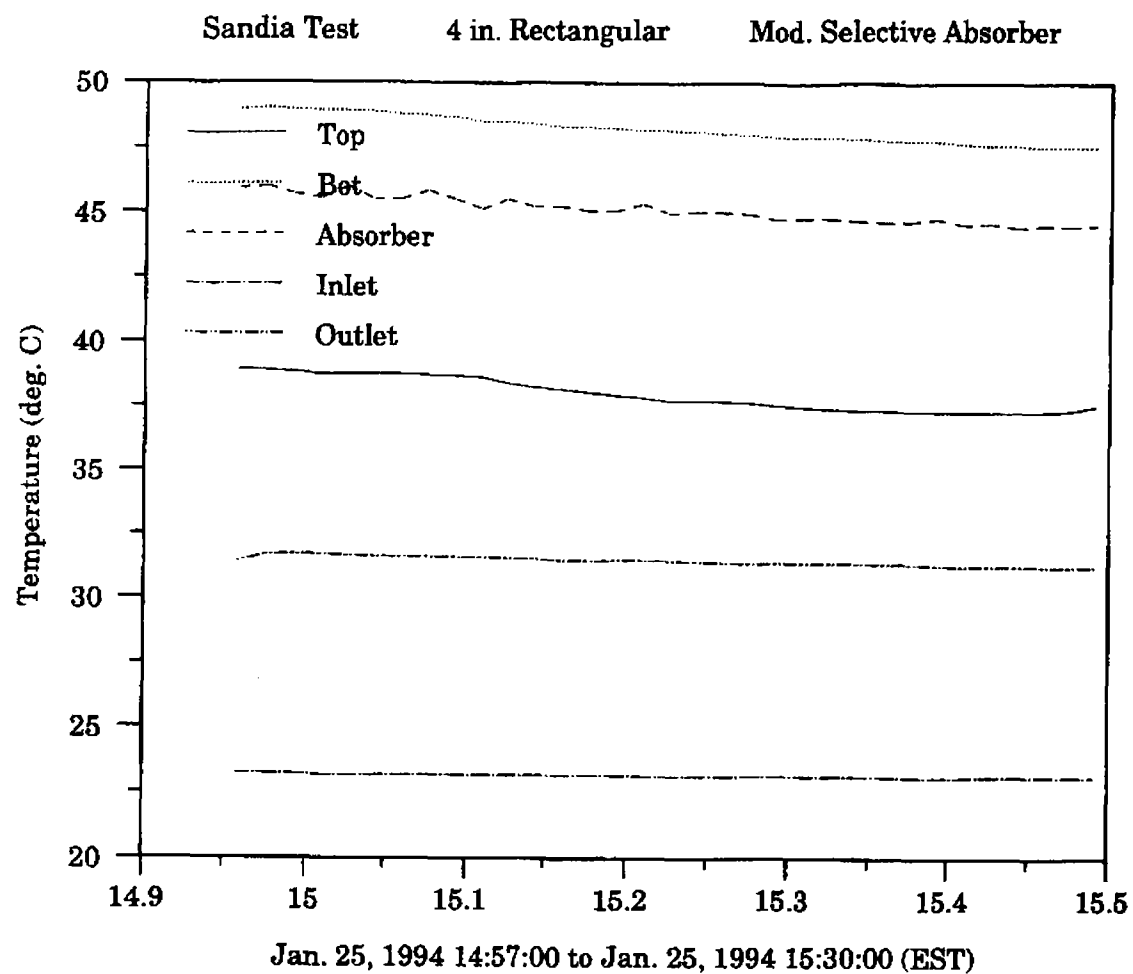
Temperatures During Testing for 93049



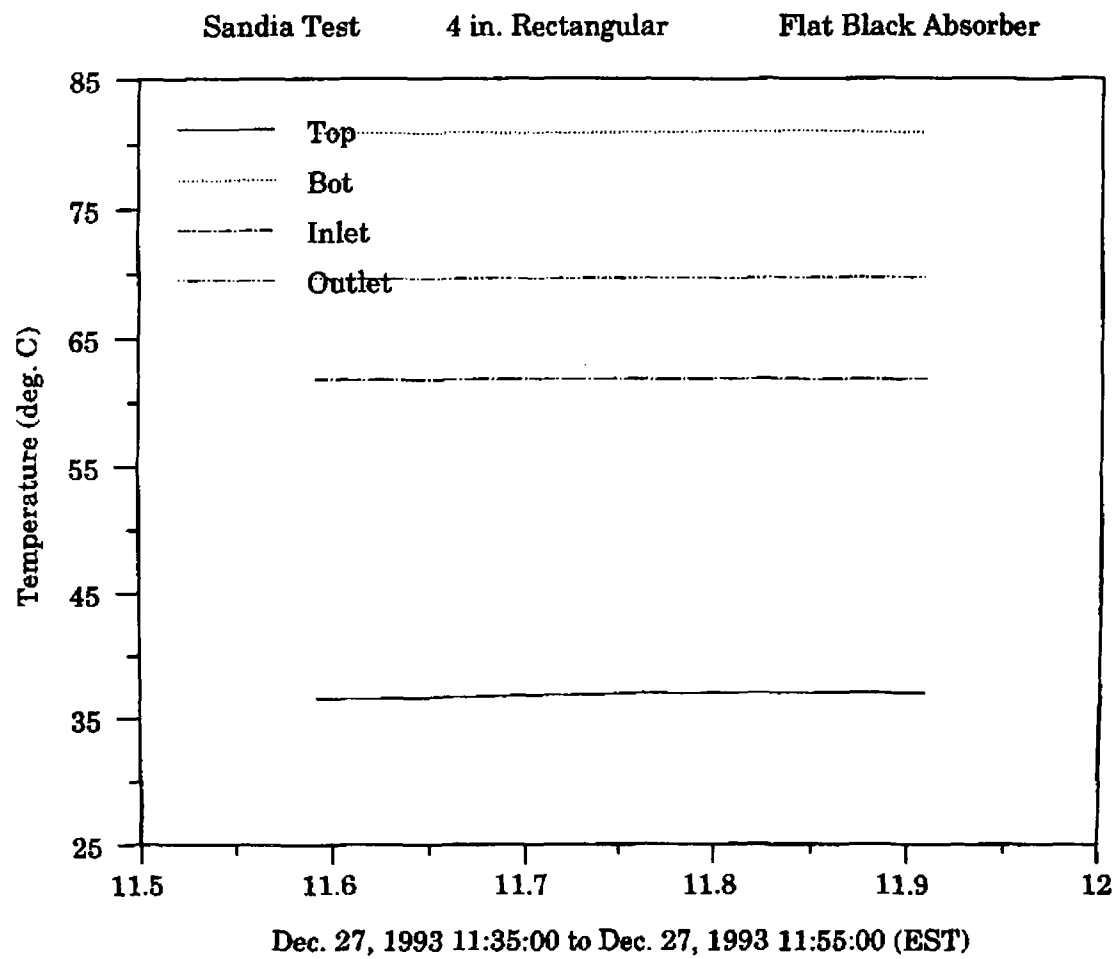
Temperatures During Testing for 93049



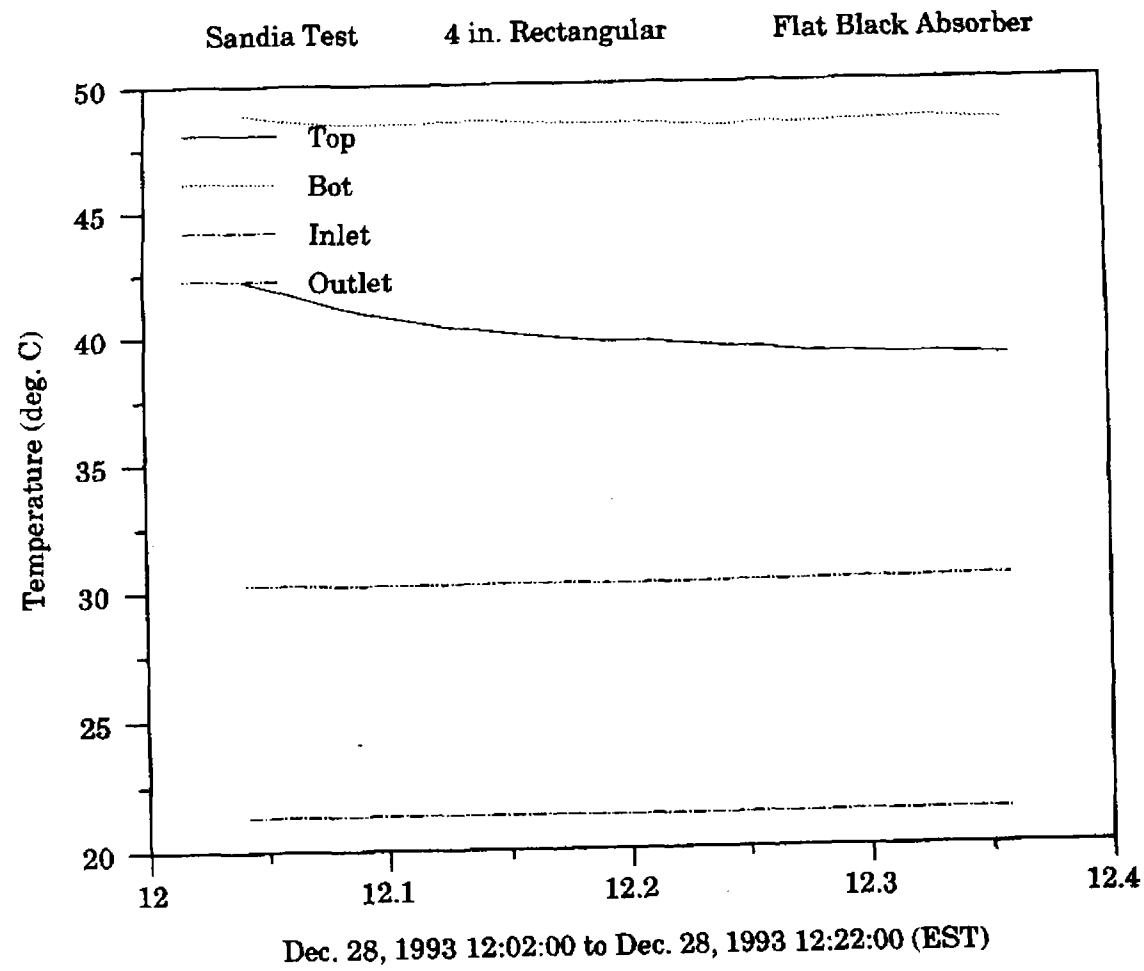
Temperatures During Testing for 93049



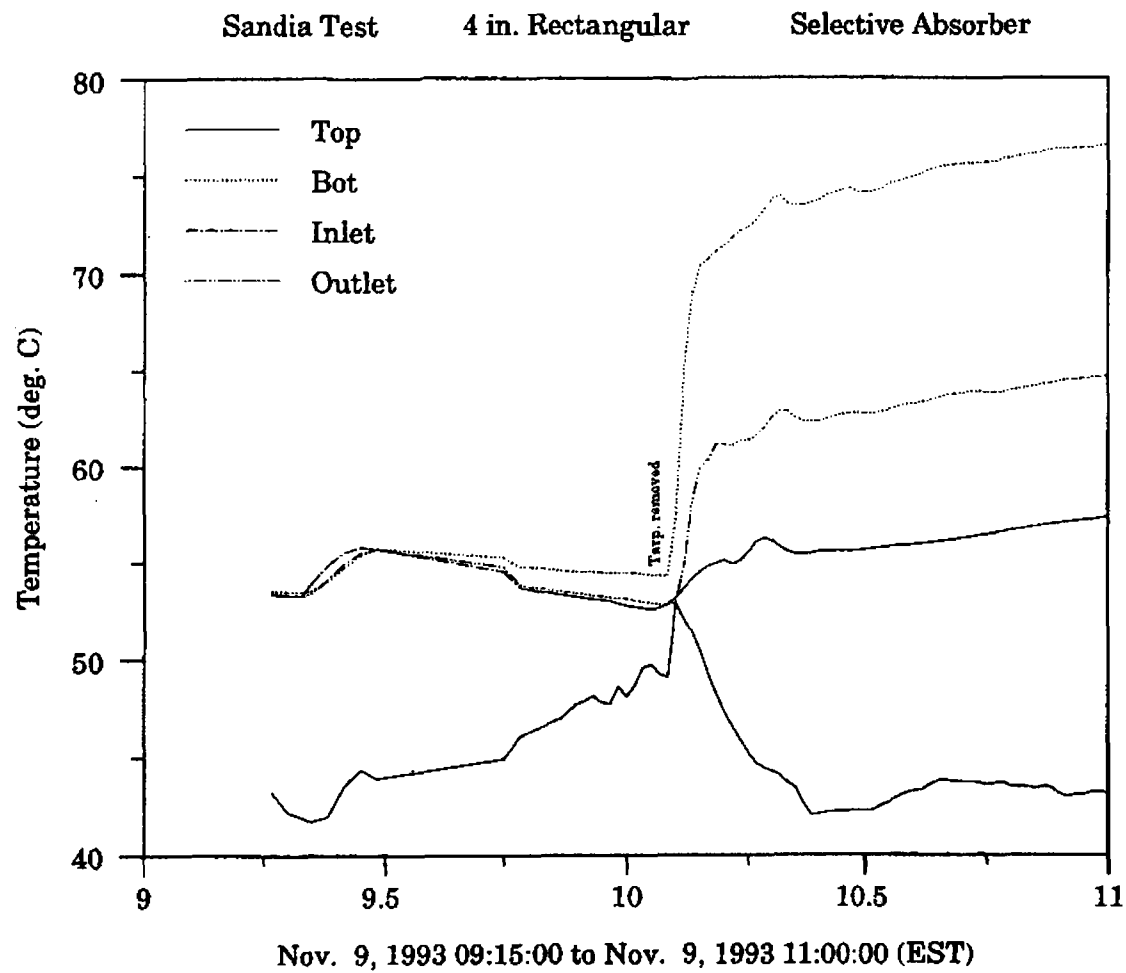
Temperatures During Testing for 93049



Temperatures During Testing for 93049



Temperatures During Collector Uncovering for 93049

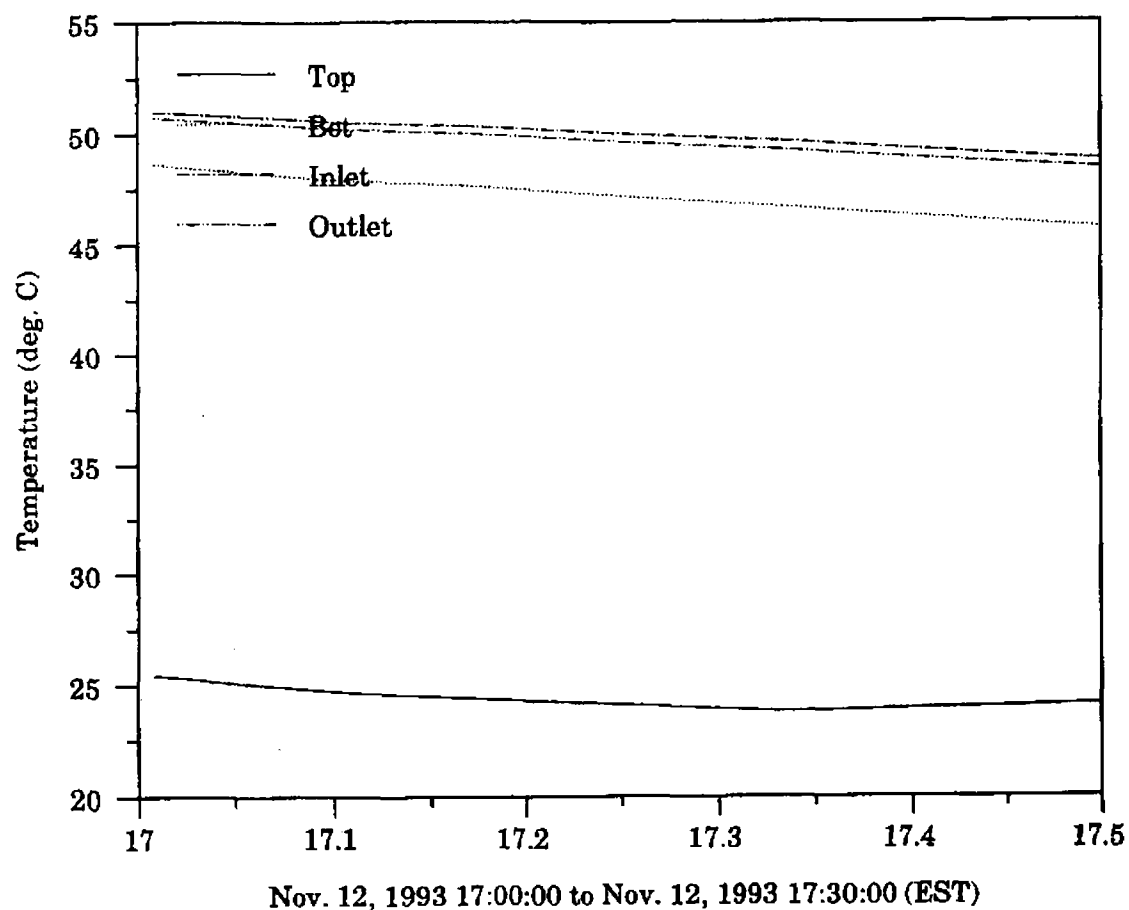


Temperatures During No Solar Input for 93049

Sandia Test

4 in. Rectangular

Selective Absorber

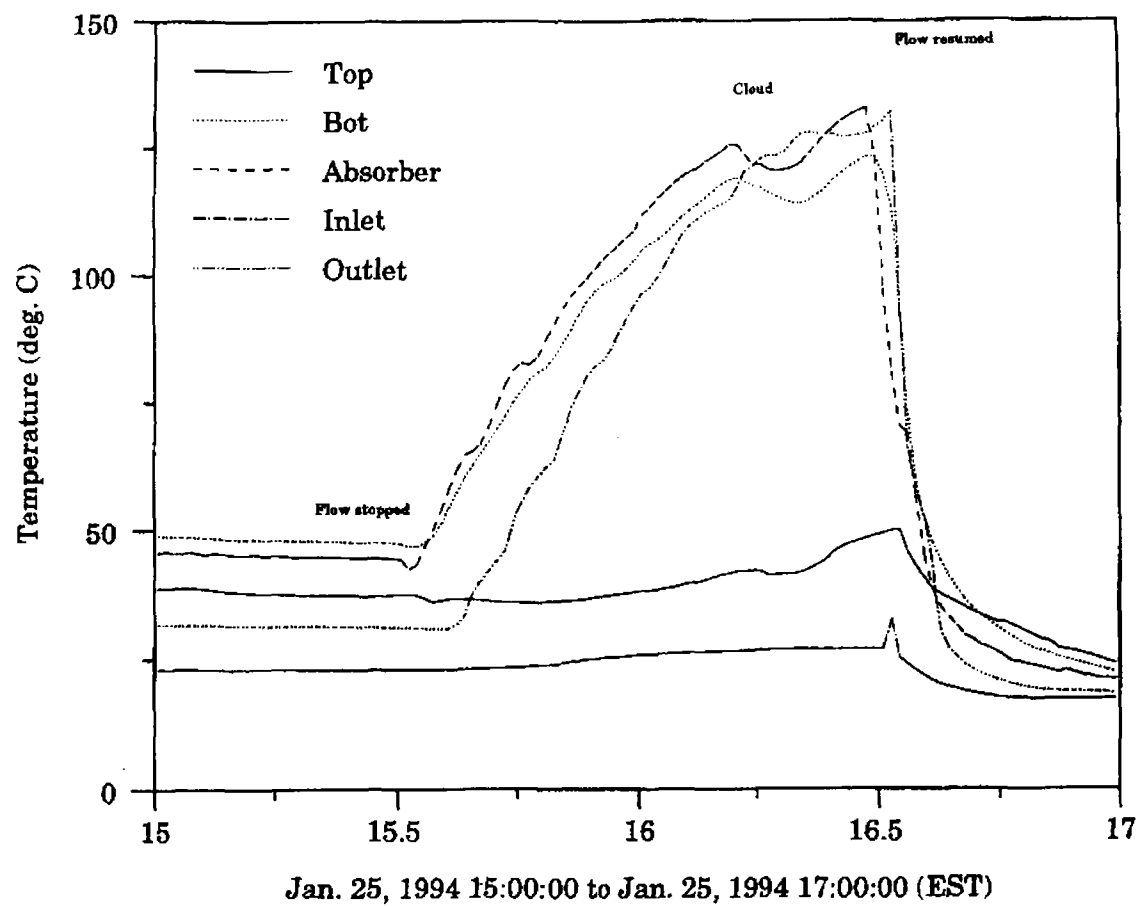


3.3.9 COLLECTOR STAGNATION

On 25 January 1994 the collectors in this series of tests were inadvertently left uncovered and facing the sun during a no fluid flow period. This constituted a wet stagnation. Although the flow was resumed about an hour later the internal temperatures had already exceeded the point where damage to some of the TIM takes place. The temperature data for this collector during that period is provided on the following page. The damage to the TIM effectively ended the comparison test. A performance test run later showed that this collector with 4" rectangular TIM showed a slight decrease in performance.

Wet Stagnation Temperatures for 93049

Sandia Test 4 in. Rectangular Mod. Selective Absorber



3.4 TEST RESULTS ON SOLAR COLLECTOR WITH 4" CAPILLARY TIM

The SDCRW(4x8) collector was modified as described in section 1.3 to contain 4" capillary transparent insulation material (TIM). The collector was then tested in accordance with FSEC Test Methods and Minimum Standards for Certifying Solar Collectors, FSEC 77-5-R80. The tests performed were:

Thermal Performance Test

Incident Angle Modifier Test

Internal temperatures during some of the tests were recorded from the installed thermocouples. Data are also included from the inadvertent wet stagnation that took place after the other testing was completed.

3.4.1 COLLECTOR IDENTIFICATION

Manufacturer and Address: Solar Development Inc.

3607-A Prospect Ave.

Riviera Beach, FL 33404

Collector Model Number: SD7CRW(4x8) with 4" capillary transparent insulation added

3.4.2 COLLECTOR CONSTRUCTION BEFORE MODIFICATION

Overall dimensions*: Length: 2.444 m (8.02 ft)

Width: 1.189 m (3.90 ft)

Depth: 0.098 m (0.32 ft)

Overall front area*: (length x width) = 2.903 m² (31.25 ft²)

Enclosure: Material: Aluminum frame, aluminum back

Surface finish: Painted aluminum

Fasteners: Stainless steel screws and aluminum rivets

Holes and cutouts: Frame has holes and gaskets for each end of both headers

Glazing: Number of cover plates: One

Material: Tempered low iron glass

Thickness: 0.32 cm (0.125 in)

Length: 2.441 m (8.01 ft)

Width: 1.167 m (3.83 ft)

Surface characteristics: Smooth on outside, textured on inside

Glazing seal: EPDM rubber

Transparent frontal dimensions*: Area: 2.743 m² (29.53 ft²)

Absorber: Flow pattern: Parallel

Number of tubes: Ten

Spacing between tubes: 11.2 cm (4.4 in)

Material: Copper tubes welded to copper fins

Length: 2.283 m (7.49 ft)

Width: 1.119 m (3.67 ft)

Area: 2.554 m² (27.49 ft²)

Plate thickness: 0.046 cm (0.018 in)

Tube diameter (OD): 1.6 cm (0.63 in)

Header diameter (OD): 2.9 cm (1.13 in)

Flow tube to header connection: Brazed

Air spacing, glazing to absorber: approx. 3.2 cm (1.3 in)

Side insulation: Type: Foil faced polyisocyanurate

Thickness: 2.5 cm (1.0 in)

Back insulation: Type: Foil faced polyisocyanurate

Thickness: 4.4 cm (1.8 in)

Caulking, sealant, and/or gasket types(s): EPDM gaskets

Heat transfer fluid: Material: Water

Density: 977.81 kg/m³ at 70°C (61.01 lb/ft³ at 160°F)

Specific heat: 4189.6 J/kg°C at 70°C (1.001 Btu/lb°F at 160°F)

Collector weight* 48.5 kg (107.0 lbs)

Collector fluid capacity*: 3.8 liters (1.0 gallons)

3.4.3 COLLECTOR MODIFICATIONS

This collector was one of a group of four being tested side by side to investigate the effects on performance of adding transparent insulation material (TIM) between the absorber and the glazing. This particular collector was modified to contain four-inch thick TIM. Aluminum extender sides were attached to the existing sides of the collector to accommodate the four-inches of TIM. These sides were bent to have a one-inch horizontal lip for the glazing to rest upon like the original collector. The extender side attachments were made to be slightly adjustable so the glazing could be placed in contact with the TIM. One-inch of foil faced polyisocyanurate insulation was placed within the extended sides to make them consistent the rest of the collector. To support the TIM off of the absorber, nine strips of wood 3/16" thick and 3/8" wide were placed widthwise across the absorber. These strips were the same size and number as in the other collectors. Six type T thermocouple were placed in the collector. Two thermocouples were attached to the absorber, two were placed in air just below the TIM, and two were placed on top of the TIM. The thermocouple wires were run along the side insulation and exited the frame through two small holes.

The TIM used in this collector was produced by Okalux Kapillarglas GmbH of 8772

Marktheidenfeld-Altfield, Germany under the product name of Kapipane. This TIM has a honeycomb like structure with circular cells. The following properties were measured:

Thickness	9.96 cm (3.92 in.)
Cell shape	Circular (capillary)
Cell size	0.33 cm (0.13 in.)
Intercell wall thickness	0.004 cm (0.0015 in.)
Material*:	Acrylic (PMMA)

All the collectors in this series of tests were covered with tarpaulins when in a no water flow condition. This prevented damage to the TIM in one collector and gave all the collectors the same amount of exposure.

Tests were run with three absorbers, each with a different coating. The manufacturer of the collectors shipped the collectors with the selectively coated absorber already installed. They also provided the two other absorbers, one with a moderately selective paint coating and one with a flat black paint coating.

After all modifications were complete the collector was measured. The final dimensions were as follows:

Gross length:	2.46 m (8.07 ft)
Gross width:	1.19 m (3.89 ft)
Gross area:	2.91 m ² (31.35 ft ²)
Transparent length:	2.41 m (7.89 ft)
Transparent width:	1.14 m (3.72 ft)
Transparent area:	2.73 m ² (29.38 ft ²)

* Information provided by manufacturer; not verified by FSEC.

3.4.4 THERMAL PERFORMANCE WITH SELECTIVE ABSORBER

The collector, outfitted with a selective black chrome coated absorber, was tested from 16 November - 16 December 1993 in accordance with ASHRAE procedure 93-1986. Results of the thermal performance tests are presented in graphical and tabular form in both the International System of Units (SI) and English units. The thermal performance equations in S.I. units developed from the empirical data are:

$$\text{first order} \quad \eta = 71.2 - 213 \quad (T_i - T_a)/I$$

$$\text{second order} \quad \eta = 71.1 - 185 \quad (T_i - T_a)/I - 848 \quad [(T_i - T_a)/I]^2$$

These equations in English units are:

$$\text{first order} \quad \eta = 71.2 - 37 \quad (T_i - T_a)/I$$

$$\text{second order} \quad \eta = 71.1 - 33 \quad (T_i - T_a)/I - 26 \quad [(T_i - T_a)/I]^2$$

TABLE 3.19 THERMAL PERFORMANCE TEST ON 4" CAP WITH SELECTIVE ABSORBER (SI UNITS)

TEST	DATE	SOLAR START	TIME END	TA (C)	TI (C)	TE (C)	FLOW L/MIN	AVE IN W/M ²	TOTAL IN J/M ²	TE-TI (C)	DEL T C-MIN	EFFIC %	(TI-TA)/I (C-M ²)/W
1	11/16/93	11:21	11:25	27.1	58.7	67.1	3.24	1007.8	302333.	8.44	42.2	63.8	0.0313
2	11/16/93	11:26	11:30	27.1	58.7	67.2	3.23	1008.9	302680.	8.47	42.3	63.8	0.0313
4	11/16/93	11:36	11:40	27.3	58.7	67.3	3.21	1010.8	303243.	8.57	42.9	64.0	0.0311
5	11/16/93	11:41	11:45	27.3	58.7	67.3	3.20	1011.5	303442.	8.59	43.0	63.9	0.0311
10	11/16/93	12:34	12:39	27.2	49.4	58.1	3.25	1008.6	302565.	8.74	43.7	66.5	0.0220
11	11/16/93	12:39	12:44	27.1	49.4	58.0	3.26	1007.5	302255.	8.67	43.3	66.2	0.0221
12	11/16/93	12:44	12:49	27.0	49.4	58.1	3.25	1008.4	302511.	8.69	43.5	66.2	0.0221
14	11/16/93	12:54	12:59	27.2	49.4	58.0	3.26	1007.6	302269.	8.68	43.4	66.3	0.0219
15	11/16/93	12:59	13:04	27.2	49.4	58.0	3.28	1006.9	302070.	8.63	43.1	66.2	0.0220
16	11/16/93	13:04	13:09	27.2	49.4	58.0	3.27	1006.3	301891.	8.63	43.1	66.1	0.0221
19	11/16/93	14:17	14:22	26.8	39.8	48.2	3.33	974.0	292210.	8.44	42.2	68.4	0.0133
21	11/16/93	14:27	14:32	26.9	39.8	48.4	3.27	965.6	289689.	8.52	42.6	68.4	0.0134
22	11/16/93	14:32	14:37	26.8	39.8	48.3	3.27	962.6	288792.	8.50	42.5	68.5	0.0135
23	11/16/93	14:37	14:42	26.8	39.8	48.3	3.26	956.1	286837.	8.46	42.3	68.4	0.0136
32	11/17/93	13:36	13:41	28.0	28.4	37.2	3.27	974.5	292355.	8.85	44.3	70.6	0.0004
33	11/17/93	13:41	13:46	27.7	28.4	37.2	3.27	969.0	290693.	8.81	44.1	70.8	0.0007
39	11/18/93	13:58	14:02	26.5	26.9	35.4	3.27	939.5	281852.	8.53	42.7	70.6	0.0004
41	11/18/93	14:08	14:12	26.2	26.9	35.4	3.27	934.1	280220.	8.50	42.5	70.8	0.0007
43	11/18/93	14:18	14:22	26.4	26.9	35.1	3.27	910.7	273212.	8.25	41.3	70.6	0.0006
45	11/18/93	14:53	14:58	26.2	39.7	47.1	3.28	853.9	256170.	7.46	37.3	68.0	0.0157
46	11/18/93	14:58	15:03	26.3	39.7	47.0	3.28	840.2	252051.	7.35	36.7	68.0	0.0159
47	11/18/93	15:03	15:08	26.1	39.6	46.9	3.28	834.5	250355.	7.33	36.7	68.3	0.0162
52	12/07/93	9:10	9:14	17.7	17.2	25.9	3.26	940.4	282115.	8.64	43.2	71.5	-0.0005
53	12/07/93	9:15	9:19	17.9	17.3	26.0	3.26	946.4	283915.	8.70	43.5	71.6	-0.0006
54	12/07/93	9:20	9:24	18.0	17.3	26.1	3.26	952.5	285745.	8.76	43.8	71.5	-0.0007
59	12/07/93	10:36	10:41	20.1	39.7	48.6	3.33	1028.5	308552.	8.88	44.4	68.1	0.0191
60	12/07/93	10:41	10:46	20.3	39.7	48.6	3.33	1029.7	308896.	8.89	44.4	68.1	0.0189
61	12/07/93	10:46	10:51	20.4	39.8	48.7	3.33	1033.2	309971.	8.90	44.5	68.0	0.0188
62	12/07/93	12:57	13:01	21.6	57.6	66.2	3.33	1039.1	311730.	8.51	42.6	64.1	0.0347
63	12/07/93	13:02	13:06	21.6	57.7	66.2	3.33	1037.4	311231.	8.49	42.5	64.1	0.0348
64	12/07/93	13:07	13:11	21.5	57.7	66.2	3.33	1034.2	310257.	8.47	42.3	64.1	0.0350
65	12/07/93	13:12	13:16	21.5	57.7	66.2	3.33	1032.1	309634.	8.45	42.3	64.1	0.0351

TABLE 3.19 THERMAL PERFORMANCE TEST ON 4" CAP WITH SELECTIVE ABSORBER (SI UNITS CONTINUED)

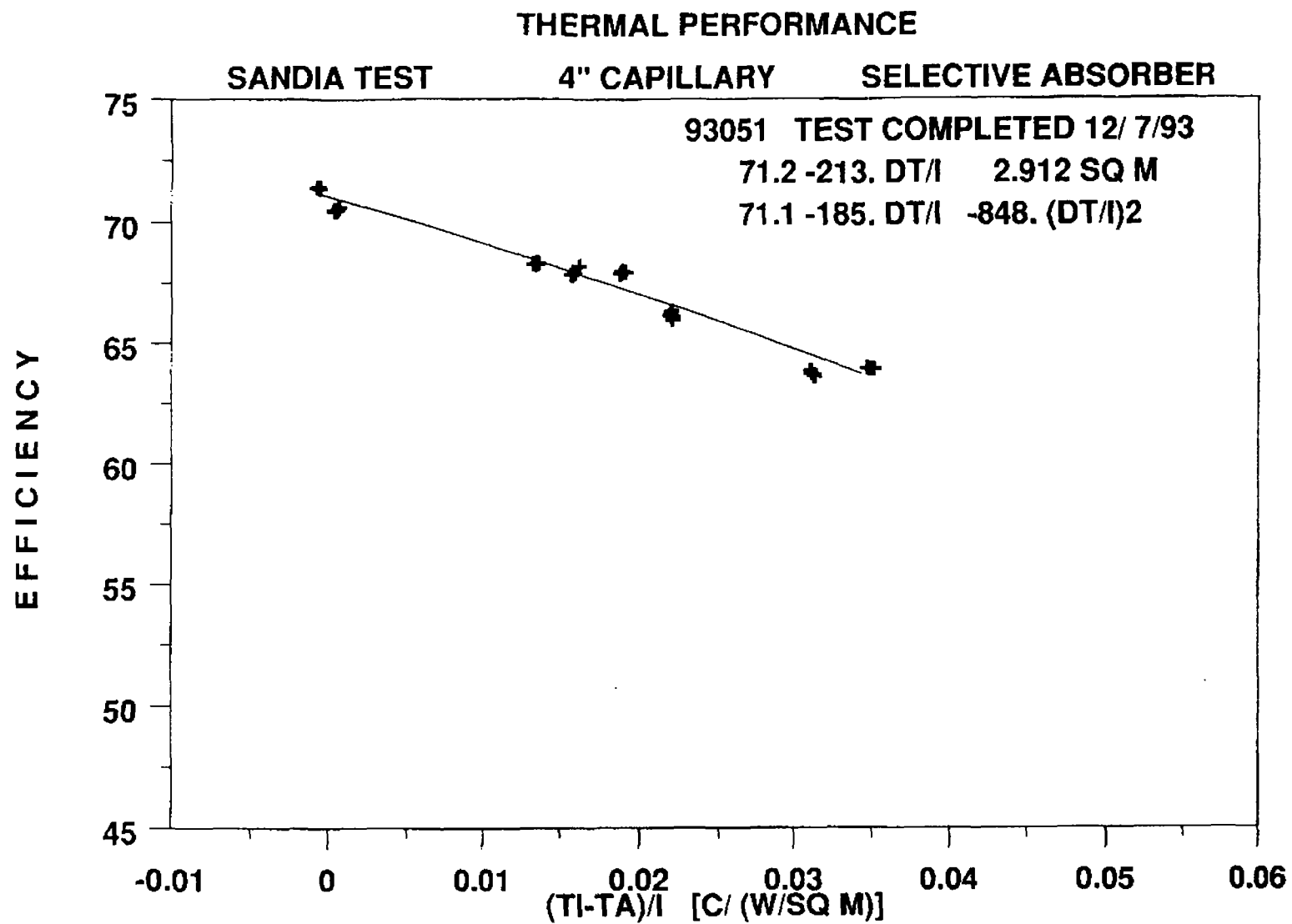
TEST	TILT DEG	AZIM DEG	INCI DEG	MASS KG/SEC	SPEC HEAT J/(KG C)	IN P KN/M ²	WIND M/S	WIND DIR	DIF IN W/M ²	% DIFF INSOL	TI-TA (C)
1	49.	11.	0.	0.0530	4185.6	62.6	2.4	99.	125.0	12.4	31.6
2	48.	10.	0.	0.0529	4185.6	62.8	2.8	97.	123.3	12.2	31.5
4	48.	7.	0.	0.0525	4185.6	64.0	2.3	96.	121.0	12.0	31.4
5	48.	5.	0.	0.0523	4185.7	64.8	3.0	107.	118.5	11.7	31.5
10	49.	-12.	0.	0.0534	4181.8	60.3	3.0	94.	123.0	12.2	22.1
11	49.	-13.	0.	0.0536	4181.7	58.7	2.4	98.	123.5	12.3	22.2
12	49.	-15.	0.	0.0535	4181.8	59.7	2.6	100.	122.7	12.2	22.3
14	50.	-18.	0.	0.0536	4181.7	46.4	2.3	104.	121.2	12.0	22.1
15	50.	-19.	0.	0.0539	4181.7	60.8	2.4	107.	120.0	11.9	22.2
16	50.	-21.	0.	0.0537	4181.8	61.1	2.2	103.	121.1	12.0	22.2
19	59.	-39.	0.	0.0550	4179.3	62.3	2.1	105.	117.9	12.1	13.0
21	60.	-42.	0.	0.0540	4179.3	63.8	2.2	107.	117.4	12.2	13.0
22	61.	-43.	0.	0.0540	4179.3	62.9	2.4	108.	116.6	12.1	13.0
23	62.	-44.	0.	0.0539	4179.3	62.6	2.0	98.	116.5	12.2	13.0
32	54.	-29.	0.	0.0542	4177.9	87.9	1.5	175.	165.9	17.0	0.4
33	54.	-31.	0.	0.0542	4177.9	87.6	2.2	173.	168.6	17.4	0.7
39	56.	-35.	0.	0.0542	4178.0	71.1	2.1	114.	184.1	19.6	0.4
41	58.	-37.	0.	0.0542	4178.0	59.0	2.0	110.	185.7	19.9	0.7
43	59.	-39.	0.	0.0543	4178.1	49.1	1.9	104.	192.1	21.1	0.5
45	64.	-47.	0.	0.0542	4179.2	70.3	1.8	100.	182.3	21.4	13.4
46	65.	-47.	0.	0.0542	4179.2	67.1	1.7	106.	180.1	21.4	13.3
47	66.	-48.	0.	0.0542	4179.2	65.5	1.9	90.	182.4	21.9	13.5
52	65.	43.	0.	0.0542	4181.5	79.8	1.3	357.	108.2	11.5	-0.5
53	64.	42.	0.	0.0542	4181.5	77.7	1.3	350.	109.0	11.5	-0.6
54	64.	41.	0.	0.0542	4181.4	79.7	1.7	349.	107.9	11.3	-0.7
59	55.	23.	0.	0.0550	4179.3	84.3	1.8	1.	111.3	10.8	19.6
60	54.	22.	0.	0.0550	4179.3	83.4	1.9	358.	112.0	10.9	19.5
61	54.	20.	0.	0.0550	4179.3	83.1	2.1	356.	111.1	10.7	19.4
62	53.	-17.	0.	0.0545	4185.1	83.4	1.5	5.	104.7	10.1	36.1
63	54.	-19.	0.	0.0545	4185.1	83.9	1.7	4.	106.3	10.2	36.1
64	54.	-20.	0.	0.0545	4185.1	84.3	1.8	7.	106.5	10.3	36.2
65	54.	-21.	0.	0.0545	4185.1	83.6	1.3	5.	107.0	10.4	36.2

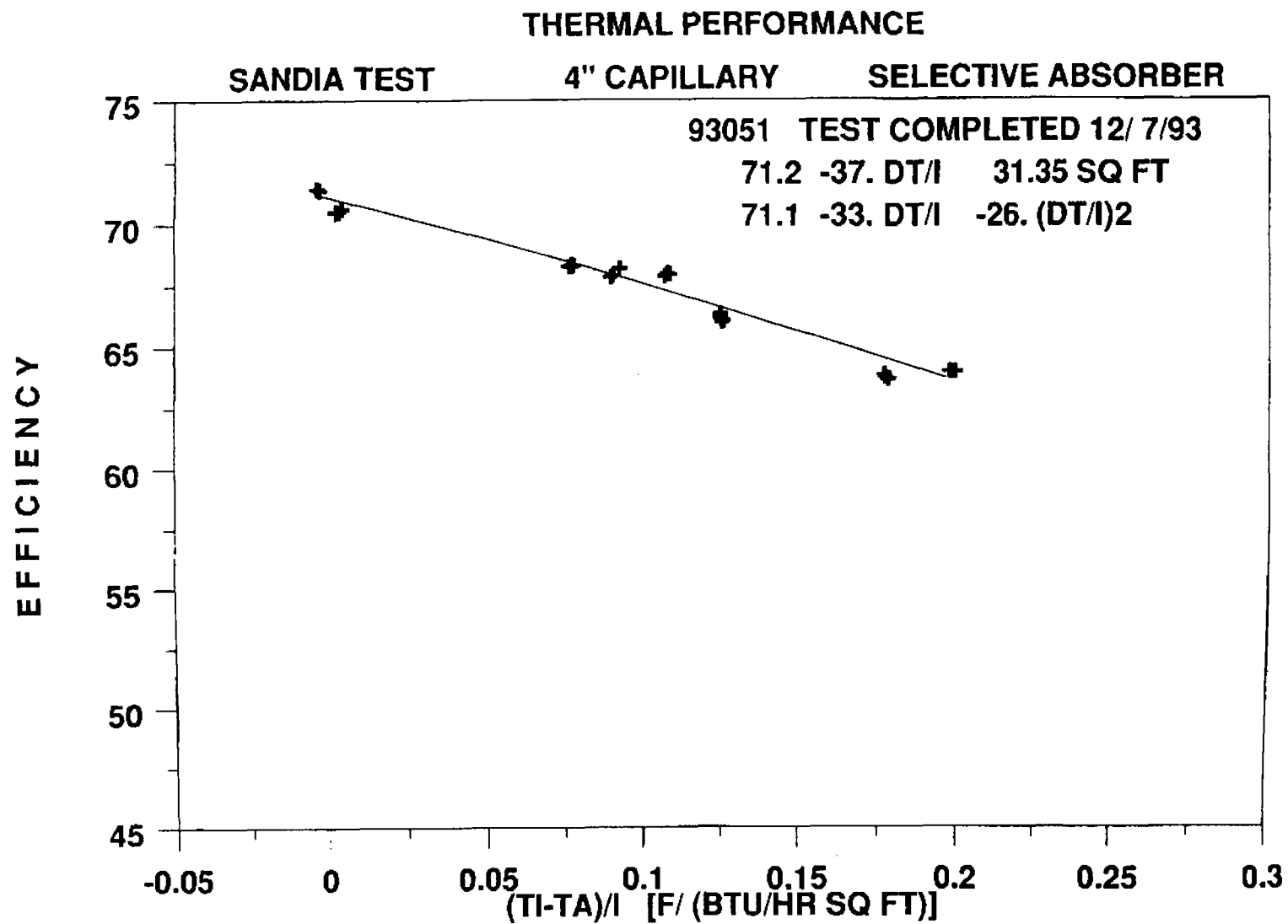
TABLE 3.19A THERMAL PERFORMANCE TEST ON 4" CAP WITH SELECTIVE ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME START END	TA (F)	TI (F)	TE (F)	FLOW GPM	AVE IN B/H-FT ²	TOTAL IN BTU/FT ²	TE-TI (F)	DEL T F-MIN	EFFIC %	(TI-TA)/I (F-H-FT ²)/B
1	11/16/93	11:21 11:25	80.8	137.6	152.8	0.856	319.7	26.6	15.19	76.0	63.8	0.178
2	11/16/93	11:26 11:30	80.9	137.6	152.9	0.854	320.0	26.7	15.24	76.2	63.8	0.177
4	11/16/93	11:36 11:40	81.2	137.7	153.2	0.848	320.6	26.7	15.43	77.2	64.0	0.176
5	11/16/93	11:41 11:45	81.1	137.7	153.2	0.845	320.8	26.7	15.47	77.3	63.9	0.177
10	11/16/93	12:34 12:39	81.0	120.9	136.6	0.859	319.9	26.7	15.73	78.7	66.5	0.125
11	11/16/93	12:39 12:44	80.8	120.8	136.4	0.862	319.6	26.6	15.60	78.0	66.2	0.125
12	11/16/93	12:44 12:49	80.7	120.9	136.5	0.860	319.9	26.7	15.64	78.2	66.2	0.126
14	11/16/93	12:54 12:59	81.0	120.8	136.5	0.862	319.6	26.6	15.62	78.1	66.3	0.125
15	11/16/93	12:59 13:04	81.0	120.9	136.4	0.866	319.4	26.6	15.53	77.6	66.2	0.125
16	11/16/93	13:04 13:09	81.0	120.9	136.5	0.863	319.2	26.6	15.53	77.7	66.1	0.125
19	11/16/93	14:17 14:22	80.3	103.6	118.8	0.880	309.0	25.7	15.20	76.0	68.4	0.076
21	11/16/93	14:27 14:32	80.4	103.7	119.0	0.864	306.3	25.5	15.34	76.7	68.4	0.076
22	11/16/93	14:32 14:37	80.3	103.7	119.0	0.864	305.4	25.4	15.31	76.5	68.5	0.077
23	11/16/93	14:37 14:42	80.2	103.6	118.9	0.862	303.3	25.3	15.23	76.1	68.4	0.077
32	11/17/93	13:36 13:41	82.4	83.1	99.0	0.864	309.1	25.8	15.93	79.7	70.6	0.002
33	11/17/93	13:41 13:46	81.8	83.0	98.9	0.864	307.4	25.6	15.87	79.3	70.8	0.004
39	11/18/93	13:58 14:02	79.7	80.4	95.7	0.863	298.0	24.8	15.36	76.8	70.6	0.002
41	11/18/93	14:08 14:12	79.1	80.4	95.7	0.863	296.3	24.7	15.30	76.5	70.8	0.004
43	11/18/93	14:18 14:22	79.5	80.4	95.3	0.865	288.9	24.1	14.86	74.3	70.6	0.003
45	11/18/93	14:53 14:58	79.2	103.4	116.8	0.867	270.9	22.6	13.43	67.1	68.0	0.089
46	11/18/93	14:58 15:03	79.4	103.4	116.6	0.867	266.5	22.2	13.23	66.1	68.0	0.090
47	11/18/93	15:03 15:08	78.9	103.1	116.5	0.867	264.7	22.1	13.20	66.0	68.3	0.092
52	12/07/93	9:10 9:14	63.8	63.0	78.5	0.861	298.3	24.9	15.55	77.7	71.5	-0.003
53	12/07/93	9:15 9:19	64.2	63.1	78.8	0.861	300.2	25.0	15.66	78.3	71.6	-0.004
54	12/07/93	9:20 9:24	64.4	63.2	79.0	0.861	302.1	25.2	15.76	78.8	71.5	-0.004
59	12/07/93	10:36 10:41	68.2	103.5	119.5	0.880	326.3	27.2	15.98	79.9	68.1	0.108
60	12/07/93	10:41 10:46	68.5	103.5	119.5	0.880	326.6	27.2	16.00	80.0	68.1	0.107
61	12/07/93	10:46 10:51	68.6	103.6	119.6	0.881	327.8	27.3	16.02	80.1	68.0	0.107
62	12/07/93	12:57 13:01	70.9	135.8	151.1	0.879	329.6	27.5	15.32	76.6	64.1	0.197
63	12/07/93	13:02 13:06	70.8	135.8	151.1	0.879	329.1	27.4	15.29	76.4	64.1	0.198
64	12/07/93	13:07 13:11	70.7	135.9	151.1	0.879	328.1	27.3	15.24	76.2	64.1	0.198
65	12/07/93	13:12 13:16	70.8	135.9	151.1	0.879	327.4	27.3	15.21	76.1	64.1	0.199

TABLE 3.19A THERMAL PERFORMANCE TEST ON 4" CAP WITH SELECTIVE ABSORBER (ENGLISH UNITS CONTINUED)

TEST	TILT DEG	AZIM DEG	INCI DEG	MASS LBM/MIN	SPEC HEAT BTU/(LBM-F)	IN P PSI	WIND MPH	WIND DIR	DIF IN B/H-FT ²	% DIFF INSOL	TI-TA (F)
1	49.	11.	0.	7.01	1.000	9.1	5.3	99.	39.6	12.4	56.9
2	48.	10.	0.	6.99	1.000	9.1	6.2	97.	39.1	12.2	56.8
4	48.	7.	0.	6.94	1.000	9.3	5.1	96.	38.4	12.0	56.5
5	48.	5.	0.	6.92	1.000	9.4	6.6	107.	37.6	11.7	56.7
10	49.	-12.	0.	7.07	0.999	8.7	6.6	94.	39.0	12.2	39.9
11	49.	-13.	0.	7.09	0.999	8.5	5.5	98.	39.2	12.3	40.0
12	49.	-15.	0.	7.07	0.999	8.7	5.8	100.	38.9	12.2	40.2
14	50.	-18.	0.	7.09	0.999	6.7	5.0	104.	38.5	12.0	39.8
15	50.	-19.	0.	7.12	0.999	8.8	5.3	107.	38.1	11.9	39.9
16	50.	-21.	0.	7.10	0.999	8.9	5.0	103.	38.4	12.0	40.0
19	59.	-39.	0.	7.27	0.998	9.0	4.6	105.	37.4	12.1	23.4
21	60.	-42.	0.	7.14	0.998	9.2	5.0	107.	37.2	12.2	23.4
22	61.	-43.	0.	7.14	0.998	9.1	5.3	108.	37.0	12.1	23.4
23	62.	-44.	0.	7.13	0.998	9.1	4.5	98.	37.0	12.2	23.4
32	54.	-29.	0.	7.17	0.998	12.7	3.4	175.	52.6	17.0	0.7
33	54.	-31.	0.	7.17	0.998	12.7	5.0	173.	53.5	17.4	1.2
39	56.	-35.	0.	7.17	0.998	10.3	4.7	114.	58.4	19.6	0.7
41	58.	-37.	0.	7.17	0.998	8.6	4.5	110.	58.9	19.9	1.3
43	59.	-39.	0.	7.19	0.998	7.1	4.3	104.	60.9	21.1	0.9
45	64.	-47.	0.	7.17	0.998	10.2	3.9	100.	57.8	21.4	24.2
46	65.	-47.	0.	7.17	0.998	9.7	3.7	106.	57.1	21.4	24.0
47	66.	-48.	0.	7.17	0.998	9.5	4.2	90.	57.9	21.9	24.4
52	65.	43.	0.	7.17	0.999	11.6	3.0	357.	34.3	11.5	-0.8
53	64.	42.	0.	7.17	0.999	11.3	2.9	350.	34.6	11.5	-1.1
54	64.	41.	0.	7.17	0.999	11.6	3.8	349.	34.2	11.3	-1.2
59	55.	23.	0.	7.27	0.998	12.2	4.0	1.	35.3	10.8	35.3
60	54.	22.	0.	7.27	0.998	12.1	4.3	358.	35.5	10.9	35.0
61	54.	20.	0.	7.28	0.998	12.1	4.7	356.	35.2	10.7	34.9
62	53.	-17.	0.	7.20	1.000	12.1	3.4	5.	33.2	10.1	64.9
63	54.	-19.	0.	7.21	1.000	12.2	3.9	4.	33.7	10.2	65.0
64	54.	-20.	0.	7.20	1.000	12.2	4.1	7.	33.8	10.3	65.1
65	54.	-21.	0.	7.20	1.000	12.1	3.0	5.	33.9	10.4	65.1





3.4.5 THERMAL PERFORMANCE WITH MODERATELY SELECTIVE ABSORBER

The collector, outfitted with a moderately selective black paint coated absorber, was tested on 25 January 1994 in accordance with ASHRAE procedure 93-1986. Only two different inlet temperatures tests were run for the moderately selective paint absorber. The customary minimum of four points was not taken because the collector was exposed to a period of wet stagnation. This stagnation may have caused some degradation to the TIM installed in this collector. Since only two points were taken only a linear fit could be developed. Results of the thermal performance tests are presented in graphical and tabular form in both the International System of Units (SI) and English units. The thermal performance equations in S.I. units developed from the empirical data are:

$$\text{first order} \quad \eta = 69.4 - 199 \quad (T_i - T_a)/I$$

These equations in English units are:

$$\text{first order} \quad \eta = 69.4 - 35 \quad (T_i - T_a)/I$$

TABLE 3.20 THERMAL PERFORMANCE TEST ON 4" CAP WITH MODERATELY SELECTIVE ABSORBER (SI UNITS)

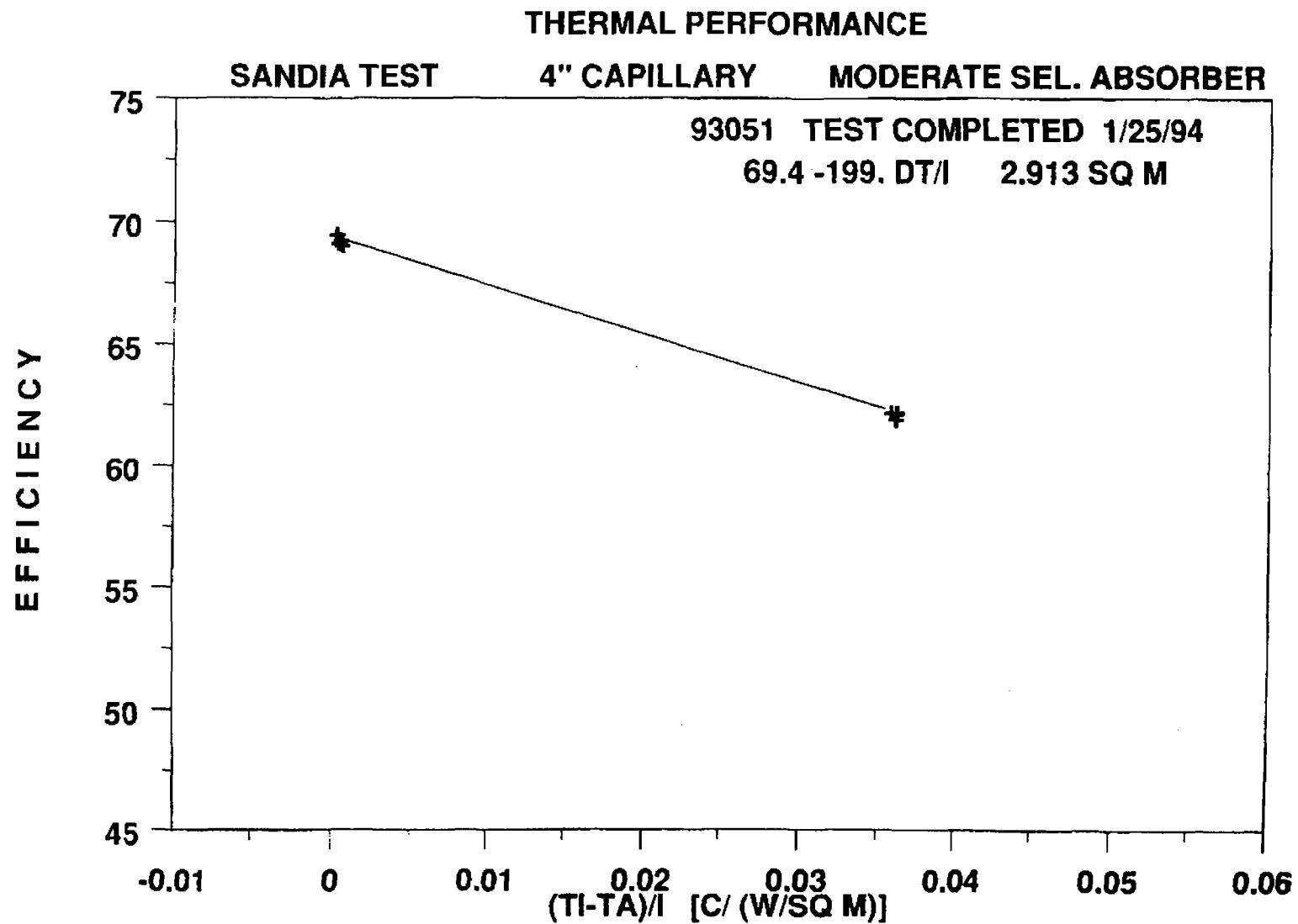
TEST	DATE	SOLAR TIME START END	TA (C)	TI (C)	TE (C)	FLOW AVE IN L/MIN W/M ²	TOTAL IN J/M ²	TE-TI (C)	DEL T C-MIN	EFFIC %	(TI-TA)/I (C-M ²)/W
4	1/25/94	13:26 13:31	23.1	59.4	67.7	3.25 1015.3	304601.	8.29	41.5	62.3	0.0357
6	1/25/94	13:36 13:41	23.1	59.5	67.7	3.24 1012.9	303863.	8.24	41.2	62.0	0.0360
7	1/25/94	13:41 13:46	23.0	59.5	67.7	3.24 1012.5	303745.	8.28	41.4	62.3	0.0361
8	1/25/94	13:46 13:51	23.0	59.5	67.7	3.24 1008.7	302599.	8.26	41.3	62.3	0.0361
11	1/25/94	14:27 14:32	22.9	23.2	32.0	3.24 971.6	291489.	8.75	43.8	69.6	0.0003
13	1/25/94	14:37 14:42	22.7	23.2	31.8	3.24 956.1	286840.	8.58	42.9	69.4	0.0005
14	1/25/94	14:42 14:47	22.6	23.2	31.7	3.24 955.4	286635.	8.55	42.8	69.1	0.0006
16	1/25/94	14:52 14:57	22.7	23.1	31.6	3.24 939.5	281848.	8.42	42.1	69.2	0.0004

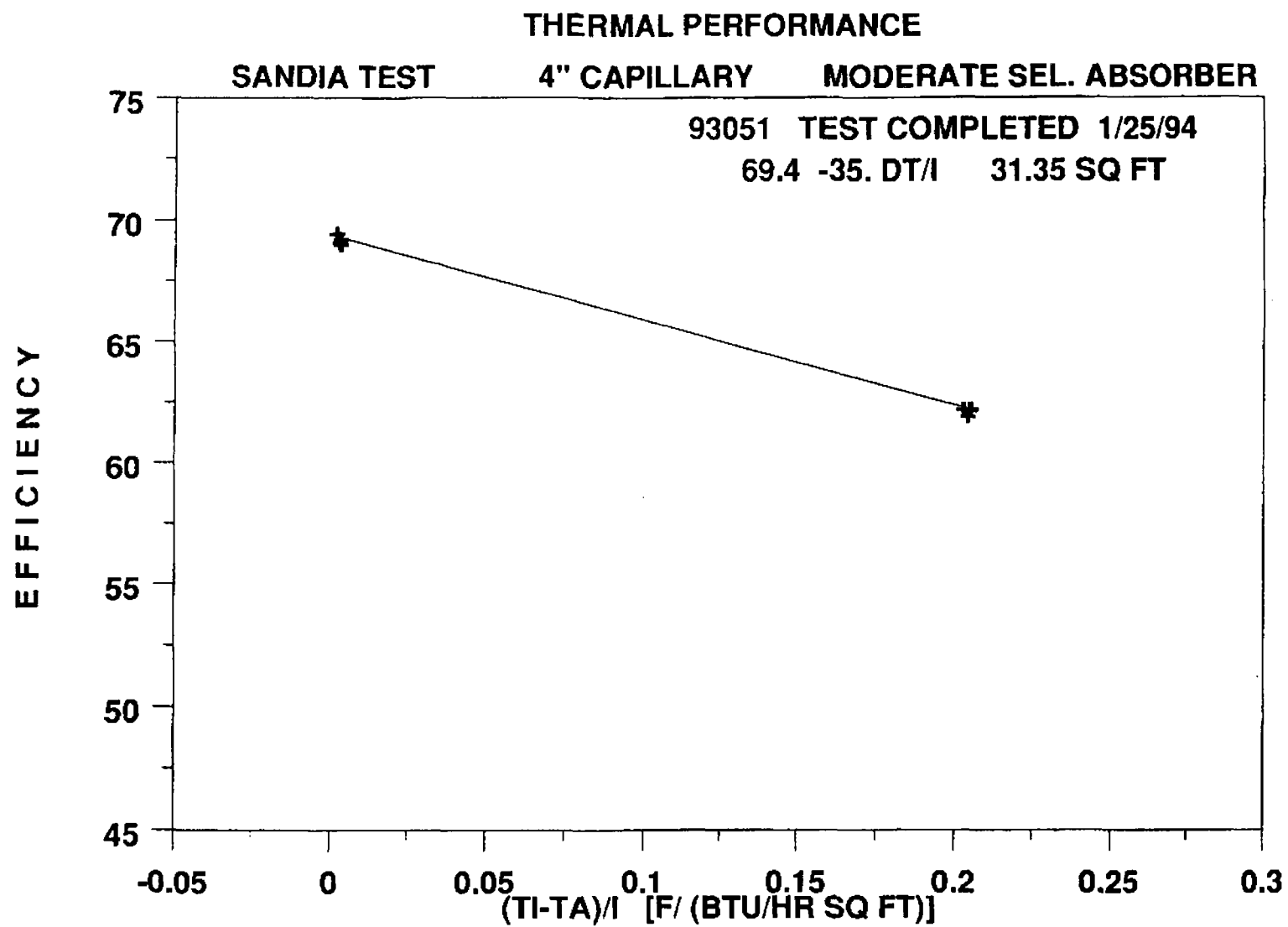
TEST	TILT DEG	AZIM DEG	INCI DEG	MASS KG/SEC	SPEC HEAT J/(KG C)	IN P KN/M ²	WIND M/S	WIND DIR	DIF IN W/M ²	% DIFF INSOL	TI-TA (C)
4	52.	-27.	0.	0.0531	4185.9	84.1	1.9	101.	139.7	13.8	36.3
6	53.	-30.	0.	0.0530	4185.9	84.1	2.0	109.	134.1	13.2	36.4
7	54.	-31.	0.	0.0530	4185.9	83.2	1.8	103.	132.2	13.1	36.5
8	54.	-32.	0.	0.0530	4185.9	83.5	2.2	106.	130.8	13.0	36.4
11	60.	-42.	0.	0.0'38	4178.8	86.1	1.8	107.	135.8	14.0	0.3
13	61.	-44.	0.	0.0539	4178.8	85.2	2.4	112.	129.1	13.5	0.5
14	62.	-45.	0.	0.0538	4178.8	84.7	2.0	109.	131.2	13.7	0.5
16	64.	-47.	0.	0.0538	4178.9	84.0	2.1	102.	132.7	14.1	0.4

TABLE 3.20A THERMAL PERFORMANCE TEST ON 4" CAP WITH MODERATELY SELECTIVE ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME START END	TA (F)	TI (F)	TE (F)	FLOW AVE IN GPM B/H-FT ²	TOTAL IN BTU/FT ²	TE-TI (F)	DEL T F-MIN	EFFIC %	(TI-TA)/I (F-H-FT ²)/B
4	1/25/94	13:26 13:31	73.6	138.9	153.9	0.858 322.1	26.8	14.92	74.6	62.3	0.203
6	1/25/94	13:36 13:41	73.5	139.1	153.9	0.857 321.3	26.8	14.84	74.2	62.0	0.204
7	1/25/94	13:41 13:46	73.3	139.0	153.9	0.857 321.2	26.8	14.90	74.5	62.3	0.205
8	1/25/94	13:46 13:51	73.5	139.1	153.9	0.856 320.0	26.7	14.86	74.3	62.3	0.205
11	1/25/94	14:27 14:32	73.2	73.8	89.6	0.856 308.2	25.7	15.75	78.8	69.6	0.002
13	1/25/94	14:37 14:42	72.8	73.7	89.2	0.857 303.3	25.3	15.45	77.2	69.4	0.003
14	1/25/94	14:42 14:47	72.7	73.7	89.1	0.856 303.1	25.3	15.39	77.0	69.1	0.003
16	1/25/94	14:52 14:57	72.9	73.7	88.8	0.856 298.0	24.8	15.15	75.7	69.2	0.003

TEST	TILT DEG	AZIM DEG	INCI DEG	MASS LBM/MIN	SPEC HEAT BTU/(LBM-F)	IN P PSI	WIND MPH	WIND DIR	DIF IN B/H-FT ²	% DIFF INSOL	TI-TA (F)
4	52.	-27.	0.	7.02	1.000	12.2	4.3	101.	44.3	13.8	65.3
6	53.	-30.	0.	7.02	1.000	12.2	4.4	109.	42.5	13.2	65.6
7	54.	-31.	0.	7.01	1.000	12.1	3.9	103.	41.9	13.1	65.7
8	54.	-32.	0.	7.01	1.000	12.1	4.9	106.	41.5	13.0	65.6
11	60.	-42.	0.	7.12	0.998	12.5	4.1	107.	43.1	14.0	0.6
13	61.	-44.	0.	7.12	0.998	12.4	5.3	112.	40.9	13.5	0.9
14	62.	-45.	0.	7.12	0.998	12.3	4.5	109.	41.6	13.7	0.9
16	64.	-47.	0.	7.12	0.998	12.2	4.7	102.	42.1	14.1	0.7





3.4.6 THERMAL PERFORMANCE WITH FLAT BLACK PAINT ABSORBER

The collector, outfitted with a flat black paint coated absorber, was tested from 27-28 December 1993 in accordance with ASHRAE procedure 93-1986. Results of the thermal performance tests are presented in graphical and tabular form in both the International System of Units (SI) and English units. The thermal performance equations in S.I. units developed from the empirical data are:

$$\text{first order} \quad \eta = 73.3 - 262 \quad (T_i - T_a)/I$$

$$\text{second order} \quad \eta = 73.0 - 182 \quad (T_i - T_a)/I - 1926 \quad [(T_i - T_a)/I]^2$$

These equations in English units are:

$$\text{first order} \quad \eta = 73.3 - 46 \quad (T_i - T_a)/I$$

$$\text{second order} \quad \eta = 73.0 - 32 \quad (T_i - T_a)/I - 60 \quad [(T_i - T_a)/I]^2$$

TABLE 3.21 THERMAL PERFORMANCE TEST ON 4" CAP WITH FLAT BLACK ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME		TA	TI	TE	FLOW AVE IN		TOTAL IN	TE-TI	DEL T	EFFIC	(TI-TA)/I
		START	END	(C)	(C)	(C)	L/MIN	W/M ²	J/M ²	(C)	C-MIN	%	(C-M ²)/W
7	12/27/93	11:11	11:16	14.7	61.2	69.8	3.28	1070.3	321094.	8.59	43.0	61.8	0.0434
8	12/27/93	11:16	11:21	15.0	61.2	69.7	3.28	1069.1	320744.	8.54	42.7	61.6	0.0432
9	12/27/93	11:21	11:26	15.3	61.2	69.7	3.28	1067.6	320279.	8.52	42.6	61.5	0.0430
10	12/27/93	11:26	11:31	15.4	61.2	69.8	3.28	1069.6	320865.	8.55	42.8	61.6	0.0428
13	12/27/93	11:59	12:04	16.1	51.8	60.7	3.29	1066.2	319854.	8.91	44.5	64.8	0.0334
14	12/27/93	12:04	12:09	16.2	51.8	60.7	3.29	1064.5	319338.	8.86	44.3	64.4	0.0334
15	12/27/93	12:09	12:14	16.5	51.8	60.7	3.29	1063.3	318988.	8.87	44.3	64.6	0.0333
16	12/27/93	12:14	12:19	16.4	51.8	60.7	3.28	1063.2	318971.	8.88	44.4	64.7	0.0333
18	12/27/93	12:53	12:57	17.9	39.6	48.7	3.30	1046.3	313891.	9.17	45.9	68.4	0.0207
19	12/27/93	12:58	13:02	18.0	39.6	48.7	3.30	1043.4	313021.	9.16	45.8	68.5	0.0207
20	12/27/93	13:03	13:07	18.2	39.5	48.7	3.30	1041.1	312327.	9.14	45.7	68.5	0.0205
21	12/27/93	13:08	13:12	18.4	39.6	48.7	3.29	1034.9	310480.	9.09	45.5	68.6	0.0204
30	12/28/93	11:37	11:42	21.3	21.3	30.9	3.28	1022.5	306762.	9.60	48.0	73.5	0.0000
31	12/28/93	11:42	11:47	21.5	21.3	30.9	3.26	1019.1	305720.	9.61	48.0	73.2	-0.0002
32	12/28/93	11:47	11:52	21.4	21.3	30.9	3.26	1024.3	307301.	9.58	47.9	72.7	-0.0001
33	12/28/93	11:52	11:57	21.5	21.3	31.0	3.23	1022.7	306812.	9.63	48.1	72.5	-0.0002

TABLE 3.21 THERMAL PERFORMANCE TEST ON 4" CAP WITH FLAT BLACK ABSORBER (SI UNITS CONTIUED)

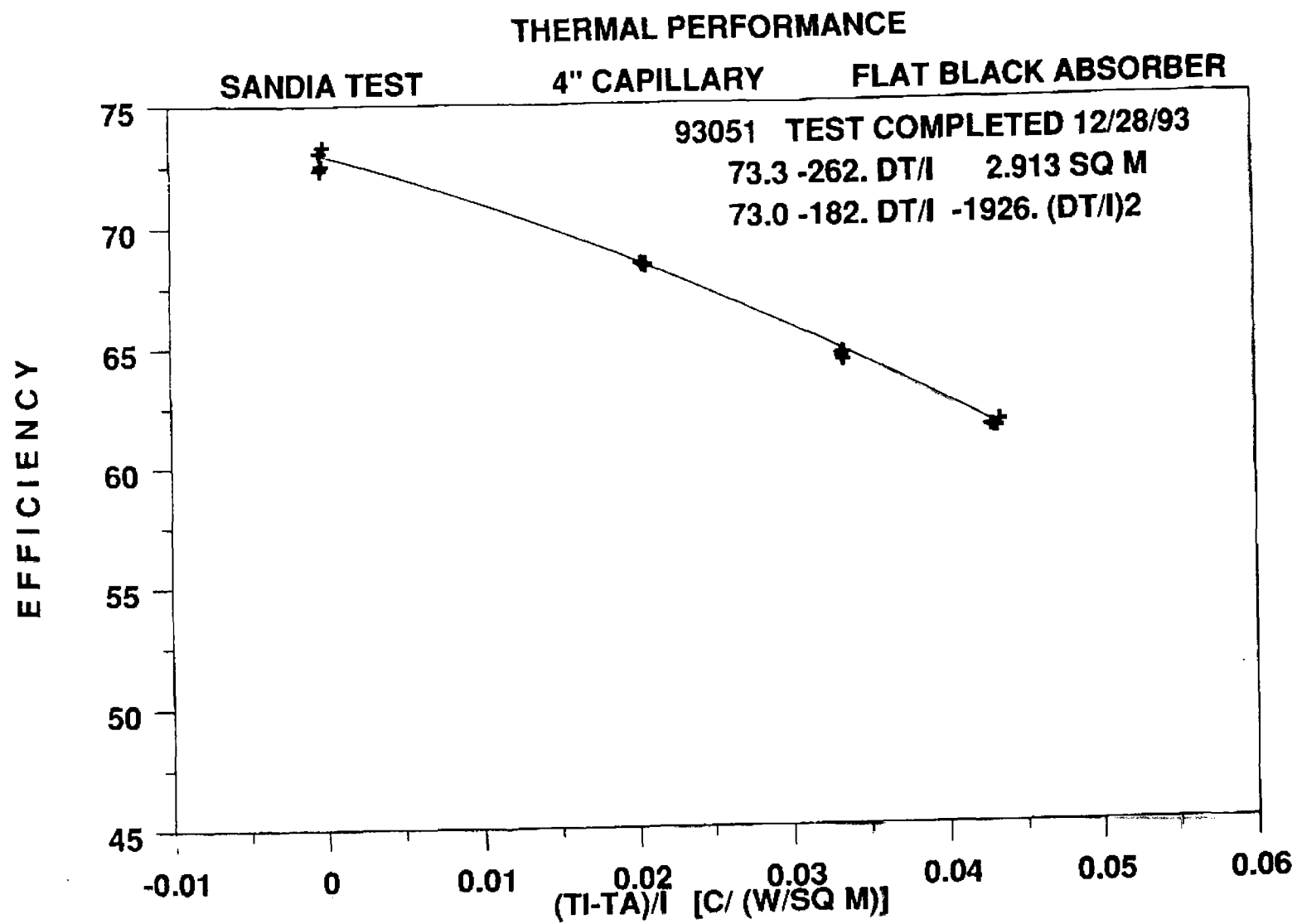
TEST	TILT DEG	AZIM DEG	INCI DEG	MASS KG/SEC	SPEC HEAT J/(KG C)	IN P KN/M ²	WIND M/S	WIND DIR	DIF IN W/M ²	% DIFF INSOL	TI-TA (C)
7	53.	13.	0.	0.0536	4186.9	78.7	1.4	350.	99.0	9.3	46.4
8	53.	12.	0.	0.0536	4186.9	78.6	1.0	351.	98.1	9.2	46.2
9	52.	10.	0.	0.0536	4186.9	79.8	1.1	356.	96.0	9.0	45.9
10	52.	9.	0.	0.0536	4186.9	80.1	1.4	356.	97.5	9.1	45.8
13	52.	-1.	0.	0.0540	4182.7	80.8	1.2	348.	101.3	9.5	35.6
14	52.	-2.	0.	0.0539	4182.7	81.9	0.9	347.	101.6	9.5	35.6
15	52.	-3.	0.	0.0539	4182.7	81.3	1.2	353.	100.6	9.5	35.4
16	52.	-5.	0.	0.0539	4182.7	81.3	1.0	355.	101.3	9.5	35.4
18	53.	-16.	0.	0.0544	4179.3	82.9	0.7	337.	95.9	9.2	21.7
19	54.	-17.	0.	0.0544	4179.3	82.0	0.5	334.	95.8	9.2	21.6
20	54.	-19.	0.	0.0544	4179.3	80.3	0.4	335.	97.0	9.3	21.4
21	54.	-20.	0.	0.0544	4179.3	82.1	0.6	344.	91.9	8.9	21.1
30	52.	6.	0.	0.0546	4179.3	81.8	1.2	335.	151.1	14.8	0.1
31	52.	4.	0.	0.0541	4179.3	80.2	0.8	336.	148.2	14.5	-0.2
32	52.	3.	0.	0.0542	4179.3	80.4	0.8	342.	140.8	13.7	-0.1
33	52.	1.	0.	0.0537	4179.3	80.3	0.8	334.	124.8	12.2	-0.2

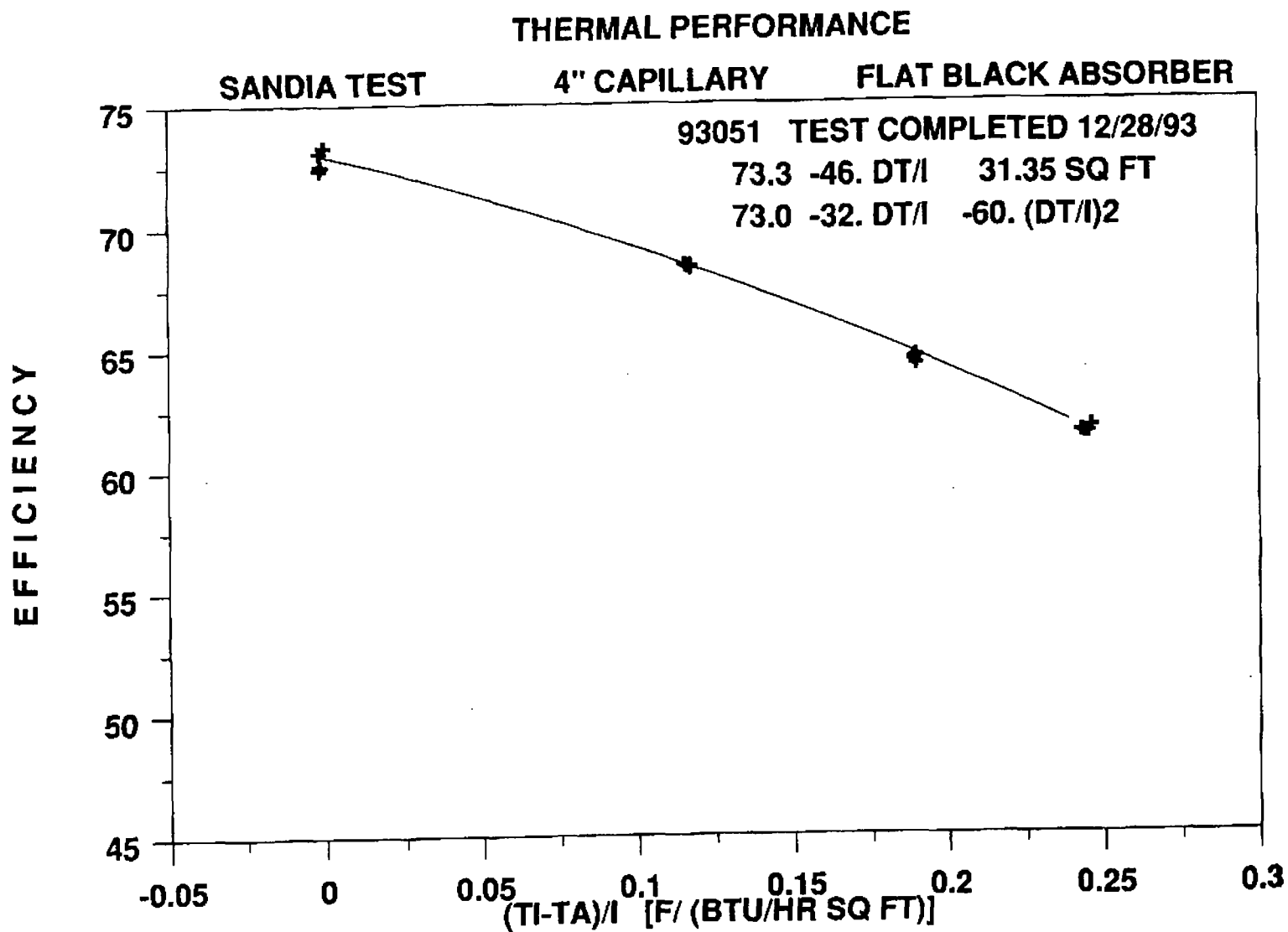
TABLE 3.21A THERMAL PERFORMANCE TEST ON 4" CAP WITH FLAT BLACK ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME START END	TA (F)	TI (F)	TE (F)	FLOW GPM	AVE IN B/H-FT ²	TOTAL IN BTU/FT ²	TE-TI (F)	DEL T F-MIN	EFFIC %	(TI-TA)/I (F-H-FT ²)/B
7	12/27/93	11:11 11:16	58.5	142.1	157.6	0.866	339.5	28.3	15.46	77.3	61.8	0.246
8	12/27/93	11:16 11:21	59.0	142.2	157.5	0.867	339.1	28.3	15.37	76.8	61.6	0.245
9	12/27/93	11:21 11:26	59.6	142.2	157.5	0.867	338.7	28.2	15.34	76.7	61.5	0.244
10	12/27/93	11:26 11:31	59.7	142.2	157.6	0.867	339.3	28.3	15.39	77.0	61.6	0.243
13	12/27/93	11:59 12:04	61.1	125.2	141.2	0.868	338.2	28.2	16.04	80.2	64.8	0.190
14	12/27/93	12:04 12:09	61.2	125.3	141.2	0.868	337.7	28.1	15.94	79.7	64.4	0.190
15	12/27/93	12:09 12:14	61.6	125.3	141.3	0.868	337.3	28.1	15.96	79.8	64.6	0.189
16	12/27/93	12:14 12:19	61.5	125.3	141.3	0.868	337.3	28.1	15.99	79.9	64.7	0.189
18	12/27/93	12:53 12:57	64.2	103.2	119.7	0.871	331.9	27.7	16.51	82.6	68.4	0.117
19	12/27/93	12:58 13:02	64.3	103.2	119.7	0.871	331.0	27.6	16.48	82.4	68.5	0.117
20	12/27/93	13:03 13:07	64.7	103.2	119.6	0.871	330.2	27.5	16.45	82.2	68.5	0.117
21	12/27/93	13:08 13:12	65.2	103.3	119.6	0.870	328.3	27.4	16.37	81.9	68.6	0.116
30	12/28/93	11:37 11:42	70.3	70.4	87.6	0.867	324.4	27.0	17.27	86.4	73.5	0.000
31	12/28/93	11:42 11:47	70.7	70.3	87.6	0.860	323.3	26.9	17.29	86.5	73.2	-0.001
32	12/28/93	11:47 11:52	70.5	70.3	87.6	0.861	324.9	27.1	17.24	86.2	72.7	0.000
33	12/28/93	11:52 11:57	70.7	70.4	87.7	0.854	324.4	27.0	17.32	86.6	72.5	-0.001

TABLE 3.21A THERMAL PERFORMANCE TEST ON 4" CAP WITH FLAT BLACK ABSORBER (ENGLISH UNITS CONTINUED)

TEST	TILT DEG	AZIM DEG	INCI DEG	MASS LBM/MIN	SPEC HEAT BTU/(LBM-F)	IN P PSI	WIND MPH	WIND DIR	DIF IN B/H-FT ²	% DIFF INSOL	TI-TA (F)
7	53.	13.	0.	7.08	1.000	11.4	3.2	350.	31.4	9.3	83.6
8	53.	12.	0.	7.09	1.000	11.4	2.3	351.	31.1	9.2	83.1
9	52.	10.	0.	7.09	1.000	11.6	2.4	356.	30.5	9.0	82.6
10	52.	9.	0.	7.09	1.000	11.6	3.1	356.	30.9	9.1	82.4
13	52.	-1.	0.	7.14	0.999	11.7	2.7	348.	32.1	9.5	64.2
14	52.	-2.	0.	7.13	0.999	11.9	2.1	347.	32.2	9.5	64.1
15	52.	-3.	0.	7.13	0.999	11.8	2.7	353.	31.9	9.5	63.7
16	52.	-5.	0.	7.13	0.999	11.8	2.3	355.	32.1	9.5	63.8
18	53.	-16.	0.	7.20	0.998	12.0	1.6	337.	30.4	9.2	39.0
19	54.	-17.	0.	7.20	0.998	11.9	1.1	334.	30.4	9.2	38.9
20	54.	-19.	0.	7.20	0.998	11.6	0.9	335.	30.8	9.3	38.5
21	54.	-20.	0.	7.19	0.998	11.9	1.2	344.	29.2	8.9	38.1
30	52.	6.	0.	7.22	0.998	11.9	2.6	335.	47.9	14.8	0.1
31	52.	4.	0.	7.16	0.998	11.6	1.8	336.	47.0	14.5	-0.3
32	52.	3.	0.	7.17	0.998	11.7	1.7	342.	44.7	13.7	-0.2
33	52.	1.	0.	7.10	0.998	11.6	1.7	334.	39.6	12.2	-0.3





3.4.7 INCIDENT ANGLE MODIFIER TEST

The collector, outfitted with a selective black chrome coated absorber, was tested from 15-18 November 1993 in accordance with the ASHRAE procedure to determine the longitudinal incident angle modifier (IAM). The definition of longitudinal IAM for this report will be incident angles where the collector's azimuth is tracking the sun while its elevation is made higher or lower than the sun's altitude, assuming the collector is mounted with its long axis parallel to the ground. A graph of the longitudinal IAM along with the data in tabular form follows. The longitudinal incident angle modifier equation was determined to be:

$$K_{\tau\alpha} = 1.0 - 0.24 (1/\cos \theta - 1)$$

The collector, outfitted with a selective black chrome coated absorber, was tested from 15 November - 16 December 1993 in accordance with the ASHRAE procedure to determine the transverse incident angle modifier (IAM). The definition of transverse IAM for this report will be incident angles where the collector's elevation is tracking the sun while its azimuth is made further right or left than the sun's azimuth assuming the collector is mounted with its long axis parallel to the ground. A graph of the transverse IAM along with the data in tabular form follows. The transverse incident angle modifier equation was determined to be:

$$K_{\tau\alpha} = 1.0 - 0.28 (1/\cos \theta - 1)$$

The collector, outfitted with a flat black paint coated absorber, was tested on 28 December 1993 in accordance with the ASHRAE procedure to determine the transverse incident angle modifier (IAM). The definition of transverse IAM for this report will be incident angles where the collector's elevation is tracking the sun while its azimuth is made further right or left than the sun's azimuth assuming the collector is mounted with its long axis parallel to the ground. A graph of the transverse IAM along with the data in tabular form follows. The transverse incident angle

modifier equation was determined to be:

$$K\tau\alpha = 1.0 - 0.23 (1/\cos \theta - 1)$$

Incident angle modifier tests were not performed on all collector-absorber configurations since results did not change significantly from one configuration to the next.

TABLE 3.22 LONGITUDINAL INCIDENT ANGLE MODIFIER TEST ON 4" CAP WITH SELECTIVE ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM	
		START END	(C)	(C)	(C)	(C)	(C)	L/M	KG/SEC	DEG	DEG	DEG	W/M ²	DIF	M/S	DEG	%	
2	11/15/93	11:50 11:54	27.3	29.3	32.3	3.06	2.0	3.3	0.0549	12.	3.	60.	454.	9.	2.2	116.	53.1	0.771
3	11/15/93	11:55 11:59	27.3	29.3	32.3	3.04	2.0	3.3	0.0550	12.	1.	60.	452.	9.	2.1	121.	53.1	0.771
7	11/15/93	12:29 12:34	27.8	29.3	34.3	4.97	1.5	3.3	0.0541	3.	-10.	45.	643.	11.	1.8	153.	60.1	0.865
8	11/15/93	12:34 12:39	27.8	29.3	34.3	4.99	1.5	3.3	0.0540	3.	-12.	45.	641.	11.	1.9	148.	60.3	0.868
9	11/15/93	13:03 13:07	27.9	29.3	38.0	8.68	1.4	3.3	0.0545	35.	-20.	15.	966.	21.	1.6	136.	70.2	1.007
11	11/15/93	13:13 13:17	27.6	29.3	37.9	8.58	1.8	3.3	0.0543	36.	-23.	15.	955.	20.	2.2	117.	70.0	1.005
14	11/18/93	10:06 10:11	26.9	27.0	30.3	3.29	0.1	3.3	0.0547	5.	32.	60.	483.	19.	1.0	330.	53.5	0.765
15	11/18/93	10:11 10:16	26.8	26.9	30.2	3.31	0.1	3.3	0.0548	5.	31.	60.	487.	19.	0.9	331.	53.5	0.765
16	11/18/93	10:41 10:46	27.4	28.0	33.2	5.19	0.7	3.3	0.0549	7.	23.	45.	691.	14.	0.8	340.	60.0	0.860
17	11/18/93	10:46 10:51	27.5	28.1	33.3	5.23	0.5	3.3	0.0549	6.	22.	45.	694.	14.	0.7	339.	60.1	0.861
21	11/18/93	11:27 11:31	27.9	28.1	35.5	7.45	0.1	3.3	0.0540	19.	10.	30.	859.	13.	0.7	350.	67.3	0.961
22	11/18/93	11:32 11:36	28.1	28.0	35.5	7.47	0.0	3.3	0.0540	19.	8.	30.	861.	13.	1.0	357.	67.2	0.960
24	11/18/93	11:42 11:46	28.1	28.1	35.5	7.46	0.0	3.2	0.0538	18.	5.	30.	857.	15.	1.0	359.	67.2	0.960
29	11/18/93	12:42 12:46	26.9	28.3	36.5	8.21	1.4	3.3	0.0543	34.	-14.	15.	929.	18.	2.3	100.	68.9	0.988
30	11/18/93	12:47 12:51	26.6	28.3	36.5	8.18	1.8	3.3	0.0543	35.	-15.	15.	925.	18.	2.3	94.	68.9	0.990
34	11/17/93	13:56 14:01	27.6	28.3	37.1	8.76	0.8	3.2	0.0539	56.	-34.	0.	962.	18.	1.8	---	70.3	1.006
35	11/17/93	14:01 14:06	27.5	28.3	37.1	8.74	0.8	3.2	0.0537	57.	-36.	0.	958.	17.	1.8	---	70.2	1.006
38	11/18/93	14:03 14:07	26.2	26.9	35.4	8.49	0.6	3.3	0.0541	57.	-36.	0.	937.	20.	2.2	---	70.4	1.008
39	11/18/93	14:08 14:12	26.2	26.9	35.4	8.50	0.7	3.3	0.0542	58.	-37.	0.	934.	20.	2.0	---	70.8	1.013

TABLE 3.22A LONGITUDINAL INCIDENT ANGLE MODIFIER TEST ON 4" CAP WITH SELECTIVE ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME START END	TA (F)	TI (F)	TE (F)	TE-TI (F)	TI-TA (F)	FLOW GPM	MASS LB/MIN	TLT DEG	AZIM DEG	I/A DEG	SOL B/FT ²	% DIF	WIND MPH	EFF DEG	IAM %	
2	11/15/93	11:50 11:54	81.1	84.7	90.2	5.51	3.5	0.874	7.26	12.	3.	60.	144.	9.	5.0	116.	53.1	0.771
3	11/15/93	11:55 11:59	81.2	84.7	90.2	5.47	3.5	0.876	7.27	12.	1.	60.	143.	9.	4.6	121.	53.1	0.771
7	11/15/93	12:29 12:34	82.1	84.7	93.7	8.95	2.7	0.862	7.16	3.	-10.	45.	204.	11.	4.0	153.	60.1	0.865
8	11/15/93	12:34 12:39	82.0	84.7	93.7	8.97	2.7	0.860	7.15	3.	-12.	45.	203.	11.	4.4	148.	60.3	0.868
9	11/15/93	13:03 13:07	82.3	84.8	100.4	15.62	2.5	0.869	7.21	35.	-20.	15.	306.	21.	3.7	136.	70.2	1.007
11	11/15/93	13:13 13:17	81.6	84.8	100.2	15.44	3.2	0.866	7.19	36.	-23.	15.	303.	20.	5.0	117.	70.0	1.005
14	11/18/93	10:06 10:11	80.4	80.5	86.4	5.92	0.2	0.871	7.24	5.	32.	60.	153.	19.	2.3	330.	53.5	0.765
15	11/18/93	10:11 10:16	80.3	80.5	86.4	5.96	0.2	0.872	7.25	5.	31.	60.	154.	19.	2.0	331.	53.5	0.765
16	11/18/93	10:41 10:46	81.3	82.5	91.8	9.34	1.2	0.874	7.26	7.	23.	45.	216.	14.	1.9	340.	60.0	0.860
17	11/18/93	10:46 10:51	81.6	82.5	91.9	9.41	0.9	0.874	7.26	6.	22.	45.	217.	14.	1.5	339.	60.1	0.861
21	11/18/93	11:27 11:31	82.3	82.5	95.9	13.42	0.2	0.860	7.15	19.	10.	30.	272.	13.	1.7	350.	67.3	0.961
22	11/18/93	11:32 11:36	82.5	82.5	95.9	13.45	0.0	0.860	7.14	19.	8.	30.	273.	13.	2.2	357.	67.2	0.960
24	11/18/93	11:42 11:46	82.5	82.5	96.0	13.42	0.0	0.857	7.12	18.	5.	30.	272.	15.	2.2	359.	67.2	0.960
29	11/18/93	12:42 12:46	80.4	83.0	97.8	14.78	2.6	0.865	7.19	34.	-14.	15.	295.	18.	5.1	100.	68.9	0.988
30	11/18/93	12:47 12:51	79.8	83.0	97.7	14.73	3.2	0.865	7.18	35.	-15.	15.	293.	18.	5.1	94.	68.9	0.990
34	11/17/93	13:56 14:01	81.7	83.0	98.8	15.76	1.4	0.858	7.12	56.	-34.	0.	305.	18.	4.0	---	70.3	1.006
35	11/17/93	14:01 14:06	81.6	83.0	98.7	15.73	1.4	0.855	7.10	57.	-36.	0.	304.	17.	4.1	---	70.2	1.006
38	11/18/93	14:03 14:07	79.2	80.4	95.7	15.29	1.2	0.862	7.16	57.	-36.	0.	297.	20.	5.0	---	70.4	1.008
39	11/18/93	14:08 14:12	79.1	80.4	95.7	15.30	1.3	0.863	7.17	58.	-37.	0.	296.	20.	4.5	---	70.8	1.013

LONGITUDINAL INCIDENT ANGLE MODIFIER

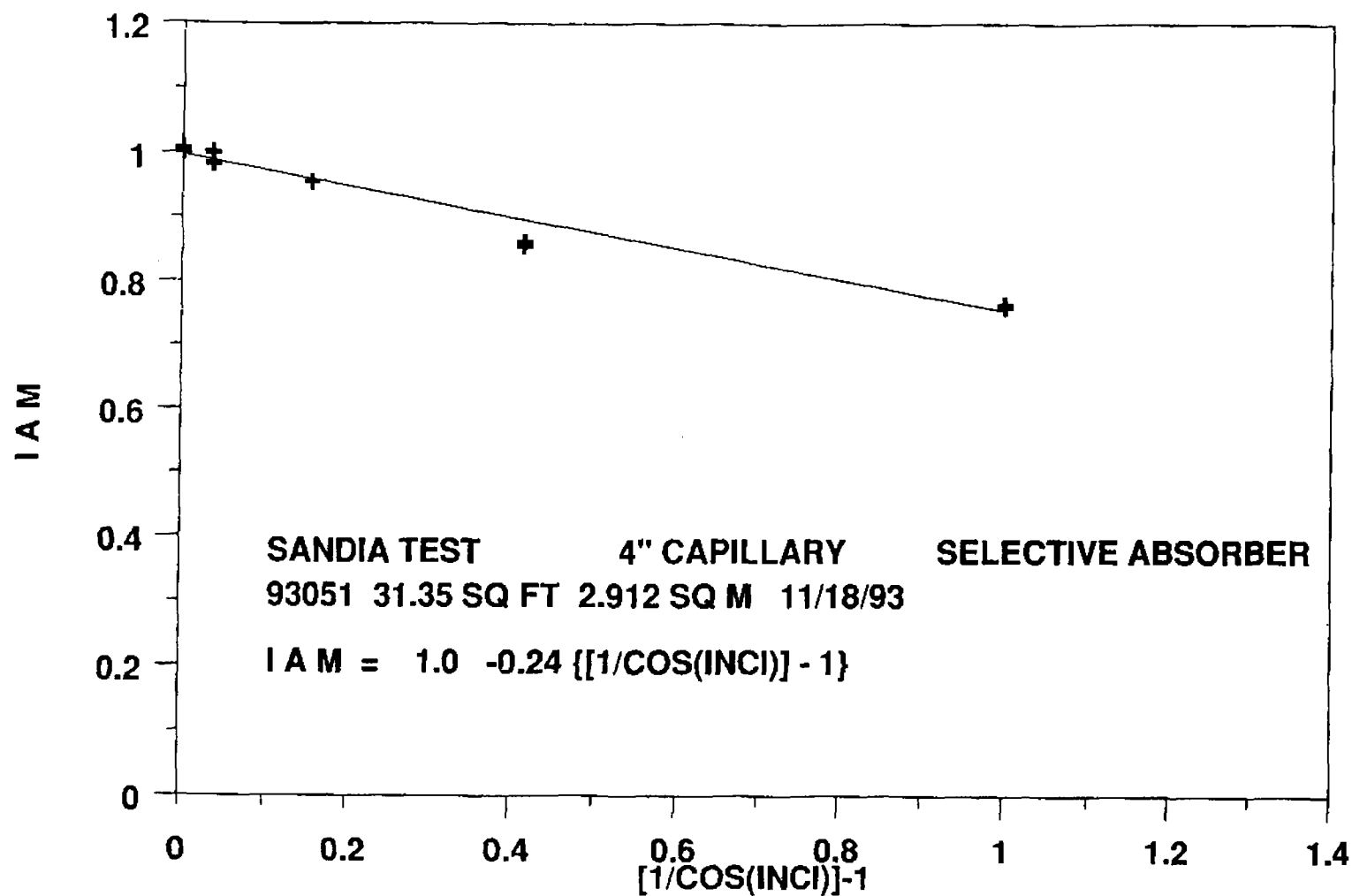


TABLE 3.23 TRANSVERSE INCIDENT ANGLE MODIFIER TEST ON 4" CAP WITH SELECTIVE ABSORBER (SI UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM
		START END	(C)	(C)	(C)	(C)	(C)	L/M	KG/SEC	DEG	DEG	DEG	W/M ²	DIF	M/S	DEG %	
2	11/15/93	11:13 11:18	27.3	29.2	33.8	4.61	2.0	3.3	0.0544	1.	14.	50.	627.	17.	2.1	136. 57.4	0.841
3	11/15/93	11:18 11:23	27.1	29.2	33.9	4.68	2.2	3.3	0.0541	1.	12.	50.	632.	18.	2.3	117. 57.4	0.842
7	12/15/93	10:54 10:59	15.5	15.8	21.4	5.53	0.3	3.3	0.0548	9.	18.	45.	739.	14.	3.4	283. 59.0	0.856
8	12/15/93	10:59 11:04	15.6	15.9	21.5	5.60	0.2	3.3	0.0543	9.	16.	45.	740.	14.	3.2	284. 59.0	0.855
13	12/15/93	13:30 13:35	18.5	19.0	26.2	7.24	0.5	3.3	0.0547	26.	-26.	30.	871.	12.	3.4	285. 65.3	0.948
14	12/15/93	13:35 13:40	18.5	19.0	26.2	7.23	0.5	3.3	0.0545	27.	-27.	30.	867.	12.	3.3	282. 65.2	0.947
18	12/15/93	15:12 15:17	17.5	18.3	21.0	2.63	0.8	3.3	0.0547	10.	-47.	60.	408.	8.	3.0	297. 50.7	0.740
19	12/15/93	15:17 15:22	17.5	18.3	20.9	2.59	0.8	3.3	0.0547	11.	-48.	60.	406.	9.	3.4	292. 50.2	0.733
27	12/16/93	13:18 13:22	14.9	14.6	23.1	8.41	-0.2	3.3	0.0547	40.	-23.	15.	974.	15.	1.9	321. 67.8	0.982
28	12/16/93	13:23 13:27	14.9	14.7	23.1	8.45	-0.2	3.3	0.0544	41.	-24.	15.	968.	15.	1.7	327. 68.2	0.987
34	11/18/93	14:03 14:07	26.2	26.9	35.4	8.49	0.6	3.3	0.0541	57.	-36.	0.	937.	20.	2.2	--- 70.4	1.022
35	11/18/93	14:08 14:12	26.2	26.9	35.4	8.50	0.7	3.3	0.0542	58.	-37.	0.	934.	20.	2.0	--- 70.8	1.028

TABLE 3.23A TRANSVERSE INCIDENT ANGLE MODIFIER TEST ON 4" CAP WITH SELECTIVE ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM
		START END	(F)	(F)	(F)	(F)	(F)	GPM	LB/MN	DEG	DEG	DEG	B/FT ²	DIF	MPH	DEG %	
2	11/15/93	11:13 11:18	81.1	84.6	92.9	8.30	3.5	0.866	7.19	1.	14.	50.	199.	17.	4.6	136. 57.4	0.841
3	11/15/93	11:18 11:23	80.7	84.6	93.0	8.42	3.9	0.861	7.15	1.	12.	50.	200.	18.	5.1	117. 57.4	0.842
7	12/15/93	10:54 10:59	59.9	60.5	70.5	9.96	0.6	0.870	7.25	9.	18.	45.	235.	14.	7.5	283. 59.0	0.856
8	12/15/93	10:59 11:04	60.1	60.6	70.6	10.07	0.4	0.861	7.18	9.	16.	45.	235.	14.	7.2	284. 59.0	0.855
13	12/15/93	13:30 13:35	65.3	66.2	79.2	13.04	0.9	0.868	7.23	26.	-26.	30.	276.	12.	7.5	285. 65.3	0.948
14	12/15/93	13:35 13:40	65.3	66.2	79.2	13.01	0.9	0.865	7.21	27.	-27.	30.	275.	12.	7.3	282. 65.2	0.947
18	12/15/93	15:12 15:17	63.5	65.0	69.8	4.74	1.5	0.868	7.24	10.	-47.	60.	130.	8.	6.7	297. 50.7	0.740
19	12/15/93	15:17 15:22	63.4	64.9	69.6	4.67	1.5	0.869	7.24	11.	-48.	60.	129.	9.	7.5	292. 50.2	0.733
27	12/16/93	13:18 13:22	58.8	58.4	73.5	15.14	-0.4	0.867	7.23	40.	-23.	15.	309.	15.	4.2	321. 67.8	0.982
28	12/16/93	13:23 13:27	58.8	58.4	73.6	15.21	-0.4	0.863	7.20	41.	-24.	15.	307.	15.	3.8	327. 68.2	0.987
34	11/18/93	14:03 14:07	79.2	80.4	95.7	15.29	1.2	0.862	7.16	57.	-36.	0.	297.	20.	5.0	--- 70.4	1.022
35	11/18/93	14:08 14:12	79.1	80.4	95.7	15.30	1.3	0.863	7.17	58.	-37.	0.	296.	20.	4.5	--- 70.8	1.028

TRANSVERSE INCIDENT ANGLE MODIFIER

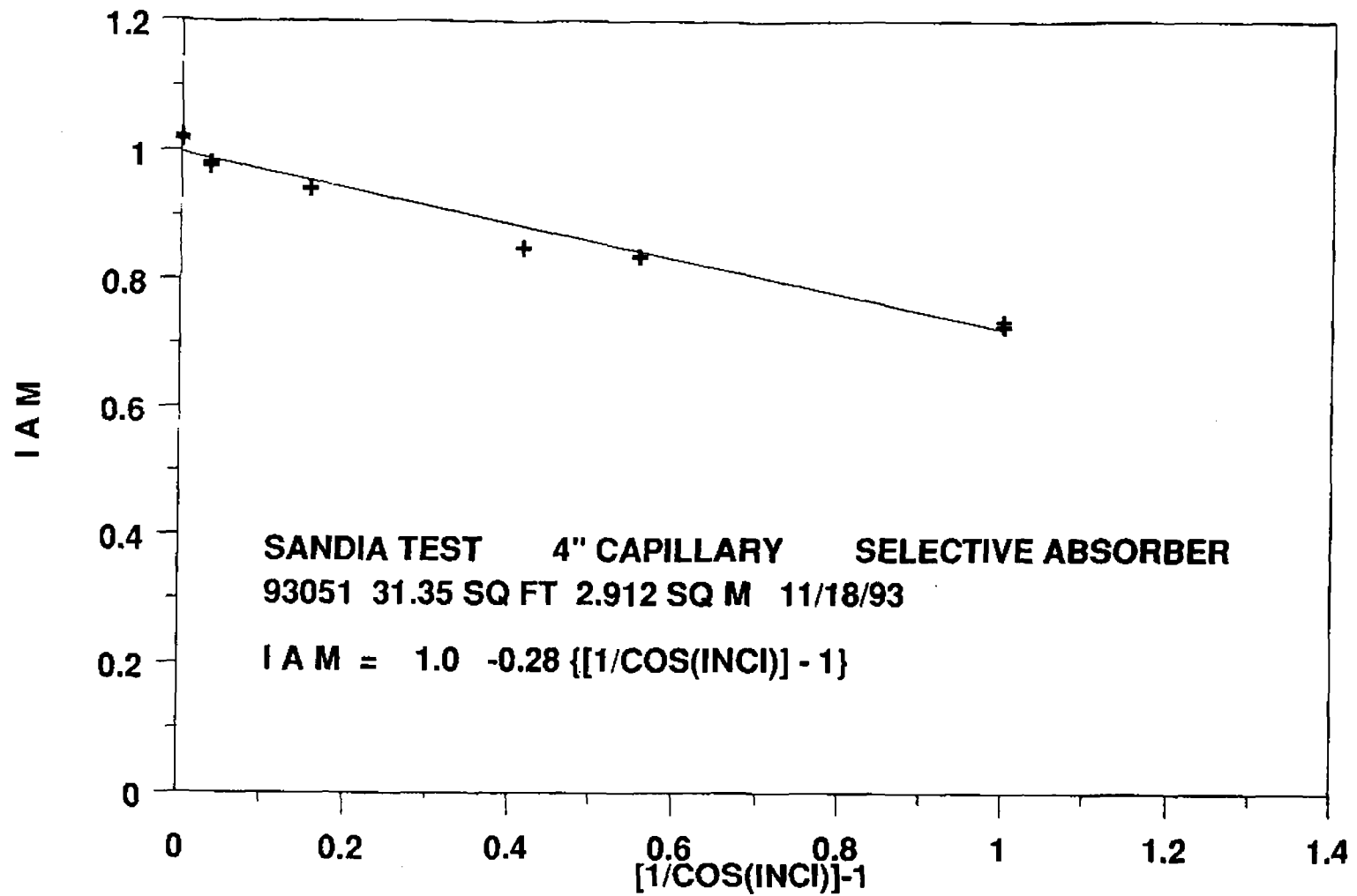


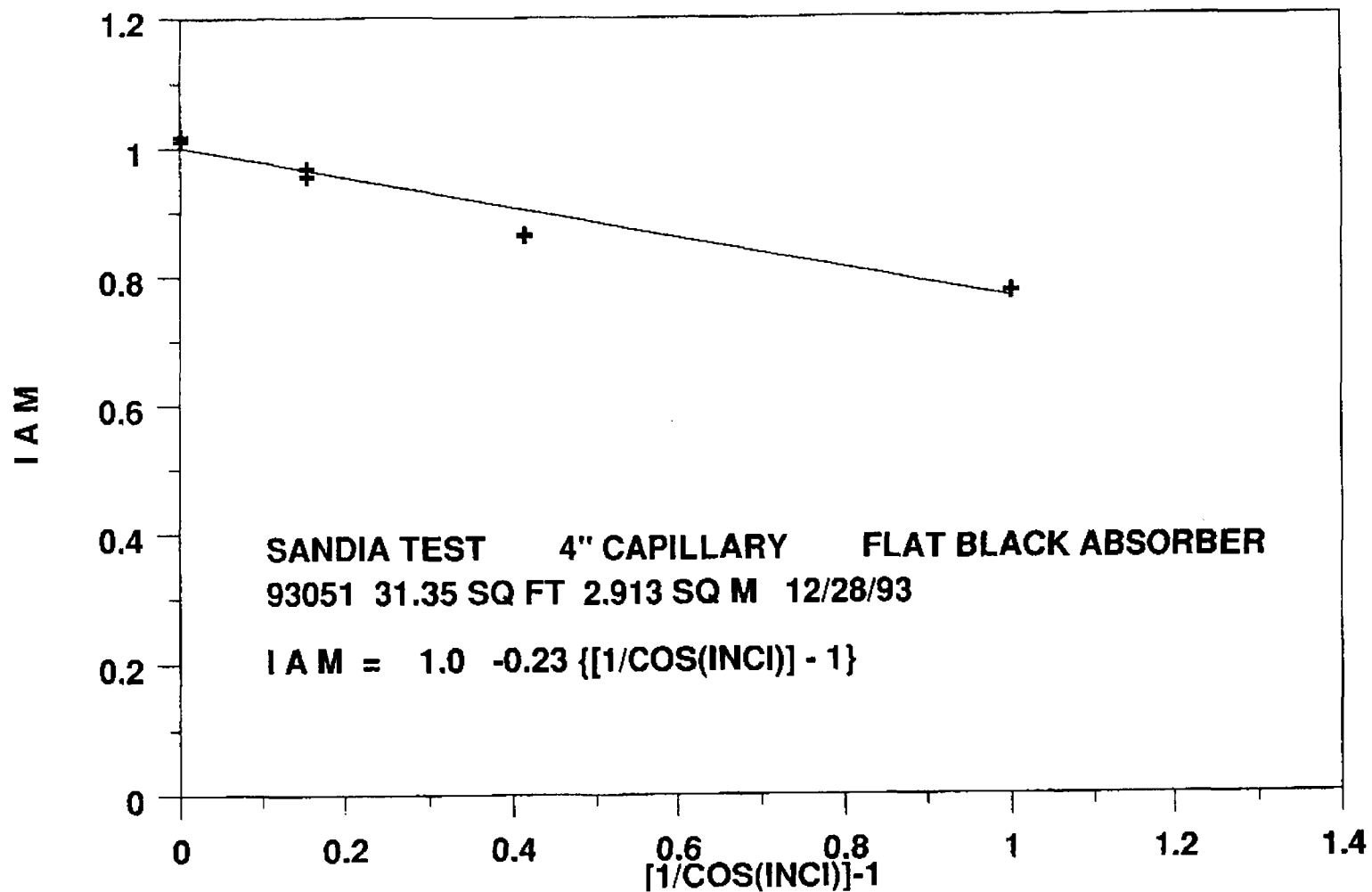
TABLE 3.24 TRANSVERSE INCIDENT ANGLE MODIFIER TEST ON 4" CAP WITH FLAT BLACK ABSORBER (SI UNITS)

TEST	DATE	SOLAR START	TIME END	TA (C)	TI (C)	TE (C)	TE-TI (C)	TI-TA (C)	FLOW L/M	MASS KG/SEC	TLT DEG	AZIM DEG	I/A DEG	SOL W/M ²	% DIF	WIND M/S	EFF DEG	IAM %	
7	12/28/93	13:22	13:26	22.3	22.3	30.0	7.76	0.0	3.3	0.0540	56.	-24.	30.	865.	13.	1.2	158.	69.5	0.973
9	12/28/93	13:32	13:36	22.4	22.3	30.1	7.81	-0.1	3.2	0.0530	57.	-26.	30.	865.	13.	1.6	154.	68.7	0.960
13	12/28/93	13:57	14:02	22.4	22.2	27.4	5.21	-0.2	3.3	0.0553	59.	-32.	45.	666.	11.	1.1	165.	62.2	0.868
14	12/28/93	14:02	14:07	22.3	22.2	27.7	5.41	-0.1	3.3	0.0550	60.	-34.	45.	685.	14.	1.4	180.	62.3	0.871
16	12/28/93	14:24	14:29	22.5	22.2	25.7	3.41	-0.2	3.3	0.0551	63.	-38.	60.	483.	16.	1.2	160.	55.8	0.779
17	12/28/93	14:29	14:34	22.3	22.2	25.5	3.33	-0.1	3.3	0.0552	63.	-39.	60.	472.	14.	1.1	157.	55.9	0.782
20	12/28/93	11:42	11:47	21.5	21.3	30.9	9.61	-0.2	3.3	0.0541	52.	4.	0.	1019.	15.	0.8	335.	73.2	1.024
21	12/28/93	11:47	11:52	21.4	21.3	30.9	9.58	-0.1	3.3	0.0542	52.	3.	0.	1024.	14.	0.8	336.	72.7	1.016

TABLE 3.24A TRANSVERSE INCIDENT ANGLE MODIFIER TEST ON 4" CAP WITH FLAT BLACK ABSORBER (ENGLISH UNITS)

TEST	DATE	SOLAR TIME	TA	TI	TE	TE-TI	TI-TA	FLOW	MASS	TLT	AZIM	I/A	SOL	%	WIND	EFF	IAM		
		START	END	(F)	(F)	(F)	(F)	GPM	LB/MN	DEG	DEG	DEG	B/FT ²	DIF	MPH	DEG	%		
7	12/28/93	13:22	13:26	72.1	72.1	86.0	13.97	0.0	0.859	7.15	56.	-24.	30.	274.	13.	2.7	158.	69.5	0.973
9	12/28/93	13:32	13:36	72.3	72.1	86.2	14.06	-0.1	0.843	7.01	57.	-26.	30.	274.	13.	3.5	154.	68.7	0.960
13	12/28/93	13:57	14:02	72.3	72.0	81.4	9.39	-0.3	0.879	7.32	59.	-32.	45.	211.	11.	2.5	165.	62.2	0.868
14	12/28/93	14:02	14:07	72.2	72.0	81.8	9.74	-0.1	0.874	7.27	60.	-34.	45.	217.	14.	3.1	180.	62.3	0.871
16	12/28/93	14:24	14:29	72.5	72.0	78.2	6.14	-0.4	0.875	7.29	63.	-38.	60.	153.	16.	2.8	160.	55.8	0.779
17	12/28/93	14:29	14:34	72.1	72.0	78.0	5.99	-0.1	0.877	7.31	63.	-39.	60.	150.	14.	2.4	157.	55.9	0.782
20	12/28/93	11:42	11:47	70.7	70.3	87.6	17.29	-0.3	0.860	7.16	152.	4.	0.	323.	15.	1.8	335.	73.2	1.024
21	12/28/93	11:47	11:52	70.5	70.3	87.6	17.24	-0.2	0.861	7.17	52.	3.	0.	325.	14.	1.7	336.	72.7	1.016

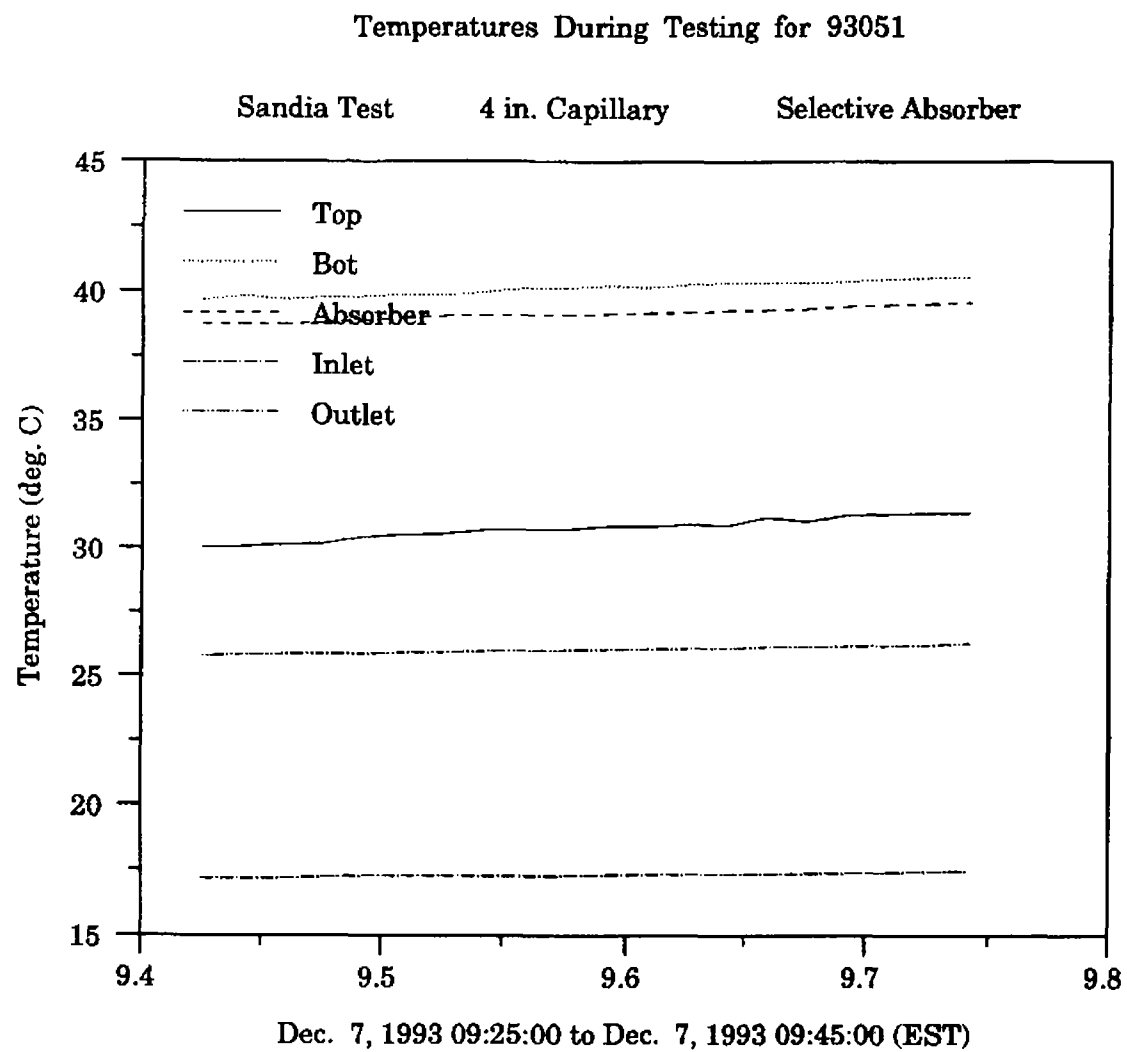
TRANSVERSE INCIDENT ANGLE MODIFIER



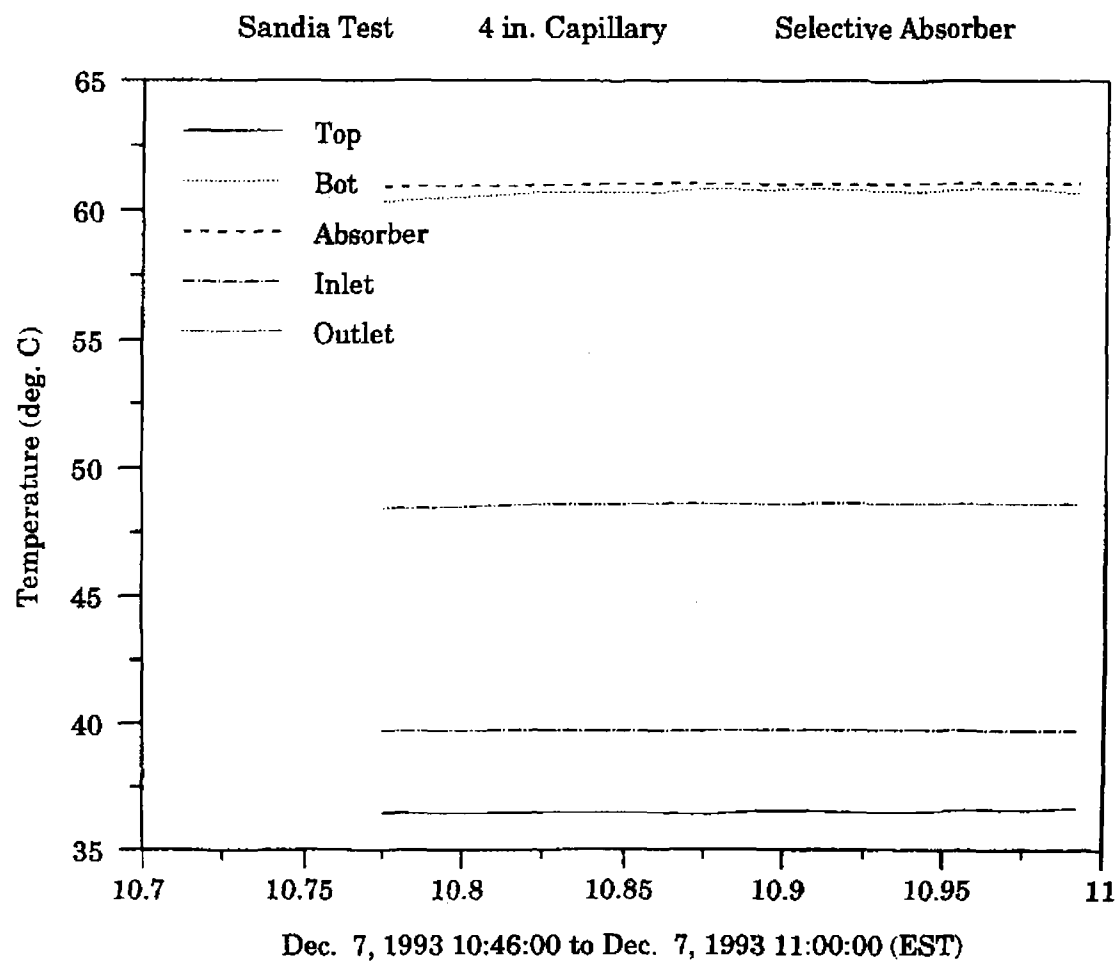
3.4.8 THERMOCOUPLE DATA

T-type thermocouples were installed inside prior to testing in order to gain insight into the temperatures internal to the collector. A total of six thermocouples were installed. Two of these were epoxied directly to the absorber. Two more were placed in air just under the TIM. The final two thermocouples were placed at the top of the TIM with the tip of the thermocouple sticking downward into a cell of the TIM. One set of thermocouples (top, bottom, absorber) were placed in the half of the collector nearest the inlet. The other set of thermocouples were placed in the half of the collector nearest the outlet. Special care was taken to keep direct sunlight from heating the top and bottom bimetal junctions and the wires leading to them. Temperature data were recorded every thirty seconds during some of the performance and IAM tests.

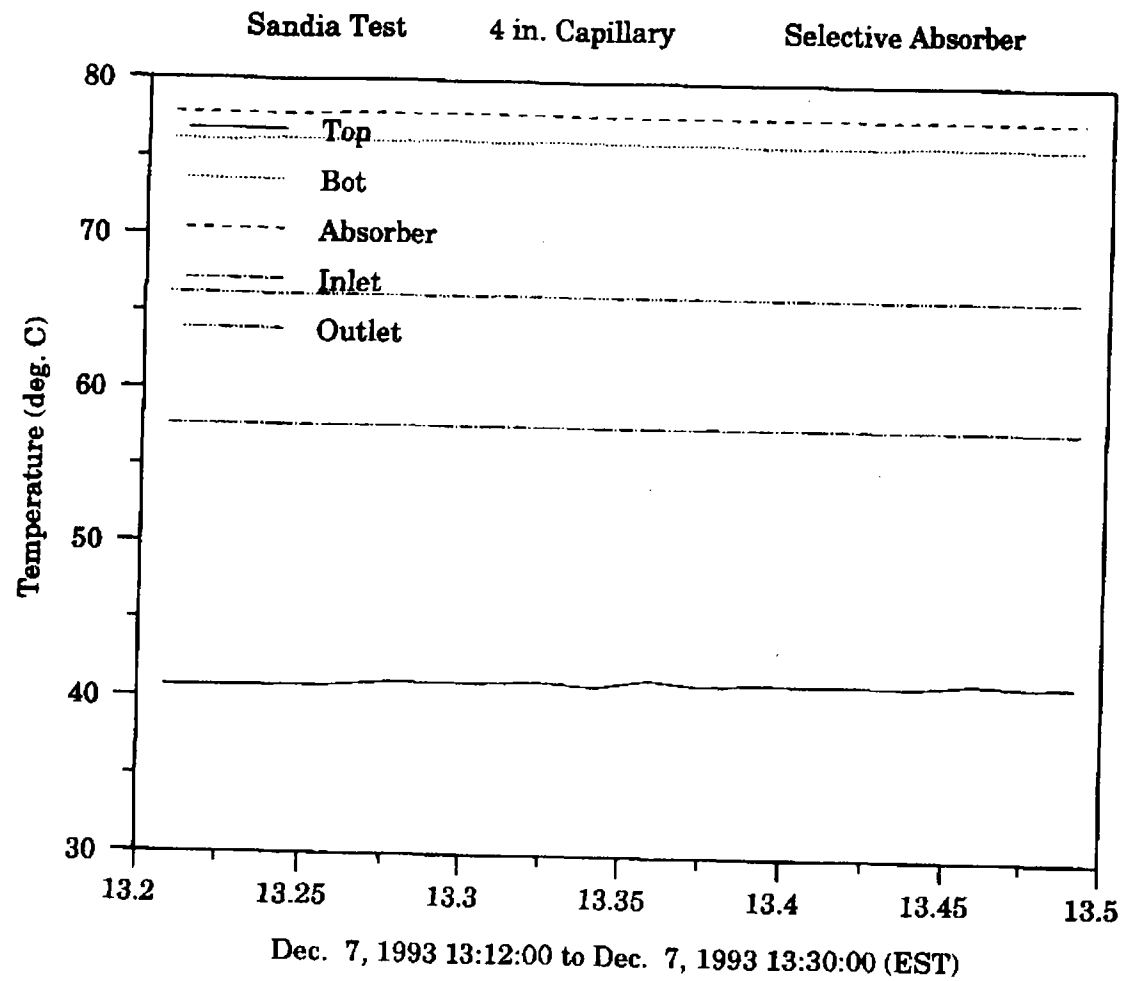
The graphs which follow give the averaged top, bottom, and absorber thermocouple temperatures along with the inlet and outlet fluid temperatures. During some periods only one of the top and one of the bottom temperatures was available. These periods are noted on the graphs by their lack of absorber temperature data. The first seven graphs present data from actual performance testing periods used in the final data reduction. The next graph shows the transients associated with removing the tarpaulins which covered the collector when not in use. This produces a sharp transition from no solar input to almost full sun. The data for the last graph were taken during a period of no solar input. Conducted at normal testing fluid flow rates, this graph demonstrates the absorber to ambient heat loss characteristics.

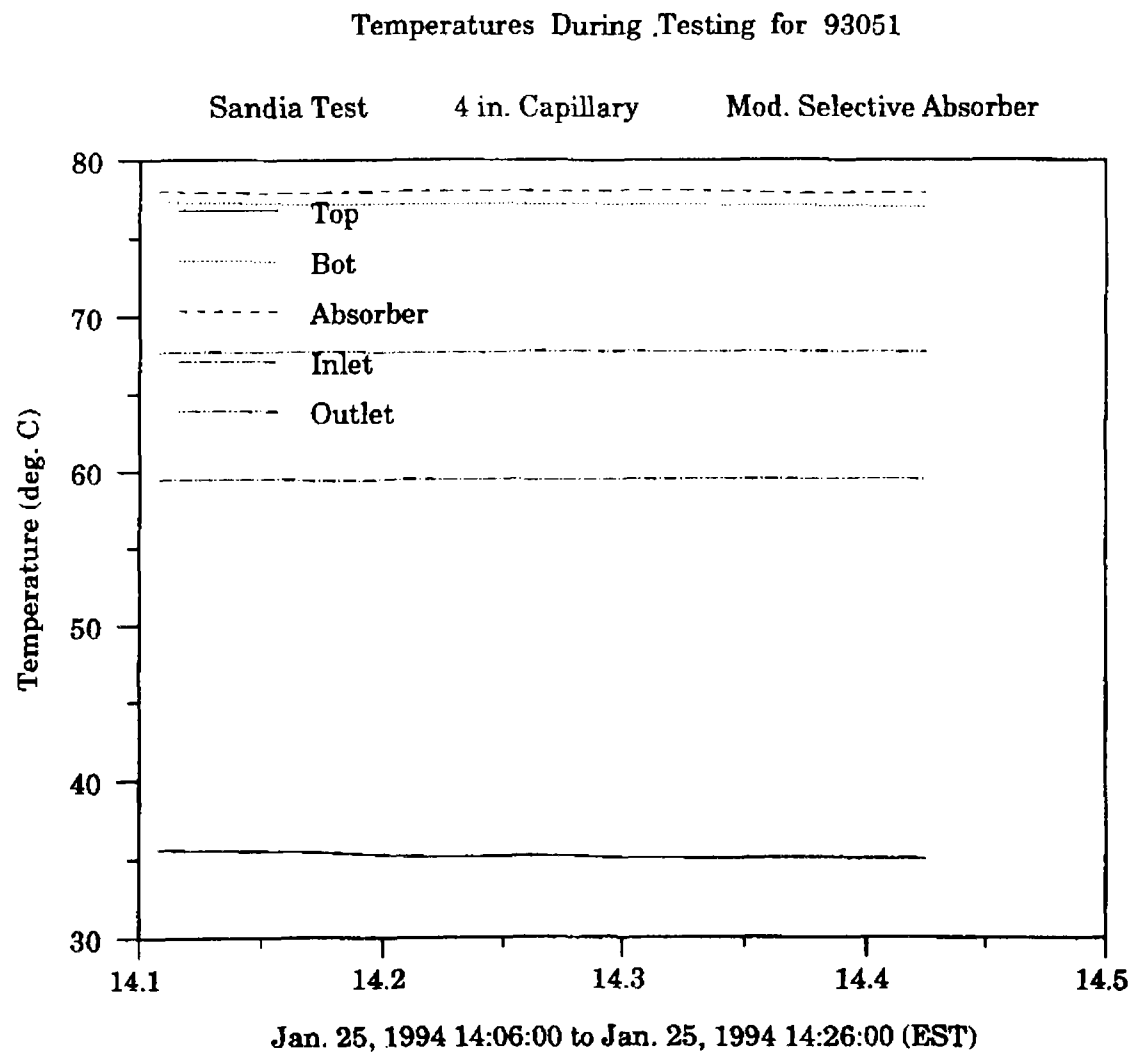


Temperatures During Testing for 93051

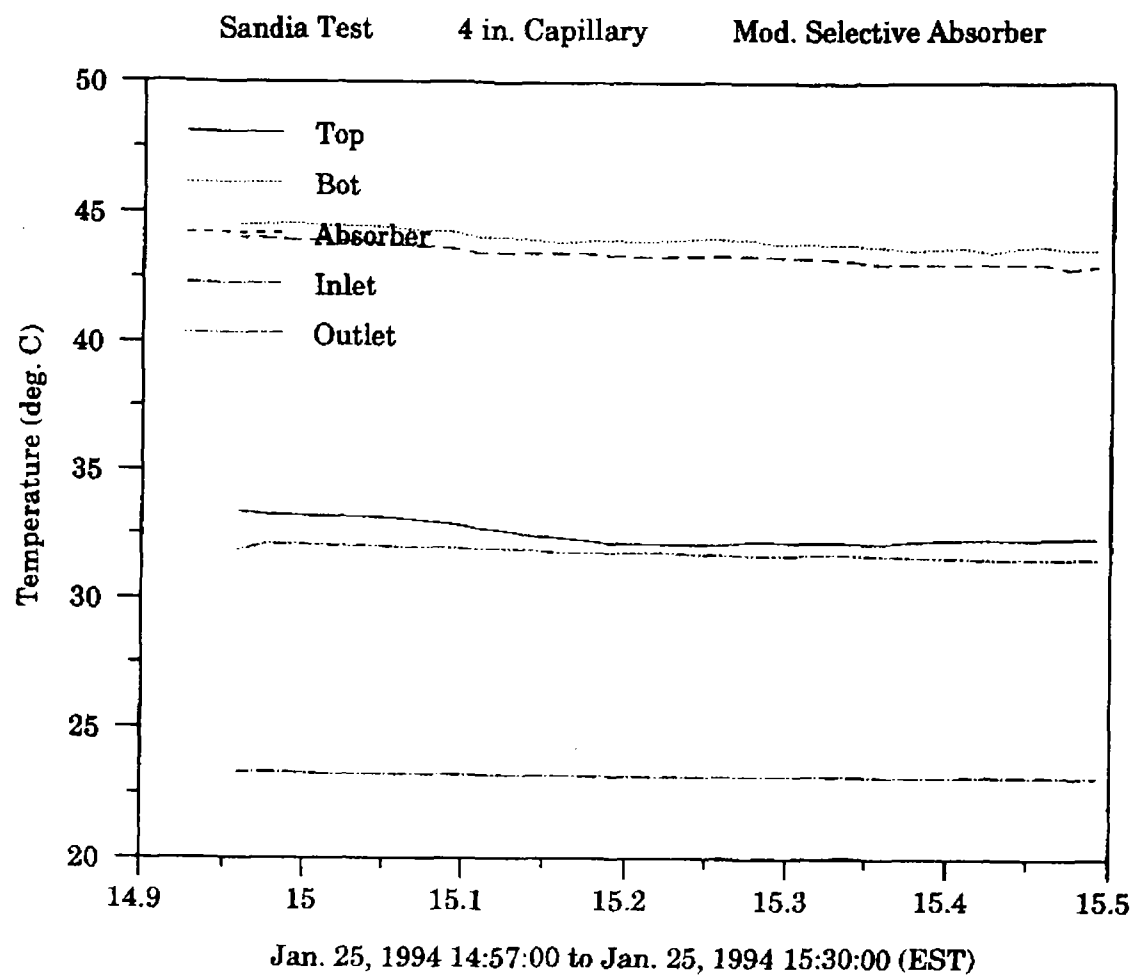


Temperatures During Testing for 93051





Temperatures During Testing for 93051

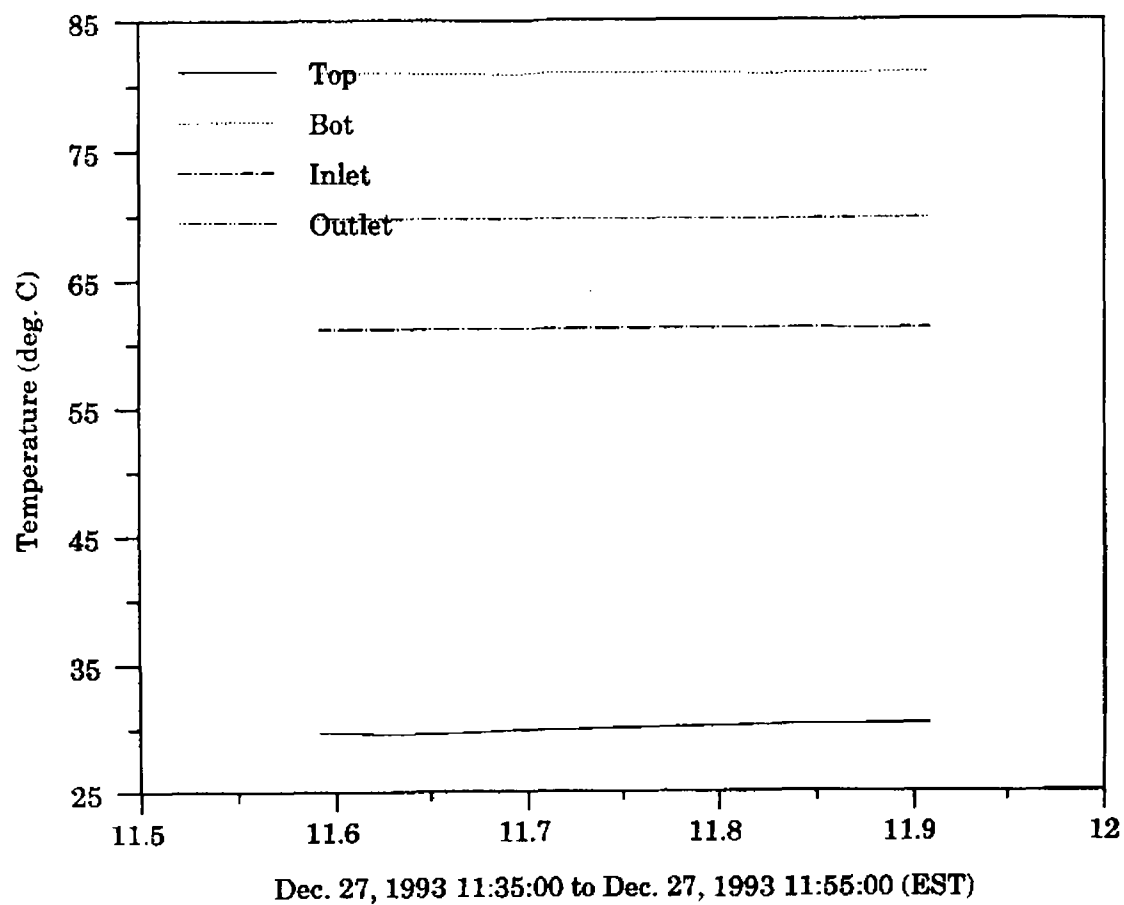


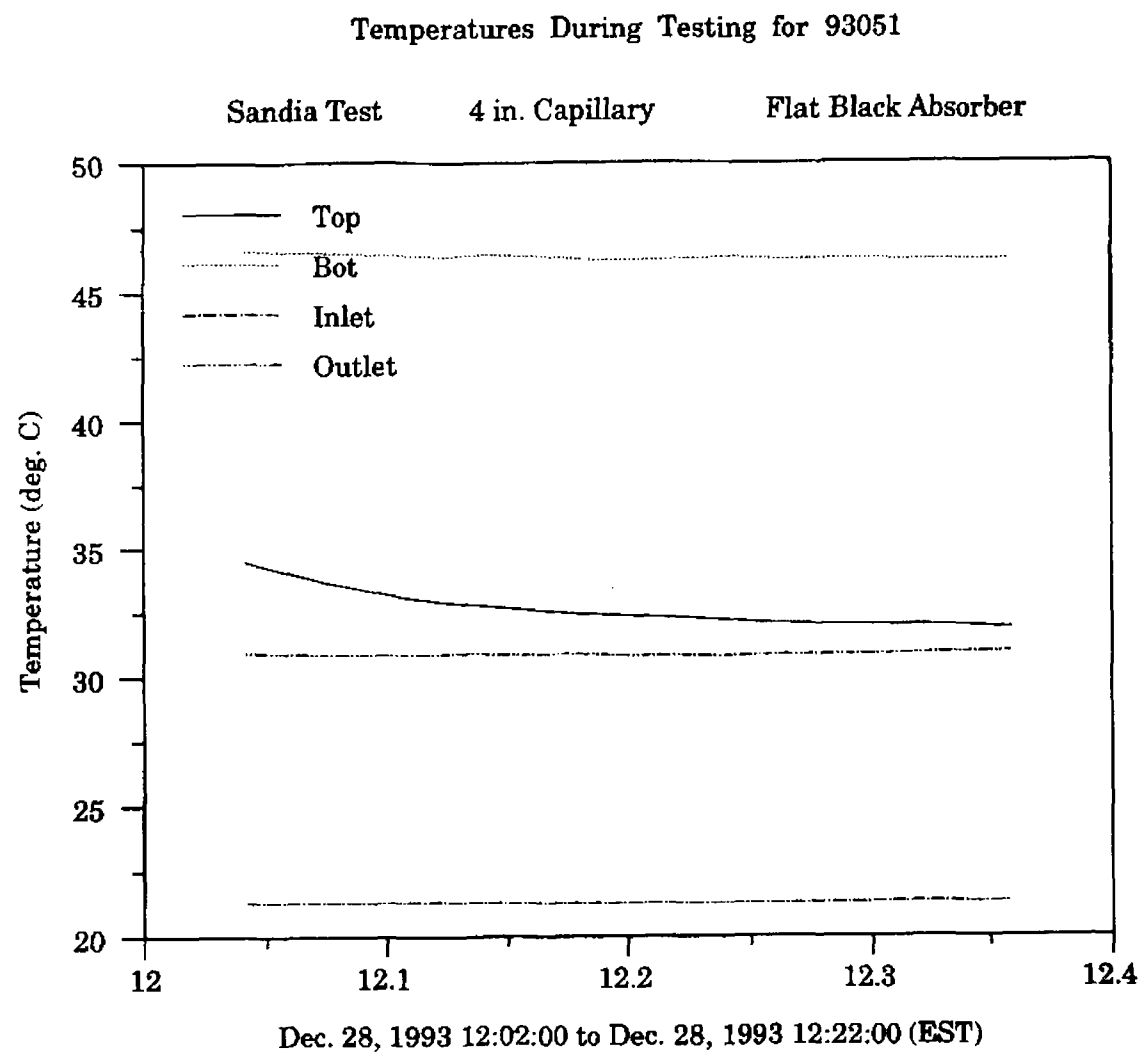
Temperatures During Testing for 93051

Sandia Test

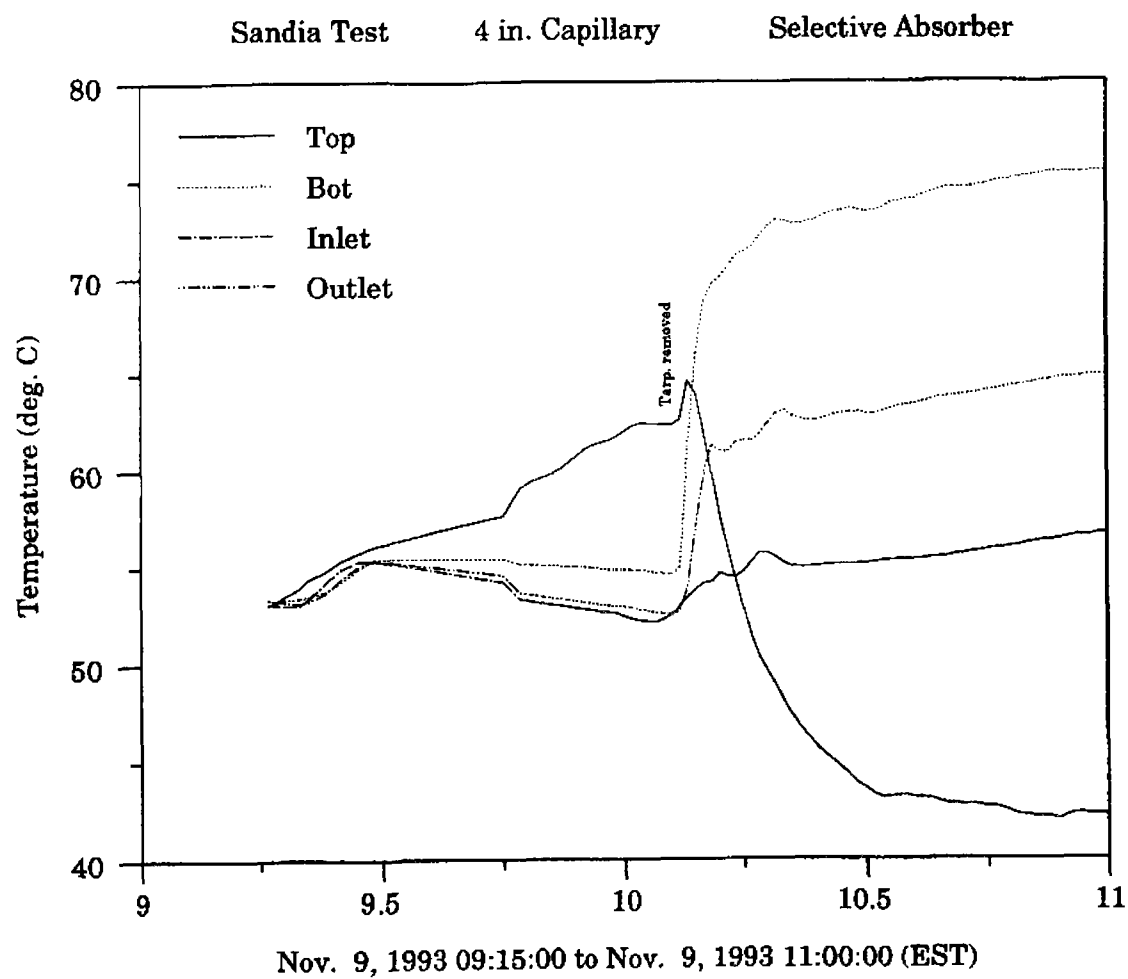
4 in. Capillary

Flat Black Absorber

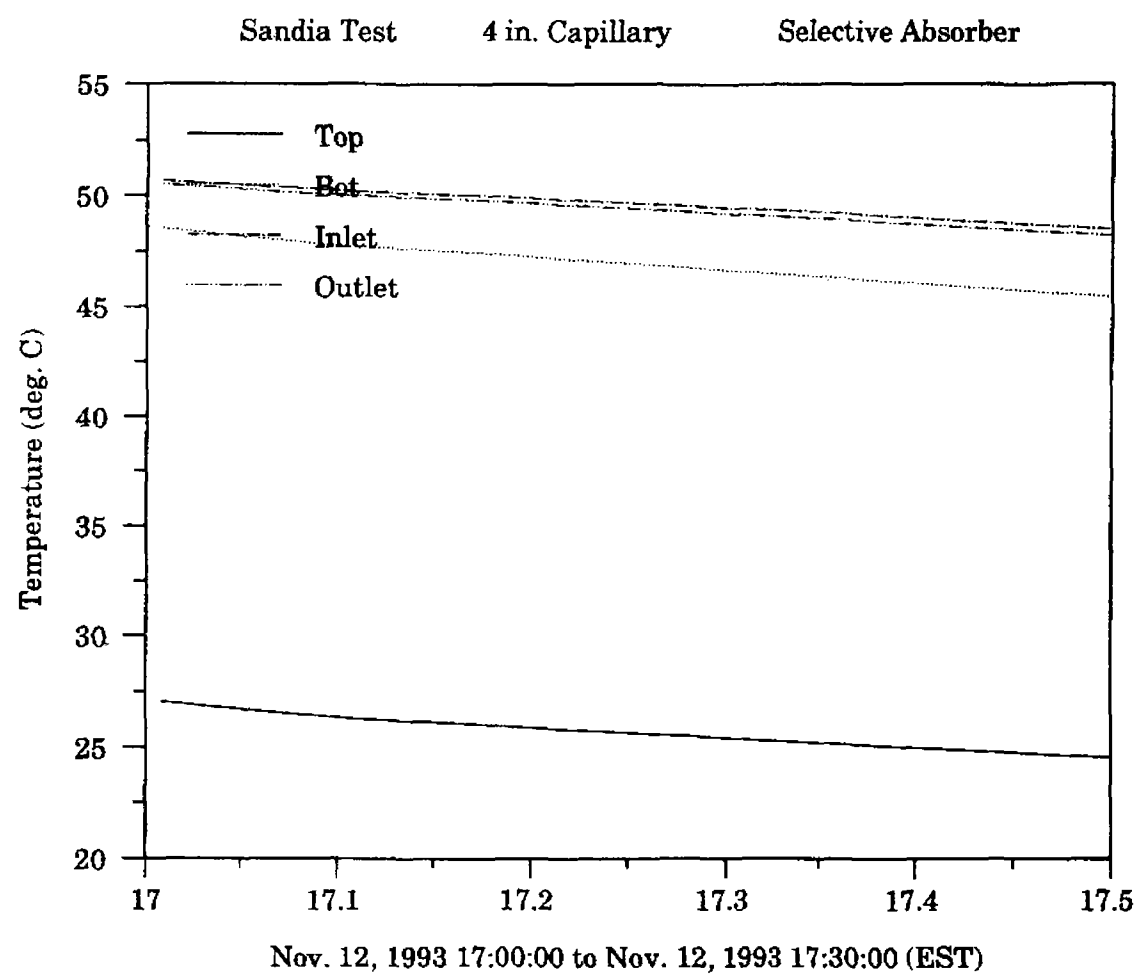




Temperatures During Collector Uncovering for 93051



Temperatures During No Solar Input for 93051

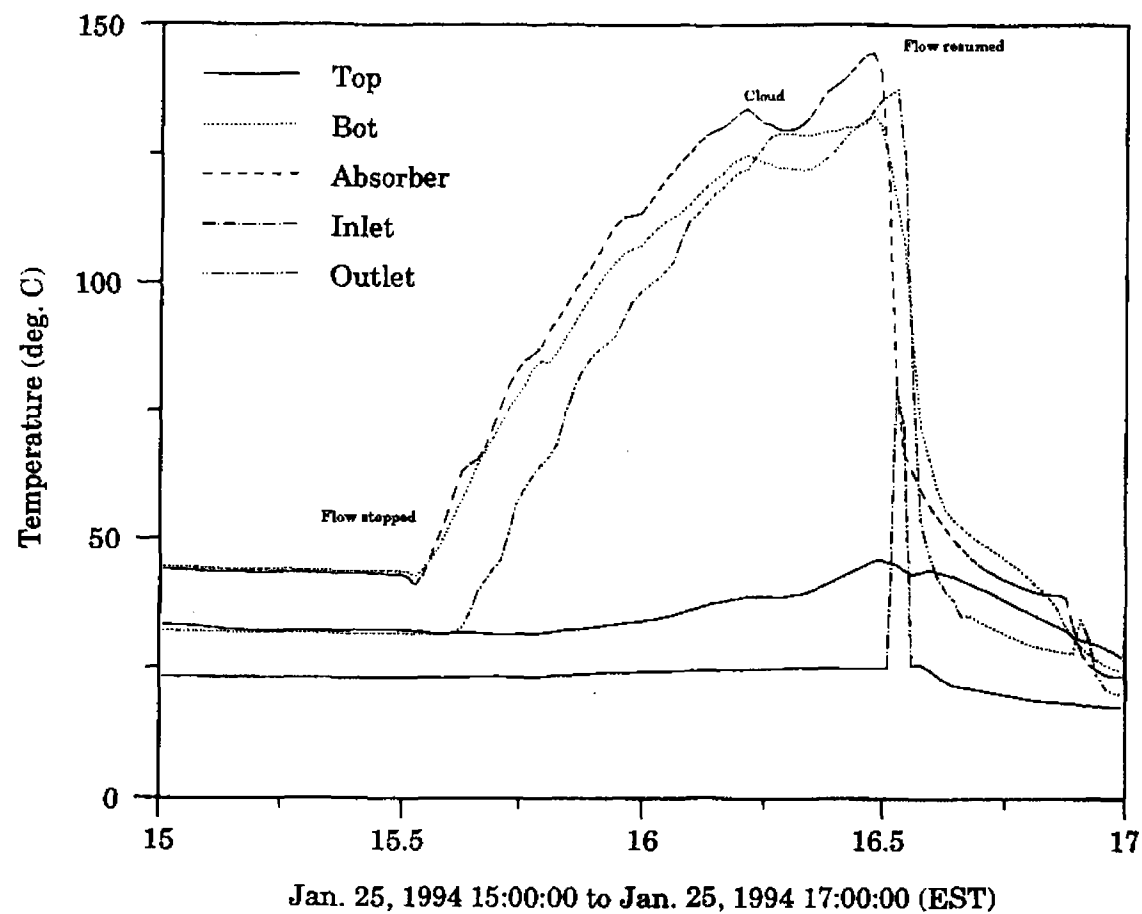


3.4.9 COLLECTOR STAGNATION

On 25 January 1994 the collectors in this series of tests were inadvertently left uncovered and facing the sun during a no fluid flow period. This constituted a wet stagnation. Although the flow was resumed about an hour later the internal temperatures had already exceeded the point where damage to this TIM takes place. The temperature data for this collector during that period is provided on the following page. The damage to the TIM was minimal toward the bottom edge of the collector. The damage increased moving upward until the maximum damage was encountered at the top edge. This makes sense since the hottest air would rise to the top edge. The damage consisted of outgassing and some melting of the lower surface of the TIM. The outgassing caused a white haziness in the TIM in the top most quarter of the collector. Each wood strip made indentions as the TIM softened. The wood slats concentrated the load on the TIM and caused the most deformation. As the TIM settled, more and more of the riser tubes on the absorber began to support it. The lower surface of the TIM had a rippling texture to it. The damage to this TIM effectively ended the comparison test.

Wet Stagnation Temperatures for 93051

Sandia Test 4 in. Capillary Mod. Selective Absorber



SECTION 4
DISCUSSION/CONCLUSIONS

4.1 DISCUSSION

This section includes comparisons of thermal performance and cost of different thicknesses of TIMs, different types of TIMs, different types of absorbers, and different types of collectors. The first order collector efficiency equation,

$$\eta = F_R \tau \alpha - F_R U \frac{(T_I - T_A)}{I} \quad (4.1)$$

derived from thermal performance test results, is used in the comparisons. In the above equation η is collector efficiency, F_R is the heat removal factor, τ is transmittance, α is the absorptance, U is the loss coefficient, T_I is inlet water temperature, T_A is ambient temperature, and I is insolation incident on the collector surface. For reference purposes, the intercept ($F_R \tau \alpha$) and slope ($F_R U$) from the first

Table 4.1 Summary of thermal performance test results (first order equations/English units)

ABSORBER/TIM	INTERCEPT	Δ INTERCEPT	SLOPE	Δ SLOPE
SELECTIVE CHROME				
NO TIM	73.9	-	76	-
1" PC RECTANGULAR	67.3	- 6.6	46	- 30
4" PC RECTANGULAR	67.6	- 6.3	43	- 33
4" ACRYLIC CAPILLARY	71.2	- 2.7	37	- 39
MODERATELY SELECTIVE				
NO TIM	69.9	-	86	-
1" PC RECTANGULAR	67.5	- 2.4	53	- 33
4" PC RECTANGULAR	67.1	- 2.8	38	- 48
4" ACRYLIC CAPILLARY	69.4	- 0.5	35	- 51
FLAT BLACK				
NO TIM	75.4	-	105	-
1" PC RECTANGULAR	71.1	- 4.3	62	- 43
4" PC RECTANGULAR	69.3	- 6.1	47	- 58
4" ACRYLIC CAPILLARY	73.3	- 2.1	46	- 59

order efficiency equations for each case, and the change in each value from the control (NO TIM) case, are displayed in Table 4.1.

As can be seen from the results, the intercept is decreased in all cases by the addition of TIMs. This is due to a further decrease in total solar transmittance by honeycomb sheets between the cover plate and the absorber. However, this decrease is small with the maximum being 6.6 percentage points from control in the case with one inch of polycarbonate rectangular honeycomb and a selective chrome absorber. The smallest decrease (-0.5) in intercept was seen with four inches of acrylic capillary honeycomb and a moderately selective absorber.

The improvement in performance with TIMs is a result of the decrease in slope (specifically, the decrease in heat loss coefficient) in all cases, due to the added insulation provided by the honeycomb sheets. The most dramatic case is a decrease from the control of 59 points with four inches of acrylic capillary TIM and a flat black absorber. Even the smallest decrease is impressive at 30 points in the case with one inch of polycarbonate rectangular TIM and a selective chrome absorber.

Incident angle modifier test results, both longitudinal and transverse, were not changed significantly by the addition of sheets of TIM even up to four inches thick. In all cases the change in the slope was less than 0.1 points from the NO TIM case.

4.1.1 COMPARISON OF DIFFERENT THICKNESSES OF TIM

Two thicknesses (one inch and four inches) of polycarbonate rectangular transparent insulation sheets were compared. Referring to Table 4.1, the change in intercept from the NO TIM case for both the selective chrome and moderately selective absorbers are not significantly different in the one and four inch TIM cases. In addition, the differences with the flat black absorber were small (a decrease of 4.3

from the NO TIM case versus a decrease of 6.1). These results support the theory that solar radiation is reflected and rereflected in a forward direction down the cell to the absorber with very little loss. Therefore, given that the cell walls are very thin, the length of the honeycomb cell will have little effect on the transmittance through the honeycomb sheet.

The slope, on the other hand, is decreased significantly in all three cases by the addition of transparent insulation. The less selective the absorber, the more dramatic the decrease. The decrease in slope from the NO TIM case is about the same for the two thicknesses with the selective chrome absorber (-30 for 1" versus -33 for 4"). However, with both the moderately selective and the flat black absorbers, adding three more inches of PC TIM dropped the slope another 15 points (-33 to -48 and -43 to -51 respectively) from the decrease seen with one inch of PC TIM.

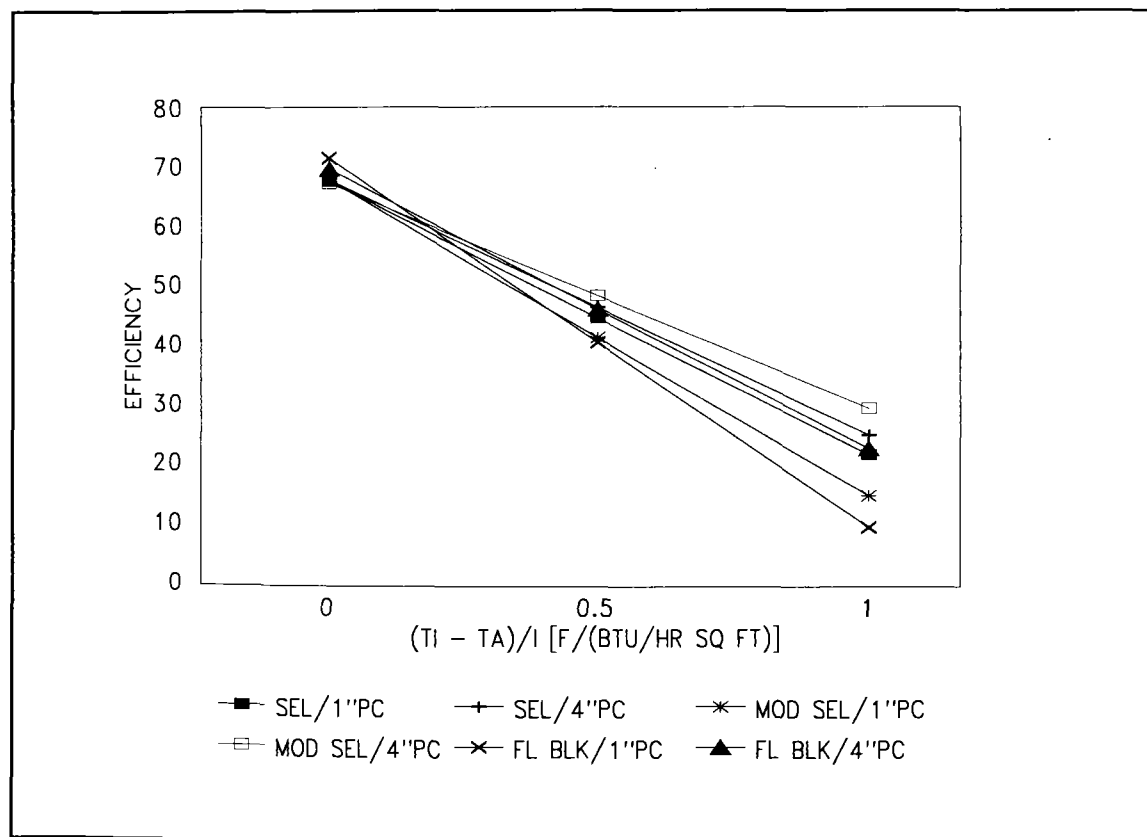


Figure 4.1 Comparison of different thicknesses of TIMs

The width of the rectangular honeycomb cells was 2.8 mm and the air gap was approximately 10 mm, so convection would be suppressed with both thicknesses. Also, conductive losses probably do not change significantly with the increased thickness. The difference is most likely due to additional blocking of radiative heat loss from the absorber provided by the increase in thickness of the honeycomb layer. Consequently, the more selective the absorber, the less dramatic this effect would be. The test results support this correlation. Referring to Table 4.1, the largest decreases in slope from the control are seen with the flat black absorbers and the smallest with the selective absorbers.

Since transparent insulation is sold by the board foot, four inch thick sheets of TIM are four times as expensive as one inch sheets. The cost per board foot was \$1.59 plus shipping charges. However, there was an additional charge for modifying the collector to accommodate four inches of TIM. The collectors chosen for this project had a large enough space between the absorber and the cover glass to accommodate a one inch thick sheet of TIM, although this would not necessarily be true of all flat plate collectors. The cost of modifying the collector will vary with the size of the collector, but averages \$100-\$200/collector. So, for example, in this project the original \$442 (4 x 8 foot) collector with a selective chrome absorber increased in cost by around \$50 with the addition of one inch of TIM and \$300-\$400 with four inches (ignoring shipping and crating costs).

4.1.2 COMPARISON OF DIFFERENT TYPES OF TIM

Two different types of honeycomb TIMs were commercially available at the time of procurement for this project. The first type was a polycarbonate rectangular honeycomb and the second type a clear acrylic capillary honeycomb. Four inch thick sheets of each were tested in flat plate collectors with three different absorber types. The capillary honeycomb performed best with all three absorbers, decreasing the intercept less from the NO TIM case, and the slope more, than did the rectangular honeycomb.

The acrylic honeycomb had a slightly larger cell width (3.3 versus 2.8 mm) and slightly thinner cell wall thickness (.04 versus .05 mm). This decrease in mass may have been a contributing factor in the increase in transmittance (and possibly a decrease in honeycomb wall heat conduction) with the acrylic honeycomb. The differences, however, are not large. Figure 4.2 compares the rectangular polycarbonate and the acrylic capillary honeycombs graphically with curves generated from first order thermal performance equations.

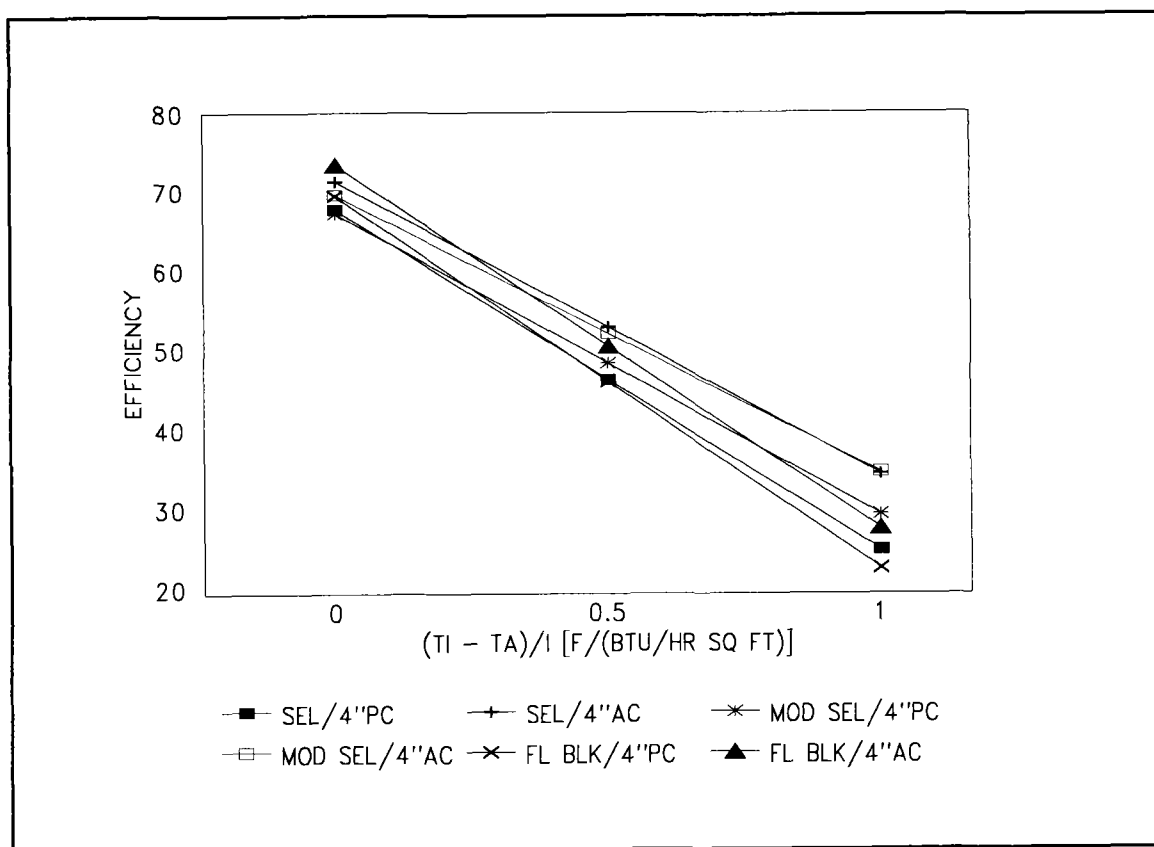


Figure 4.2 Comparison of different types of TIMs

One disadvantage of the acrylic is its lower melting temperature. This became evident when, during the moderately selective absorber tests, the collectors were accidentally allowed to stagnate (with internal temperatures exceeding 140°C). The capillary honeycomb was visibly damaged. The acrylic changed from clear to hazy white and deformed at the lower surface, especially near the wooden supports and the riser tubes on the absorber. The rectangular honeycomb showed no visible damage

as a result of this wet stagnation; however, it would not be able to withstand a prolonged period of stagnation since its melting temperature is 180°C.

The cost of these two types of TIM were the same per board foot. The shipping and handling costs differed since there is a local (in Georgia) distributor for the rectangular honeycomb; whereas, the capillary honeycomb had to be shipped from Germany.

4.1.3 COMPARISON OF DIFFERENT TYPES OF ABSORBERS

Without transparent insulation, the more selective the absorber, the better the performance. Specifically, a flat black absorber has a slightly higher intercept due to increased absorptance, but a selective absorber has a much flatter slope due to decreased emittance. This distinction is not as pronounced in collectors with transparent insulation. Consistently, the intercepts of TIM collectors are decreased most from the NO TIM case when selective chrome absorbers are used, and least when moderately selective absorbers are used. The slopes are decreased most from the NO TIM case in TIM collectors with flat black absorbers and least in those with selective absorbers.

Figure 4.3 shows a graphical comparison of curves generated from the first order efficiency equations for the NO TIM cases, and the 4" acrylic honeycomb cases, with all three types of absorbers. From the graph, the collector with 4" acrylic capillary transparent insulation and a selective chrome absorber appears to be the best performer. But these curves are theoretical. In reality, the acrylic TIM could not withstand temperatures above 90°C.

Most collectors are sold with selective or moderately selective absorbers. The cost for this project was \$200 for a flat black absorber, \$225 for a moderately selective absorber, and \$250 for a selective chrome absorber when sold separately, all of which were sized for a 4' x 8' flat plate collector.

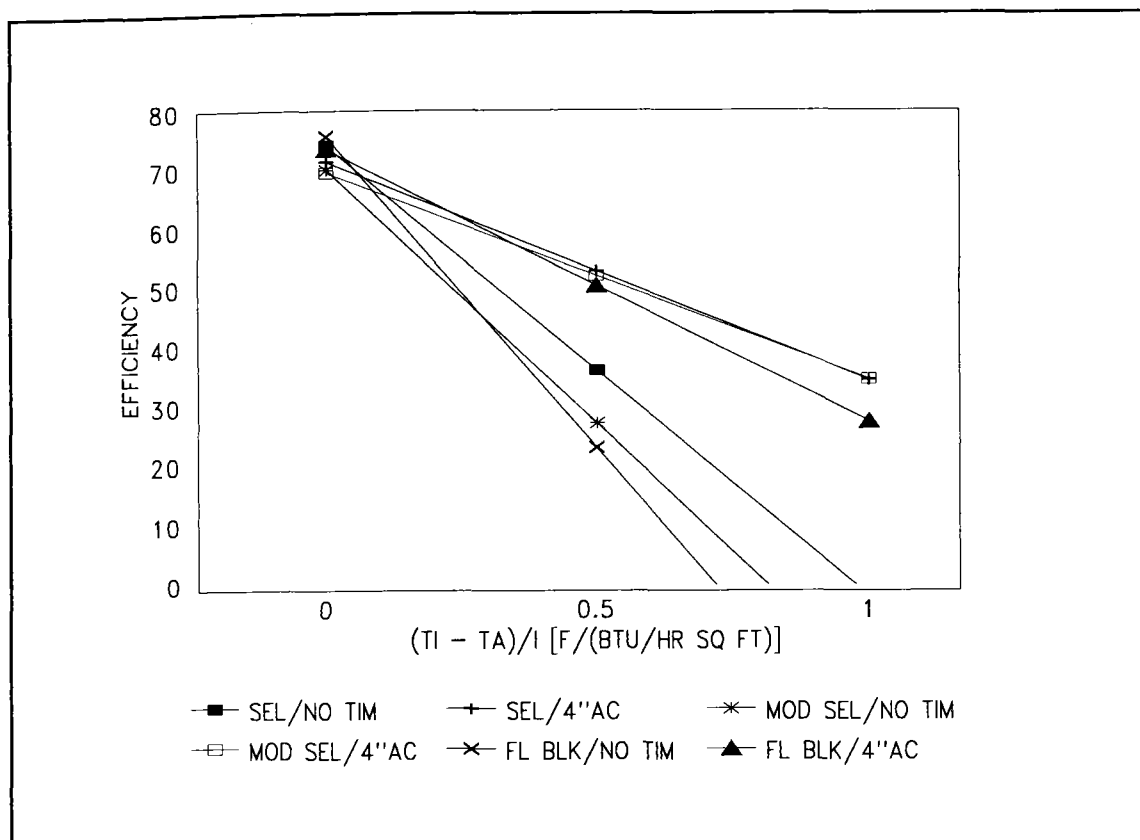


Figure 4.3 Comparison of different types of absorbers

4.1.4 COMPARISON OF DIFFERENT TYPES OF COLLECTORS

For comparison purposes, Table 4.2 includes thermal performance test results from two Solar Resources International concentrating collectors (no longer commercially available) and two Nippon evacuated tube collectors. Summary Information Sheets for these collectors are included in Appendix C. In Figure 4.4, the best performers of each type are compared with the NO TIM and the 4" acrylic capillary honeycomb collectors with selective and flat black absorbers. As with the other graphs, these curves were generated from first order efficiency equations. Again, from the graph the TIM collectors appear to be the best performers, but in reality the performance would drop off due to TIM damage from high internal temperatures.

Table 4.2 Summary of thermal performance test results (first order equations/ English units)

COLLECTOR TYPE	INTERCEPT	SLOPE
CONCENTRATING (SB201)	56.3	32
CONCENTRATING (SB301)	45.1	25
EVACUATED TUBE (PK-10)	61	47
EVACUATED TUBE (DP6-2800)	50	27

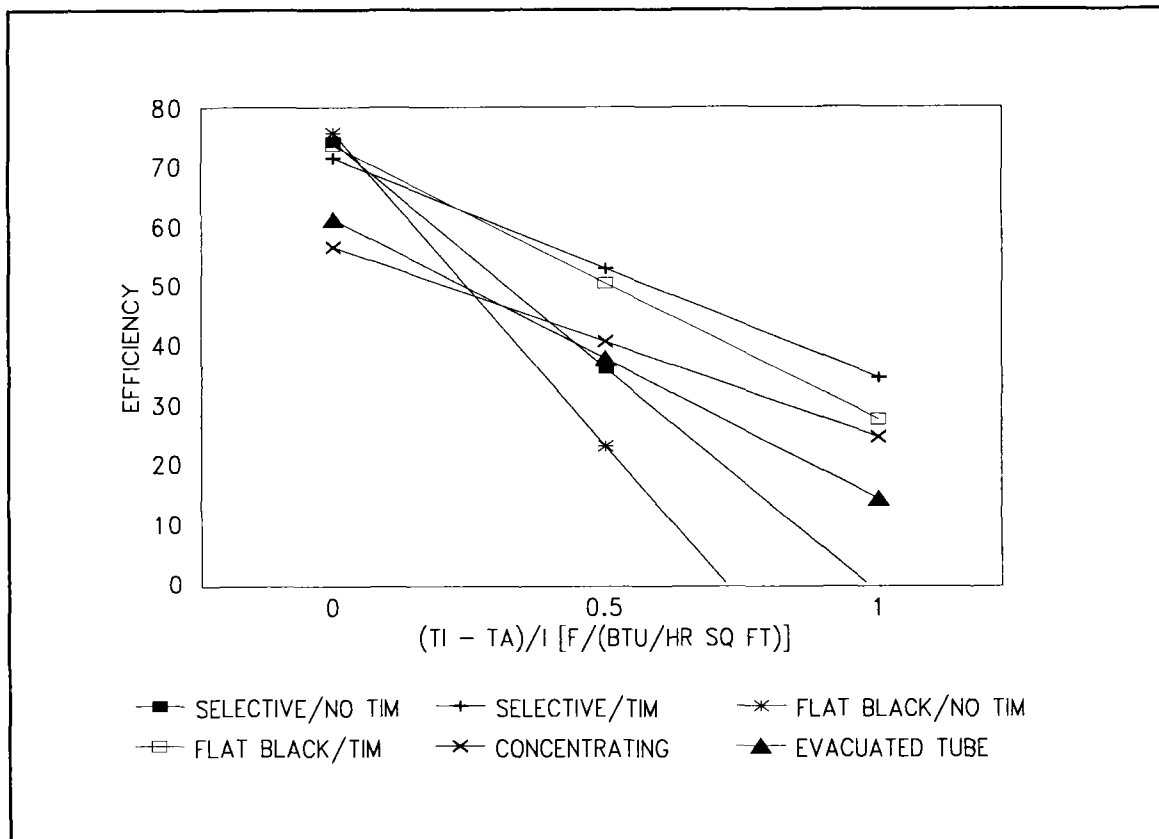


Figure 4.4 Comparison of different types of collectors

The concentrating collectors used in this comparison are no longer commercially available. However, Industrial Solar Technology is in the process of having their concentrating collector tested, and preliminary performance test results (included in Appendix C) are much better those used for comparison in the Figure 4.4. For example, with a black nickel selective absorber and Solgel receiver

glass, their tough collector test results were fitted with the following efficiency equation;

$$\eta = K [76.25 - 0.006836 (\Delta T)] - 14.68 (\Delta T/I) - 0.1672 (\Delta T^2/I) \quad (4.2)$$

where η is collector efficiency in percent, K is incident angle modifier, I is incident direct normal solar irradiance in W/m^2 , and ΔT is receiver fluid temperature above ambient air temperature in $^{\circ}\text{C}$.

The manufacturer's quoted cost for a system using Industrial Solar Technology concentrating collectors was $\$22/\text{ft}^2$ and Nippon evacuated tube collectors, $\$29/\text{ft}^2$. Flat plate collector system costs vary widely, but a ballpark range would be between $\$25\text{-}35/\text{ft}^2$. These costs do not include installation.

4.2 CONCLUSIONS

Installing sheets of transparent insulation materials between the cover plate and the absorber does improve the thermal performance of flat plate collectors. However, honeycomb TIMs currently commercially available are made of polycarbonate or acrylic with unacceptably low melting temperatures. This makes TIM collectors impractical, since they fail to meet one important performance criterion for solar collectors; they must be able to withstand high stagnation temperatures which can exceed 300°C . Future research in this area would be useful when TIMs with acceptable transmittance and temperature resistance become commercially available.

APPENDIX A
ANNOTATED BIBLIOGRAPHY

ANNOTATED BIBLIOGRAPHY

Adamu A., Yang H.X., Marshall R.H., Brinkworth B.J., "Comparison of Honeycomb Transparent Insulation Material Optical Properties using a 1.2 m Integrating Spheroid and an Illuminated Hot Box", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 46-49.

Comparisons of experimental results of the optical properties of TIMs are performed using irradiation from a solar simulator. The angular optical transmittance is measured with an integrating spheroid and an illuminated hot box. The reflectance is measured with the integrating spheroid using an internal and an external light source.

The reflectance of the TIM is measured using an external collimated light beam and an internal light source within the spheroid. The arrangement for the optical transmittance measurement consists of the solar simulator array, the sample holder and the integrating spheroid. The results for the three methods agree quite closely. The angular hemispherical transmittances measured with the integrating spheroid/sphere are a little higher than those of the angular dependent transmittance from the Illuminated Hot Box. The reflectance results with the light source inside the integrating spheroid have a higher reflectance value than those from the external source.

Al-Daini A.J., Abdel-Gayed R.G., Chaudhry S.U., "Modelling and Computer Simulation of a Solar Operated Air Conditioning System Utilizing Flat Plate Solar Collectors", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 26-29.

A solar operated air conditioning system is being installed at the Solar Energy Unit, Coventry University. It consists of three solar collectors with a total surface area of 4.32 m², covered with transparent insulation material (TIM), a heat storage unit, a 3 kW auxiliary heater and two pumps. Thermostatic controllers and motorized valves are used to control the circulation of the solar fluid in the desired direction. A vapor absorption air conditioning system is planned to be installed in the near future using solar heat, boosted by an electric heater, to drive out the refrigerant from the carrier fluid. This paper describes the proposed system in detail.

Alexander-Katz R., "Morphological Effects on the Transparency of Optically Inhomogeneous Composites", SPIE Optical Materials Technology for Energy Efficiency and Solar Energy Conversion IX, Vol. 1272, 1990, pp. 309-316.

There are optically inhomogeneous core-shell particle structures with extinction coefficients of one or more orders of magnitude smaller than a structureless inclusion with the same radius and particle composition. These spherical inclusions are made of two components with close to the perfect index matching composition. The effect on transparency of the radius, particle composition, shell thickness, and wavelength for these structures is discussed. These optically inhomogeneous inclusions are more wavelength selective than the homogeneous ones with the same global composition. This addresses non-absorbing materials in the visible region composed of polyvinylchloride (PVC) ($n=1.5415$) as a medium and the core-shell particles made of polystyrene (PS) ($n=1.591$) and polymethylmethacrylate (PMMA) ($n=1.492$) as the inclusions.

The authors show that under situations where the inclusions of a composite are close to a perfect index

matching composition, there are optically non-homogeneous structures which are more transparent than an homogeneous particle with the same particle composition regardless the size of the particle. They analyze the influence of the various parameters on a core-shell type particle with constant particle composition, and arrived at the following conclusions: (1) Even in poly-disperse samples (sizewise), non-homogeneous structures could yield a more transparent specimen. For a change in size, the morphology that gives a minimum extinction coefficient will also change; however, it will still be inhomogeneous. (2) The extinction coefficient is not very sensitive to the thickness of the shell under constant composition. (3) A composite with the most transparent structured inclusions, will be more wavelength selective than one with optically homogeneous inclusions of the same radius and global composition. One could extend the previous analysis also to the effect of temperature on transparency or any other external field that brings about an imbalance in the indices of refraction. (4) Finally, the core-shell structure that yields the most transparent composite is very sensitive to particle composition. In any application of the previous ideas to produce transparent composites, this should be one of the most important variables to control.

Ayling G., "Transparent Insulation and Sustainable Energy Policy in the UK", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 74-77.

This paper evaluates government policy for the UK energy sector and resulting implications for the establishment of sustainable energy policies. The main focus of interest is on the removal of state control from energy markets. The effect of an increasingly market-led energy policy is considered with reference to official publications, recent developments in the energy sector, and the "Coal Crisis". The paper then deals more specifically with transparent insulation as a case study. Its potential role in sustainable energy strategy is outlined and the effect of current UK energy policy on its implementation is discussed.

Current British government policy of allowing market forces to dictate energy policy has resulted in very little consideration of energy strategy. Government policy currently relies on insufficient financial incentives to support alternative energy sources, and there is much speculation that there will be no further renewable orders. Large scale imports will have a high social cost on domestic industry and energy supply will be vulnerable to international politics. Without some form of intervention in the market, renewable energy sources will be unable to compete with cheap fossil fuels and nuclear power.

Bakker L., van Dijk D., Bottger W., "Measuring and Processing Optical Transmission Distribution Functions of Transparent Insulation Materials", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 54-57.

To investigate complex scattering behavior, one has to realize that the transmitted distribution depends on the polar angle of incidence and the azimuthal angle of incidence. In addition the distribution itself can be measured depending on the polar and azimuthal angle of refraction. Motivated by the physical aspects of the scattering behavior of most TI materials a (semi-automated) prototype device was constructed by which the scattered irradiance distribution can be measured. More accurate measurements were necessary to be able to identify irregular patterns, small peaks, etc.

To measure the distribution function, the use of a CCD camera or still video camera connected to a computer seems an attractive alternative because when using a light source with a relatively large

parallel beam, the intensity as a function of the polar and azimuthal angle of refraction can be measured with a relatively large solution without moving the camera. Obviously, there are restrictions with respect to accuracy (color, stability, range, maximum angle, etc.). Also, measuring samples with relatively large inhomogeneous patterns could cause problems.

First measurements with a consumer type CCD camera were carried out. The results showed that in principle this method is possible and that unfortunately this type of camera is not suitable for quality measurements, mainly due to the automatic corrections and limited resolution. A possible suitable camera could be the KODAK DS2000 Digital Camera. This is a NIKKON N801S photcamera-body equipped with a KODAK CCD-chip mounted in the back with 1524 x 1012 pixels. A wide variety of lenses are available and full manual control is possible making measuring optical transmission distribution function with a CCD camera a serious option.

Bakker L.G., van Dijk H.A.L., "Moisture and Pollution Problems in Transparent Insulation Systems", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 98-101.

Following studies on the application of TIM on opaque walls and a feasibility study of the application of TIM in windows for daylighting purposes, a study has been started on the problem of potential moisture and pollution problems in TI systems.

To avoid pressure and stress problems in the wide air gaps necessary to apply TI material, a number of solutions are possible. Using one of the most applied solutions to this problems, venting the gap with outside air, moisture and pollution problems can occur and are in fact observed in various projects.

For each of the alternative methods studied, instead of venting the air gap with two or more openings, only one 'breath' opening is used so the maximum amount of potential condensation can be restricted to approximately the relatively small amount of moisture contained by the gap air. Also, some ways to filter the in and outgoing air are compared.

The results of the simulations show that the amount of occurring condensation due to ventilation or due to the decrease of the gap air temperature is very limited in similar systems and applications. However, the water absorbed by the TI-material could cause a considerable amount of condensation. Other potential causes for condensation in a TI-system are leakage of water from the outside, leakage of air or water from inside the room and absorption of water by the window system. Discoloration of TIMs due to atmospheric dust and the use of fine filters to avoid this are also discussed in this paper.

Balk W., "Integrated Solar Element (ISE) - Collector, Storage, Radiator for Heating and Hot Water Systems", Proceedings of the 2nd International Workshop on Transparent Insulation in Solar Energy Conversion for Buildings & Other Applications, Freiburg, F.R.G., March 24-25, 1988, pp. 27-28.

Radiators belonging to an usual hot water heating system are black colored and situated in mirror boxes with transparent insulation, which are part of a facade facing the sun. The radiators are warmed alternatively by the heating system or by the sun. In wintertime the radiators give their heat directly to the rooms they belong to. In summertime the heat is given to a domestic water boiler. At the facade there are reflectors being part of the mirror boxes, which cast a shadow on the windows under them in summertime at noon, so that there is a little cooling effect, too. The system is diagrammed in detail in this paper.

Beck A., Hoffmann T., Korner W., Fricke J., "Thermochromic Gels for Control of Insolation", Solar Energy, Vol. 40, No. 5, 1993, pp. 407-414.

Thermochromic gels consist of a mixture of water, a gelling agent, and a polyether reaction compound. They show a drastic increase of scattering when a characteristic switching temperature is surpassed. The hemispherical transmission consequently decreases from about 90 to 50% for a 1 mm thick layer sandwiched between two glass panes. The increase in scattering is caused by a dramatic increase in number density and particle size of created scattering centers. The latter consists of agglomerated polyether chains with reduced water content, i.e., increased index of refraction. The authors measurements cover the directional-directional transmission, as well as the directional-hemispherical transmission and reflection, using a double-beam spectrophotometer with an integrating sphere. For structural information a light-scattering apparatus was employed. Multiflux calculations allow predictions of the switching behavior for nonvertical incidence and for arbitrarily thick layers. The thermochromic material is a low-cost, non-toxic product. The achieved switching action is reliable; however, it may need improvement to allow application in solar architecture.

Beckman W.A., "Solution of Heat Transfer Problems on a Digital Computer", Solar Energy, Vol. 13, 1971, pp. 293-300.

This paper presents a nodal formulation of heat-transfer systems which can be applied to a large class of practical problems. The form of the resulting equations is either a system of nonlinear ordinary differential equations or a system of nonlinear algebraic equations. Traditionally, the numerical solution of these two classes of heat-transfer problems have stressed methods that were originally developed for hand calculations. With the general availability of high-speed digital computers, more powerful numerical methods can be used. A solution technique which utilizes a digital computer is presented for both steady and transient problems.

The specular-diffuse model is used so that each surface is assumed to have a portion of the incident radiation reflected diffusely and a portion reflected specularly. The wavelength dependence of the surface properties can be accommodated by using wavelength bands. The two-band approach which is particularly useful in solar energy systems and is used here. This assumption, also called the semi-gray assumption, accounts for absorption and reflection but no emission in the short wavelength (solar) portion of the electromagnetic spectrum and absorption, reflection and emission in the long wavelength (infrared) region. With this assumption, the solar energy transfer can be calculated independent of the infrared radiation interchange. It is not the intention of this paper to compare the various methods for solving systems of equations, but only to point out that the traditional methods used in heat-transfer work are not necessarily the best when high-speed digital computers are available.

Bollin E., Yuan Q.S., Guang L.Z., "Transparently Insulated Walls for Buildings of Low Latitude, A Pilot Project in Shanghai, China", Proceedings of the World Solar Congress of ISES, Denver, Colorado, 1991, pp. 2965-2970.

In Shanghai two test houses were built in 1990 to demonstrate transparently insulated walls as an efficient passive solar component for space heating under the climatic conditions of a site at low altitude. The facade construction was appropriate to the Chinese conditions and built with materials available at the site. An extensive monitoring will help to analyze performance and solar gains of the TI wall. The transparently insulated facade had as energy transmittance of about 60% in total. The TI wall had a U-value of 0.75 W/m²K in total. For overheating protection white venetian blinds were

used.

Braun P.O., Goetzberger A., Schmid J., Stahl W., "Transparent Insulation of Building Facades - Steps from Research to Commercial Applications", Solar Energy, Vol. 49, No. 5, 1992, pp. 413-427.

Transparent insulation materials (TIM) represent a class of new materials for application in solar thermal conversion systems. An U-value below $1 \text{ W/m}^2\text{K}$ and an energy transmittance greater than 70% characterize TI materials. With these physical properties TI materials outperform all conventional glazing systems and further increase the efficiency of thermal conversion of solar radiation. In winter, low elevation solar irradiance on vertical surfaces can be used effectively. Experiments, simulation calculations, and results from demonstration projects have shown the space heating potential of transparently insulated walls. A properly built passive TI element on a sun-facing massive building facade can save heating energy by up to 200 kWh/m^2 each annual heating period. This paper describes the transparent insulation of building facades from the basic idea to the satisfying results of demonstration projects. Fundamental considerations for TIM and wall parameters, a list of properties, exact description of TI wall constructions, the reduction of space heating demand and future developments form part of this paper. It is a summary of the work done in this specific field over the past 10 years, giving examples of the dynamic developments in solar energy from the basic ideas to commercial systems. A Self-Sufficient Solar House, which is almost totally heated with transparently insulated walls, is an outstanding culmination of TI research and TI application.

This paper gives a summary of the TI wall projects of the Fraunhofer-Institut für Solare Energiesysteme. The basis for the paper's content is the research work of the Institute including 20 projects with TI applications. Together with partners from different companies, over 5000 m^2 of TI wall systems have been constructed. The physical behavior of a TI wall is well understood. The theoretical description was implemented in simulation programs. Results from simulation programs have been validated with measurements. The TRNSYS simulation software is a powerful tool for predicting the complex interactions of TI wall systems with the overall thermal behavior of a building. Because of the large expenditure for experiments with real buildings, simulation calculations are valuable in saving time and money.

Vertical sun-facing TI walls are characterized by: solar conversion efficiency of 30%, solar energy gains of $100\text{-}200 \text{ kWh/m}^2$ per year, a price of approximately 1040 DM/m^2 , and a large application potential. Further material research will enhance the solar conversion efficiency. New materials are under development; for example, a capillary structure made from glass tubes appears very promising. The aerogel material still has a large potential for development. A very important step not only in the application of TI, but in the overall field of solar energy applications, is expected from the so-called "smart window" developments. Electrochromic or liquid crystal switchable windows may replace the unreliable and high-maintenance mechanical shading devices. A very promising development is that of inexpensive thermotropic gels. The commercial production of TI elements is in its infancy. Further projects are necessary to determine the cost of TI elements and to allow these to penetrate the market. TI walls are a new component in solar architecture. Contrary to conventional opaque insulation, a TI wall not only reduces transmission losses of a building's wall to zero, but heats the room behind the TI wall as well. Of great architectural interest is the change of the building's appearance due to open or closed shading devices. In daytime the building looks dark for solar absorption in winter time; it looks essentially white for solar reflection in summer. Just as people choose to wear a shirt or a pullover, depending on the outdoor temperature, the building changes color like a chameleon. Architectural constraints to reduce heating demand by minimizing the ratio of the building surface to building volume are removed. New aspects are relevant for the shape of low-energy buildings with TI walls. Increasing the south facing TI walls area decreases the heating demands.

The passive design of a TI wall does not allow the distribution of the energy and the use of the elements, for example, for warm water production in summer. A variety of active TI "wall-collector" systems have been proposed. The Institute has begun experimentation in this direction. The large number of different active TI "wall-collector" systems makes it difficult to decide on the best approach. The development of new TI wall systems and the promotion of further passive TI wall applications will be the Institute's main activities in the future in this field.

Braun P., "Transparent Insulation of Building Facades - Steps from Research to Commercial Applications", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 154-159.

In 1981, the Fraunhofer Institute for Energy Systems started research in the field of transparent insulation applications in the building sector. From 1983 until the present, a large number of demonstration projects have been established, mostly supported by the German Ministry of Research and Technology. The program led to fruitful cooperation between different research institutes, and also initiated and provided financial support for cooperation with companies interested in producing and marketing TI systems. This paper gives a short summary of the work done in this specific field in the past 12 years. It is an example of the dynamic developments in solar energy from the basics to commercial systems.

Braun P.O., Schmid J., Bollin E., Stahl W., Vahldiek J., Voss K., Wagner A., "Transparent Insulation Material Demonstration Projects and Future Prospects", Proceedings of the World Solar Congress of ISES, Denver, Colorado, 1991, pp. 2959-2964.

In this paper realized demonstration projects with transparent insulation materials and applications in the field of solar hot water systems are presented. Further applications of TIMs, especially for daylighting purposes are developed.

The new concept of external insulation of massive house walls with TIMs combines the advantages of conventional opaque insulations and of solar collector systems. Of the large variety of TIMs the polycarbonate honeycomb structure (PCHC), and the polycarbonate (PC) or polymethylmethacrylate (PMMA) capillary structure are used most frequently. Materials now available reach heat loss coefficients of $0.7 \text{ W/m}^2\text{K}$ with typical diffuse transmission values of more than 0.7. Summarizing the authors experience from measurements and simulation calculations, the contribution of TI to the heating energy demand amounts 100 to 200 kWh/m^2 . Incorporating the advantages of TIM, it is now planned to build an energetically self-sufficient house in Freiburg, which will obtain its entire energy from the solar systems on its facade.

Standard flat plate collectors can be tremendously improved by using highly effective transparent insulation materials as the front cover. With a 10 cm honeycomb structure made of polycarbonate, the front losses can be reduced to values of $0.9 \text{ W/m}^2\text{K}$ at $T=100 \text{ C}$. The application of the TIM as a front cover of integrated storage collectors will allow the usage of these collectors in winter weather conditions in Central Europe and also may help to cut down the cost of the solar domestic hot water systems.

The experimental, theoretical and practical work during the last few years has led to an essential understanding of transparent insulation materials. Materials now available reach heat loss coefficients of $0.8 \text{ W/m}^2\text{K}$ with diffuse transmission values of more than 0.7. The theoretical models have been validated by experimental set-ups. Such models and further experiments will be used for further improvement of the materials.

Brouwer G., "Performance Criteria for Transparent Insulation Materials in Buildings", Proceedings of the World Solar Congress of ISES, Denver, Colorado, 1991, pp. 2977-2982.

In Task X of the IEA Solar Heating and Cooling Programme, titled Solar Materials Research and Development, the focal point of concern is to investigate and to improve material efficiency with respect to energy performance and durability of solar buildings and solar systems. The scope of the cooperative Subtask A research described here is the establishment of performance criteria for new materials; a part of this research covers transparent insulation materials on buildings, especially for dwellings. The research provides firstly a means of material selection for various solar applications and locations and secondly, a methodology to estimate the energy efficiency. Tools for material selection were given using climate data, operating and boundary conditions, simulation programs and related material properties. A database of material properties directed to the application field solar energy was performed as a support to designers and manufacturers for selecting materials. A methodology is presented, developed in cooperation with the Fraunhofer Institute FRG and the TNO Institute for Applied Physics NL on the energy benefits of transparent insulation.

Buchberg H., Edwards D.K., "Design Considerations for Solar Collectors with Cylindrical Glass Honeycombs", Solar Energy, Vol. 18, 1976, pp. 193-203.

A properly designed cell structure placed between the solar absorber and outer cover glass can substantially reduce natural convection and infrared reradiation heat losses. Glass has merit for such a cellular structure or honeycomb because it is an inexpensive, abundant and stable material with low thermal conductivity and outstanding optical characteristics. To optimize the design of the honeycomb structure, i.e. to minimize the cost of the solar energy collected (Z), requires the determination of the honeycomb solar transmission (a function of incidence angles of the sun), infrared effective emittance, cell Nusselt number, and cell wall conductance as well as an estimate appropriate costs. For an array of circular tubes, the design parameters are wall thickness (b), cell diameter (d), and cell length (L). It is difficult to make b less than about 0.2 mm. Typically, d must be no larger than 1.6 cm. Increasing L/d decreases reradiation and conduction losses, but also decreases solar energy transmission. For $d=9.53$ mm and $b=0.198$ mm, optimum L/d values ranged from 3 to 12 for collector temperatures (above ambient air temperature) between 22 and 100°C. Since the Z vs L/d curves have fairly broad minimums, L/d values less than 9 can be used with less than a 3% penalty in cost at the higher temperatures.

A comparison of collector efficiency characteristics indicated that cylindrical glass honeycomb collectors with nonselective-black absorbers were markedly superior to single-glazed selective-black and double-glazed nonselective-black collectors, especially at higher collector temperatures. Cost effectiveness studies also indicated honeycomb collector superiority at temperature difference between the working fluid and ambient air greater than about 35°C.

The following conclusions were made: (1) cylindrical glass honeycombs, placed over hot solar absorbers, transmit solar radiation while effectively blocking infrared reradiation and suppressing natural convection, (2) for a specified cell diameter, no larger than about 1.6 cm, increasing the aspect ratio decreases the infrared effective emittance but also decreases the solar transmittance, requiring the determination of optimum geometries for different operating temperature regimes, (3) the cost of the solar energy collected is a satisfactory functional criterion for determining optimum cell geometries, (4) spectral and directional cell transmittance and cell Nusselt number are the basic data required for identifying optimum cell geometries and for predicting the performance of honeycomb solar collectors, (5) the optical quality of the glass has a significant influence on the performance of glass honeycombs, particularly for solar angles of incidence greater than about 30°, and (6) properly designed cylindrical

glass honeycomb collectors exhibit superior performance particularly at temperature differences between fluid temperature at collector inlet and ambient air temperature greater than about 35° C.

Cane R.D.L., Hollands K.G.T., Raithby G.D., Unny T.E., "Free Convection Heat Transfer Across Inclined Honeycomb Panels", Transactions of the ASME Journal of Heat Transfer, February 1977, pp. 86-91.

Experimentally obtained Nusselt number-Rayleigh number plots are presented for free convective heat transfer across honeycomb panels, heated from below, and inclined with respect to the horizontal at angles of 0, 30, 45, 60, and 90 degrees. Aspect ratios of honeycomb cells of 2,3,4 and 5 are included; the fluid contained in the cells is air. Substantial suppression of free convection is observed when compared with an air layer of the same depth but not containing a honeycomb. Heat transfer associated with the base flow is found to be of only moderate importance at angles near horizontal, but of considerable consequence for angles near the vertical. The honeycomb walls used were partly transparent to thermal radiation, and a strong radiative coupling is indicated. A correlation equation for the Nusselt number, valid over part of the experimental range, is presented.

Very little information exists for predicting free convective heat transfer across inclined panels. An important proposed use of honeycombs is for the purpose of suppressing the free convective heat transfer which would otherwise occur in an inclined layer of fluid, heated from below. The present paper presents an extensive set of measurements on this problem, for a square-celled, diathermous honeycomb. Experimental plots of Nusselt versus Rayleigh number are presented for angles of inclination, measured from horizontal ranging from 0 to 90°, and for aspect ratios from 2 to 5. The fluid used is air and in all cases (except at the angle of 90°) heating is from the lower face of the honeycomb.

The major engineering application of this study is to the design of a class of flat plate solar collectors in which a honeycomb is placed between the absorber plate and the glass cover in order to suppress free convective and radiative heat losses. The honeycombs were constructed from 0.038 mm thick polyethylene film, by heat-sealing preslit strips at periodic join-lines. Polyethylene was chosen for the honeycomb material because in thin films it has a very high transmittance to long-wave (3-30 micrometers) thermal radiation.

It is interesting to note that the results obtained show that at some Rayleigh number, and at low aspect ratios, the effect of the honeycomb can be to increase the heat transfer over that which would occur with no honeycombs present. This result is felt to be due to the honeycomb breaking up the thick, insulative boundary layers which would otherwise form along the heated and cooled faces. The hexagonal-celled honeycomb had a higher wall emissivity when compared to a square-celled honeycomb having the same hydraulic diameter.

Free convection heat transfer across an air layer can be effectively suppressed by a thin-walled square or hexagonal-celled honeycomb, even in the inclined position. It was concluded that even through a honeycomb material may be largely transparent to thermal radiation, a coupling of the radiative and free convective modes may still be evident. Stability theories accounting for radiant coupling, but based upon opaque sidewalls can be used with reasonable accuracy to predict critical Rayleigh numbers for partly transparent sidewalls; however, for better results, the theories should be based upon specularly reflecting sidewalls, rather than diffuse.

Caps R., Fricke J., "Infrared Radiative Heat Transfer in Highly Transparent Silica Aerogel", Solar Energy, Vol. 36, No. 4, 1986, pp. 361-364.

The radiative heat transfer in silica aerogel is determined by measuring the spectral infrared extinction (absorption) between 2.5 and 14 μm . From this the authors calculated a temperature-dependent Rosseland mean for extinction. Using a suitable diffusion model for the infrared radiation the temperature-dependent radiative conductivity was determined. For $T = 280\text{ K}$, a mean temperature within the insulation, a value as low as $.002\text{ W/mK}$ results. Between $T = 250\text{ K}$ and 450 K , the value increases proportionally with $T^{5.6}$.

Chattha J., Jesch L., "Heat-loss through Transparent Honeycomb Insulation", Proceedings of the 2nd International Workshop on Transparent Insulation in Solar Energy Conversion for Buildings & Other Applications, Freiburg, F.R.G., March 24-25, 1988, pp. 43-45.

The use of the transparent honeycomb structure for insulation is viable because it suppresses convective and radiative losses while increasing passive solar gains. The development of reliable methods for calculating the overall heat transfer through the honeycomb materials helps predicting and optimizing the thermal performance of honeycomb insulated buildings. Mathematical models have been created which yield design parameters for optimal geometry, material selection, and application of honeycomb transparent insulation. The effects of these parameters on the U-value are discussed.

It is concluded that the best transparent insulation is a high emissivity, thin walled honeycomb material with a high aspect ratio and an air gap of about 20 mm thickness in front of a selectively absorbent mass wall. The overall U-value has been calculated as a function of the emissivity of the sidewalls and conductivity of honeycomb is presented on a graph.

Chaudhry S.U., "Simulation of a Solar Space Heating System Utilizing Transparently Insulated Flat Plate Solar Collectors", Proceedings of the 4th International Workshop on Transparent Insulation Technology, Birmingham, UK, May 28-30, 1991, pp. 151-154.

A simplified model for the approximation of angle dependent solar transmittance of honeycomb transparent insulation is discussed and its use in a computer simulation is demonstrated. The solar transmittance for various aspect ratios of honeycomb insulation are obtained from the model at different incidence angles. Simulation of an active solar space heating system utilizing flat plate collectors with transparent insulation (TI) incorporated into the cover were performed.

The system was operating most of the time in the low temperature range (below 60°C). Therefore, the collector with 100 mm thick honeycomb did not increase the efficiency or improve the solar fraction over that of the single glazed system. The authors attributed this to the fact that in transparent insulation collectors the improvement in the front cover losses can only be achieved by sacrificing some of the solar transmittance. However the collectors with 75 and 50 mm of transparent insulation did perform better than the single glazed collectors.

Simulation results using TI solar collector modules and other related subroutines developed for TRNSYS show that there is not much room for improvement of flat plate collectors when they are selectively coated and operating at moderate temperatures. The stagnation temperature of the absorber can go as high as 250°C and therefore an emergency cooling mechanism has to be used to prevent TI melting. Further development and cost reduction can make the application of transparent insulation in solar collectors a more promising option.

Collins R.E., Fischer-Cripps A.C., Tang J.Z., "Transparent Evacuated Insulation", Solar Energy, Vol. 49, No. 5, 1992, pp. 333-350.

The article gives the historical overview of development of research and design of the transparent evacuated insulation (TEI). It describes the operating principles and two basic concepts of (TEI): with a flexible edge seal and with a fused edge seal. The range of issues related to the science and technology of (TEI), such as target performance requirements, heat transport processes, evacuation, stresses, stored mechanical energy, production technology, measurement of thermal conductance are discussed. The results of the research of the TEI accomplished at the University of Sydney are presented, though it is mentioned that, in several cases, they are of a preliminary nature.

Dengler J., Apian-Bennewitz P., Platzner W., Wittwer V., "Advanced Transparent Insulation Materials", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 126-129.

The newest TIMs, plastic capillaries with improved temperature stability up to 160° C and glass capillaries with superior optical performance, make potential TI applications more interesting. Potential applications include high temperature collectors for process heat generation, and daylighting systems. This paper presents thermal and optical properties of these new materials and provides data to assess their suitability for daylighting.

Diehm W., Jaeger L., "First Results on the Development and Production of Glass Capillaries for Transparent Insulation Applications", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 118-121.

The strong interest in TIMs made from glass capillaries is based on various advantages in the different fields of application. For the development of TIM-improved, high-temperature flat plate collectors, the most important advantage is temperature stability. Furthermore, the very good optical properties of glass capillaries and the avoidance of aging problems of the capillary structure should be mentioned. For the application on facades and as daylighting elements of buildings, the non-inflammability of glass capillary structures is a most important property. They therefore fulfill the building regulations concerning fire-protection. Due to the very regular appearance of glass capillaries, a very good basis exists for impressive architectural approaches to transparently insulated facades.

Measurements on the optical and thermal properties of new samples have been carried out at Fraunhofer Institute for Solar Energy Systems in Freiburg. The results of these measurements as well as a comparison of properties of glass and plastic are given in this paper.

Digel R., Fisch N., Hahne E., "High-Efficiency Solar Flat-Plate Collectors with Capillary Structures", Proceedings of the 3rd International Workshop on Transparent Insulation Technology for Solar Energy Conversion, Freiburg, Germany, September 18-19, 1989, pp. 37-41.

High efficiency flat plate solar collectors with an inner translucent capillary tube structures were tested. Air passes through the capillary tubes which, in this way, act as heat exchangers. Modules with glass capillary tubes were examined for their thermal behavior. The investigation includes the determination of the efficiency curve according to the ASHRAE Standards 93-77 (1978) and the determination of the thermal efficiency, the time constant, and the pressure drop as a function of the mass flow. Provided that the inlet temperature is not much higher than the ambient temperature, the collector has a very good thermal efficiency.

Einarsrud M., Haereid S., Wittwer V., "Some Thermal and Optical Properties of New Transparent Silica Xerogel Material with Low Density", Solar Energy Materials and Solar Cells, Vol. 31, No. 3, 1993, pp. 341-347.

In this work the authors studied a new type of monolithic silica aerogel (xerogel) made without supercritical drying. The xerogels are produced by performing washing and ageing treatments on the alcogel before drying at ambient pressure. Densities as low as 0.26 g/cm^3 have so far been obtained and the thermal conductivity of air-filled xerogels has been measured down to 18 mW/mK . Properties of this new type of silica xerogels have been compared to the properties of silica aerogel made by supercritical drying. Density, pore size, thermal conductivity, and optical transmittance are reported, and some application advantages are discussed.

Fischbach H.P., Gerber A., Rommel M., "Performance and Systems Technology of Newly Developed Storage Collectors", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 22-25.

A very promising approach to reduce the specific system costs for solar domestic hot water (DHW) systems is to integrate the hot water storage tank and the absorber into the unit. Simple and inexpensive DHW systems can be constructed using these storage collectors. In order to benefit from the cost reduction associated with industrial mass production, the Fraunhofer Institute for Solar Energy Systems has developed a storage collector in close co-operation with an industrial partner. Its construction, performance, and systems technology are presented in this paper.

The u-value, the heat loss power of the storage collector per m^2 aperture area, represents an important criterion for the quality of a storage collector. However, the large thermal mass of the collector makes its experimental determination difficult. A special procedure, which takes into account the high thermal inertia of the system allows the data obtained experimentally to be analyzed. Depending on the quality of the transparent insulation and the absorber coating, u-values of less than $2 \text{ W/m}^2\text{K}$ up to maximally $3 \text{ W/m}^2\text{K}$ can be achieved. Despite the integration of the storage tank into the collector, the heat losses are thus comparable to those of good flat-plate collector systems.

Goetzberger A., Rommel M., "New Applications for Transparent Insulation Materials", Proceedings of the 1st International Workshop on Transparent Insulation Materials for Passive Solar Energy Utilization, Freiburg, F.R.G., Nov. 27-28, 1986, pp. 37-38.

The overview of the application of the existing transparent insulation materials is given. The topics presented includes house heating by means of external transparent insulation on massive house walls, integrated storage collectors (ISC) for domestic hot water, flat plate collectors for process heat of $100 - 150^\circ \text{C}$, seasonal storage of thermal energy by radiatively heated storage walls.

Goetzberger A., "Transparent Insulation - a New Solar Energy Component", Proceedings of the 3rd International Workshop on Transparent Insulation Technology for Solar Energy Conversion, Freiburg, FRG, September 18-19, 1989, pp. 4-12.

The experimental, theoretical and practical work during the last few years has led to an essential understanding of transparent insulation materials. Materials now available reach heat loss coefficients of $0.8 \text{ W/(m}^2 \text{ K)}$ with diffuse transmission values of 0.7. The theoretical models and the experimental set-ups have been validated and will be used for further improvements of materials. The initial applications have demonstrated that well-known thermal solar systems can be significantly improved

by the use of TIMs (e.g. process heat collectors), and completely new concepts are made possible (e.g. house heating with TIM-walls). In order to develop more economic systems, cost reductions are now required for the materials as well as for the whole systems.

A concept for a completely self-sufficient solar house has been created at the Fraunhofer Institute combining TIM-systems with photovoltaic and hydrogen/oxygen units. Transparently insulated walls will provide energy for space heating, and the integrated storage collector with TIM-cover will be used for domestic hot water. Photovoltaic cells drive a closed loop hydrogen/oxygen system for high energy demands, and pressurized gas storage are planned for compensating differences in solar supply and energy demand. The realization of this project within the next few years will demonstrate the possibility of meeting all the residential energy needs by the solar radiation incident on the surface of a house without any fossil back-up or connection to the electric grid. This is an outlook into the distant future, because it will take a long time before such a house will be economical, but it points the direction in which solar energy applications can be developed.

Goetzberger A., Dengler J., Rommel M., Gottsche J., Wittwer V., "A New Transparently Insulated, Bifacially Irradiated Solar Flat-Plate Collector", Solar Energy, Vol. 49, No.5, 1992, pp. 403-411.

A new type of transparently insulated flat-plate collector was developed. It reaches higher efficiencies at low irradiation values or high operating temperatures than any other collector type known. Both sides of its absorber are covered with transparent insulation material and both sides are irradiated. Thus, the heat losses of the collector related to the total absorber area are distinctly reduced. An optical efficiency and a temperature dependent U-value were measured with an outdoor test facility. The bifacial-absorber collector is considered to be the best option for the DHW system of the energetically self-sufficient solar house in Freiburg because of its outstanding winter performance.

The design of a solar flat-plate collector with a transparently insulated, bifacially irradiated absorber leads to minimal heat losses related to the radiation capturing absorber area. This concept is only practical due to the application of transparent insulation materials with superior thermal insulation and optical transmission qualities. The constructed prototypes reach better efficiencies than any other known nonconcentrating solar collector, including evacuated tube collectors. Since the available transparent insulation materials were not temperature resistant above 130° C, investigations on a high temperature bifacial-absorber collector are planned for the near future, when a new generation of thermally stable transparent insulation materials will be available. Two bifacial-absorber collectors are under construction for the energetically self-sufficient solar house in Freiburg.

Goetzerberger A., Dengler J., Rommel M., Wittwer V., "Flat Plate Collector with Bifacially Irradiated Absorber", Proceedings of the 4th International Workshop on Transparent Insulation Technology, Birmingham, UK, May 28-30, 1991, pp. 62-65.

A new flat plate collector has been developed which especially during times of low radiation conditions, reaches higher efficiencies than any other collector known so far. The absorber plate is insulated with transparent insulation material (TIM) on the front and on the rear side and both sides are irradiated. A prototype was built. Indoor and outdoor measurements were carried out to determine the optical efficiency and the U-value of the collector. However, because of its very high stagnation temperature, it is not possible to operate at its highest achievable temperature with currently available TIMs.

Hartwig H., Haller A., Schneider P., "Performance Measurements of a Transparently

Insulated Wall Comparing Movable and Fixed Shading", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 38-41.

TI used with massive walls contributing to the space heating demand of a building has proved its potential during several prototype projects. Experiments and thermal simulations demonstrate that overheating protection is indispensable in most applications to prevent intolerable temperatures. Movable shadings raise the currently non-competitive price of a TI-wall even more. Furthermore, moveable parts in a traditionally fixed facade increase the maintenance costs. Therefore the potential of low-cost fixed shadings is being evaluated in a three year research project supported by the Federal Swiss Department of Energy Management.

A prototype facade equipped with 25 m² of transparent insulation was constructed, half shaded by roller blinds and the other half shaded with a specifically developed lamella sheet. Temperature and radiation measurements were started in December 1992. Absorber temperature reached 68° C unshaded (roller blind open) and 44° C on the lamella sheet shaded surfaces. The energy gain with TI is reduced 45% with the lamella sheet compared to the unshaded TI wall. A TI-wall with an open roller blind and 50 W/m²K irradiation has no losses. A TI-wall with the lamella sheet needs 70 W/m²K. However, even in January an average effective U-value of -0.21 W/m²K is reached with the lamella sheet.

Measurements of improved sheets started recently. Improvements are possible with thinner lamella sheet materials and less support structures.

Hellstrom B., Karlsson B., "Evaluation of a Honeycomb Glazing for High Temperature Solar Collectors", Proceedings of the 4th International Workshop on Transparent Insulation Technology, Birmingham, UK, May 28-30, 1991, pp. 82-85.

Solar transmittance and U_L-values of a polycarbonate honeycomb have been measured and used for estimating annual collector performance. Different thicknesses have been investigated in order to find the optimum. The results are compared with those of a Teflon film and indicate that it would be possible to gain 45-50 kWh/m² or 10-15% annually by replacing the Teflon film with a 30 mm Arel honeycomb in a solar collector operating around 70° C in a Swedish climate. This result is confirmed by estimating the increase in annual performance from outdoor collector measurements of daily efficiency. Furthermore, the results indicate that the gain is higher if the thickness of the honeycomb is increased. The gain with 50 mm would be around 80 kWh/m² and the optimum is found between 70 and 100 mm, where the increase would be 90-100 kWh/m² or 20-30% on an annual base.

A lot of approximations have been made using the model which leads to uncertainties in the results. Some errors also come from extrapolation of the measured transmittance values for large angles of incidence. Furthermore, the energy gain from the solar radiation absorbed by the TIMs has not been taken into account. But the simplicity of the model makes it attractive to use as an instrument for estimating the effect on the annual performance for specific changes in the collector design. However, its validity should be further investigated and the model further improved.

Hollands K.G.T., Goetzberger A., "Coating, Shielding and Honeycombing. Approaching the Ideal of Transparent Insulation", Sun World, Vol. 15, No. 2, 1991, pp. 14-21.

In this paper, realized demonstration projects with Transparent Insulation Materials (TIM) and applications in the field of solar hot water systems are presented. Further applications of TIM,

especially for daylighting purposes, were developed.

The authors describe the evolution of the practical devices that approach the ideal transparent insulator - the surface that admits solar energy but blocks heat loss. Optical coatings, semiconductors, vacuum, honey-combs, inert gases, aerogel and combine approachers. A primer on thermal radiation and the physics of transparent insulators is cited. The main manufacturers are also mentioned: of capillary transparent insulation material - Okalux Kapillarglas GmbH, Federal Republic of Germany and Solar Energy Systems (Fraunhofer-ISE) of Freiburg, Federal Republic of Germany; manufacturer of the square-celled polycarbonate honeycombs - Arel Energy in Yavne, Israel. Both the Arel and the Okalux honeycombs, in appropriate thickness of about 130 mm, achieve the insulative value of 50 mm of fiberglass and transmit about 60 % of the incoming solar energy.

A domestic hot water system using the tubular type of vacuum transparent insulation, is now being test-marketed by Nippon Electric Glass of Japan. A DHW system using honeycomb transparent insulation, recently developed at Fraunhofer-ISE, has been licensed to two German manufacturers.

Many techniques are available for making advanced transparent insulation, and no single approach seems the best one. Aside from evacuated tube collectors, which are in limited production, only two advanced transparent insulations have entered the market-place in a significant way: multiple parallel partitions with low-e coatings and the plastic honeycomb. Many future applications are possible for transparent insulation, including storing heat from summer to winter. A transparently-insulated and blackened container can store hot water with little heat loss for long periods of time, from summer to winter if the transparent insulation properties are adequate. Long-term heat storage using opaquely-insulated tanks is considered unfeasible unless enormous buried tanks are used like the ones Sweden has for solar district heating systems that serve whole towns.

The properties of transparent insulation have virtually no thermodynamic limitations if the required temperature of the solar heat is sufficiently low (say less than 300 C). In other words, in principle nothing can prevent an insulation from transmitting all the solar energy striking it, while transferring essentially no other heat. If transparent insulation materials follow the same course as other commercially interesting devices, such as heat engines or transistors, they will steadily improve in quality, longevity and price. Their potential widescale use will contribute significantly to easing the severe shock faced by a world of dwindling energy reserves and a deteriorating environment.

Hollands K.G.T., Iynkaran K., "Analytic Model for the Thermal Conduction of Compound Honeycomb Transparent Insulation, with Experimental Validation", Solar Energy, Vol. 51, No. 3, 1993, pp. 223-227.

This article extends a first-principal analytical model for the heat transfer across a convection-suppressing honeycomb to the case where an air gap is left between one of the plates bounding the honeycomb and the honeycomb itself. The leaving of such an air gap (for example between the absorber plate and the honeycomb in a honeycomb solar collector) has been shown to dramatically increase the honeycomb's insulative effect, by helping to decouple the radiative and conductive heat transfer modes. The model is based on analyzing an isolated honeycomb cell, by invoking the exponential approximation to the relevant "ring-to-ring" specular view factor as well as linearizing of the 4th power temperature dependence of radiant heat transfer. This article gives the solution for the heat transfer in terms of the elements of an 8 x 8 matrix, which must be inverted to obtain the heat transfer. Comparison between the predictions of the model and 132 experimental measurements of heat transfer show agreement to within a maximum error of 15% and a mean bias error of 6%.

Hollands K.G.T., Goetzberger A., "Transparent Insulation", Hardcopy of original manuscript for the Sun World article.

The comprehensive illustrated description of the evolution and development of the transparent insulation is presented, highlighting the basic physical processes, techniques, operational principles and the plurality of the design solutions and applications. It is mentioned that there is virtually no thermodynamic limitation on the properties of transparent insulation, provided the required temperature of the solar heat is sufficiently low. So one can expect a steady improvement in the TIM properties, as well as their longevity and price.

The illustrations of transparently insulated buildings in Europe are cited: a student residence at the University of Glasgow in Scotland, a row house in Dusseldorf-Hellerhof in West Germany (both projects were carried out by Kaizer Bautechnik of Dusseldorf), and an apartment building in Freiburg West Germany.

Hollands K.G.T., "Designing Honeycombs for Minimum Material and Maximum Transmission", Proceedings of the 2nd International Workshop on Transparent Insulation in Solar Energy Conversion for Buildings & Other Applications, Freiburg, F.R.G., March 24-25, 1988, pp. 40-42.

Hollands briefly discusses a key problem facing the designer of honeycombs, or transparent insulation of the forward-reflecting type (TIFT) which is optimum cell size. Convection suppression requires a cell size of typically about 10 mm for the hydraulic diameter. To effectively suppress radiation losses, on the other hand, requires a cell size of about 3 mm. From the point of view of minimizing the material content, it may be better to obtain the radiant reduction through the use of a low emissivity surface at the bounding faces, rather than through the honeycomb itself.

New abbreviations are proposed for the major three classes of transparent insulation: for absorber-perpendicular types the classification would be "transparent insulation of the forward-reflecting type", or TIFT, the absorber-parallel arrangement would be called "transparent insulation of the rear-reflecting type" or TIRT, and lastly the quasi-continuum type would be called "transparent insulation of the continuum type", or TICT.

Hollands K.G.T., Iynkaran K., "Proposal for a Compound-Honeycomb Collector", Solar Energy, Vol. 34, No. 4/5, 1985, pp. 309-316.

The performance of a flat plate solar collector combining a selective surface on the absorber plate and a plastic honeycomb in the air gap is not as high as might be expected because of a certain coupling between the radiative and (gaseous) conduction heat transfer modes. To decouple the modes and achieve the desired low heat loss coefficient, this paper suggests leaving an air gap of about 10 mm between the plate and the honeycomb - the air gap and the honeycomb together comprising a compound honeycomb air layer. The paper evaluates the suggestion through three basic studies. The first two experimentally and theoretically studied the heat transfer in the case where the air is artificially maintained stationary, and the third experimentally studied the effect of the convective air motion on this heat transfer. These studies demonstrated that leaving the air gap effectively decouples the modes but does not significantly alter the free convection suppression at the design condition. It is concluded that the compound honeycomb collector should have very good performance at high temperatures.

It is concluded therefore that an air gap about 10 mm does not invalidate the honeycomb's ability to

suppress free convective heat transfer but does provide the decoupling necessary to obtain low values of total heat transfer coefficient of an air layer. Consequently collectors with selective surface and compound honeycombs are predicted to have very good performance at high temperature. Indeed, such performance has already been realized in a compound collector recently tested by Symons et al.

Presented are the plots of total heat transfer coefficient across a honeycomb air layer with a selective surface on the absorber plate, plotted as a function of honeycomb wall emissivity, for various cell aspect ratios, and for the following assumed conditions: plate temperature = 100° C, cover glass temperature = 30° C; cover glass emissivity = 0.88; selective surface emissivity = 0.1, diameter of honeycomb cell = 10.6 mm. Measured and predicted values of the total heat transfer coefficient across a quiescent compound honeycomb air layer, plotted as a function of air gap for various aspect ratios, for the following conditions: hot plate (absorber) temperature = 33° C, cold plate (glass cover) temperature = 26° C, hot plate emissivity = 0.1, cold plate emissivity = 0.88. The graph of the Nusselt-Rayleigh number plots for the simple and compound honeycomb air layers is also cited.

Hollands K.G.T., Iynkaran K., Ford C., Platzer W.J., "Manufacture, Solar Transmission, and Heat Transfer Characteristics of Large-Celled Honeycomb Transparent Insulation", Solar Energy, Vol. 49, No. 5, 1992, pp. 381-385.

A method for manufacturing thin-walled (about 20 micrometers wall thickness), large-celled (about 10 mm hydraulic diameter of cell) honeycomb from FEP plastic is described. The honeycomb manufacturing method uses heat-sealing to join adjacent strips of plastic along thin lines. The honeycomb is sized to be just small enough to suppress convection, but in itself it provides little radiant suppression, so it is intended to be used in conjunction with low emissivity surfaces at one or both of its bounding faces to provide the necessary radiant reduction. In addition to the method for manufacture, measurements of the honeycomb's thermal conductance and solar transmittance are also reported. Mounted adjacent to a face with a thermal emittance of 0.1, a 40 mm deep honeycomb achieved thermal conductance values ranging from 1.4 to 2.4 W/m²K when the temperature difference ranged from 10 to 80 K and the mean temperature from 290 to 360 K. At an angle of incidence of 45 degrees, the honeycomb achieved a solar transmittance of 92%.

Honeycomb transparent insulations designed to just provide convection suppression can, if used in conjunction with a low emissivity surface at one of its faces, provide satisfactory thermal resistance and yet have a lower material content and higher solar transmittance than those designed to provide both radiant and convective suppression. For example, the honeycomb described in this paper had a material content from 100 to 200 g/m², and achieved a solar transmittance of over 90%. While the method for their manufacture described in this paper still needs further development, these honeycombs hold theoretical promise as an interesting transparent insulation material.

Hollands K.G.T., Marshall K.N., and Wedel R.K., "An Approximate Equation for Predicting the Solar Transmittance of Transparent Honeycombs", Solar Energy, Vol. 21, 1978, pp. 231-236.

An approximate equation is presented for predicting the solar transmittance of transparent honeycombs. The method accounts for scattering which occurs in such honeycombs by introducing diffuse components for both the reflectivity and transmissivity of the honeycomb wall. Required inputs to the equation are the optical properties of the honeycomb wall material, averaged over the solar spectrum. Methods of determining these properties are described. Although strictly applicable to a square-celled honeycomb, the equation should be approximately valid for hexagonal honeycomb as well. The equation is compared to the measured transmittance of a hexagonal-celled Lexan honeycomb

with good results.

Analytical methods for predicting the efficiency of the plastic and glass transparent honeycomb flat-plate solar collectors prior to testing are useful for optimization and design trade-off studies. An important required element for such an analytical predictive method is the ability to predict the transmittance of the transparent honeycomb to solar radiation. The paper presents an approximate treatment which yields an explicit set of equations for the honeycomb transmittance. The method incorporates specular reflections, absorption and scattering; the polarization effects are not included, although the method could be modified to include them. Spectral variations are incorporated by use of solar-averaged values of the input spectral radiation properties. A method for measuring the material scattering properties, without constructing the honeycomb, is described.

Measurements of the transmittance of a plastic honeycomb as a function of the angle of incidence are reported and compared with the predictions of the theoretical equation. In a physical model considered the honeycomb was assumed to be square-celled and the collimated solar radiation is assumed to have a direction parallel to the plane of the two sets of parallel walls which form the square-celled array.

Properties were measured spectrally using the Gier-Dunkle integrating sphere reflectometer. The honeycomb chosen for solar transmittance measurements was a hexagonal-celled honeycomb having a height of 4.76 cm and a distance across the hexagonal flats of 0.96 cm giving a value for the aspect ratio of 5. The honeycomb was fabricated from the 0.076 mm thick Lexan sheet, using the "Hexcel" technique, and glue joints. The graphs show the collector efficiencies and honeycomb transmittance as a function of the angle-of-incidence and the transmittance of a square-celled Lexan honeycomb having the same aspect ratio, as predicted from the theory and film property measurements. It is concluded that the measurement technique and theory outlined here should be expected to be very useful for system optimization, interpretation of experimental results, and for the screening of candidate honeycomb materials.

Hollands K.G.T., "Honeycomb Devices in Flat-Plate Solar Collectors", Solar Energy, Vol. 9, No. 3, 1965, pp. 159-164.

The results are presented of a theoretical study on the performance of a flat-plate type solar collector in which a selectively transmitting honeycomb panel is mounted between the absorbing flat plate and the outer glass cover. An analytic study of the natural convection process in such panels has shown that, under certain conditions, natural convection losses can be suppressed. Further, the honeycomb significantly reduces the radiation heat losses from the absorber. If the honeycomb cell walls are sufficiently thin, heat losses by conduction directly through the honeycomb wall material need not be important, and a high transmittance to solar radiation can be achieved. Efficiency curves for this type of collector are given and compared with those of a more convectional design. Higher efficiencies in the 200 to 300° F plate-temperature range are predicted. The importance of the honeycomb wall thickness in the overall efficiency is pointed out.

This paper presents a theoretical study of a flat-plate solar collector in which a honeycomb panel is mounted between the flat plate and the outer cover. The honeycomb is assumed to be made of a material, (such as glass or some plastics), that transmits solar rays but is black to long-wave radiation. Four aspects of honeycomb panels are discussed: natural-convection heat transfer; thermal-radiation heat transfer; conduction heat transfer directly through the honeycomb walls; and finally the transmittance of the honeycomb to solar radiation. The results are then applied to predict the efficiency of a particular solar collector with a glass honeycomb, as a function of mean plate temperature and honeycomb wall thickness.

In the treatment of the three modes of heat transfer it is assumed that there is no interaction between any two modes. The justification for this assumption is (a) the effect of any interaction would be difficult to predict theoretically, and (b) provided the honeycomb cell walls are sufficiently thin, the contribution of the interaction to the overall heat transfer should be quite small. The theory outlined above is still subject to experimental verification. However the author feels that the preliminary calculations presented here indicate that further research in this direction may lead to an economic flat-plate collector, capable of high efficiencies in the 200 to 300° F temperature range.

Jahn K., Bertram A., Christoffers D., "Transmission Spectra of Capillary Structures - A Comparison of Simulation and Measurement", Proceedings of the 4th International Workshop on Transparent Insulation Technology, Birmingham, UK, May 28-30, 1991, pp. 16-19.

The transmission spectra for several capillary structures measured with incident angles between 0° (normal incidence) and 60° are presented. These spectra also deliver the values of the solar transmission when folded with an AM 1.5-spectrum. Both the data for the solar and the spectral transmission are compared with the results of a simulation program. This program is based on a model that was proposed by Hollands and extended to three dimensions by Platzer. Our measurements of the diffuse transmission and reflection of foils show that dependence of the diffraction index should be included in the calculation.

The comparison of the theoretical and experimental results confirms that the model allows a good prediction of the solar transmission and of the main features of the spectral transmission. But the detailed calculation of the spectra fails when absorption is no longer negligible.

Jahn J., Christoffers D., "Valuation of Transparent Insulation Devices", Proceedings of the World Solar Congress of ISES, Denver, Colorado, 1991, pp. 2951-2956.

To evaluate basic types of transparent insulating components and to optimize the solar transmission and the heat transfer coefficient, several test elements were built. A size of 20 x 30 cm was chosen and wood was selected as a frame material. The details of the construction were changed gradually so that the influence of each measure could be examined. The authors started with a very simple element - 10 cm of transparent insulation embedded in two glass panes. To simulate the possible mounting in houses, spaces between the insulation and the surfaces of the elements were introduced. Afterwards foils were situated in the spaces to improve the thermal insulation. The global transmission and the heat transfer coefficient were determined at all stages of the development.

To reduce the weight of the components the transparent insulation can be fixed to the cover pane by an adhesive and the other glass pane can be substituted by a plastic foil. Therefore, the transmission and the aging under radiation of several adhesives were investigated. On the basis of the results of the experiments and with respect to the costs and the handling of the components, two constructions are selected. The measurement of the heat transfer coefficient and the transmission spectra of nine test elements of basic constructions for transparent insulation devices showed that a U-value of 1.13 W/m²K can be realized with simple structures. Spaces between the cover panes and the insulation material and the introduction of foils reduce the U-value to 0.94 W/m²K. But simultaneously the solar transmission drops.

Jankovic L., Jesch L., "Honeycomb Transparent Insulation Modelled by a Second Generation TRNSYS Module", Proceedings of the 3rd International Workshop on

Transparent Insulation Technology for Solar Energy Conversion, Freiburg, FRG, September 18-19, 1989, pp. 122-125.

A mathematical model of the honeycomb transparent insulation was developed using general purpose modules of TRNSYS. This has given TRNSYS a new ability to handle building elements with transparent insulation. Unlike with other simulations programs, development for this new application lasted less than a day due to specific use of TRNSYS programming syntax and specific manipulation of its components.

The developed model was applied to a typical room of a multistory residence with honeycomb transparent insulation. Interaction of the building with its environment, implications on energy consumption and on comfort were investigated and are presented. A climate potential to offset overheating is discussed.

Javed M.A., Al-Samarraie R.F., "Parametric Studies of the Thermal Performance of a Honeycomb Solar Pond", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 42-45.

In solar ponds, the biggest heat loss occurs through the top surface by convection and evaporation. Transparent insulation on the solar pond surface reduces these losses and provides an efficient way of collecting and storing solar energy. Jesch constructed a 8.64 square meter area and 1.2 meter deep solar pond in Birmingham UK for experimental purposes in 1990. The solar pond was monitored for two year. From these results Javed developed a simulation model and tested it by comparing its predictions with the measured data. The predicted temperature of the pond water was in good agreement with the measured temperature.

A module for a transparently insulated pond was developed and incorporated into the transient simulation program TRNSYS. Several computer experiments were conducted to determine the effects of different parametric changes in surface area, pond depth, side insulation, and load. Javed found that a circular pond was optimum and that pond size becomes an insignificant factor in determining loading for ponds larger than 1000 m². Increasing pond depth resulted in higher temperature in the winter months, thus improving performance. Likewise using 0.5 W/m² conductance insulation a reduction of 65 percent in side losses and an increase of 174 percent in energy storage was realized. Finally, in the case of heat removal from the pond, increasing the load resulted in lower water temperatures and lower heat losses from the pond. Specifically, with a withdrawal rate of 1 liter/hm² 14 % of the global radiation was collected at the expense of a 20° C drop in temperature. In summary, according to Javed's computer simulations the best options for a 1.5 meter deep pond in the UK climate are a fixed load of 20 W/m² and a withdrawal rate of 1 liter/hm².

Jesch L., Chattha J., Deleuze M., Massat C., "Optimization of Honeycomb Cell Geometry for Transparent Insulation", Proceedings of the 3rd International Workshop on Transparent Insulation Technology for Solar Energy Conversion, Freiburg, FRG, September 18-19, 1989, pp. 29-31.

Two different models have been used to determine the convection suppressive cell diameter of the transparent honeycomb insulation. The sample calculations of the critical diameter which represent the onset of the convection, are made at an angle of inclination of 45 degrees, mean temperature of 300° K for different temperature differences. Calculations of the critical diameter are presented in graphical form. For sample calculations a cell length of 100 mm has been fixed for all cases. Also to demonstrate the outstanding quality of the transparency the typical Arel honeycomb of an aspect

ration of 30 has been simulated for a vertical wall at surface azimuth angle 0 the 360°. The yearly performance of the Arel honeycomb is shown. From figures presented it could be concluded that Hollands' (1976) equation gives a more conservative value of the critical diameter than does velocity calculations.

Johnstone C.M., Twidell J.W., "Experience of Transparent Insulation: Air Pollution, Solar Blinds and Internal Wall Surface; Strathclyde University's Solar Residences", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 30-33.

The 1989 Strathclyde University Solar Residences of 376 students are a European Community demonstration of TI technology within a low energy building of high internal mass with air to air heat recovery. The five blocks of east-west oriented flats have large areas of south glazing covering 1000 m² of transparent insulation in a LEGIS wall. The north facades have heavy brick construction with reduced size triple-glazed and low emissivity windows and 150 mm cavity insulation. The Energy Studies Unit has monitored thermal performance of the TI, energy efficiency, comfort, effect of external environment and social factors. This paper reports additional studies made as potential problems emerged during monitoring: TI staining, solar blind strategy, affect of internal south wall shelving.

These buildings have been a successful demonstration of TI technology in higher latitudes. There has been a continuous net gain of energy through the South wall, into the building, over the three year period of monitoring. If replication of this building is to be considered, then the lessons from the Strathclyde development should be closely considered. Staining of the TI could be averted by the use of a preconstructed, air-tight, factory encapsulated module with integral shading device. Solar shading should be from a slatted blind system to increase the systems mechanical reliability. Heat transfer between internal zones could be assisted by the installation of conductive plates in the floors and ceilings. To maximize the thermal conductance of the TI wall and heat dissipation into the building, internal surfaces should be free from additional fittings.

Karlsson S., "Transparent Insulation for High Temperature Flat Plate Collectors", Proceedings of the 2nd International Workshop on Transparent Insulation in Solar Energy Conversion for Buildings & Other Applications, Freiburg, F.R.G., March 24-25, 1988, p. 39.

A very long ground based (LGB) flat plate collector is developed, which is connected to the district heating net-work which requires operating temperatures between 60 and 90°C. This means that the collector has to be well insulated and equipped with some kind of transparent insulation between the glass and the absorber.

The developed collector is furnished with a double glazing composed of a low-iron glass and a flat teflon film. The authors compare the performance of this glazing with double teflon films, V-corrugated films of teflon, tedlar, mylar, and a newly developed AREL-honeycomb. The characteristic parameters of these materials needed for applying the relation above are obtained from measurements of solar-transmittance in a large integrating sphere and heat loss factors from a hot-box.

The analysis shows that most of structures demonstrate a better performance than the flat teflon film, but from a cost effectiveness point of view it is difficult to compete with the high transmitting teflon film.

Kaushika N.D., "Honeycomb Passive Water Heating Systems", Proceedings of the World

Solar Congress of ISES, Denver, Colorado, 1991, pp. 2983-2987.

Transparent honeycomb insulated passive water heating systems using ground (concrete/sand) as solar collector storage media are investigated. It is pointed out that a ground based water channel placed beneath a honeycomb insulated slab (thickness 0.3 m) of concrete sand material can continuously supply hot water ($\Delta T = 60^\circ \text{C}$) at solar conversion efficiency of 40%.

In recent years transparent honeycomb structures have been considered for application in solar ponds and other water storage systems. However, containment of the a large storage volume of water and the temperature stratification therein is an outstanding problem in such systems. It is, therefore, of interest to investigate other solar collector/storage media for above application. The ground (sand/concrete) having equally large thermal capacity and insulation characteristics as water is investigated in the scope of present article. The proposed system consists of a network of pipes buried in top region of the ground whose surface is blackened and covered with an air filled honeycomb. The simple analysis for steady state is accomplished. Numerical computations have been made for the efficiency of heat collection.

Kouhia I., Nieinen J., "Transparent Insulation - Cold-Region Applications in Walls", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 50-53.

Structures for study in a full-scale experimental house were selected from computationally examined applications of transparent insulation materials. In Finland's climate the maximum energy consumption of buildings occurs in mid-winter, when there is very little solar radiation. Passive solar walls perform best in the spring and autumn, when heating is necessary. However, the benefit of passive applications is quite small. The preheating of the building's domestic hot water is a very promising area of application for transparent insulation materials. The consumption of water is fairly constant throughout the year, so the utilization of solar energy saves more energy in the preheating of water than the heating of the building.

The apparent efficiency of the domestic hot water preheating system is approximately 25%. The system can supply about half (2000 kWh) of the energy necessary to heat the domestic hot water for a four person family.

Kuhnke K., Hammer G., "Directional Selective Transmission with Cylindrical Lenses", Solar Energy, Vol. 52, No. 1, 1994, pp. 127-136.

Directional selective transmission (DST) is a new principle involving the absorption of solar radiation in winter and its reflection in summer. Its main application is in combination with transparent insulation. The beam radiation is focused on a pattern of transmitting and reflecting strips by means of a field of cylindrical lenses. Radiation from lower sun positions (winter) is transmitted, whereas that from higher sun positions (summer) is reflected. Diffuse radiation is partly transmitted in winter and summer. Applied to transparent insulation, DST is a means to protect buildings from overheating in summer. DST systems have no moveable parts, are passive and maintenance-free. They are self-switching between the seasons with a quasi-step characteristic between transmission and reflection. The maximum beam radiation transmission of south oriented systems at Osnabruck (north Germany) on a winter day is up to 64% and less than 5.5% on a summer day; global radiation is transmitted with 50% (winter) and 25% (summer); on clear days with 53% and 17% respectively. The relation improves in many other climates with more beam radiation. In this paper the principle of DST is explained, a prototype is shown with construction details, and an energy evaluation is presented with

both experimental and simulation data. There is a satisfactory coincidence of experimental and calculated results.

Landabaso A., Colombo R., "Transparent Insulation Projects supported by the Directorate General XVII of the CEC within the Demonstration and Thermie Programmes", Proceedings of the 4th International Workshop on Transparent Insulation Technology, Birmingham, UK, May 28-30, 1991, pp. 13-15.

Demonstration projects in solar energy form part of the overall Energy Demonstration Programme of the Commission of the European Communities (CEC). Applications in the building sector have always been particularly important, and have always formed between 50-80% of the annual number of solar projects supported by the Commission. Given that 35-45% of the Community's total primary energy consumption takes place in buildings, this bias is well justified. Recently attention has moved from active solar systems to passive solar systems. Among its solar projects the Community is supporting some of the largest transparent insulation projects in the world, some of which are describe in this paper.

Liersch G., Dill F.U., "A Ventilated Transparent Insulation System for Wall Applications", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 18-21.

A compound modular TI wall system without any moving parts in the facade is investigated. Heat protection during the summer is effectively provided by opening an air gap and leading a natural convection air stream away from the facade. The heat transfer mechanisms are investigated theoretically with a numerical Finite Volume program and experimentally with solar simulator measurements under constant boundary conditions.

The optimal system configuration was tested under real outdoor conditions. With a 6 cm TIM layer and 4 cm air gap, a U_{TOT} -value of $0.67 \text{ W/m}^2\text{K}$ and a solar efficiency factor of 0.28 were obtained. Optimal values for the air gap were found to be 4-5 cm. The optimal values for the absorber back surface emissivity range was from 0.1 to 0.25. The ventilated TI wall system enables closed TIM modules without any dust or condensation problems to be used.

Liersch G., Platzer W., "Parametrizing a Transparent Insulation Wall System in a Simulation Program: Studies for a Convection System", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 58-61.

A characterization method for TI wall systems was developed. Existing numerical building simulation programs can easily be extended by using this method as a subroutine. Any given transparent insulation system can be treated as a "black box" system mounted on a house wall. In a similar was to TI materials, it can be described by a systematic energy gain factor g_{SYS} and a systematic u-value u_{SYS} . A ventilated TI wall system was parameterized and thus included in a building simulation program. The results show that the complex convective heat transfer can be described with the parameters introduced above. Here g_{SYS} as well as u_{SYS} are dependent on the wall temperature, the ambient temperature and the solar radiation.

Marcus S.L., "An Approximate Method for Calculating the Heat Flux Through a Solar

Collector Honeycomb", Solar Energy, Vol. 30, No. 2, 1983, pp. 127-131.

An approximate calculation of the radiative-conductive flux of heat from the absorber to the cover plate of a flat plate collector equipped with a convection-suppressing honeycomb is developed, using an exponential kernel approximation to the passage transmittance function of the honeycomb cells. Fluxes predicted by this method are found to be in satisfactory agreement with the results of previously reported calculations and experiments. If a selective absorber plate is used in a collector of this type, heat transport by the air in the collector eliminates temperature discontinuity (radiation slip) between the honeycomb and the absorber plate, so that thermal emission by the walls of the honeycomb in close proximity to the hot absorber may largely cancel out the advantage gained by making the absorber plate selective.

A separate mode analysis may seriously underestimate the heat flux when selective surfaces are used. A simplified analytical treatment, including mathematical basis and analytical expressions of heat flux for the combined mode is given. This treatment is based on the passage transmittance function (PT) introduced by Edwards and Toxin. The values of the heat flux computed by this method are compared with experimental data collected by Hollands et al.

To investigate the implications of the radiative-conductive interaction for the design of high-temperature flat plate collectors, calculations of heat flux were made for several configurations with a cover plate emissivity of 0.88 and the temperatures of the absorber and the cover plates held fixed at 400 and 320° K respectively. Heat flux may be decreased either by decreasing the absorber plate emissivity or by increasing the honeycomb aspect ratio (which increases the separation between the plates). For a high aspect ratio, the 2π steradian field of view "seen" by the cover plate is occupied mostly by honeycomb, so reducing the absorber plate emissivity in this case gives a relatively small decrease in the total heat flux. Thus if a honeycomb is being used mainly for convection suppression, there may be little advantage in using a selective absorber plate unless the emissivity of the honeycomb material itself is very low. For a highly selective absorber plate ($\epsilon \approx 0.1-0.2$), calculations using a separate mode analysis were found to underestimate the heat flux by about a factor of two.

Nordgaard A. and Beckman W.A., "Modelling of Flat-plate Collectors Based on Monolithic Silica Aerogel", Solar Energy, Vol. 49, No. 5, 1992, pp. 387-402.

This paper presents a new method based on "F-hat" for predicting the radiative transfer in an absorbing and isotropically scattering, non-gray plane-parallel atmosphere. The angular dependence of solar transmittance of diffuse and ground reflected radiation is evaluated along with the "transmittance-absorptance product" of a collector. The "F-hat" technique is also used to determine the infrared transmission of the cover from which the overall loss coefficient for a flat-plate collector constructed with aerogel filled covers is determined. The performance of a system using aerogel collectors is compared to systems using other types of high performing collectors. It is shown that, at least for the system investigated, the decrease in solar transmittance of monolithic silica aerogel is more than compensated by the decrease in thermal losses.

Flat-plate collector efficiency can be significantly improved by filling the air gap between absorber and cover with monolithic silica aerogel (MSA), and evacuating the system to 0.1 bar. The MSA optical thickness in the solar spectrum (from 400 to 2300 nm which includes 95% of the terrestrial solar spectrum) is largest in the near ultra violet region. The paper represents a new method for predicting the radiative transfer in an absorbing and isotropically scattering plane-parallel atmosphere. The technique was developed to determine the radiative heat transfer at short wavelengths for MSA. The model underpredicts the measured heat loss coefficient by about 10%. This was expected due to the deviations from the ideal preconditioning of MSA used in the collector as stated by Svedsen.

Novick O., "Application of Honeycomb Materials in Active and Passive Systems", Proceedings of the 1st International Workshop on Transparent Insulation Materials for Passive Solar Energy Utilization, Freiburg , F.R.G., Nov. 27-28, 1986, pp. 50-51.

A heat resistant thermoplastic honeycomb structure was developed and optimized for use as transparent insulation. Typical thermodynamic and optical properties for 100 mm honeycombs are $U \approx 1.0 \text{ W/m}^2\text{K}$ and $\tau \approx 0.78$ respectively. A series of applications of this honeycomb for fluid heating/thermal storage and climate control of buildings for direct mounting on vertical walls and glazing is reported. Typical performance data achieved in the various applications are summarized as follows: (a) flat plate collectors: stagnation temperatures of 110°C at insolation level of 200 W/m^2 , 54% collector efficiency at $120\text{-}130^\circ \text{C}$ delivery at insolation level of 1000 W/m^2 , (b) integral units: 45% total system efficiency (24 h), delivery at 50°C , at total insolation of 5.3 kWh/d , (c) solar ponds: heat recovery of 700 kWh/m^2 at temperatures ranging $45\text{-}55^\circ \text{K}$ above ambient when the yearly insolation is $1950 \text{ kWh/m}^2\text{y}$, (d) thermal storage: positive thermal balance at 60°K above ambient, where yearly insolation levels do not exceed $1300 \text{ kWh/m}^2\text{y}$. Economic analysis shows the profitability of all the above mentioned applications in comparison with most existing systems as well as in competition with fossil fuels in large geographic domains.

Olive F., Platzer W., Chevalier J.L., "Franco-German Experimental Programme for the Optical Characterization of Transparent Insulation Materials", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 82-85.

Within a Franco-German research program on energy, one topic, the optical and thermal characterization of innovating transparent materials, is being undertaken by Centre Scientifique et Technique du Batiment, Service Materiaux and Fraunhofer-Institut fur Solare Energiesysteme. Each team performed measurements using its own experimental capabilities on selected samples. The measurements included directional hemispherical transmittance over the solar range using a spectrometer with a 3 meter integrating sphere and broadband measurements with an integrating sphere. The samples tested were glazing units including two glass panes with transparent insulation materials in between or just capillary samples without glazing. The results are presented and discussed in this paper, with special emphasis on the difference occurring for similar measurements on the same sample. This work will permit the assessment of agreed measurement methods to be used to characterize any new complex semi-transparent material in each country. Generally the coincidence was good between the two labs, but for thick samples results differed appreciably.

Panno G., Aleo F., "Aging Tests on Transparent Insulation Materials", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 94-97.

This paper deals with the aging effect on some transparent insulation materials having large diffusion in the market and being cost-effective in the energy application. AREL, OKALUX, ISOFLEX samples, bare and covered with a single glass and a teflon film, have been tested. The ageing effect investigation required both the optical characterization and the accelerated UV exposure of the samples. The first one has been realized arranging any sample on the outdoor solar tracking apparatus on which transmittance measurements for different incidence angle of the solar beam were performed. The second one consisted of an accelerated weathering 500 hours cycle in a thermostatic UV chamber simulating only UV-A and B radiation's effect. Finally, further optical transmittance measurements have been carried out, in order to verify a possible optical and physical

loss of performance of the tested samples.

Two general considerations can be drawn. First, OKALUX samples always gave the best optical performances. The second, teflon film covering appears to be better than glass, especially when coupled with OKALUX bare sample.

Concerning measurements performed before the UV exposure, all three AREL samples remarkably reduce their direct transmittance as the incidence angle of the beam radiation increases. For incidence angles greater than 40 degrees, this similar reduction occurs to three OKALUX samples. Only for lowest values of incidence angle OKALUX and AREL samples have comparable values of direct transmittance. On the contrary, ISOFLEX samples do not seem to show the effects of angular modification.

Different transmittance measurements have been obtained following the accelerated weathering of the samples. AREL sample without covering showed the most important losses of the optical performance: direct and total transmittance as well as the diffuse one are reduced to about 20 - 30%. Furthermore, this sample appeared much more yellow. Neither optical nor physical appearance modifications occurred to other tested samples.

Perez Segarra C.D., Oliva A., Schweiger H., Costa M., "Numerical Evaluation of Natural and Forced Convection Heat Transfer in Transparent Insulation Wall Systems", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 70-73.

A two dimensional numerical model for the simulation of the convection, along with conduction and radiation phenomena, in transparent insulation wall systems has been implemented. Natural and forced convection in both laminar and turbulent regime have been considered. Turbulence is modeled with low k - ϵ low Reynolds turbulence models. The couple set of governing equations (continuity, momentum, energy, turbulence quantities, radiative exchange) are solved in the whole domain using the SIMPLEX algorithm proposed by Van Doormaal and Raithby. Control volume formulation of the differential equations, in implicit form, using a first order difference scheme has been employed. The present simulation model allows one to analyze the flow in complex geometries consisting of a transparent insulation cover, an air channel, and an absorbing wall with inlet and outlet flow zones of arbitrary shape and position. Illustrative results of the applied simulation are presented in this article.

Perincioli L., Muhlethaler F., "Using Glass Capillaries as Transparent Insulation Material", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 122-125.

A new technology allows the production of glass capillaries with extremely thin walls. They may be used for transparent insulation due to their low heat conduction. This provides an ecological alternative to the transparent insulation based on polycarbonate. Test modules of glass capillary plates were produced, their transmittance as well as their U-values were determined and they were optimized by improving the techniques of cutting and gluing the glass capillaries to form capillary plates.

The brothers Hans-Joachim and Otto Dietzsch developed the technique of producing thin walled glass capillaries with diameters far below one millimeter for the use of reinforcing plastics. In order to develop this further for solar use, the Dietzsch brothers cooperated with Infraconsult Ltd. in Bern,

Switzerland. With their own financing and funds from the federal ministry of energy in Switzerland, Infraconsult and the Dietzsch brothers further developed the technique of producing and processing glass capillaries. Within this process they built various samples of cubicels and plates. Their physical data were measured by the Fraunhofer Institute for Solar Energy Systems in Feiburg, Germany.

Peter R. W., "P-Layer Insulation (P-Folienplatte) a New Transparent Thermal Insulation Material", Proceedings of the 2nd International Workshop on Transparent Insulation in Solar Energy Conversion for Buildings & Other Applications, Freiburg, F.R.G., March 24-25, 1988, pp. 9-11.

A new transparent insulation material is presented, which is assembled of stacked self-supporting layers of transparent film whose formed surface consists of closely adjoining cones or "pyramids". Solar radiation and heat transmission of P-layer, capillary and foam transparent insulation materials were measured and compared. P-layer and capillary insulation were found to be nearly comparable and superior in performance to foam insulation.

The graph on solar energy and heat transmission computed for P-layer insulation (cone angle 60°) is presented, which indicates that the measured heat transmission value is considerably higher than the simplified theory indicates. The quality factor for the P-layer insulation (the ratio of radiation and heat transmission) as a function of layer thickness and total insulation thickness is cited which allow one to find a flat optimum quality factor of the number of layers for a given thickness. The limited experimental information on the P-layer TIM indicates that it looks promising. It is an easy assembled, potentially cheaply producible material. Present results show that the new multi-layer P-material approaches capillary material and is clearly superior to foam material in its quality factor for transparent materials.

Pfluger A., "Calculation of Thermal Conductivities from Spectral Data", Proceedings of the 2nd International Workshop on Transparent Insulation in Solar Energy for Buildings & Other Applications, Freiburg, F.R.G., March 24-25, 1988, pp. 12-13.

It is shown that for the approximate calculation of the thermal conductivity from spectral data of structured materials such as multi-film layers and honeycomb structures, the Planck mean of the spectral emittance of a layer may be used. - A new numerical algorithm is outlined, which allows exact calculation of the thermal conductivity from spectral data and bulk material conductivity. First results are given.

An exact numerical procedure was developed for homogeneous materials, which turned out to be fast and stable in all ranges of optical thickness. The graph of apparent thermal conductivity of a 2 cm aerogel layer is presented.

Platzer W.J., "Total Heat Transport Data for Plastic Honeycomb-Type Structures", Solar Energy, Vol 49, No. 5, 1992, pp. 351-358.

The total heat transport within honeycomb type structures consists mainly of radiation and conduction heat transport, as convection is usually suppressed. For surface emissivities larger than 0.7, independent mode analysis may be used, and a splitting of the measured total heat transport into parts is possible. Only a few parameters used in simple modelling equations are needed to describe the heat transport in this approximation. They have been obtained by fitting the functions to

experimental results and are presented in tabular form for 11 different materials. The thickness and temperature dependence is included in the results. The presented data may be used as input parameters either for simple calculations in an independent mode analysis (IMA) or for a dependent mode analysis (DMA). Thus even selective flat-plate honeycomb collectors may be modelled reliably.

The paper gives thermal data for 11 different plastic small-celled honeycomb materials. The experimental set-up of the hot-plate apparatus for the determination of the heat conductance is described in detail. For the commercial small-celled honeycombs the detailed data on temperature and thickness dependence, necessary for optimizing a specific system, are not available. Therefore, heat conductance measurement data have been analyzed in this paper in terms of the simple independent mode analysis, which is valid for the experimental conditions which were high surface emissivities (larger than 0.7), convection suppressed, no air gap.

Although selected experimental information and test values have been published, a consistent set of numbers describing the properties of available honey-comb materials is lacking. Using the simple IMA, the parameters needed to describe the total heat transport through a honeycomb layer between two boundary surfaces were fitted to heat conductance measurements, where convection was excluded. Only four parameters including volume fraction of the honeycomb cell walls, thermal conductivity of the cell wall, and two fit coefficients for the inverse effective IR-extinction coefficient are necessary to characterize the heat transport in commercial honeycomb-type structures with sufficient accuracy for different thicknesses and temperatures between 10 C and 80 C. An additional temperature dependent correction of the inverse effective IR-extinction coefficient is small and can be neglected. The fit coefficients determine the thickness dependence of the inverse effective IR-extinction coefficient. The heat conductance for nonselective flat-plate collectors may be directly calculated in independent mode analysis.

Platzer W.J., Apian-Bennewitz P., Wittwer V., "Measurement of Hemispherical Transmittance of Structured Honeycomb-Like Transparent Insulation Materials", SPIE Optical Materials Efficiency and Solar Energy Conversion IX, Vol. 1272, 1990, pp. 297-308.

The determination of the hemispherical-hemispherical (or diffuse-diffuse) solar transmittance of transparent insulation materials like honeycomb structures or of shading devices like venetian blinds is important to estimate the efficiency of passive solar components using these materials. The diffuse-diffuse solar transmittance may be calculated from the measured angle-dependent hemispherical (or diffuse) transmittance. Alternatively one may try to measure the quantity directly by using a large radiation source for isotropic irradiation of the sample. The measuring device in both cases is a large integrating sphere. A calculation of the diffuse-diffuse solar transmittance needs an underlying physical model for the radiation transmittance of the sample. This model might not be available for complicated structures and is idealized for samples in practice. The arising problems for a honeycomb structure are discussed in detail.

The main problem is a practical one, not a fundamental one. In order to save measurement time and costs, only two scans along the principal directions of the cell walls are selected, thus essentially varying only the polar incidence angle. These two curves can be fitted with a transparent model. Then for every arbitrary incidence angle the transmittance can be calculated using the theoretical model, i.e. also the diffuse-diffuse solar transmittance may be determined. The selection of the right model, however, needs information about the azimuthal dependance. This in principle can be obtained by varying the azimuthal angle systematically in additional scans. Information about this dependance can be obtained also from a scanning radiometer, where both angles for incident and outgoing radiation can be chosen without restrictions. However, this is rather time-consuming and poses new problems as well. Therefore the use of isotropic irradiation of the sample certainly is the fastest way.

This approach may be realized in different ways. Two of them are discussed in the article and possible areas are identified.

Platzer W.J., "Calculation Procedure for Collectors a with Honeycomb Cover of Rectangular Cross Section", Solar Energy, Vol. 48, No. 6, 1992, pp. 381-393.

For a highly efficient collector with a honeycomb cover, an optimization procedure has to take into account a lot of parameters like material choice, geometric dimensions, cell wall thickness, and aspect ratio of the honeycomb. An approximate, but comprehensive theoretical description of the optical properties and the heat transport within a honeycomb absorber system is given and discussed in this paper. Selective absorbers and air gaps with convecting air can be treated within the model. Solar transmittance and heat ransport are treated with a consistent model, which in principle needs only film data and the geometric parameters as input. Theoretical results compare quite favorably with experimental data from honeycomb structures. The main innovative features of the model are its use of an effective optical thickness, and the inclusion of both convective boundary conditions and solar absorption in a coupled mode analysis leading to an analytical solution.

Platzer W., "Tilted Honeycombs for Optimal Collector Covers", Proceedings of the 4th International Workshop on Transparent Insulation Technology, Birmingham, UK, May 28-30, 1991, pp. 33-36.

Tilting honeycomb structures in principle provides a cheap way of improving heat resistance as well as solar transmittance of collector covers. Monthly average transmittance for different orientations may be increased when compared to vertical honeycombs (VHC). From experimental values it can be shown that the heat resistance increases with tilt angle due to reduced radiation transport. In this paper results from a theoretical model for solar transmittance and heat transport of tilted honeycombs (THC) are compared with experimental values. Although some simplifications are inherent in these models, the comparison is quite satisfactory.

Platzer W.J., "Solar Transmission of Transparent Insulation Material", Solar Energy Materials, Vol. 16, 1987, pp. 275-287.

Transparent insulation materials for solar energy applications are described in this paper. Platzer classifies them by their geometrical structure highlights the four sufficient categories: absorber-parallel cover, absorber-vertical TIMS, cavity structures, and quasi-homogeneous material. An experimental setup with an integrating sphere for the whole global spectrum range having a large entrance port is capable of measuring angle-dependent directional-hemispherical transmittances for planar samples and nonplanar structures with acceptable accuracy up to 70 degrees. The theoretical description of such structures allows calculation of directional transmittances even for combinations of different kinds of layers.

If one uses TIMs in passive applications as collector covers, only the energy reaching the absorber behind the cover is important. Therefore the physical entities to measure are the directional-hemispherical transmittance or, integrated over the solid angle, the hemispherical-hemispherical transmittance. The measuring devices and techniques are described in detail. Also the calculation methods and formulae are presented. Platzer recommends using the embedding technique for absorber-parallel structures and the net-radiation method for a single angle of incidence, polarization state, and wavelength. The insertion of the total hemispherical values into the given formulae is not recommended, because the transmittances will be extremely underestimated.

For the absorber-vertical structures the two-dimensional analytical theory and a three-dimensional Monte Carlo model are compared for the rectangular honeycomb. Methods of measuring the transmittances, spectral scattering and absorption coefficients of cavity structure's homogeneous layers transmission-absorption product for multiple layers are covered also.

The discussion of theoretical methods for transmittance in transparent insulation materials showed that models are powerful enough to cope with many different material types and applications if experimental global parameters are used. Spectral transmittances of the structures may be calculated in principle from spectral data of the constituents, but experimental errors may critically influence the results. Nevertheless the results can be used to determine influences of the radiation spectrum, and heat transport mechanisms in these type of materials. It is also possible to optimize with respect to certain parameters and applications. Still some work is to be done: Experimental methods should be refined to become more accurate, radiation data to determine spectral influences on the transmission will be needed, and even more importantly, in solar energy applications, experimental and theoretical work has to be devoted to the more relevant physical value, the total energy transmission (including the remission of the absorbed radiation in the structures).

Platzer W., "Optimization Problems of Transparently Insulated Systems", Proceedings of the 2nd International Workshop on Transparent Insulation in Solar Energy Conversion for Buildings & Other Applications, Freiburg, F.R.G., March 24-25, 1988, pp. 14-16.

The optimization of a honeycomb transparent insulation material (TIM) combined with a selectively coated integrated storage collector (ISC) is discussed in this paper. In order to find the optimum material, characterized by the heat loss coefficient and solar transmittance, a theoretical model of the honeycomb absorber system for heat transport and solar transmission will be used. The modelling of the ISC itself is solved by a rather simple short-term simulation of representative days of each month. The optimization aim is to change parameters of the TIM in order to find the optimum balance between solar gains and heat losses, which results in a maximum yearly output or a minimum auxiliary energy demand for a one square meter collector. The effect of two different scattering mechanisms in determining the combination and distribution of mass, and different aspect ratios for rectangular honeycombs are considered.

The optimization of rectangular honeycomb structures for a given application is possible with the procedure described, if the input data for the plastic films are known. The critical points are the exact determination of scattering coefficients and mechanisms. Depending on these data different optimum designs will result. However, optima are relatively flat, so the choice of the material parameters volume density, aspect ratio and lateral aspect are not that critical. To choose the mass distribution, i.e. the film thickness used, more knowledge about the scattering mechanism is needed. As mentioned before, the production of the thinner films may also change the optical film properties. Therefore, a recommendation of an optimum mass distribution can not be given safely. These questions have to be resolved experimentally in the future.

Platzer W., Wittwer V., "Future Development in the Field of Transparent Insulation Systems", Proceedings of the 4th International Workshop on Transparent Insulation Technology, Birmingham, UK, May 28-30, 1991, pp. 20-23.

The utilization of solar energy active and passive thermal systems requires covers or glazings which have both high energy transmittance and good thermal insulation qualities. The recent development of transparent insulation materials (TIMs) allows design of optimized transparent insulation systems for application fields from flat-plate collectors to daylighting systems. When TIMs are combined with

selective coatings, low pressure or spectral gas fillings, heat resistances from the absorber to the ambient of more than $1.5 \text{ m}^2\text{K/W}$ may be achieved, where the total energy transmittance (equivalent to the effective transmittance-absorptance product) still is around 85% for vertical and 70% for diffuse irradiation.

Platzer W.J., "Directional-Hemispherical Solar Transmittance Data for Plastic Honeycomb-Type Structures", Solar Energy, Vol. 49, No. 5, 1992, pp. 359-369.

The directional-hemispherical (also sometimes called direct-diffuse) solar transmittance for several different honeycomb-type structures has been measured with an outdoor solar simulator and a 40 cm diameter integrating sphere for incidence angles up to 70 degrees. The samples have been fabricated by commercial companies from different plastics, with cell wall thickness $(15...70)\text{E-6 m}$ and have approximately square or circular cell cross sections. After a discussion of the measurement errors and problems associated with a limited number of nonideal samples, a fit procedure based on a physically based transmittance model is presented and applied to the data. The resulting coefficients describe the angular and thickness dependence of the solar transmittance for each type of material. They may be used in order to feed data and flexibly into simulation models for solar collectors, windows or buildings. The seven capillary materials tested are produced by Okalux Kapillarglass GmbH (Marktheidenfeld, FRG), and honeycombs are produced by Arel Ltd. (Yavne, Israel) and Kaiser Bautechnik (Duisburg, Germany).

Directional-hemispherical transmittance data for several honeycomb structures has been presented in terms of the parameters of fitted curves. Since only a limited number of samples was available, the aim of this data treatment was not to obtain a best fit for a single sample, but a set of fitting parameters for each material type. The measurement errors were discussed which restrict the precision of the results. The overall description of honeycomb structures with different properties seems to be satisfactory, when their fitting function is used. This model has the advantage of a small number of coefficients. More importantly, it avoids unphysical features such as an increase of transmittance with large thickness or incidence angle, which may occur, if polynomials are used as fit functions.

The "effective absorption" parameters are not proportional to thickness, in contradiction to a rudimentary physical model, at least for the capillaries, where scattering and surface effects are too important to be neglected. However, for the square-celled honeycombs with well-cut surfaces, the constant term in the "effective absorption" parameter is negligibly small. From a comparison of several polycarbonate materials, it is a reasonable assumption that the existing materials have a considerable potential for improvement.

Platzer W., Wittwer V., "Transmittance Characteristics of Transparent Insulation Materials", Proceedings of the 1st International Workshop on Transparent Insulation Materials for Passive Solar Energy Utilization", Freiburg, F.R.G., Nov. 27-28, 1986, pp. 20-22.

The experimental set-up and results from transmittance measurements of transparent insulation materials are given in this paper. Theoretical understanding of the structures is briefly outlined. Presented are the four categories of geometrical classification of the materials which are absorber-parallel, absorber-vertical, cavity structure, and quasi-homogeneous. The experimental set-up for the measuring of the angular and spectral properties of the TIM are discussed. Theoretical based fit curve and experimental values for angle dependent transmission and losses due to badly cut rims are included. The article gives the overview of measured materials, which are only in part commercially

available at the moment.

Platzer W.J., "A Simple Monthly Calculation Procedure for Transparently Insulated Houses", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 62-65.

An extension to the monthly correlation method for houses with direct solar gains has been developed. It is based on the ratio between the additional solar gain through the TI-walls and the heat load for the house with equivalent opaque insulation. This approach seems to be adapted to the question whether one should choose between the alternatives of opaque or transparent insulation for a fixed house design.

Using a single zone simulation program for the TI-building with time-steps of 20 minutes or less, a simple correlation function could be determined using a nonlinear fitting function. In order to achieve this, monthly results from 18 house simulation cases with different TI-wall orientation and TI-wall area have been analyzed.

Results for average monthly heat gains and average room temperatures show good agreement. Up to now neither different types of heating systems nor other building types have been analyzed. However, the methodology is flexible enough to cope with these variations in the future. For first approximations of the heat demand of a TI-house, the method can be easily programmed as a spreadsheet.

Rommel M., Wittwer V., Goetzberger A., "Thermal Energy Collector and Storage with Radiatively Heated Walls", Proceedings of the Biennial Congress of ISES, Hamburg, Germany, Sept. 13-18, 1987, pp. 1553-1557.

Experimental results of a small storage cube with transparently insulated walls are given. In 1986, the storage cube was insulated with silica aerogel pellets. In 1987, the cube was insulated with a honeycomb structure made of polycarbonate. First results of the simulation calculations of bigger storages are reported in this paper.

Rommel M. and Wagner A., "Application of Transparent Insulation Materials in Improved Flat-plate Collectors and Integrated Collector Storage", Solar Energy, Vol. 49, No. 5, 1992, pp. 371-380.

Within the work on new collector designs for the Central European climate, investigations on two different collector systems using Transparent Insulation Materials (TIMs) are presented in this paper. The thermal and optical properties of a polycarbonate honeycomb material are discussed with respect to the design of improved flat-plate collectors and integrated storage collectors with TIMs. Measurements on a collector with this material improved the collector performance in the temperature range of 80 to 140 degrees C. But the collector is not stagnation proof, as the honeycombs start melting at 120 degrees C. The paper also describes a collector with newly developed, temperature resistant glass capillaries, with which a stagnation temperature of 261 degrees C was measured. Finally, new measurements of an integrated collector storage with polycarbonate honeycomb are reported which confirm the good performance of this simplified solar domestic hot water system.

The properties of polycarbonate honeycomb, as an example, enable the design of thermal collector systems with cover heat losses below $1 \text{ W/m}^2\text{K}$, while still having a high solar transmittance. The

measurements on an integrated collector storage system show that very effective simplified SDHW system can be developed with the help of TIMs. Improved flat-plate collectors with polycarbonate honeycombs show that such collectors reach high efficiencies especially for system temperatures above 80 °C. But the improvement of the collectors leads to high stagnation temperatures which cause material problems. However, first samples of temperature resistant TIMs made of glass capillaries were developed, which enabled us to build a flat-plate collector that reached a stagnation temperature of 261 °C. In the future, even higher temperatures may be reached with better TIMs and new collector designs.

Rommel M., Wittwer V., "Flat Plate Collector for Process Heat with Honeycomb Cover - An Alternative to Vacuum Tube Collectors", Proceedings of the Biennial Congress of ISES, Hamburg, Germany, Sept. 13-18, 1987, pp. 641-645.

A flat plate collector for process heat applications has been developed incorporating a polycarbonate honeycomb structure in the cover. This paper describes the collector design, indoor and outdoor efficiency measurements, and the resulting collector performance data. At $\Delta T = 100^\circ \text{C}$ and 800 W/m^2 , an efficiency of 48% is reached. Some results of a system with 11 m^2 absorber area and 300 liters of storage, operating at temperatures of 80 to 100°C are reported.

Rommel M., Wittwer V., "Transparent Insulation - New Collector Developments", Proceedings of the 3rd International Workshop on Transparent Insulation Technology for Solar Energy Conversion", Freiburg, FRG, September 18-19, 1989, pp. 46-49.

Transparent insulation materials (TIM) offer the chance to improve thermal collectors considerably. Using a 10 cm honeycomb material, a flat plate collector has already been developed which, at operating temperature around 80°C , shows performance comparable to that of evacuated tubular collectors. Due to the theory of TIM, further improvements are possible with larger air gap between the absorber and the TIM, if the convection within the air gap is suppressed. This can be accomplished, for example, by evacuating the cover system to approximately 0.001 bar. First experiments have been made in this field.

Secondly, a shallow solar pond has been set up to investigate the possibilities of integrated storage collectors supplying thermal energy for 24 hours a day. Simulation calculations show that in certain applications, for example, for seawater desalination by transmembrane distillation or for operating a thermal pump, this may have system advantages.

Schmidt C., Goetzberger A., Schmid J., "Test Results and Evaluation of Integrated Collector Storage Systems with Transparent Insulation", Solar Energy, Vol. 41, No. 5, 1988, pp. 487-494.

Two integrated collector storage (ICS) prototypes with about 1 m^2 absorber surface each have been installed and investigated. Each consists of a water tank with an integrated collector, which is covered with a highly transparent insulating material and is very well insulated on the sides and at the back. During the test period from November 1986 to October 1987 one of them was operated at water-main pressure, and 40 liters (corresponding to the hot water consumption of one person) were withdrawn every day. The solar fraction was 58% (68% with a system efficiency of 28% (36%) (the values in parentheses also take the surplus energy in summer into account). The second one has been installed to study the stagnation (no water flow) performance during the same period.

Detailed computer simulation programs have been developed and compared with the experimental results. Based on the U-value and the transmittance-absorptance product, the annual performance can be predicted with the accuracy of 4%. The influence of various parameters such as specific water withdrawal, angle of inclination, profile of water withdrawal, required for water temperature, etc. on the yearly solar fraction and yearly efficiency of the ICS unit can be studied. Some of the results are presented here.

Integrated collector storage systems, with highly transparent insulating covers consisting of thin polycarbonate films arranged in a honeycomb structure, can be used without risk of damage caused by freezing in colder climates. The characteristics of this structures are heat transmittance (heat transfer coefficients to the surroundings not taken into account): 1.0 to 1.5 W/m²K, depending on the mean temperature of the material, diffuse-diffuse-transmittance: 64%, for 10 cm thickness, selective absorber ($\epsilon = 0.1$) and a 4 mm low iron glass pane. Apart from this, by using highly efficient transparent insulating materials for the collector storage cover, the system efficiency of ICS systems is considerably increased due to low heat losses so that they can compete with conventional solar collector systems. The two types of integrated collector storage were investigated. The tanks are coated with a layer of a selectively absorbing film (absorptance 0.95, emissivity 0.11). A sheet of fluorinated plastic film above the absorber serves to support the transparent insulating material and prevent convection. The collectors are protected from the weather by an outer glass cover. The tilt angle is 45° C.

The main design difference between the two ICS prototypes is their specific water volume: for the prototype with the aluminum flat tank, it is 96 liter/m² absorber surface compared to 117.8 liter/m² absorber surface for the prototype with the tubular subunits (the subunits are connected in series in order to simulate a well stratified tank). This means that the thermal inertia of the ICS with the flat tank design is smaller so that if this design does not lead to overheating or freezing problems in the stagnation condition (as tested) the design with the cylindrical subunits does not lead to such problems either (for the same climatic conditions). Damage caused by freezing of the ICS prototypes did not occur, even for the stagnation condition during the coldest winter periods (although at times the ICS was covered by snow). The boiling point was only reached a few times (in stagnation condition), so that, in a pressurized system, the maximum temperature would have been about 105° C.

The monthly measured and calculated solar fraction and efficiency are shown. Connection losses from pipes have not been taken into account. The accuracy of the calculated yearly performance is about 4%. The simulations are based on the measured values of the prototype and hourly weather data. The figure shows the solar fraction (which is defined as thermal output/demand) and efficiency as a function of the angle of inclination. The solar fraction reaches its maximum at an angle lower than the latitude, because most of the solar energy is available in summer at a lower zenith angle than of the latitude.

Using highly transparent, highly insulating materials, single-circuit operation of ICS systems is possible in central or northern Europe. The yearly solar fraction and efficiency are equal to or even better than those of conventional DHW systems. During 12 months of operation the solar fraction of the ICS prototype at Institute für Solare Energiesysteme (ISE) Freiburg, West Germany was 58% (68%) with an efficiency of 28% (36%) (specific water withdrawal: 40 l/day/m²). For simulating ICS systems, a computer model has been developed. Based on the Test Reference Year for Freiburg, parameter variations have been carried out in order to predict ICS performance. With the ISE prototypes, a yearly solar fraction of up two-thirds can be reached. The yearly solar fraction and efficiency depends on the temporal profile of the water withdrawal. Both increase by about 10% if the water is withdrawn immediately after sunset rather than continuously throughout the day.

Schweiger H., Oliva A., Costa M., Perez Sergarra C.D., "Optimization of Total Energy Transmittance and Heat Transfer in a Solar Collector with Honeycomb Glazing - A Numerical Study", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 66-69.

A two-dimensional numerical study of the combined conduction, convection and radiation heat transfer and solar radiation in a solar collector with a honeycomb glazing is presented. Two types of collectors are studied: a collector with a black painted absorber without a gap (type A) and a collector with a selective absorber and a 12 mm air gap between the absorber and the honeycomb (type B). The optimum geometry for honeycomb materials has been shown to lie at the maximum honeycomb thickness, at an optimum material content depending on the operation conditions and the climate, and at a very fine distribution of the material (i.e. a small wall thickness and high aspect ratio). In this limit convection is negligible. However, problems of manufacturing thin walled high aspect ratio honeycombs result in high fabrication costs. Therefore economical arguments may lead to compromise at larger cells just small enough to suppress convection. As few experimental data about combined radiation-convection in honeycomb structures are available, the presented simulation model may be a useful tool for the design of optimum honeycomb geometries. However, the two-dimensional simulation is restricted to nearly vertical inclination angles (75 - 90°). To obtain physically realistic results for other inclination angles, a three-dimensional simulation will be necessary.

Sick F., "Transparent Insulation - Simulation Programme", Proceedings of the 3rd International Workshop on Transparent Insulation Technology for Solar Energy Conversion, Freiburg, FRG, September 18-19, 1989, pp. 126-129.

Correct design and reliable performance estimates of active and passive solar systems incorporating transparent insulation materials (TIMs) require computer simulation programs capable to handle the special TIM characteristics. There are several programs available at the Fraunhofer-Institute for Solar Energy Systems: WANDSIM does dynamical calculations of TIM-insulated walls using finite differences and is the base module for HAUSSIM, a multi-zone model describing the thermal behavior of buildings. Several TIM wall modules were developed for the simulation package TRNSYS, one based on WANDSIM, and one using detailed transfer functions. Based on the latter, a simplified model was developed. Also for TRNSYS, an integrated collector storage model was written. With the help of the described TIM software, design procedures can be accelerated and improved. Examples for verification of the programs are given.

Sick F., Kummer J.P., "Simulation of Transparently Insulated Buildings", Solar Energy, Vol. 49, No. 5, 1992, pp. 429-434.

Computer models of transparently insulated walls are required in order to determine the effects these components have on building energy requirements. A simplified model of the optical portion of a transparently insulated wall has been developed. It is both fast and reasonably accurate. Using this simplified model the multizone component ("Type 56") of the simulation program TRNSYS has been extended to account for transparent or translucent massive or massless layers in the envelope of the building. This extension is based on the version 12.2 (1988) of TRNSYS. It is no problem, however, to link it with the current version 13.1. Any reasonable combination of transparent and opaque layers, including controllable shading devices, can be defined. The user-friendliness of the "Building Input Description" (BID) program has been maintained. A comparison of measured and simulated wall temperatures of a transparently insulated building in Freiburg is given.

Besides the proof of correct treatment of a transparently insulated wall, it was checked and validated

that the roller blind "mechanism" works accurately. The energy balances show good agreement with the measured data. The new windows work significantly better than the old ones due to the use of angle-dependent transmittance values. The conventional part of the TRNSYS TYPE 56 was checked and used before by many users many times and seems to be a reliable tool for building energy analysis. It is one of the most comprehensive, flexible, easy-to-use, and at the same time inexpensive programs for this purpose. The modified TYPE 56 component is based on the TRNSYS version 12.2 but fully compatible with the current version 13.1. The new component is available through the first author.

Soler S., Gery M., Chevalier J.L., "Theoretical and Experimental Study of the behavior of Multi-Wall Ribbed Materials Under Solar Radiation", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 114-117.

This paper is dedicated to one family of geometric media called "multi-wall ribbed materials". They are made of transparent or colored polymeric walls separated by parallel ribs. The authors developed a theoretical model especially for these materials, and they present it in this paper with applications to double and triple wall ribbed materials. This model simulates the track of a beam through the structure of the material, and this analytic approach gives a value of the directional/hemispherical transmittance. In parallel, the same optical characterization has been measured using the "megasphe", a large scale spectrophotometer for large size samples, with a 3 m diameter integrating sphere. Finally, the theoretical and experimental results are compared and discussed, in terms of improvement of the model for its expected use for luminous or energetic performance characterization and material design.

A sensitivity study was performed and the result is that the model is very dependent on the input data. For instance, the accepted variation of the dense material transmittance is 3% for the transparent one and 5% for the colored and diffusing ones. Given the structure parameters and the dense material transmittance, this model can calculate the optical behavior of the multi-wall ribbed materials. It may be a useful tool for material design and performance prediction.

Stahl W., Wilke W.S., "The Space Heating Concept of the Self-Sufficient Solar House Feiburg", Proceedings of the World Solar Congress of ISES, Denver, Colorado, 1991, pp. 2927-2932.

Even on overcast winter days, the solar radiation flux on vertical house walls exceeds the conductive heat flux outwards through the walls, which is caused by the temperature difference between indoors and outdoors. On transparently insulated house walls the insolation even on such days can be utilized to compensate for the conductive heat losses and to serve as an effective direct solar space heating system. The Self-Sufficient Solar House (SSSH) which is going to be built in Freiburg is heated with a solar fraction of more than 90% by such a wall with transparent insulation. The space heating demand of the SSSH is reduced to 300kWh/area (2 kWh/m² heated living area) auxiliary heating energy.

The optimal ground-plan for the SSSH was found to be a sector of a circle. This shape gives the best ratio between north oriented walls with energy losses and the south oriented TI wall. The energetic optimization of the SSSH was done by computer with the simulation program HAUSSIM. This program has been developed to simulate the new TI wall heating system. The TI wall heating system is combined with other measures to minimize heating energy demand. Windows with a U-value of 0.6 W/m²K, opaque wall insulation with $U < 0.2$ W/m²K, and an air ventilation system with highly

efficient heat recovery are the main components.

Svendsen S., Jensen K.I., "Flat Plate Solar Collector with Monolithic Silica Aerogel", Proceedings of the Biennial Congress of ISES, Hamburg, Germany, Sept. 13-18, 1987, pp. 620-624.

A monolithic silica aerogel has recently been developed and the material has been proved to have perfect qualities as transparent insulation in solar collectors. The heat transfer in a collector with MSA has been calculated. A full scale collector with MSA used as a top insulation has been designed, constructed, and tested in the solar simulation facility of the laboratory. The efficiency obtained from the testing was in relatively good agreement with the calculated efficiency and showed significant improvements compared to typical collectors with selective absorber coatings.

Svendsen S., "Solar Collector Based on Monolithic Silica Aerogel", Proceedings of the Biennial Congress of ISES, Kobe, Japan, Sept. 4-8, 1989, pp. 711-715.

A new design of a flat plate solar collector based on evacuated monolithic silica aerogel used on both sides of the absorber is described. The results of the calculation and test of the efficiency are presented and evaluated. Annual performance of the aerogel collector in a medium temperature application is compared with a conventional high temperature flat plate collector.

In order to evaluate the aerogel collector the annual performance was calculated for a fixed operating temperature of 60° C. This temperature is the minimum useable temperature for collectors connected to a district heating system. Under typical Danish climatic conditions the aerogel collector produced 700 kWh/m² per year or roughly twice as much energy as the conventional high temperature collector.

For application in DHW systems the advantage of the aerogel collector is of course smaller. For high temperature applications in solar autoclaves and solar freezers, where temperature of 130° C are necessary, the aerogel collector is much better than conventional high temperature flat plate collectors.

Twidell J.W., "The World's Largest Demonstration of Transparent Insulation for Buildings", Proceedings of the World Solar Congress of ISES, Denver, Colorado, 1991, pp. 2939-2944.

The new 376-student residences at the University of Strathclyde have been designed using low-energy principles of insulation and heat recovery, and with 1000 square meters of transparent insulation on the south facade. The building is a European Commission energy demonstration, first occupied in November 1989 and since monitored by the Energy Studies Unit. Early results are reported, indicating the success of the principles, but also mentioning the difficulties of practical implementation.

Twidell J.W., Johnstone C., Zuhdy B., Scott A., "Strthclyde University's Passive Solar, Low-Energy Residences with Transparent Insulation", Solar Energy, Vol. 52, No. 1, 1994, pp. 85-109.

These innovative buildings for 376 student are described from planning to the results of three years of monitoring. They are to date the world's largest demonstration of transparent insulation, being a demonstration project supported by the European Community and Scottish Enterprise. The factors considered are; design, construction, occupation, comfort, energy characteristics, performance of the

transparent insulation, including staining by pollution, overall energy consumption, cost effectiveness, practical aspects and important lessons learned. Monitoring shows that commercial energy use is 40% less than the "good" category of official UK indicators and a survey quantifies encouraging user satisfaction generally. The solar fraction of useful gain in winter is 20% of total energy. The south faces of the building have a monthly net gain of energy into the building throughout the year even in mid winter in Glasgow.

Van Dijk H.A.L., "Translucent Insulation for Passive Solar Energy Application", Proceedings of the World Solar Congress of ISES, Denver, Colorado, 1991, pp. 2933-2938.

A number of studies are being carried out at TNO Building and Construction Research in the Netherlands on the effect of translucent insulation materials for application in walls. For the Dutch situation, the feasibility of translucently insulated walls has been investigated. The possible energy savings of the current wall designs are estimated on 700 to 1200 MJ per m² facade. During the summertime the overheating may be a serious problem. Natural ventilation of the air gap is one of the possibilities to reduce the overheating. A preliminary test in one of the PASSYS test cells at the TNO showed promising results. Further and more detailed research and development has been started, like building simulations with TIM-walls and a second TIM-wall test in the PASSYS test facility.

Van der Leun C., Zegers F., "Application of Transparent Insulation Materials in Domestic Hot Water Systems", Proceedings of the 3rd International Workshop on Transparent Insulation Technology for Solar Energy Conversion, Freiburg, FRG, September 18-19, 1989, pp. 42-45.

The effect of application of transparent insulation materials in the cover of flat-plate collectors on the performance of a domestic hot water (DWH) system were studied. First, efficiency curves for collectors with a polycarbonate honeycomb structure in the cover were calculated. Using these curves, simulations with meteorological data from a Test Reference Year were done for a DHW-system, varying a number of system parameters.

Results indicate that a considerable reduction in collector area is possible. Addition of a 50 mm honeycomb to the glass cover of a collector with spectral selective absorber would result in an area reduction of 18%. Practical application in the drain back systems as used in the Netherlands will only be possible with a protection strategy or transparent insulation materials able to withstand the high collector stagnation temperatures. A prototype collector was built and measurements under a solar simulator are being done for verification of the calculated efficiency curves.

Wagner A., Asmussen J., Gimpel M., "Experimental Results of Two Different Solar Hot Water Systems Using Transparent Insulation", Proceedings of the 4th International Workshop on Transparent Insulation Technology, Birmingham, UK, May 28-30, 1991, pp. 66-69.

As a part of the Fraunhofer Institute's work on transparent insulation, two different solar hot water systems have been investigated on the outdoor test-field in Freiburg during summer 1990. The results of the performance tests of a transparently insulated collector storage were used for long term predictions. An annual system efficiency of 0.35 with a yearly solar fraction of 0.51 was calculated, assuming an absorber surface of 4.2 m². Additional measurements showed that the efficiency of a supplementary continuous-flow gas heater varied between 0.6 and 0.8 according to the working mode

of the burner.

First experiments with a newly designed multi-effect solar still show the possibility of increasing the system's productive capacity by the use of transparent insulation. A higher system temperature and the efficient recovery of latent heat lead to a high production rate of desalinated water.

Wilson H.R., "Transmission Switching Using Micro-Encapsulated Liquid Crystal Films", Solar Energy, Vol 49, No.5, 1992, pp. 435-445.

Micro-encapsulated liquid crystal devices have been prepared, which switch the amount of direct-hemispherical transmitted radiation in the solar spectral range by values up to 35%, depending on the film thickness and applied voltage. Examples of spectrally dependent transmittance, voltage dependence and angular distribution of the scattered radiation are presented. Such switchable devices can be considered for nonmechanical variable shading elements to prevent overheating in TIM systems.

Wilson H.R., Eck W., "Thermotropic Layers for Light Transmission Switching", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 102-105.

Thermotropic layer, which are characterized by a variable light transmittance depending on the temperature, have been developed to provide an alternative to mechanical systems for shading TI elements to prevent overheating. The type of layer investigated consists of a cross-linked polymer blend which changes reversibly from a transparent to light-scattering state when heated. It can be applied as a thin film onto the glass pane, and causes only a slight reduction (about 2%) in the light transmittance in its clear state. Above the switching temperature, the direct-hemispherical transmittance is decreased due to backward light scattering by 50% or more, depending on the thickness of the layer, which is typically between 300 μm and 1 mm. The switching temperature itself depends on the chemical composition of the blend and has been varied between 30 and 100° C in the investigated samples.

This paper presents a range of switching behavior (light transmittance vs. temperature) which has been achieved, results from long-term stability tests, approaches for large-area production, and the predicted effect on the light transmission control on complete TI systems, obtained with computer simulation.

The light transmission switching performance and the results of stability tests on thermotropic polymer layers indicate that these are suitable materials to prevent overheating behind TI facades. The results of initial simulation calculations of their effect on a standard building are also sufficiently positive to justify taking the next step and testing the suggested approaches for producing thermotropic polymer layer in architectural dimensions.

Wittwer V., Platzer W., "Transparent Insulation Materials", SPIE Optical Materials Technology for Energy Efficiency and Solar Energy Conversion IX, Vol. 1272, 1990, pp. 284-295.

Transparent or translucent insulation materials (TIM) represent a new class of materials with a high potential for increasing the efficiency of solar thermal systems. A large number of materials and material combinations have been subjected to theoretical and experimental investigation. An overview

of generic TIM's and existing materials available on the market, characterization methods and the future potential of transparently insulated systems follows.

A thorough description of the generic types of transparent insulation materials and experimental characterization of TIMs. The fundamental experimental set-ups which give global information about the basic physical quantities, heat transmittance coefficient U , solar transmittance and total energy transmittance are described. Measurements of solar transmittance and reflectance, measurement of heat transport, total energy transmittance are discussed. The systems and materials that are available on the market are examined in detail: honeycombs, capillary structures, and homogeneous materials (aerogel). Future potential of TIM's is outlined.

There are many applications for the various transparent insulation materials in the field of thermal solar energy. Prototypes have been designed, tested, and improved under laboratory and outdoor conditions during the last few years and some of these devices are now in use in pilot projects: space heating by transparently insulated walls, daylighting, integrated collector storage (ICS) for domestic hot-water, flat plate collector for process heat (90 to 150° C). The experimental, theoretical and practical work during the last few years has led to an essential understanding of transparent insulation materials. Materials now available reach heat loss coefficients of 0.8 W/m²K with diffuse transmission values of more than 0.7. The theoretical models and experimental set-ups have been validated and will be used for further improvements in the material. The initial applications have shown that well-known thermal solar systems can be significantly improved by the use of TIM's (e.g. process heat collectors) and completely new concepts are made possible (e.g. space heating with TI-walls). In order to develop more economic systems, cost reductions are now required for the materials and for the complete systems.

Wittwer V., Dengler J., "Granular Aerogel Windows", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 6-9.

Silica aerogel has ideal characteristics for solar-thermal applications. High transparency for solar radiation is combined with extremely low thermal conductivity. The chemical company BASF is developing a granular form of aerogel which will be on the market in the near future. The application potential of this material in window systems was tested as part of a CEC-JOULE project in cooperation with four other industrial companies and two research institutes under the leadership of FhG/ISE in Freiburg. A typical U -value for a double glazed window with a 16 mm thick layer of granular aerogel is 1.0 W/m²K and the solar transmission for diffuse light is about 45%. Both parameters are variable over a wide range depending on the particle size distribution, thickness of the layer, and choice of filling gas.

Wittwer V., "Transparent Insulation Materials", Proceedings of the 2nd International Workshop on Transparent Insulation in Solar Energy Conversion for Buildings & Other Applications, Freiburg, F.R.G., March 24-25, 1988, pp. 2-4.

Transparent insulation materials are characterized by physical properties which place them in a different class to both opaque insulation materials and conventional transparent systems. From the geometrical point of view, four different types can be distinguished: structures parallel to the absorber (multiple glazing), structures perpendicular to the absorber (honeycomb, capillary), scattering structures (foams, bubbles, fibers), homogeneous materials (aerogel). Equations for solar transmittance, total energy transmission, thermal conductivity and heat transfer coefficient are cited. Transmittance for diffuse solar irradiation, heat loss coefficient at 10° C mean temperature and thermal radiation penetration depth of transparent insulation materials (polycarbonate, polystyrol, polyamide,

polyvinylchloride, double glazing and aerogel windows) are tabulated.

Wittwer V., Platzer W., "Transparent Insulation - Materials", Proceedings of the 3rd International Workshop on Transparent Insulation Technology for Solar Energy Conversion, Freiburg, FRG, September 18-19, 1989, pp. 33-36.

Three fields of material development can be identified. If one uses granulated aerogel with different mean sphere diameters, the conductivity scales approximately linearly with this diameter, whereas transmittance measurements show a markedly reduced value below 3 mm, but minor variation of transmittance above 3 mm diameter. Capillary structures produced from different plastics, which may withstand higher temperatures than the usual ones, have been investigated. Some materials, in particular a special PMMA capillary, showed very good performance, whereas others have difficulties in reaching sufficiently high solar transmittances. From preliminary results of an optimization of rectangular polycarbonate honeycombs, new material has been produced which, in spite of some limitations due to the production process, show a 10% decrease in thermal conductance when compared to the previous design. The solar characteristics of the materials are identical.

Heat transfer coefficient and diffuse-diffuse transmittance of aerogel windows (filling 22 mm) with different granule size is graphed. Fractioned aerogel granules for window fillings, capillary structures from plastics with higher temperature-resistance and optimization of honeycombs with rectangular cross-section are reflected.

Wood M., "Economics of Transparent Insulation", Proceedings of the Sixth International Meeting on Transparent Insulation Technology, Birmingham, UK, June 3-5, 1993, pp. 86-89.

The energy benefits provided by the transparent insulation to one room of the Bournville demonstration house, Birmingham, UK, are presented in this paper. A thermal simulation model was set up of one room of the house with transparent insulation on the south n east walls. The simulation program used was TRNSYS. The model was verified with monitored results from the demonstration house. The model was then run for a design year. Three other models were set up of the same room without transparently insulated walls. The transparent walls were replaced with a concrete wall, wall of U-value specified by UK Building Regulations, or a highly insulated cavity wall. These three models were also run for a design year. The energy benefits due to transparent insulations were compared to those of the three references as determined by simulation results.

The author concluded that transparent insulation installation at the demonstration house is cost-effective. The payback period for Transparent insulation compared to the three reference walls was between 12.65 and 13.22 years. For increased uptake of the technology, when this is based on just economic incentives, the payback period will have to be reduced even further. The average homeowner would not live in a house for more than 13 years so they would not profit from the energy savings provided by the transparent insulation.

Yang H.X., Brinkworth B.J., Marshall R.H., "The Potential Utilization of TIM in Passive Solar Buildings in China", Proceedings of the World Solar Congress of ISES, Denver, Colorado, 1991, pp. 2945-2050.

This paper describes some simulation results for the potential utilization of transparent insulation material in passive solar buildings in China. Since northern and central China have a very long

winter and clear weather, and southern China has a shorter winter but not a very low temperature climate, the potential for applying TIM to new passive solar buildings or to existing houses is very great. The measured meteorological data are processed for six different locations over China. They are used as input for the TIMWAL simulation model, developed for simulating TIM passive solar buildings. Results show that the increment of indoor air temperature could reach 5 to 10 degrees, depending on the location of the building considered.

Zegers F.T.S., van der Leun C.J., "Application of Transparent Insulation Materials in Flat Plate Collectors", Proceedings of the 4th International Workshop on Transparent Insulation Technology, Birmingham, UK, May 28-30, 1991, pp. 78-81.

The effect of application of transparent insulation materials in the cover of flat-plate collectors has been studied. In earlier studies, efficiency curves for collectors with a polycarbonate honeycomb structure in the cover were calculated and using these curves, simulations were done for a domestic hot water (DHW) system. Results indicated that for a given solar fraction a considerable reduction in collector area is possible.

Following this work a prototype honeycomb collector was constructed. The collector was equipped with a spectrally selective absorber, a 2 cm air gap and 10 cm polycarbonate honeycomb below the low-iron glass cover. Efficiency curves of this collector were determined under a solar simulator to verify the calculated curves. After correction, the correspondence of the calculated efficiency curves with the measured ones was within 4%. An efficiency improvement was of 22% was reached, compared to a similar collector with single glass cover.

One of the remaining limitations for practical application of polycarbonate honeycomb structures is the sufficient heat resistance during stagnation. A solution to this problem could be the application of aerogel transparent insulation materials which are more heat resistant. The authors are conducting computer simulations to prepare the construction of a solar collector with monolithic aerogel tiles in the cover for testing purposes.

Zhao M., Kuhnke K., "Solar Energy Transmission of Horizontal Honeycomb Structures", Proceedings of the 3rd International Workshop on Transparent Insulation Technology for Solar Energy Conversion, Freiburg, FRG, September 18-19, 1989, pp. 24-28.

Based on transmittance measurements, the transmitted solar energy has been calculated for structures of vertical (VHC) and tilted (THC) polycarbonate honeycomb structures. Transmitted beam/circumsolar and global radiation was calculated for locations of different geographic latitudes. From northern to tropical regions, THC perform better than VHC, and only for equatorial locations, VHC perform less than 5% better than THC.

From transmittance measurements with 10 cm VHC and 10 cm 45° THC, and from numerical radiation simulations, it can be concluded that horizontal THC transmit significantly more solar energy than VHC of the same thickness at all locations from high to subtropical latitudes. This effect is due to the tilted optical axis of the THC cells which matches better with the frequent south-inclined positions of the sun in these areas in the northern hemisphere (and north-inclined sun positions in the respective southern areas). The transmitted uniform part of the diffuse radiation is approximately the same for both types of HC. Even in tropical areas, THC perform slightly better than VHC, and only at equatorial locations, VHC transmit more solar energy than THC.

Because the thermal insulation of THC is also more effective than that of VHC of the same thickness,

THC are the better transparent insulation material for all horizontal applications like solar ponds, transparent roof insulation, solar cookers, etc.

Zupan M., Bostjancic J., "Solar Gains by Transparent Thermal Insulation, Comparative Measurements on Test Cells over one Heating Season", Proceedings of the World Solar Congress of ISES, Denver, Colorado, 1991, pp. 2971-2976.

A test facility with four identical test cells was designed and built to make comparative tests of solar energy efficiency on different types of walls and passive solar elements. Measurements were made on a wall with 6 cm capillary structure TIM, compared to opaque wall, once without and once with thermal insulation, and a wall with a window. These three types represent the most commonly used walls in Slovenia. The measurements were performed from October 16, 1989 to May 29, 1990.

The results on the four test walls pointed out that the wall with the transparent thermal insulation had only about 45% energy losses compared to the wall with opaque thermal insulation. The efficiency for the solar gains is very high and it shows promise for the region where the measurements were performed (the basin) and even better for the regions with low temperatures and a clear sky (the mountains).

APPENDIX B
TRANSPARENT INSULATION SPECIFICATION SHEETS

TRANSPARENT INSULATION MATERIAL

FACT SHEET

Specific Material Description:	The product is a honeycomb structure or panel that consists of an array of cells with thin walls that are shared on a cell to cell basis. The cell cross section can be round, square, hexagonal, sinusoidal and other geometries. An individual cell can have various cell diameter to length ratios and still provide high transmission of short wave radiant solar energy and be substantially black to the transmission of infrared radiation. The infrared radiation is from the material below the honeycomb that has been heated by the absorption of solar radiation. Further enhancement of heat trapping is also accomplished by the honeycomb through reduction of convective and conductive heat transfer. The material of the cell can be glass or any number of natural or plastic type materials as long as they transmit light or solar radiation. Polycarbonate material has been commercialized as the prime material for the honeycomb, has been extensively analyzed, tested and indicates a cost/benefit ratio attractive for the applications indicated below.	
Capability:	Transmit over 80% light with R values up to 2 per inch	
History:	More than 30 years in concept, test and commercial development	
Suppliers:	Several international (Sterling Energy in USA)	
Material of Choice:	General Electric Lexan 141 (or equivalent) See Polycarbonate Specifications	
Shape of Choice:	Honeycomb with 1/8" diameter holes and .001" wall thickness and depth of 2" to 4". Aspect ratio of 14 or greater for 1/8" diameter holes.	
UV Stability:	Poor, requires protection	Density: 2 pounds per cubic foot
Wet Service Temperature:	176°F	Dry Service Temperature: 266°F
Melting Temperature:	356°F	Processing Temperature: 536°F
Applications:	Skylights, facades, passive and active solar water heating, solar pond covers and novelty consumer products	

**POLYCARBONATE SPECIFICATIONS
TYPICAL PROPERTY VALUES
ENGLISH UNITS (SI UNITS)**

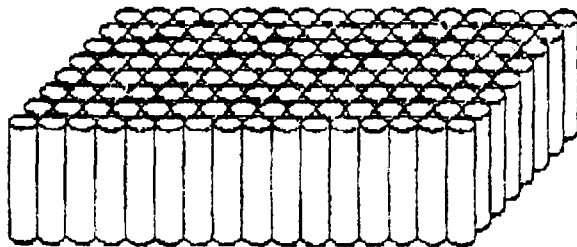
<u>Mechanical</u>		<u>Value</u>
Tensile Strength, psi (MPa)	Yield	9,000 (62)
	Ultimate	10,000 (69)
Elongation, %	Rupture	130
Compressive Strength, psi (MPa)		12,500 (86)
Shear Strength, psi (MPa)	Yield	6,000 (40)
	Ultimate	10,000 (70)
Tensile Impact Strength, ft-lbs/in ² (kJ/m ²)	S-type	275 (578)
Rockwell Hardness	M	70
	R	118
Taber Abrasion Resistance, weight loss,	mg/1000 cycles	10
<u>Thermal</u>		
Specific Heat, Btu/lb/°F (kJ/kg/°K)		0.30 (1.25)
Thermal Conductivity	Btu-in/hr-ft ² -°F (W/km)	1.35 (0.19)
Coefficient of Thermal Expansion	in/in/°F (m/m/°C)	3.75 x 10 ⁻⁵
Flammability Ratings	ASTM D635	AEB < 1"
<u>Electrical</u>		
Dielectric Strength, volts/mil (kV/mm)	Short time, 125 mils (3.2 mm)	380 (15.0)
Dielectric Constant	60 Hz	3.17
	10 ⁶ Hz	2.96
Volume Resistivity, ohm-cm	@ 73°F, dry (23°C)	> 10 ¹⁶
<u>Physical</u>		
Weight/Volume, lbs/in ³ (g/cm ³)		0.043 (1.20)
Water Absorption, %	24 hrs @ 73°F (23°C)	0.15
	Equilibrium, 73°F (23°C)	0.35
	Equilibrium, 212°F (100°C)	0.58
Light Transmittance, % @ 0.125"		89
Refractive Index		1.586

KAPIPANE

Transparent Insulating Material (TIM)
Capillary slab for Passive Solar Energy Gain

Construction:

KAPIPANE transparent insulating material is made of clear plastic tubes arranged like a honeycomb vertically to the surface of the panel. The diameter of the tubes is approx. 4 mm.



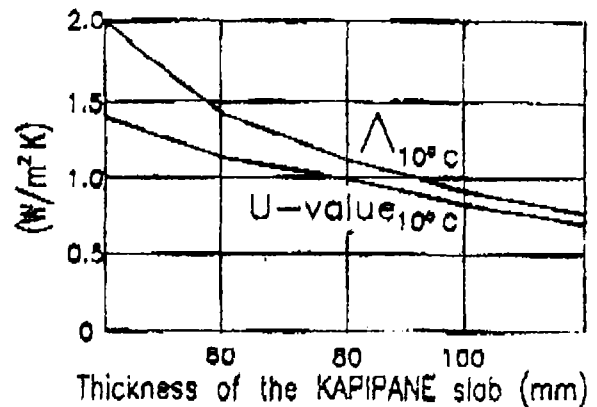
Material:

The basic material of KAPIPANE is clear acrylic (Plexiglas[®], Degalan[®]). The maximum application temperature is 90 °C. The density of the capillary slab is approx. 30 kg/m³.

Properties:

KAPIPANE has high transmittance for solar radiation and good thermal insulation. Thermal insulation is due to suppression of convection in the long tubes and attenuation of long wave IR radiation in the acrylic material. The tubes of the capillary slab transmit solar radiation in the manner of optical

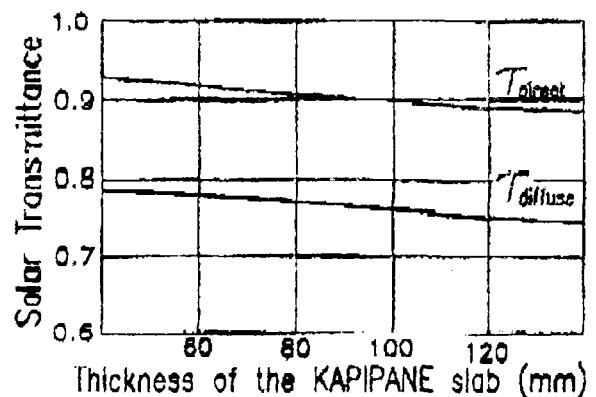
fibres, thus achieving high transmittance almost irrespective of thickness.



Availability:

Thickness (mm):	62	82	122
U-value (W/m²K):	1,2	1,0	0,65
T _{diffus} (%) :	78	77	75

KAPIPANE is manufactured in sizes to order. The KAPIPANE slab is difficult to handle because of its brittleness. For reasons of handling, the dimensions of units should not exceed 1 m². KAPIPANE slabs can be joined to bigger units. The slabs can easily be cut to required size.



APPENDIX C
COLLECTOR SUMMARY INFORMATION SHEETS

SUMMARY INFORMATION SHEET

FLORIDA SOLAR ENERGY CENTER

300 STATE ROAD 401, CAPE CANAVERAL, FLORIDA 32920, (305) 783-0300



April 1982

FSEC # 820780

MANUFACTURER

Solar Resources International
1735 E. Indian School Road
Phoenix, Arizona 85016

Collector Model

SOL-R-BEAM #SB201

This solar collector was evaluated by the Florida Solar Energy Center (FSEC) in accordance with prescribed methods and was found to meet the minimum standards established by FSEC. This evaluation was based on solar collector tests performed at DSET Laboratories, Phoenix, Arizona. The purpose of the tests is to verify initial performance conditions and quality of construction only. The resulting certification is not a guarantee of long term performance or durability.

DESCRIPTION

Gross Length	2.438 meters	8.00 feet
Gross Width	0.559 meters	1.83 feet
Gross Depth	0.203 meters	0.67 feet
Gross Area	1.363 square meters	14.67 square feet
Transparent Frontal Area	1.249 square meters	13.44 square feet
Volumetric Capacity	2.6 liters	0.7 gallons
Weight (empty)	11.3 kilograms	25.0 pounds
Recommended Flow Rate	40 ml/s	0.6 gpm
Maximum Operating Pressure	552 kPag	80 psig
Maximum Wind Load	1197 Pa	25 psf
Number of Cover Plates	One	
Flow Pattern	Series	
Number of Flow Tubes	One	

MATERIALS

Enclosure	Aluminum frame
Glazing	Polyvinyl fluoride film, 0.01 cm thick
Absorber	Copper tube with concentrator
Absorber Coating	Black chrome selective coating
Insulation	None

THERMAL PERFORMANCE

Tested per ASHRAE 93-77

$$\text{Incident Angle Modifier } K_{\tau\alpha} = 1.0 - 0.67 \left(\frac{1}{\cos\theta} - 1 \right)$$

Based on
Total Radiation

Efficiency Equations

$$\eta = 56.3 - 184 (T_i - T_a)/I$$

$$\eta = 56.3 - 32 (T_i - T_a)/I$$

$$\eta = 55.8 - 126 (T_i - T_a)/I - 726 [(T_i - T_a)/I]^2 \quad \eta = 55.8 - 22 (T_i - T_a)/I - 22 [(T_i - T_a)/I]^2$$

Units of $T_i - T_a/I$ are $\text{Watt}/^\circ\text{C}\cdot\text{m}^2$

Units of $T_i - T_a/I$ are $\text{Btu}/^\circ\text{F}\cdot\text{ft}^2\cdot\text{hr}$

RATING

The collector has been rated for energy output on measured performance and an assumed standard day. Total solar energy available for the standard day is 5045 watt-hours/ m^2 (1600 Btu/ ft^2) distributed over a 10 hour period.

Output energy ratings for this collector based on the second-order efficiency curve are:

Collector Temperature		Energy Output	
Low Temperature, 35°C (95°F)	292	13,300 Kilojoules/day	12,600 Btu/day
Intermediate Temperature, 50°C (122°F)		12,100 Kilojoules/day	11,500 Btu/day
High Temperature, 100°C (212°F)		7,400 Kilojoules/day	7,000 Btu/day

SUMMARY INFORMATION SHEET

FLORIDA SOLAR ENERGY CENTER

300 STATE ROAD 401, CAPE CANAVERAL, FLORIDA 32920. (305) 783-0300



May 1984

FSEC # 84044D

MANUFACTURER

Solar Resources International
1735 E. Indian School Road
Phoenix, Arizona 85014

Collector Model

SB 301

This solar collector was evaluated by the Florida Solar Energy Center (FSEC) in accordance with prescribed methods and was found to meet the minimum standards established by FSEC. This evaluation was based on solar collector tests performed at DSET Laboratories, Phoenix, Arizona. The purpose of the tests is to verify initial performance conditions and quality of construction only. The resulting certification is not a guarantee of long term performance or durability.

DESCRIPTION

Gross Length	2.458 meters	8.06 feet
Gross Width	0.587 meters	1.93 feet
Gross Depth	0.184 meters	0.60 feet
Gross Area	1.444 square meters	15.54 square feet
Transparent Frontal Area	1.275 square meters	13.72 square feet
Volumetric Capacity	2.3 liters	0.6 gallons
Weight (empty)	13.6 kilograms	30.0 pounds
Recommended Flow Rate	32 ml/s	0.5 gpm
Maximum Operating Pressure	552 kPag	80 psig
Maximum Wind Load	1987 Pa	41.5 psf
Number of Cover Plates	One	
Flow Pattern	Series	Forced circulation
Number of Flow Tubes	One	

MATERIALS

Enclosure	Aluminum frame
Glazing	Polyvinyl flouride film, 0.15 cm thick
Absorber	Copper tube with concentrator
Absorber Coating	Black chrome selective coating
Insulation	None

THERMAL PERFORMANCE

Tested per ASHRAE 93-77

Incident Angle Modifier Non-Linear

Efficiency Equations

*: Total Radiation
**: Direct Normal Radiation

$$\begin{aligned} \eta &= 45.1 - 145 \frac{(T_i - T_a)}{I}^* - 55.3 - 147 \frac{(T_i - T_a)}{I}^{**} \\ \eta &= 44.7 - 107 \frac{(T_i - T_a)}{I} - 452 \left[\frac{(T_i - T_a)}{I} \right]^2 * - 54.8 - 106 \frac{(T_i - T_a)}{I} - 390 \left[\frac{(T_i - T_a)}{I} \right]^2 ** \end{aligned}$$

$$\begin{aligned} \eta &= 45.1 - 25 \frac{(T_i - T_a)}{I}^* - 55.3 - 26 \frac{(T_i - T_a)}{I}^{**} \\ \eta &= 44.7 - 18 \frac{(T_i - T_a)}{I} - 14 \left[\frac{(T_i - T_a)}{I} \right]^2 * - 54.8 - 19 \frac{(T_i - T_a)}{I} - 12 \left[\frac{(T_i - T_a)}{I} \right]^2 ** \end{aligned}$$

Units of $T_i - T_a / I$ are $^{\circ}\text{C} \cdot \text{m}^2 / \text{Watt}$

Units of $T_i - T_a / I$ are $^{\circ}\text{F} \cdot \text{ft}^2 \cdot \text{hr} / \text{Btu}$

RATING

The collector has been rated for energy output on measured performance and an assumed standard day. Total solar energy available for the standard day is 5045 watt-hours/m² (1600 Btu/ft²) distributed over a 10 hour period. These ratings are based on total global radiation.

Output energy ratings for this collector based on the second-order efficiency curve are:

Collector Temperature		Energy Output	
Low Temperature, 35°C (95°F)	293	11,300 Kilojoules/day	10,700 Btu/day
Intermediate Temperature, 50°C (122°F)		10,300 Kilojoules/day	9,700 Btu/day
High Temperature, 100°C (212°F)		6,500 Kilojoules/day	6,200 Btu/day

SUMMARY INFORMATION SHEET

FLORIDA SOLAR ENERGY CENTER

300 STATE ROAD 401, CAPE CANAVERAL, FLORIDA 32920-4099, (407) 783-0300



January 1993
FSEC # 92030

MANUFACTURER

Nippon Electric Glass America
650 E. Devon Ave., Suite 100
Itasca, Illinois 60143

Collector Model
PK-10 Sunfamily

This solar collector was tested by the Florida Solar Energy Center (FSEC) in accordance with prescribed methods and was found to meet the minimum standards established by FSEC. The purpose of the tests is to verify initial performance conditions and quality of construction only. The resulting certification is not a guarantee of long term performance or durability.

DESCRIPTION

Gross Length	2.477	meters	8.13	feet
Gross Width	0.674	meters	2.21	feet
Gross Depth	0.165	meters	0.54	feet
Gross Area	1.504	square meters	16.19	square feet
Transparent Frontal Area	1.169	square meters	12.58	square feet
Volumetric Capacity	76.1	liters	20.1	gallons
Weight (empty)	42.5	kilograms	93.8	pounds
Recommended Flow Rate	23	ml/s	0.4	gpm
Maximum Operating Pressure	552	kPag	80	psig
Maximum Wind Load	3591	Pa	75	psf
Number of Cover Plates	One			
Flow Pattern	Parallel/series combination		Forced circulation	
Number of Flow Tubes	Four			

MATERIALS

Enclosure	Galvanized steel frame
Glazing	Evacuated glass tubes, 0.20 cm thick
Absorber	Copper Tank
Absorber Coating	Selective coating
Insulation	Evacuated tube, 0.64 cm thick; Fiberglass, 5.1 cm thick

THERMAL PERFORMANCE

Tested per ASHRAE 93-1986

Incident Angle Modifier $K_{\tau\alpha} = 1.0 - 0.05 \left(\frac{1}{\cos\theta} - 1 \right)$ Longitudinal $K_{\tau\alpha} = 0.905 + \sqrt{[0.293 * (0.0212 + \left(\frac{1}{\cos\theta} - 1 \right))]}$ Transverse

Test Flow Rate 5.7 ml/s 1.5 gpm

Efficiency Equations

$$\eta = 61.0 - 268 (T_i - T_a)/I$$

$$\eta = 61.0 - 47 (T_i - T_a)/I$$

$$\eta = 60.2 - 190 (T_i - T_a)/I - 967 [(T_i - T_a)/I]^2 \quad \eta = 60.2 - 33 (T_i - T_a)/I - 30 [(T_i - T_a)/I]^2$$

Units of $T_i - T_a/I$ are $^{\circ}\text{C}/\text{Watt}/\text{m}^2$

Units of $T_i - T_a/I$ are $^{\circ}\text{F}/\text{Btu}/\text{hr ft}^2$

RATING

The collector has been rated for energy output on measured performance and an assumed standard day. Total solar energy available for the standard day is 5045 watt-hours/m² (1600 Btu/ft²) distributed over a 10 hour period.

Output energy ratings for this collector based on the second-order efficiency curve are

Collector Temperature

Energy Output

Low Temperature, 35°C (95°F)	15,500	Kilojoules/day	14,700	Btu/day
Intermediate Temperature, 50°C (122°F)	13,600	Kilojoules/day	12,900	Btu/day
High Temperature, 100°C (212°F)	7,000	Kilojoules/day	6,600	Btu/day

SUMMARY INFORMATION SHEET

FLORIDA SOLAR ENERGY CENTER

300 STATE ROAD 401, CAPE CANAVERAL, FLORIDA 32920-4099. (407) 783-0300



October 1992
FSEC # 92010N

MANUFACTURER

Nippon Electric Glass America
650 E. Devon Avenue, Suite 110
Itasca, Illinois 60143

Collector Model
Suntube DP6-2800

This solar collector was evaluated by the Florida Solar Energy Center (FSEC) in accordance with prescribed methods and was found to meet the minimum standards established by FSEC. This evaluation was based on solar collector tests performed at National Solar Test Facility, Mississauga, Ontario, Canada. The purpose of the tests are to verify initial performance conditions and quality of construction only. The resulting certification is not a guarantee of long term performance or durability.

DESCRIPTION

Gross Length	2.972 meters	9.75 feet
Gross Width	0.930 meters	3.05 feet
Gross Depth	0.185 meters	0.61 feet
Gross Area	2.764 square meters	29.75 square feet
Transparent Frontal Area	2.452 square meters	26.39 square feet
Volumetric Capacity	3.0 liters	0.8 gallons
Weight (empty)	63.5 kilograms	140.0 pounds
Recommended Flow Rate	189 ml/s	3.0 gpm
Maximum Operating Pressure	552 kPag	80 psig
Maximum Wind Load	7182 Pa	150 psf
Number of Cover Plates	One	
Flow Pattern	Parallel	Forced circulation
Number of Flow Tubes	Six	

MATERIALS

Enclosure	Galvanized steel frame
Glazing	Evacuated glass tubes, 0.20 cm thick
Absorber	Copper tubes mechanically bonded to steel sheet
Absorber Coating	Selective coating
Insulation	Evacuated tube; Fiberglass, 5.1 cm thick

THERMAL PERFORMANCE

Tested per ASHRAE 93-1986

$$\text{Incident Angle Modifier } K_{\tau\alpha} = 1.0 - 0.21 \left(\frac{1}{\cos\theta} - 1 \right)$$

Test Flow Rate 55 ml/s 0.87 gpm

Efficiency Equations

$$\eta = 50.0 - 154 (T_i - T_a)/I \quad \eta = 50.0 - 27 (T_i - T_a)/I$$

$$\eta = 49.8 - 111 (T_i - T_a)/I - 513 [(T_i - T_a)/I]^2 \quad \eta = 49.8 - 19 (T_i - T_a)/I - 15 [(T_i - T_a)/I]^2$$

Units of $T_i - T_a/I$ are $^{\circ}\text{C}/\text{Watt}/\text{m}^2$

Units of $T_i - T_a/I$ are $^{\circ}\text{F}/\text{Btu}/\text{hr ft}^2$

RATING

The collector has been rated for energy output on measured performance and an assumed standard day. Total solar energy available for the standard day is 5045 watt-hours m^2 (1600 Btu ft^2) distributed over a 10 hour period

Output energy ratings for this collector based on the second-order efficiency curve are

Collector Temperature		Energy Output	
Low Temperature, 35 $^{\circ}\text{C}$ (95 $^{\circ}\text{F}$)		24,100 Kilojoules/day	22,900 Btu/day
Intermediate Temperature, 50 $^{\circ}\text{C}$ (122 $^{\circ}\text{F}$)	295	22,100 Kilojoules/day	21,000 Btu/day
High Temperature, 100 $^{\circ}\text{C}$ (212 $^{\circ}\text{F}$)		14,200 Kilojoules/day	13,500 Btu/day

PRELIMINARY TEST RESULTS OF THE IST TROUGH COLLECTOR

Black Nickel selective absorber, Solgel receiver glass

$$\eta = K [76.25 - 0.006836 (\Delta T)] - 14.68 (\Delta T/T) - 0.1672 (\Delta T^2/T) \quad (1)$$

Black Nickel selective absorber, Pyrex receiver glass

$$\eta = K [72.36 - 0.006836 (\Delta T)] - 14.68 (\Delta T/T) - 0.1672 (\Delta T^2/T) \quad (2)$$

Black chrome selective absorber, Solgel receiver glass

$$\eta = K [74.52 - 0.009764 (\Delta T)] - 23.26 (\Delta T/T) - 0.1355 (\Delta T^2/T) \quad (3)$$

Black chrome selective absorber, Pyrex receiver glass

$$\eta = K [70.75 - 0.01028 (\Delta T)] - 23.27 (\Delta T/T) - 0.1355 (\Delta T^2/T) \quad (4)$$

Incident Angle Modifier, K

$$K = \cos (I_a) + 0.0003178 (I_a) - 0.00003985 (I_a)^2 \quad (5)$$

In performance equations (1) through (5):

- η = Collector efficiency, in percent
- K = Incident angle modifier
- I = Incident direct normal solar irradiance, W/m^2
- ΔT = Receiver fluid temperature above ambient air temperature, $^{\circ}C$
- I_a = Solar beam incident angle, in degrees

APPENDIX D
NOMENCLATURE

NOMENCLATURE

A	aspect ratio of the honeycomb (L/D)
a	extinction coefficient of the honeycomb wall material
$\alpha(\phi)$	absorptivity of honeycomb wall of thickness δ , when radiation is incident at angle ϕ
$b(\theta)$	$e^{-b(\theta)}$ is the fraction of top-face radiation striking the bottom face
B	fraction of honeycomb crosssection occupied by cell wall material
D	honeycomb cell hydraulic diameter
η	collector efficiency in percent
$\eta(\theta)$	solar collector efficiency for solar radiation at angle θ
ϵ	emissivity
F'	collector efficiency factor
F_R	collector heat removal factor
F_{a-b}	view factor for radiative exchange between surfaces a and b
F_{a-b}^s	specular view factor for radiative exchange between surfaces a and b
$\mathcal{F}_{a-b}$	Hottel's script F factor for radiative exchange between surfaces a and b
h_{conv}	convective heat transfer coefficient
I	incident direct normal
K	incident angle modifier
k_a, k_s	absorption and scattering coefficients of honeycomb wall material, respectively
κ	thermal conductivity
δ	thickness of the honeycomb cell wall
L	height of the honeycomb
n	index of refraction
q	heat flux (used with subscripts rad for radiative, cond for conductive, and conv for convective)
σ	Boltzmann's constant
$\rho(\phi)$	reflectivity of honeycomb wall for radiation incident at angle ϕ
ϕ	angle of incidence of solar radiation on the honeycomb wall ($\theta = \pi/2 - \phi$)
R	relection counter
$r(\theta)$	single interface reflectivity for a smooth surface bounded by air and honeycomb wall material, when unpolarized radiation is incident at angle θ
T	temperature
$T(\theta)$	transmittance of total honeycomb to radiation incident at angle θ
$T_c(\theta)$	transmittance to solar radiation for radiation striking the honeycomb cell contained between side-walls
$T_E(\theta)$	transmittance to solar radiation for radiation striking the top edge of the honeycomb side-walls
$T_D(\theta)$	the fraction of the radiation striking the honeycomb cell top surface which arrives at the absorber surface via specular reflections only
$\tau(\phi)$	transmissivity of honeycomb wall for radiation incident at angle ϕ
θ	angle of incidence of solar radiation with the top of the honeycomb sheet
θ_c	critical angle
ψ	dimensionless heat flux

Distribution STDAC-FSEC

Advanced Thermal Systems
Dave Gorman
7600 East Arapahoe Rd. Suite 215
Englewood CO 80112

American Energy Technologies, Inc.
Mr. G. Peebles
3530 Enterprise Way
Green Cove Springs FL 32043-1865

Arizona Department of Commerce
Arizona Energy Office
Frank P. Mancini, Ph.D.
3800 N. Central, Suite 1200
Phoenix AZ 85012

Arizona Public Service Company
Peter E. Eckert
1500 E. University
Tempe AZ 85281

Arizona State University
College of Engineering and Applied Sciences
Byard D. Wood, Ph.D., P.E.
Director and Professor
Tempe, AZ 85287-5806

Ascension Technology
Ed Kern
Box 314
Lincoln Center MA 01773

California Energy Commission
Promod Kulkarnj
1516 - 9th Street
Sacramento CA 95814

Commonwealth of Virginia
Department of Mines, Minerals, Energy
Susie Thomas
Ninth Street Office Blvd.
8th Floor
202 North Ninth St.
Richmond VA 23219

Cummins Engine Company
Dr. Isoroku Kubo
Mail Code 50160
Box 3005
Columbus IN 47202-3005

DynCorp Meridian
Robert E. N. Muhn
Technical Director, International Projects
4300 King Street, Suite 400
Alexandria, VA 22302-1508

Electric Power Research Inst.
E. DeMeo
3412 Hillview Avenue
Palo Alto CA 94303

Energy Concepts Co.
Don Erickson
627 Ridgely Ave.
Annapolis MD 21401

ESELCO
Sheldon L. Levy
8116 Fontana
Prairie Village KS 66208

FAFCO
Freeman Ford
2690 Middlefield Road
Redwood City CA 94063

Federal Energy Management Activities
CE 10.1
U.S. Department of Energy
1000 Independence Ave.
Washington DC 20585

Florida Solar Energy Center (4)
David Block
Kirk Collier
Jim Huggins
John Harrison
300 State Road 401
Cape Canaveral FL 32920

Hawai'i Energy Extension Service
Andrea Gill Beck
Department of Business and Economic Development
Hawai'i Business Center
99 Aupuni Street #214
Hilo HI 96720

Hawaii Solar Energy Association
Ron Richmond
PO Box 23350
Honolulu Hawaii 96823

Heliodyne, Inc.
Jurg H. Bieri, Ph.D.
4910 Seaport Ave.
Richmond CA 94804

Hydrogen Engineering Associates
Harry W. Braun
PO Box 62892
Phoenix AZ 85082

Industrial Solar Technology
Randy Gee
5771 West 52nd Ave.
Denver CO 80212

Brian Johnson
Energy, Minerals, and Natural Resources Dept.
(EMNRO)
2040 S. Pacheco St.
Santa Fe NM 87505

Kearney & Associates
David W. Kearney
14022 Condessa Drive
Del Mar CA 92014

KJC Operating Company
Gilbert Cohen
41100 Highway 395
Boron CA 93516

National Renewable Energy Lab (2)
Jim Jones
Russ Hewett
1617 Cole Blvd.
Golden CO 80401-3393

National Renewable Energy Lab
Mary Jane Hale
1617 Cole Blvd.
Golden CO 80401

National Renewable Energy Lab
Tom Williams
1617 Cole Blvd.
Golden CO 80401

New Mexico State University
Southwest Technology Development Institute
Steve Durand
Box 30001/Dept. 3SOL
Las Cruces NM 88003-0001

New Mexico State University
Southwest Technology Development Institute
Andrew L. Rosenthal
Box 30001/Dept. 3SOL
Las Cruces NM 88003-0001

New Mexico State University
Southwest Technology Development Institute
Dr. Rudi Schoenmackers
Box 30001/Dept. 3SOL
Las Cruces NM 88003-0001

Nippon Electric Glass Co., Ltd.
Bernard L. Steierman
11801 Rockville Pike Suite 1704
Rockville MD 20852

NREL
Chuck Kutscher, P.E.
Senior Engineer
1617 Cole Boulevard
Golden CO 80401

Packerland Solar System
Richard Lane
PO Box 8262
Green Bay WI 54308

Pennsylvania Energy Office
Director
116 Pine Street
Harrisburg PA 17101-1227

Portland State University
Jean P. Murray, Ph.D.
PO Box 751
Portland OR 97207-0751

Radco Products, Inc.
George O. Radford
President
2877 Industrial Parkway
Santa Maria CA 93455

SAIC
Barry L. Butler, SEIA Chairman
Room 2043, M/S C2J
10260 Campus Point Drive
San Diego CA 92121

Scholfield Solar
Allen Carrozza
2450 Channel Drive, Suite A
Ventura CA 93003

Science Applications International Corp.
Kelly Beninga
Division 448
15000 West 6th Ave., Suite 202
Golden CO 80401

SMUD
Don Osborne
Box 15830
Sacramento CA 95852-1830

Solar Energy Industries Association
Ann Polansky
777 North Capital Street, NE
Suite 805
Washington DC 20002-4226

Solar Energy Industries Assn (3)
Ken Sheinkopf
Linda Ladas
Scott Sklar
Suite 805
777 N. Capitol St. NE
Washington DC 20002-4226

Solar Kinetics, Inc.
Paul Schertz, Vice President
10635 King William Drive
Dallas TX 75220

Solar Steam
D. E. Wood
PO Box 32
Fox Island WA 98333

State of California (2)
California Energy Commission
Energy Technology Development Division
Research and Development Office
Promod Kulkarni
Phil Misemer
1516 9th Street
MS-43
Sacramento CA 95814-5512

State of Hawaii
David A. Rezachek, Ph.D., P.E.
Department of Business and Economic Development
335 Merchant St., Room 110
Honolulu HI 96813

State of New Mexico
Energy, Minerals and Natural Resources Department
Anita Lockwood
2040 South Pacheco Street
Santa Fe NM 87505

Sustainable Energy Systems
David N. Borton, Ph.D., President
Hilltop Road
Troy NY 12180

3M-Solar Optics Program
Paul Jaster
3M Center
Bldg. 225-2n-06
St. Paul MN 55144-1000

University of Central Florida
Dr. Gerard G. Ventre
Research Scientist
Institute for Simulation and Training
12424 Research Parkway
Suite 300
Orlando FL 32826

University of Colorado, Boulder
Dr. Jan F. Kreider, P.E.
Dept. of Civil Environmental and Architectural
Engineering
Boulder CO 80309

U.S. Department of Energy
Frank (Tex) Wilkins
1000 Independence Ave., SW
Washington DC 20585

University of Arizona
George V. Mignon
Environmental Research Lab.
Tucson AZ 85706-6985

University of Houston Energy Laboratory; SPA
Lorin Vant-Hull
Houston TX 77004

University of New Mexico
M. W. Wildin
Department of Mechanical Engr.
Albuquerque NM 87131

Yankee Environmental Systems, Inc.
Mark C. Beaubien
Senior Engineer
101 Industrial Road
PO Box 746
Turners Falls, MA 01376

Zomeworks
1011 A Sawmill Rd NW
Albuquerque NM 87104

Australian National University
Department of Engineering Physics
Prof. Stephen Kaneff
PO Box 4
Canberra ACT 2600
AUSTRALIA

CONDUMEX
 Ing. Enrique Hill B.
 So juana ines de la Cruz
 34402o. Piso Tiainepantia. Edo. de Mexico
 C.P. 54000
 MEXICO

Florida Solar Energy Center (6)
 Carol Emrich (3)
 Roy Coffman (3)
 300 State Road 401
 Cape Canaveral, FL 32920

Instituto de Investigaciones Electricas
 Dr. Jorge M. Huacuz Villamar
 Interior Internado Palmira
 Apartado Postal 475
 62000 Cuernavaca, Mor., MEXICO

National Rural Electric Cooperative Association
 Pete Smith
 Manager
 5a. Avenida 16-28, Zona 10, 01010
 Guatemala, Guatemala, C.A.

National Rural Electric Cooperative Association
 Ron Orozco
 5a. Avenida 16-28, Zona 10, 01010
 Guatemala Guatemala C.A.

MS #	Name	Org. #
1127	J.M. Chavez	6215
1127	V.E. Dudley	6215
1127	R.M. Edgar	6215
1127	R.A. Mahoney	6215
1127	E.E. Rush	6215
1127	J.W. Strachan	6215
0703	C.E. Tyner	6216
0703	J.R. Anderson	6216
0703	C.W. Bennett	6215
0703	L.R. Evans	6216
0703	T.R. Mancini	6216
0703	D.F. Menicucci (20)	6216
0753	H.N. Post	6218