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Modeling and Testing of a Solar Energy Intensifier System

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MODELING AND TESTING

OF A

SOLAR ENERGY INTENSIFIER SYSTEM

BY

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This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Advisor Date

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INTRODUCTION

Widespread adoption of solar energy as an alternate energy source is dependent upon careful engineering design. Mathematical models are among the best engineering design tools, because design alternatives can be evaluated without extensive testing and solar systems can be sized and oriented to suit each particular application.

Research has been conducted at South Dakota State University since 1976 to develop, through design and testing, a portable, low-cost, concentrating solar system for agricultural applications. Solar energy can readily be substituted for other energy sources in agriculture because many such applications do not require a continuous, uninterrupted energy supply and may efficiently utilize the low-quality heat produced by simple, inexpensive solar systems. Farm operators traditionally possess the technical and mechanical skills and equipment to install and maintain solar systems. Usually sites adequate in area and orientation are available near agricultural applications.

Concentrators, which intercept solar radiation and concentrate it into a smaller area on a receiver, can be used to increase the solar radiation striking a flat plate collector. This results in higher temperature rises and increased thermal efficiency because there is less collector surface area per unit of effective intercepted sun area. Solar concentrators are particularly adaptable to situations where, as in the SDSU reflector, the collector or absorber cost is higher than the reflector cost. By designing the flat plate collector large enough relative to the reflector surface, the need for expensive tracking equipment can be eliminated, while the cost advantage of minimizing collector area and maximizing reflector area can be retained.

Precise solar system and component evaluation and redesign of solar systems are vital and are needed to further improve the potential of solar energy as an alternate energy resource. A mathematical prediction model based on fundamental laws of heat transfer and thermodynamics can be used to evaluate design considerations and sizing of collector components for specific applications. Although the concept of solar collection is relatively simple, no existing model is available which can predict the performance of the solar energy intensifier system.

Therefore research was initiated with the following objectives:

1. Redesign the multipurpose solar energy intensifier system.
2. Test the solar energy intensifier collector system for grain drying under actual operating conditions.
3. Evaluate the performance and economic feasibility of the solar energy intensifier system.
4. Develop a generalized computer program for predicting the energy collected from the solar energy intensifier collector system.
5. Validate the performance of this computer simulation using measured data gathered from the corn drying studies.

LITERATURE REVIEW

Solar Availability

Solar energy is an inexhaustible energy source that has the potential to make significant contributions to the energy needs of the world. Although comparatively dilute, the solar energy reaching the earth far exceeds the energy requirements of the world (Kreider and Kreith, 1975).

At the earth's atmosphere, the intensity of solar radiation on a surface normal to the sun's rays at the mean earth-sun distance is 1353 W/m^2 and is defined as the solar constant (ASHRAE, 1977). Only a fraction of this energy is available to a solar collector depending upon time of day, time of year, weather conditions, site latitude, and tilt angle (MWPS, 1980).

Solar radiation that passes directly from the sun to the earth's surface is referred to as direct or beam radiation, while scattered radiation is called diffuse. On clear days, approximately 85 percent of the solar radiation is direct and 15 percent is diffuse. When clouds are present, more solar radiation is absorbed and scattered, so more radiation is diffused. Because cloud cover varies on a daily and annual basis, daily solar radiation is averaged over a number of years to find the percent possible sunshine, which can be used to predict annual solar energy available to a collector at a particular site (MWPS, 1980).

Flat plate collectors absorb both direct and diffuse radiation, so small amounts of energy can be produced even on overcast days when all the solar radiation is diffuse. The area of the absorber in a flat plate collector approximately equals the energy intercepting area. Reflectors can be added to a flat plate collector system to produce greater temperature rises. Reflectors are often used to increase the solar energy intercepted area and concentrate the radiation on the flat plate collector (MWPS, 1980). A solar concentrator can reduce the system costs if the reflector component has a lower unit cost than the collector (Hellickson, 1980).

Development of the SDSU Solar Energy Intensifier System

1976-77 Study

Research was initiated in 1976 at South Dakota State University to develop an economical, low temperature rise solar energy intensifier system, incorporating both concentrating and flat plate principles and to evaluate its performance under actual operating conditions. The solar system was designed both for in-storage drying of shelled corn and for supplemental heating of ventilation air for a livestock confinement building. System design consisted of a 3.6 m by 11.0 m, \$20.58/m^2 parabolic trough reflector and a 0.8 m by 7.3 m, \$51.20/m^2 vertical, dual sided collector. Air entered the bottom of the collector, flowed upward over the south side, and then flowed downward over the north side to the insulated plenum leading to the solar application. Corrugated sheet steel painted black on both sides formed the absorber plate, and was covered with an inside transparent cover of polyester film and an outside cover of weather resistant composite polyester film. Tempered masonite sheets covered with an adhesive-backed aluminum having a reflectivity of 80 to 90 percent comprised the concentrator surface. Problems developed from warping of the reflector support material and leaking of the collector glazing (Saienga, et al., 1977 and Julson, et al., 1977).

1977-78 Study

Retaining the same basic concept, but redesigning to correct some of the problems encountered in 1976 and 1977, a new solar energy intensifier was tested in 1977 and 1978. Sheet steel replaced the masonite reflector support and a layer of clear fiberglass replaced the outer glazing of the collector. A diurnal tracking mechanism powered by a 10-watt synchronous motor was added to allow the reflector to track the sun and therefore to reduce the needed height of the collector. Problems occurred with expansion and contraction of fiberglass glazing in the collector and with peeling of the aluminum film from the steel support on the reflector (Seigel, et al., 1978).

1978-79 Study

Major system design changes were made for the 1978 to 1979 study. A collector, triangular in cross section, provided a more optimum sun angle while incorporating the needed volume between collector faces to serve as the thermal energy storage unit. Tempered, low-iron glass was used for the collector glazing and the reflective material was cemented to the steel reflector. Air entered from the end of the collector, turned 180 degrees and flowed the same length through the rock storage unit, then was transported to the solar application. Improved performance for the system was noted, however, excessive pressure drop occurred in moving the air through the rock storage and poor collector efficiency was noted near the exit end of the airflow channel. Decreasing the length of the airflow path and the distance air moves through the rock storage should reduce pressure losses resulting in improved collector performance (Hellevang and Hellickson, 1979 and Heber and Hellickson, 1979).

Existing Solar Collector Models

Methods to estimate long-term performance of solar energy systems are needed to optimize the design and operation of systems (Klein, 1978). The plate-efficiency factor, which is a ratio between actual useful heat collected for a given design and the useful heat collected if the absorber plate was at the average fluid temperature, can be used for design and performance calculations (Bliss, 1959). This procedure is a simple to use, empirical approach which is acceptably accurate for typical solar systems like flat plate collectors for residential space heating but is not reliable for less common designs and applications, such as a concentrating solar system for grain drying. Since the plate-efficiency factor is determined by testing, this empirical method does not provide insight on the energy interactions between the collector and its surroundings.

Chau (1980) developed a procedure based on heat transfer theory to analyze flat-plate air collectors under steady-state conditions. All the conductive, convective and radiative heat transfer interactions were expressed mathematically and the resulting equations were solved by the Newton-Raphson method. The solution predicted the collector efficiency and the heat loss components in the collector.

A computer model was developed by Ting (1980) to simulate the performance of a single cover, air heating, solar collector for grain drying. The implicit finite difference method determined the energy balance conditions for each section of collector and the Gauss-Siedel iteration technique was used to solve the nonlinear, simultaneous equations.

A mathematical model, developed by Romberger (1980), simulated an evacuated-tube solar collector which was used for a pasteurization process. Differential equations from the heat balances were simultaneously solved by using a fourth-order Runge-Kutta method.

Modeling Solar Energy Intensifier Performance

Mathematical models which accurately simulate the energy transfer in a flat plate collector can be a valuable tool for developing a more effective overall working system (Romberger, et al., 1980). However, no models exist which can be directly adapted to the solar energy intensifier system. Therefore development of a solar energy intensifier performance model would logically be derived from fundamental laws of heat transfer and thermodynamics.

Heat transfer predicts the rate of energy transfers between material bodies as a result of temperature differences, while thermodynamics predicts the equilibrium state which will result from a disturbance. The first and second laws of thermodynamics coupled with experimentally determined heat transfer knowledge provide the foundation for most solar system modeling (Holman, 1976).

Energy balances in the solar collector system are based on the first and second law of thermodynamics. The first law states that energy cannot be created or destroyed, while the second law of thermodynamics declares energy must be transferred from a region of higher temperature to a region of lower temperature (Threlkeld, 1970).

Energy transferred from one body to another because of temperature difference results in heat storage. Specific heat is the heat energy required to raise the temperature of a unit mass of substance one unit temperature. The heat transferred to a substance and stored can be calculated using the relationship described by (Threlkeld, 1970):

$$q = M_a \, C_p \, \Delta t$$

where q = heat quantity involving specific heat, W

M_a = amount of moving fluid, kg/hr

C_p = specific heat of fluid, W-hr/(kg·^oC)

Δt = temperature change, ^oC

Heat is transferred by three mechanisms: conduction, convection, and radiation. Modeling solar energy conversion systems requires a knowledge of each mechanism and its interactions (Kreith and Kreider, 1978).

Conduction

Heat conduction is the exchange of heat between adjacent molecules that are at different temperatures. Fourier's equation predicts the rate of heat conduction through a substance (MWPS, 1978):

$$q_k = -A \, k \, (dt/dx)$$

where q_k = heat conduction rate, W

A = cross sectional area normal to the direction of heat flow, m^2

k = thermal conductivity of material, $W/(m \cdot {}^oC)$

dt/dx = temperature gradient, $^oC/m$

Convection

When fluid comes in contact with a solid surface at a different temperature, the thermal energy is exchanged by movement of fluid particles, referred to as convection, as well as by the intermolecular exchange called conduction. Convection is termed natural or free convection if the fluid motion which results in the energy transfer is caused solely by differences in buoyancy of the fluid particles and forced convection if the fluid motion is caused by an external force moving the fluid. Whether convection is free or forced, the rate of heat transfer can be derived from Newton's law of cooling (Kreith and Kreider, 1978):

$$q_c = h_c A (T_s - T_f)$$

where q_c = convection heat rate, W

h_c = convection heat transfer coefficient, $W/(m^2 \cdot {}^oC)$

A = surface area in contact with the fluid, m^2

T_s = surface temperature, ^oC

T_f = fluid temperature, ^oC

This convection equation is a definition of the average unit thermal convective conductance, h_c, rather than an explanation of convection heat transfer. The convective heat transfer coefficient is actually a complicated, experimentally derived function of the fluid flow, fluid properties, and system geometry. Frequently, similitude theory has been utilized to derive equations for predicting heat transfer coefficients, therefore the heat transfer coefficient is often expressed in terms of the Nusselt number (Kreith and Kreider, 1978).

$$Nu = \frac{h_c L}{k_f}$$

where Nu = Nusselt number

L = length dimension of the system, m

k_f = thermal conductivity of the fluid, $W/(m \cdot {}^oC)$

In general, the Nusselt number for forced convection can be related to the Reynolds number, Re, and the Prandtl number, Pr, by a relation of the form (Kreith and Kreider, 1978):

$$Nu = C\ Re^n\ Pr^m$$

where C, n, and m are empirically determined constants. Reynolds number is a dimensionless quantity that includes velocity, hydraulic diameter or a length dimension, fluid density, and fluid viscosity. Prandtl number is a dimensionless parameter defined by the fluid properties: specific heat, viscosity, and thermal conductivity.

Correlation equations for Nusselt number vary according to geometry and flow conditions encountered in solar energy conversion systems. Considerable variations among the empirically determined coefficients relating the Nusselt number to the Reynolds and Prandtl numbers have been noted.

For fully developed turbulent flow in smooth tubes the following equation is recommended (Holman, 1976, and Kreith and Kreider, 1978):

$$Nu = 0.023\ Re^{.8}\ Pr^{.4}$$

For turbulent flow between two parallel flat plates with only one surface heated and with air as the fluid, the relationship

$$Nu = 0.0196\ Re^{.8}\ Pr^{1/3}$$

is recommended (Kreith and Kreider, 1978). For fully developed turbulent gas flow inside tubes, Kays (1966) recommends:

$$Nu = 0.022\ Re^{.8}\ Pr^{.6}$$

For fully developed turbulent airflow between flat plates with one side heated, that equation reduces to:

$$Nu = 0.0158\ Re^{.8}$$

According to Kreith and Kreider (1978) a suitable expression for Nusselt number for a smooth, air-heating solar collector is:

$$Nu = \frac{0.0192\ Re^{3/4}\ Pr}{1 + 1.22\ Re^{-1/8}\ (Pr - 2)}$$

Tan and Charters (1970) studied heat transfer characteristics within a flat plate solar air heater with rectangular passages and experimentally determined the relationship:

$$Nu = 0.018\ Re^{.8}\ Pr^{.4}$$

In earlier work, Tan and Charters (1969) found that the heat transfer rates in the thermal entrance section of a solar heater differ significantly from heat transfer rates in fully developed flow. The following equation, which describes the variation of the local Nusselt number with the collector length, was derived:

$$Nu_{local} = [1.78 - 0.9864(L/De)^{.531}]\ Nu$$

where Nu_{local} = local Nusselt number

L = collector length, m

De = hydraulic diameter, m

$$Nu = .018\ Re^{.8}\ Pr^{.4}$$

Convective heat losses from flat plates exposed to outside winds was found from an expression which relates the convective heat transfer coefficient in $W/(m^2 \cdot {}^oC)$ to the wind speed, V, in m/s (Duffie and Beckman, 1974).

$$h_{wind} = 5.7 + 3.8\ V$$

Radiation

Thermal radiation is the transfer of heat from one body to another by electromagnetic waves. An ideal radiator, or black body, will emit energy at a rate proportional to the fourth power of the absolute temperature of the body. However, most bodies of practical consideration are not black bodies, so radiant heat transfer is generally expressed as (Holman, 1976):

$$q_r = \varepsilon\ \sigma\ A\ (T_1{}^4 - T_2{}^4)$$

where q_r = radiation heat transfer rate, W

ε = emissivity, the factor which accounts for the non-ideal radiating conditions

σ = Stefan-Boltzmann constant, $W/(m^2 \cdot {}^oK^4)$

T_1, T_2 = absolute surface temperatures, ^oK

SOLAR SYSTEM DESIGN AND TESTING

This section describes the design and testing procedure for the multipurpose solar energy intensifier-thermal energy storage system, which consists of a collector, triangular in cross section, and a concentrating parabolic reflector (Figure 1). System design considered basic solar principles, economic factors, material properties, maintenance and construction simplicity, and performance results from previous similar models.

Collector-Storage Unit

The triangular shaped collector storage unit (Figure 2) was 9.8 m long, 1.2 m wide, and 0.9 m high. Collector sides were tilted at 60 degrees from the horizontal because that was near the optimum for maximizing solar collection during the fall and winter months. For ease of transportation and construction, the collector was built in four equal length sections. Fiberglass batt (R = 3.7 $m^2 \cdot {}^oC/W$) insulated the base and ends of the collector.

The absorber plate was 0.6 mm thick sheet steel coated with a lacquer base, flat-black paint. Absorptivity and emissivity of this paint were 0.95 for both the short and long wavelength regions.

One glazing layer of low iron, tempered glass served as the collector cover plate. Five panels (0.4 x 86.4 x 193.0 cm) were mounted end to end on each side of the collector. Transmissivity of the glass, according to manufacturer specifications, was 90.1 percent.

Plywood (1.3 cm) provided structural support and served as one side of the airflow channel behind the absorber plate. When the system

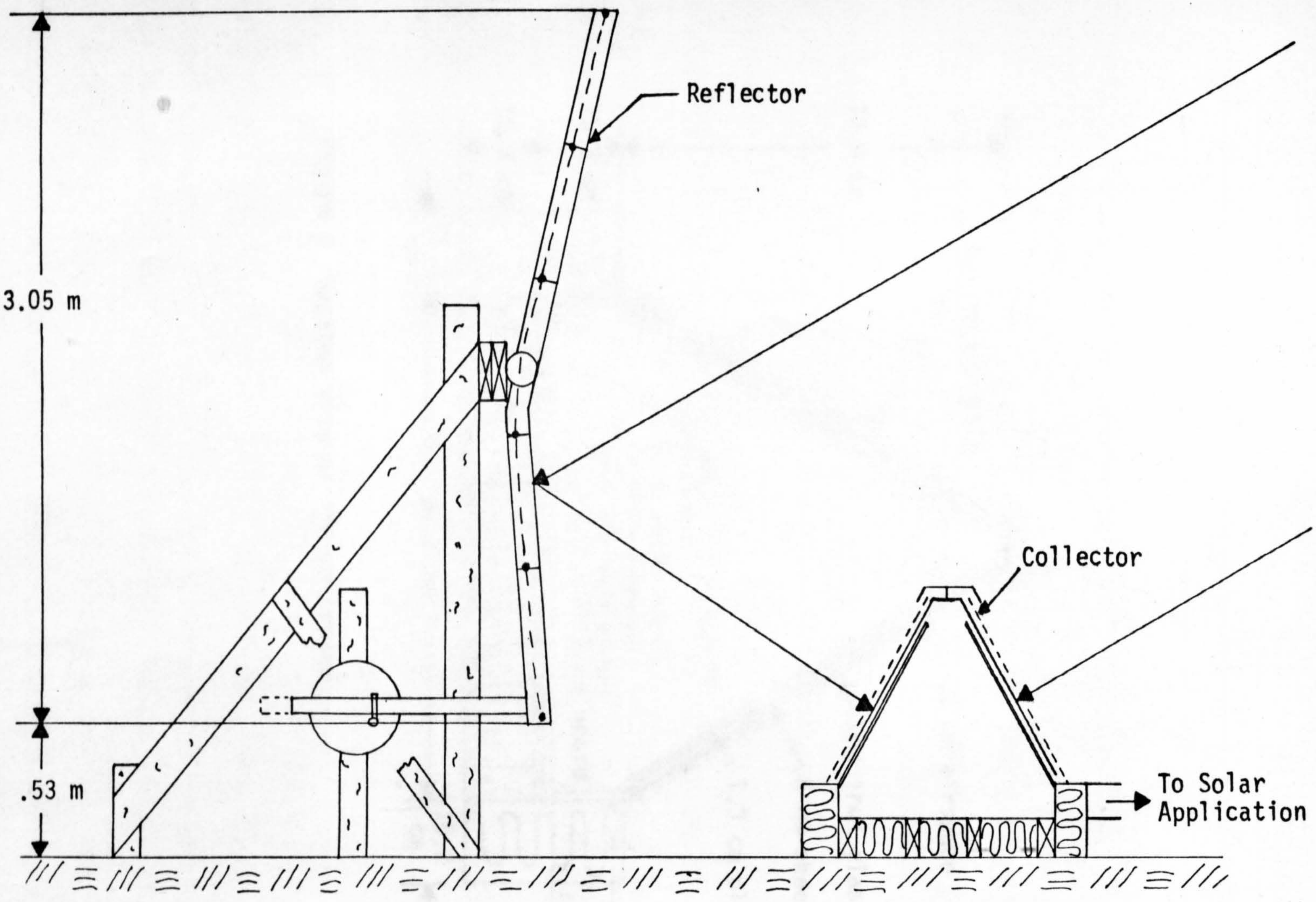


Figure 1 Solar collector and reflector cross sectional schematic.

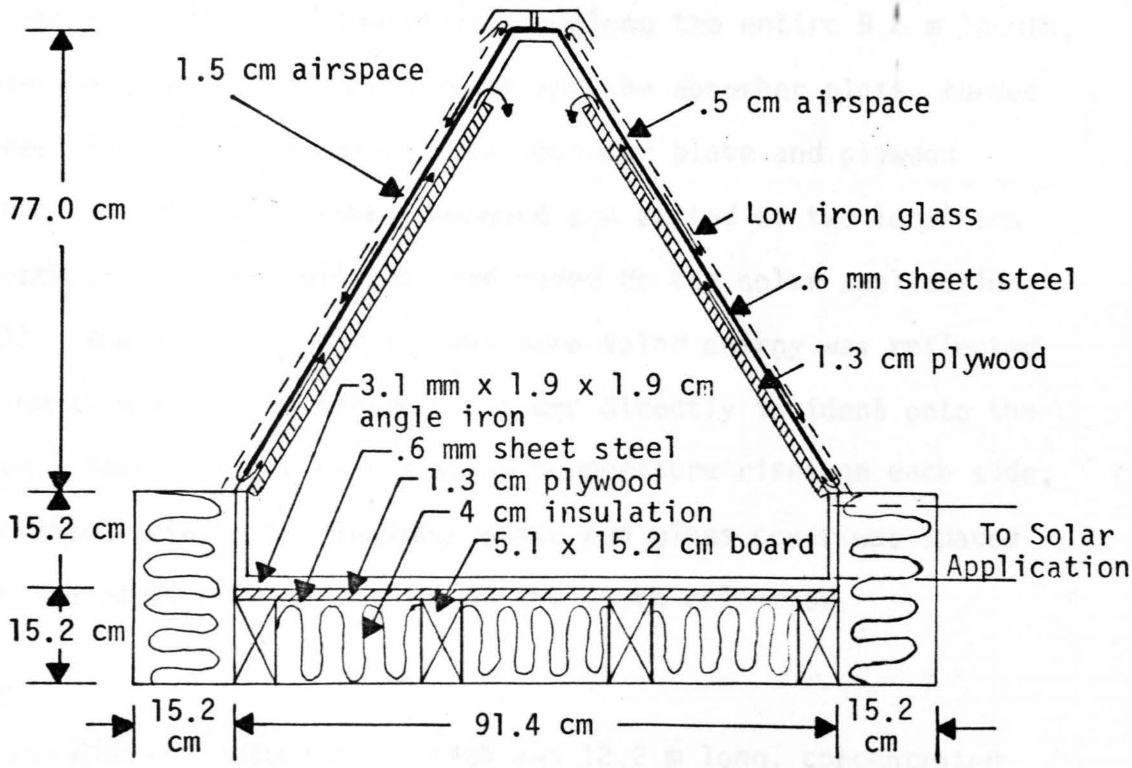


Figure 2 Section view of the collector.

was used for livestock building heating, thermal storage was added by placing rocks in the cavity formed by the plywood and the collector base. The plywood served to insulate and support the storage area. Rocks were not used in the corn drying study, because corn in the drying bin provided sufficient storage capacity.

Air entered the top of the collector along the entire 9.8 m length, flowed downward between the glass cover and the absorber plate, turned 180 degrees, flowed upward between the absorber plate and plywood, entered the storage unit, flowed downward and exited at two locations on the south side of the collector and moved to the solar application (Figure 2). Approximately three times more solar energy was reflected onto the north side of the collector as was directly incident onto the south side. Therefore, to have similar temperature rises on each side, the air channel between the absorber plate and glass cover was spaced 1.5 cm on the north side and 0.5 cm on the south collector.

Reflector

A parabolic reflector, 3.0 m high and 12.2 m long, concentrated energy on the north side of the collector. The reflector was constructed in four sections, each consisting of five individually focused, 0.6 m wide by 3.0 m long sheets connected to the reflector frame (Figure 1). Polished aluminum 0.1 mm thick with adhesive backing mounted on 0.8 mm sheet steel provided the 90 percent reflective surface. The reflector was designed 2.4 m longer than the collector to achieve full utilization of the more expensive collector from 900 to 1500 solar time. Every two weeks the reflector was adjusted by a center pivot to maintain the focus on the north facing collector.

Ductwork and Fan

Air exited the solar energy system from two points along the south side of the collector (Figure 3). The duct from the collector to the mixing chamber was constructed of 1.3 cm plywood and insulated with 2.5 cm polystyrene to provide a total thermal resistivity of 0.9 $m^2 \cdot {}^oC/W$. A sliding door on top of the mixing chamber was used to adjust the amount of ambient air entering the grain bin and to control the airflow rate through the collector. Inside dimensions of the air duct were 25.4 by 53.3 cm. Air was drawn through the system by a vane axial, aeration fan already installed in the grain bin.

Instrumentation

Air temperatures at 24 locations (Figure 4) were measured with copper constantan thermocouples and registered on a multipoint, strip chart, recording potentiometer. Temperature readings were recorded eight times between 800 and 1700 hours.

An Epply pyranometer mounted on a 60 degree slope indicated the solar radiation striking the tilted collector. Solar radiation was recorded continuously from 700 to 1800 hours on a strip chart recorder.

Air velocity was measured with a hot wire anemometer. Collector system airflow rate was determined from several velocity measurements in the duct between the collector and the mixing chamber. Airflow was also measured entering the north and south sides of the collector, but with the small air channel spacing, these measurements were not acceptably accurate.

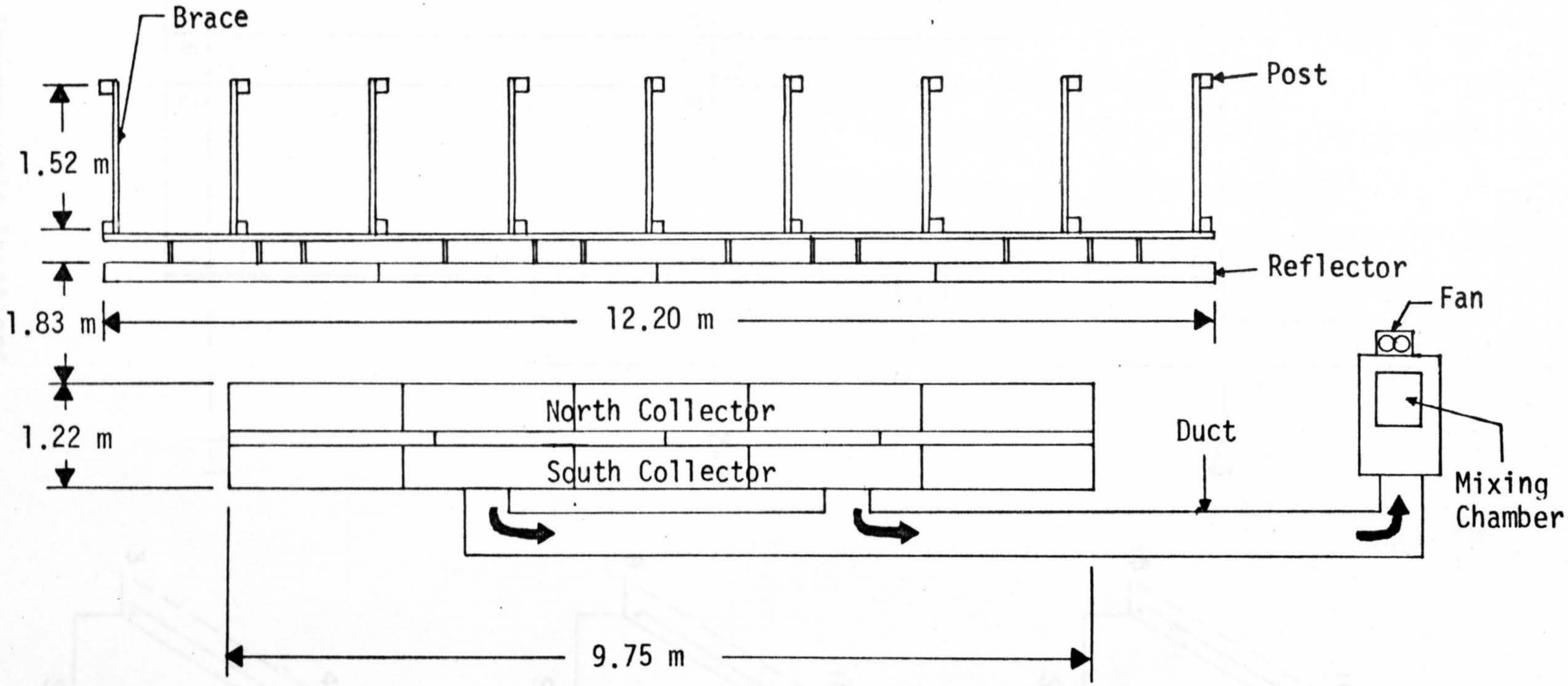


Figure 3 Plan view of the solar energy intensifier system.

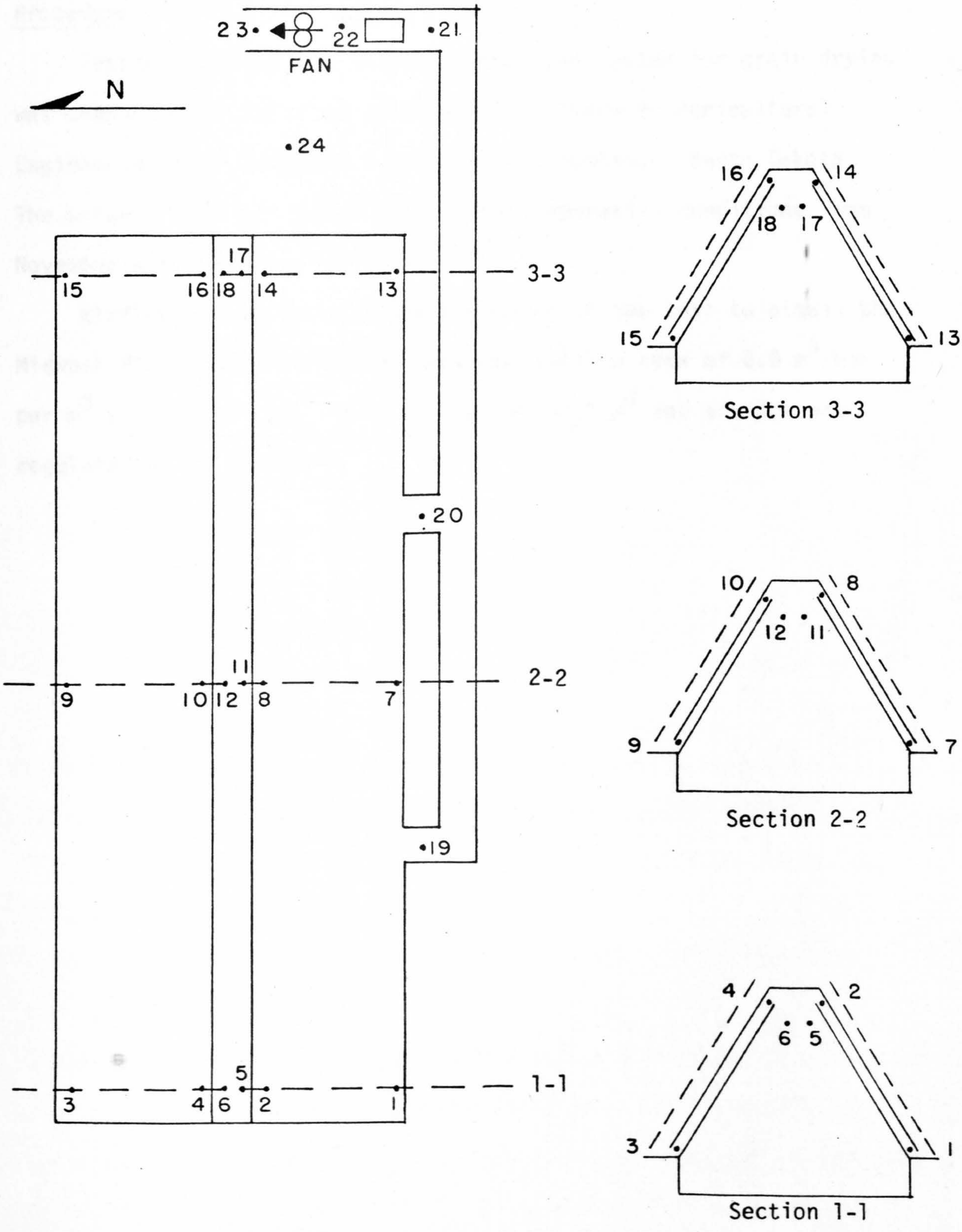


Figure 4 Thermocouple locations.

Procedure

Testing of the solar energy intensifier system for grain drying was conducted at the South Dakota State University Agricultural Engineering Farm located 9.7 km south of Brookings, South Dakota. The solar system was tested under actual operating conditions from November 8 to December 17, 1979.

Airflow was adjusted at the beginning of the test to attain the Midwest Plan Service (1980) recommended airflow rate of 0.8 m^3/min per m^3 of shelled corn. Corn volume was 35.2 m^3 and airflow was regulated at 27.9 m^3/min.

MODEL DEVELOPMENT PROCEDURE

A mathematical model was developed to simulate the performance of the solar energy intensifier system. Equations defining the model were derived from fundamental laws of heat transfer and thermodynamics. Principal considerations during model development were defining energy balances, selecting the correct south side to north side collector airflow ratio, choosing appropriate convective heat transfer coefficients, assuming reasonable initial heat transfer values, and finally validating the resultant model.

Conceptualization

Analysis of the solar energy system considered the unit as two separate flat plate collectors. The south facing collector receives radiation directly from the sun, while radiation is concentrated in a band on the north facing collector. Solar radiation is considered evenly distributed over the north absorber plate to simplify the computer model. This assumption is believed valid because the high rate of airflow across the absorber plate plus the high thermal conductivity of the absorber material tends to minimize temperature variations along the absorber resulting from uneven distribution of the reflected solar radiation.

Energy transfers and temperature changes are calculated using an iterative procedure. The collector is divided into 30 equally spaced increments in the direction of airflow over the front of the absorber plate, followed by 30 equally spaced increments behind the absorber plate continuing in the direction of collector airflow. Three energy balances are performed at each increment to predict the unknown temperatures (Figure 5). These three energy balance equations include eight unknown heat transfers and three unknown temperatures, which are determined by solving 11 equations at each increment along the airflow path. The 11 equations are not independent, so an iterative trial and error process is used.

Energy Balances

Absorber Plate Energy Balance

Absorber plate temperature is predicted from an energy balance at the absorber plate. Solar radiation absorbed by the absorber plate must be either convected from the plate to the airstream, radiated from plate to cover, or convected from the back of the absorber plate to the airstream behind the plate (Figure 5: Step I).

$$QSOL = QCPA + QRPC + QBL$$

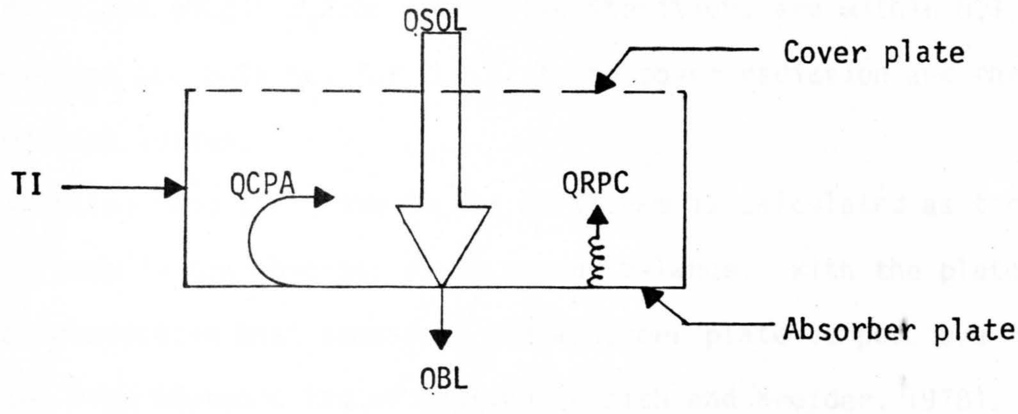
where QSOL = solar radiation absorbed by an increment of absorber plate, W

QCPA = energy convected from the absorber plate to the airstream, W

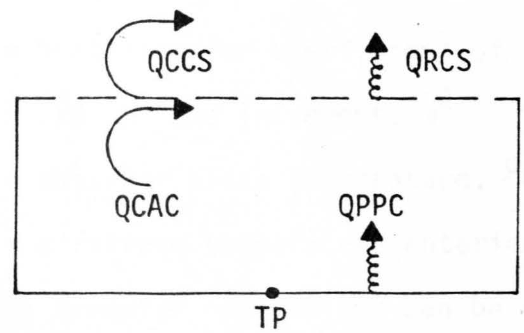
QRPC = plate to cover radiation, W

QBL = convected back losses from the plate to the airstream behind the absorber plate, W

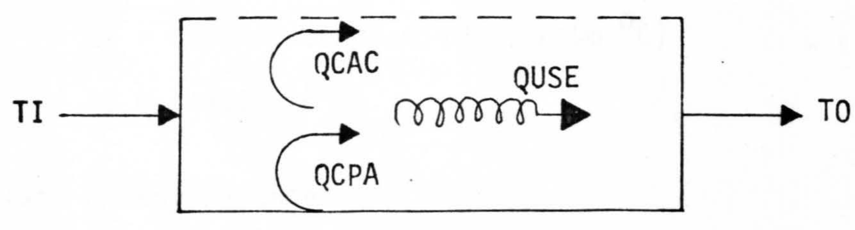
Solar radiation is available from weather record data. Initially, assumed values are used for plate to cover radiation and convected back losses. Subsequently, these values are calculated from the predictions of the preceding iteration. By continuing the iteration process until



Step I: Absorber plate energy balance



Step II: Cover plate energy balance



Step III: Airstream energy balance

Figure 5 Energy balances of an increment for airflow in front of the absorber plate.

predicted values obtained from successive iterations are within 0.1 kW, correct values are obtained for the plate to cover radiation and the convected back losses.

Convection from the plate to the airstream is calculated as the remaining term in the absorber plate energy balance. With the plate to airstream convective heat transfer, the absorber plate temperature is determined from Newton's law of cooling (Kreith and Kreider, 1978):

$$QCPA = HC * AREA * (TP - TI)$$

where HC = heat transfer coefficient of the airstream, $W/(m^2 \cdot {}^oC)$

AREA = area of the increment, m^2

TP = absorber plate temperature, ^oC

TI = airstream temperature entering the increment, ^oC

The convective heat transfer coefficient can be calculated from the relation (Kreith, 1973):

$$HC = Nu \frac{kf}{L}$$

where Nu = Nusselt number (Holman, 1976)

kf = thermal conductivity, $W/(m\ {}^oC)$

L = length, m

Cover Plate Energy Balance

Glass cover temperature is predicted from an energy balance at the transparent cover layer (Figure 5: Step II). A cover temperature is assumed so radiative and convective cover to sky losses, convective airstream to cover heat transfer, and plate to cover radiation can be calculated. Cover temperature is incremented by a trial and error process until cover to sky energy losses equal plate to cover energy gains. Cover to sky losses include the cover to sky convective and radiative heat transfer.

$$QCCS = HW * (TC - TS) * AREA$$

$$QRCS = \sigma * \varepsilon_c * (TCA^4 - TSA^4) * AREA$$

where QCCS = cover to sky convective heat transfer (Kreith and Kreider, 1978), W

HW = wind heat transfer coefficient (Duffie and Beckman, 1974), $W/(m^2 \cdot {}^oC)$

TC = cover temperature, ^oC

TS = sky temperature, ^oC

QRCS = cover to sky radiation (Holman, 1978), W

σ = Stefan-Boltzmann constant, $W/(m^2 \cdot {}^oK^4)$

ε_c = cover plate emissivity.

TCA = absolute cover temperature, ^oK

TSA = absolute sky temperature, ^oK

Plate to cover radiation and airstream to cover convection are the plate to cover heat gains.

$$QRPC = \frac{\sigma * (TPA^4 - TCA^4) * AREA}{1/\varepsilon_c + 1/\varepsilon_p - 1}$$

$$QCAC = HC * (TI - TC) * AREA$$

where TPA = absolute plate temperature, ^oK

ε_p = absorber plate emissivity

QCAC = convective airstream to cover heat transfer (Kreith and Kreider, 1978), W

Plate to cover radiation found in this step becomes the plate to cover radiation in the following increment.

Airstream Energy Balance

Airstream temperature exiting the increment is obtained by an energy balance of the airstream increment. Convected plate to airstream heat transfer equals the airstream to cover convection losses plus the useful energy collected (Figure 5: Step III). Since convected plate to airstream and airstream to cover heat transfer are already calculated, the useful energy is found by subtraction

$$QUSE = QCPA - QCAC$$

where QUSE = useful energy collected, W

The useful energy results in a temperature rise of air defined by (Threlkeld, 1970):

$$QUSE = M * CP * (TO - TI)$$

where M = amount of air, kg/hr

CP = specific heat of air, W·hr/(kg·^{o}C)

TO = airstream temperature exiting the increment, ^{o}C

The temperature exiting this increment will be used as the entrance temperature in the next increment.

Back Loss Energy Balance

Once flow is analyzed over the front of the absorber plate, back losses are predicted from the definition of convection (Figure 6) (Kreith and Kreider, 1978).

$$QBL = HCB * (TP - TI) * AREA$$

where HCB = heat transfer coefficient for the back side based on Nusselt number, W/(m^{2}·^{o}C)

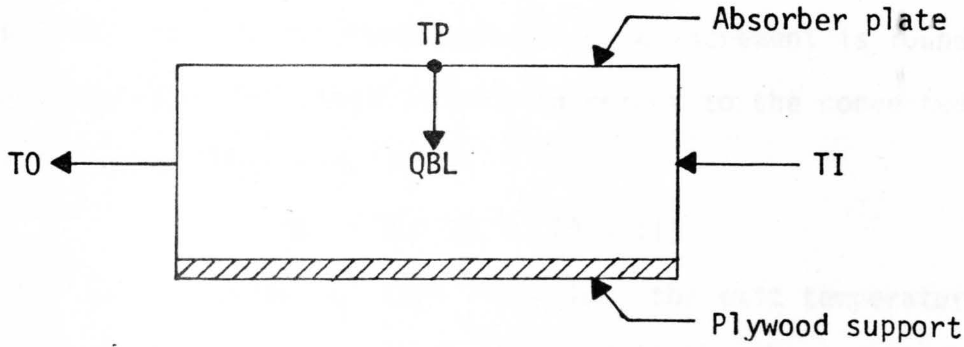


Figure 6 Energy balance of an increment for airflow behind the absorber plate.

TP = plate temperature found when flow was analyzed over the front of the absorber plate, ^{o}C

These back loss values are used across the front of the absorber plate in the next iteration. Correct back loss values are obtained by continuing the iteration process until predicted energy collected converges within 0.1 kW. Exit temperature from the back increment is found by relating temperature increases at each increment to the convected energy transferred using (Threlkeld, 1970):

$$QBL = M * CP * (TO - TI)$$

In the last increment of each iteration, the exit temperature and the temperature entering the system are used in the above equation to find the predicted energy collected from the solar collector. This iteration process continues until predicted energy collected converges within 0.1 kW or until the process is repeated ten times.

Airflow Ratios

Airflow was measured at the entrances of the north and south sides of the collector, but due to the small air channel spacings and instrument limitations, these measurements were not acceptably accurate. Therefore, the airflow through the south and north sides of the collector were calculated based on the total system airflow measurements and the south to north ratio of air channel thickness, which was 1:3. Relative airflow is not necessarily the same ratio as the channel cross sectional area, so airflow ratios ranging from 1:2 to 1:4 were analyzed in the resultant model. These variations proved to have relatively little effect on prediction of overall energy collected.

The south to north airflow ratio of 1:3 was assumed except where otherwise indicated in this text, since that also was the plate spacing ratio.

<u>Convective Heat Transfer Coefficient</u>

The Nusselt number is a convenient measure of the convective heat transfer coefficient because, once its value is known, the convective heat transfer coefficient can be calculated from the definition of Nusselt number. For a given Nusselt number, the convective heat transfer coefficient is directly proportional to the significant length dimension that describes the system.

Nusselt number for forced convection can be related to the Reynolds number and Prandtl number (Kreith and Kreider, 1978)

$$Nu = C\ Re^{n}\ Pr^{m}$$

where C, n, and m are empirically determined constants. The equations, shown in Table 1, give an acceptable range of Nusselt numbers which can be related to heat transfer characteristics in a flat plate air collector. Nusselt numbers, determined from these equations, ranging from 13.24 to 22.60 were tested in the mathematical program. Since there was a small effect of varying Nusselt number, 17.02 was selected as the dimensionless value of Nusselt number, because the equation

$$Nu = 0.023\ Re^{.8}\ Pr^{.4}$$

was the most accepted equation used to relate Nusselt number to solar air heating.[1]

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[1]Percent difference between measured and predicted energy collected ranged from -0.6 to 4.1 percent as explained later in the results.

Table 1 Nusselt number defining equations.

Equation	Nusselt Number
$Nu = 0.018\ Re^{.8}\ Pr^{.4}$ (Tan and Charters, 1970)	13.24
$Nu = 0.0158\ Re^{.8}$ (Kays, 1966)	13.43
$Nu = 0.0196\ Re^{.8}\ Pr^{1/3}$ (Kreith and Kreider, 1978)	14.84
$Nu = 0.022\ Re^{.8}\ Pr^{.6}$ (Kays, 1966)	15.19
$Nu = \frac{0.0192\ Re^{3/4}\ Pr}{1 + 1.22\ Re^{-1/8}\ (Pr - 2)}$ (Kreith and Kreider, 1978)	16.82
$Nu = 0.023\ Re^{.8}\ Pr^{.4}$ (Holman, 1976 and Kreith and Kreider, 1978)	17.02
at entrance: $Nu_{local} = [1.78 - 0.0864\ (L/De)^{.531}]\ Nu$ where $Nu = 0.018\ Re^{.8}\ Pr^{.4}$ (Tan and Charters, 1970)	22.60

Initial Values

Plate to cover radiation was initially assumed for the north facing collector to be 25 percent of the radiation absorbed by the north collector and 10 percent of radiation absorbed by the south collector for the south facing collector. This assumption started the iteration process with reasonable values. After the first iteration, the initial two radiative plate to cover values from the previous iteration were averaged to establish the plate to cover radiation to start the next iteration process. By averaging plate to cover radiation for the initial value in each consecutive iteration, convergence occurred.

Convected back losses for the first iteration were assumed to be zero, since there was no known plate or back airflow temperature. Once through the first iteration, airflow temperatures entering back increments are known and plate temperatures from the airflow over the front of the plate can be used. For the first two increments on the back side, plate temperature was assumed the same as plate temperature on the front plate at that increment. After that, the back plate temperature was found by a weighted average[1] of three calculated front plate temperatures. Averaging plate temperatures was valid because the process converged.

Model Validation

The model was validated by comparing the predicted energy collected

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[1]The previous three absorber plate temperatures were weighted .3, .5 and .2, respectively, and the weighted sum was used as each back temperature.

to the measured useful energy. Also airflow temperatures were predicted at several locations along the absorber plate and compared to actual measured temperatures.

RESULTS

Solar System Performance

Average daily thermal efficiency of the solar energy system from November 8, 1979, to December 17, 1979, was 50.9 percent. Total energy collected was 1815.2 kW-hr, total available solar radiation was 3567.6 kW-hr and average daily direct normal insolation during testing was 270.6 langleys (Figure 7).

Usually corn drying takes place during October in the Brookings, South Dakota, area. Average direct normal insolation at this time and location is 353.5 langleys/day which is 23.5 percent higher than occurred during testing (Lytle, 1979).

Daily amounts of heat collected, radiation available and efficiency from 800 to 1700 hours are listed in Appendix B. Figure 8 shows the energy collected and available for each day of testing. Maximum daily energy collected was 103.0 kW-hr on December 13, 1979, and daily efficiency was 68.0 percent. Efficiency ranged from 0.0 to a maximum of 75.0 percent on December 1, 1979.

Energy collected, radiation available and efficiency for a typical clear day, December 13, 1979, formed a bell-shaped curve when plotted against time (Figure 9). Efficiency was higher during the late afternoon. This could result from the collector materials storing some heat and creating a thermal lag in the system. Thermal lag would affect hourly efficiencies but would have minimal influence on daily efficiencies.

Average hourly temperature rises during the 40-day test period

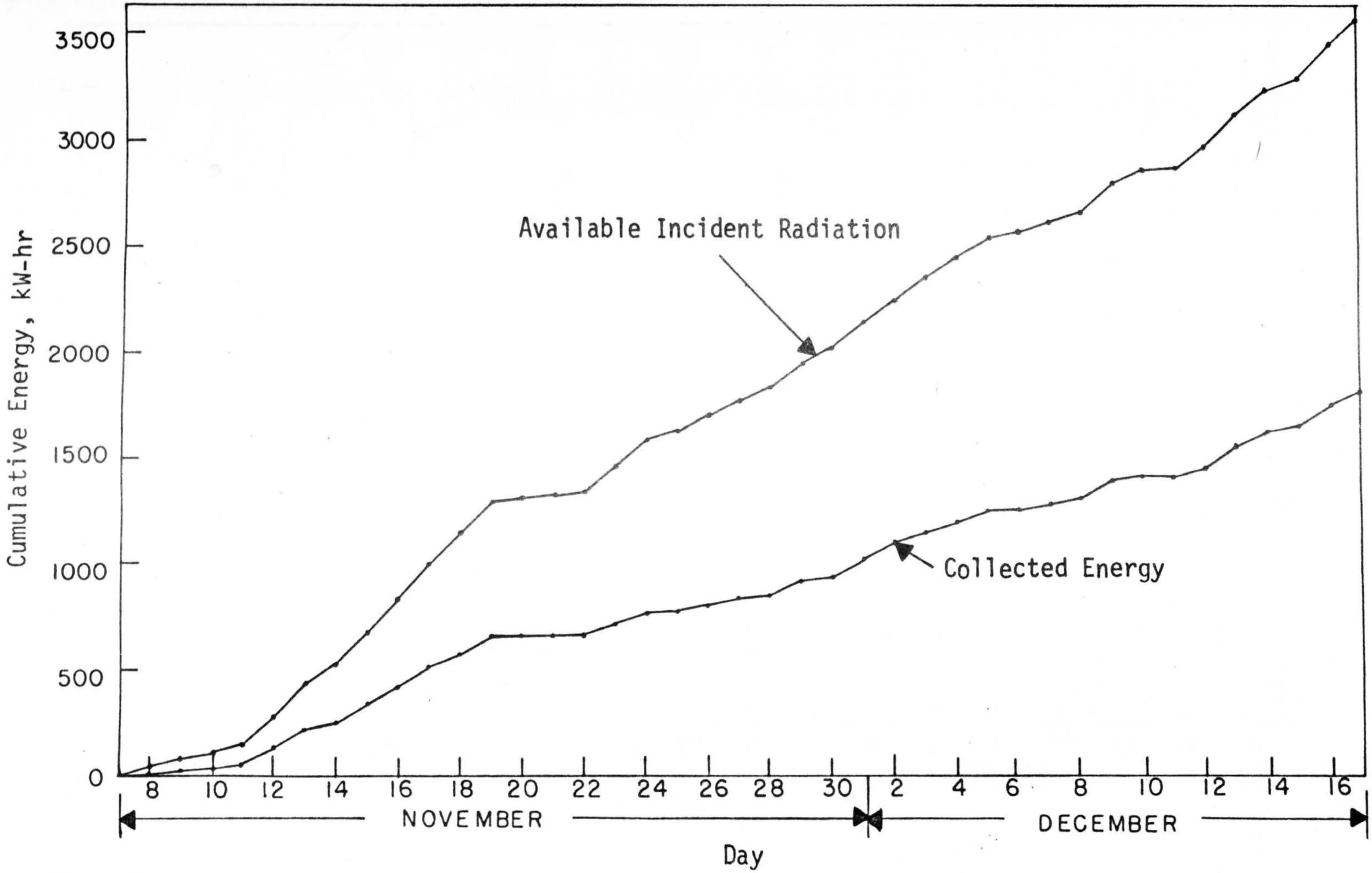

Figure 7 Cumulative available normal radiation and collected thermal energy.

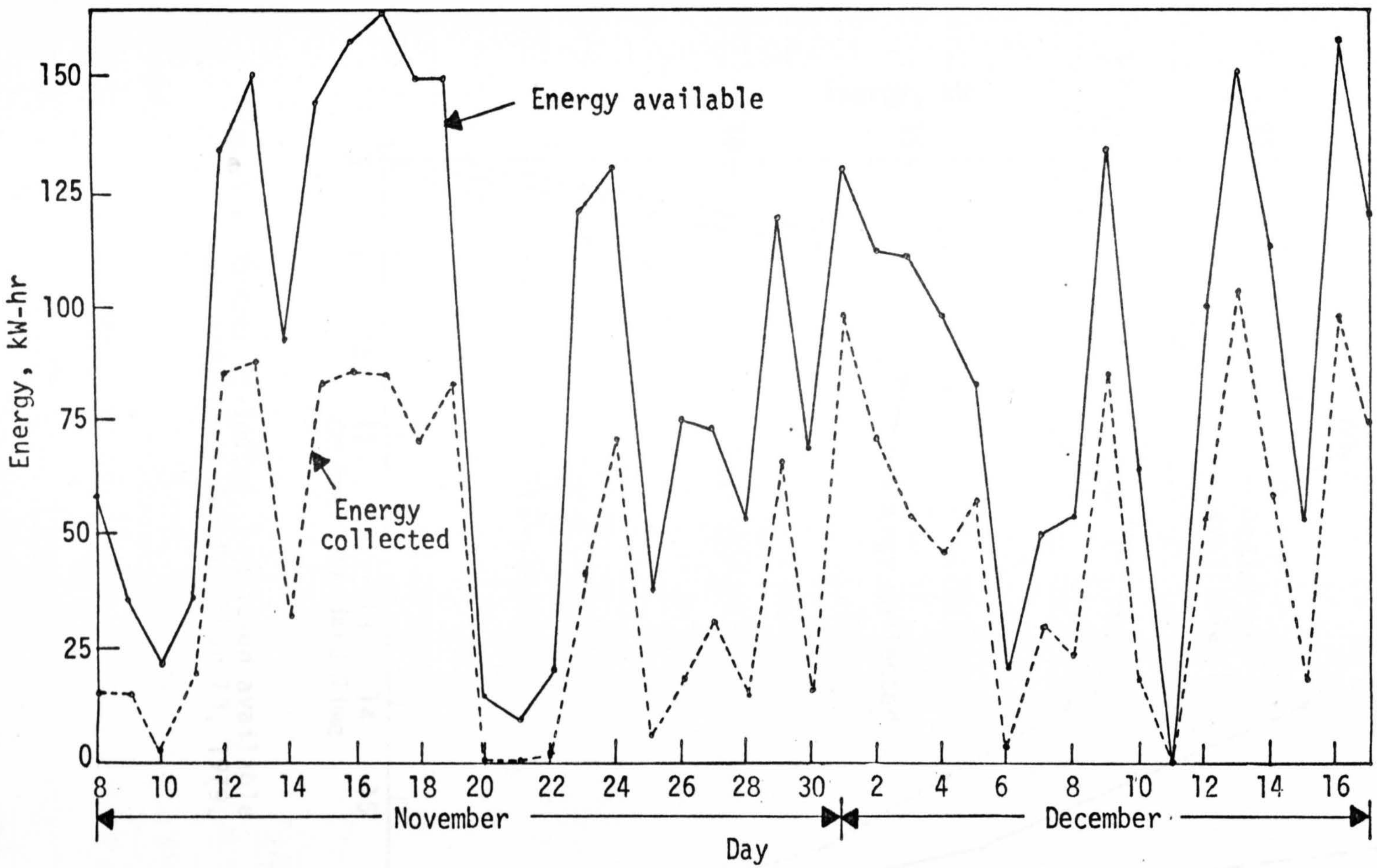

Figure 8 Daily energy collected and available normal radiation.

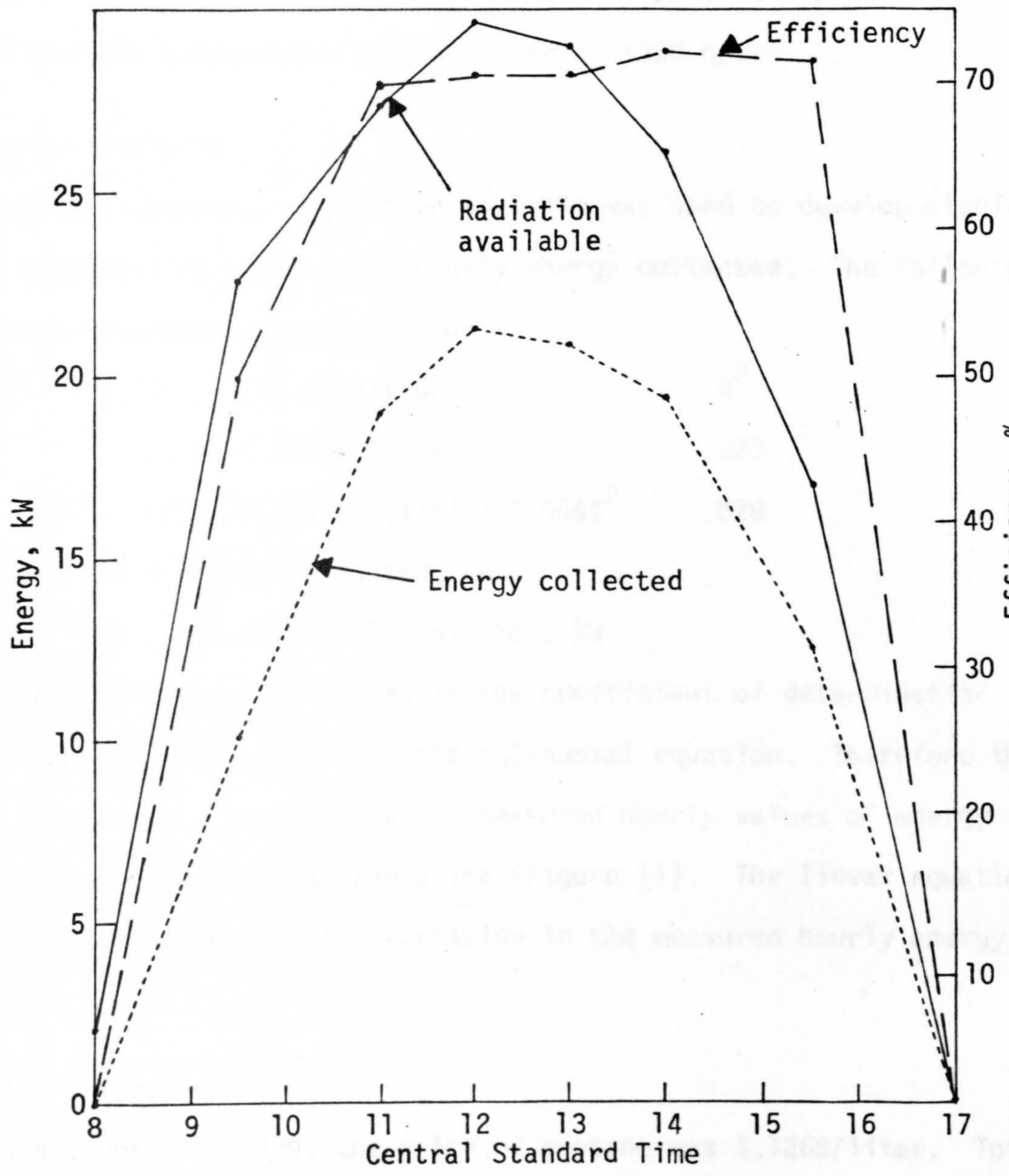

Figure 9 Energy collected, radiation available and efficiency for December 13, 1979.

are shown in Figure 10. Temperature rises formed a bell-shaped curve, and the maximum temperature rise occurred at 1300 hours.

Statistical Analysis

Multiple stepwise, regression analysis was used to develop significant equations for predicting hourly energy collected. The following regression equations were developed:

Equation	R^2
$EC = -0.883 + 0.584I$	.823
$EC = -0.429 + 0.426I + 0.006I^2$	.828

where EC = energy collected, kW

I = direct normal radiation, kW

Little difference was noted in the coefficient of determination between the linear equation and the polynomial equation. Therefore the linear equation was graphed against measured hourly values of energy collected and direct normal radiation (Figure 11). The linear equation explained 82.3 percent of the variation in the measured hourly energy collected.

Economic Performance

On November 19, 1979, the price of propane was $.1268/liter. Total heat collected (1815.2 kW-hr) during the 40-day test period was thermally equivalent to 410.2 liters of propane burned and was utilized at 65 percent efficiency. Over the 40-day test period, the solar system energy savings averaged $1.30/day. Maximum daily propane savings was $4.53 on December 13, 1979. Compared with electric heat over the same 40-day test period, the solar system would save an average of $1.36/day

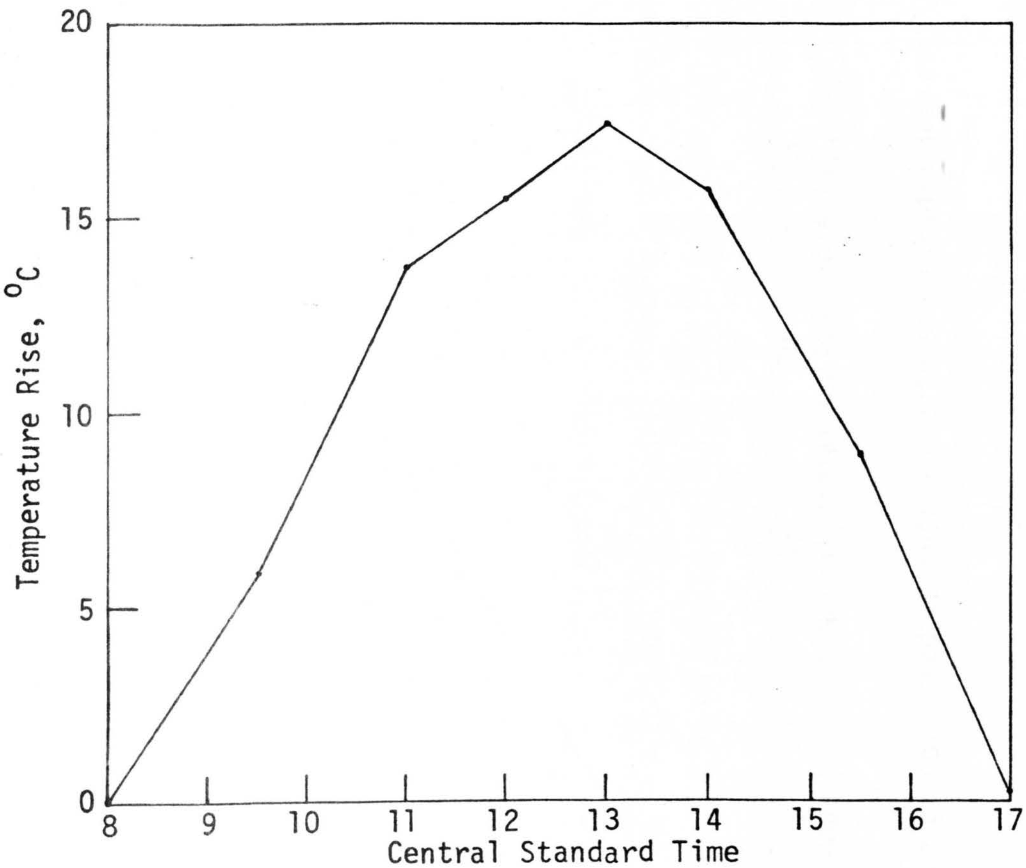

Figure 10 Average temperature rise during the period of testing from November 8 to December 17, 1979.

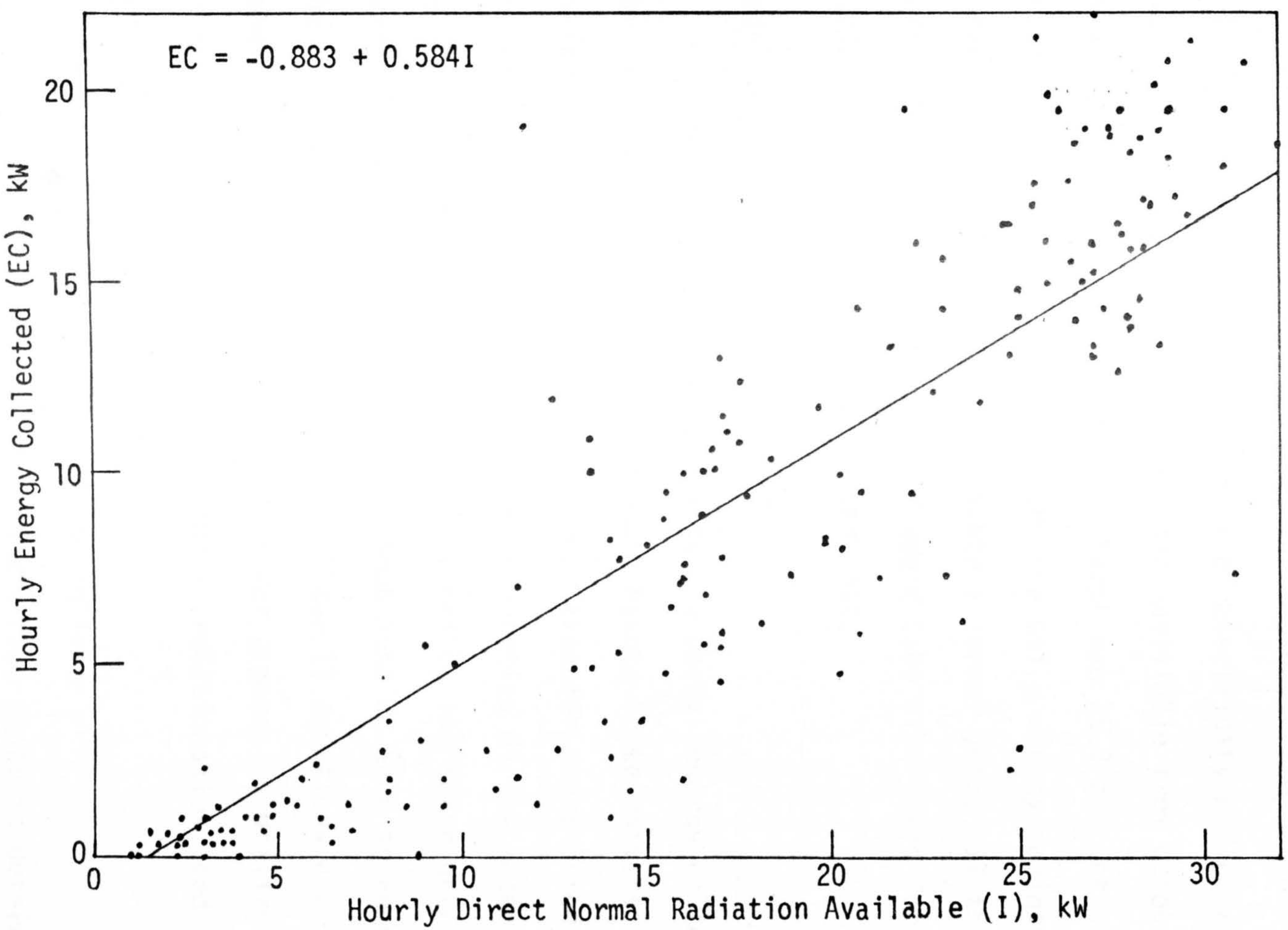

Figure 11 Hourly energy collected as influenced by solar radiation available.

at \$0.03/kW-hr.

If the solar system was used for 180 days from October to March, \$313.33/yr of propane or \$327.56/yr of electricity could be saved, based on average daily solar radiation available from October to March. Average insolation from October to March was 25.3 percent higher than occurred during testing. Therefore the daily energy savings were also increased 25.3 percent to approximate a normal year. If the fuel inflation rate was 13 percent, it would take five years for the fuel savings to equal the initial system cost.

Model Description

The mathematical model predicts the useful energy collected and the airflow temperatures in the South Dakota State University solar energy intensifier system. Using heat transfer and thermodynamic laws, the solar system geometry, physical properties of the materials, and weather data, eight unknown energy transfers and three unknown temperatures are determined by solving 11 equations at each increment along the airflow path in the collector. These 11 equations are not independent, so an iterative trial and error process is utilized. Table 2 describes each unknown and lists the 11 relationships used to obtain the solution to these unknowns.

The calculation procedure is as follows:

1. Solar radiation absorbed by the absorber plate is determined from the reflectivity of the reflector, transmissivity of the glass cover, absorptivity of the absorber plate, the direct normal radiation, and the perpendicular solar intercepted area (Duffie and Beckman, 1974).

Table 2 Description of the simulation model concept.

1. Solar radiation absorber by the absorber plate

$$QSOL = \rho * \tau_g * \alpha_p * RAD * SAREA$$

where: QSOL = solar radiation absorbed by an increment of absorber plate, W
ρ = reflectivity of the reflector for the north side, 1.0 for the south side
τ_g = transmissivity of glass
α_p = plate absorptivity
RAD = available direct normal radiation, W/m^2
SAREA = intercepted area perpendicular to solar radiation, m^2

2. Plate-to-cover net radiation

$$QRPC = \frac{\sigma * (TPA^4 - TCA^4) * AREA}{1/\varepsilon_c + 1/\varepsilon_p - 1}$$

where: QRPC = plate-to-cover net radiation, W
σ = Stefan-Boltzmann constant, $W/m^2 \cdot K^4$
ε_p = plate emissivity
ε_c = cover emissivity
TPA = absolute plate temperature, ^oK
TCA = absolute cover temperature, ^oK
AREA = area of the increment, m^2

3. Energy convected from plate-to-airstream behind the absorber plate

$$QBL = HCB * (TP - TI) * AREA$$

where: QBL = convected back losses from the plate-to-airstream behind the absorber plate, W
HCB = heat transfer coefficient for the back side, $W/m^2 \cdot {^oC}$
TP = absorber plate temperature, ^oC
TI = airstream temperature entering the increment, ^oC

4. Energy convected from plate-to-airstream in front of the absorber plate

$$QCPA = QSOL - QRPC + QBL$$

where: QCPA = energy convected from the absorber plate to the front airstream, W

Table 2 (cont.)

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5. Absorber plate temperature

$$TP = QCPA/(AREA * HC) + TI$$

where: HC = heat transfer coefficient of the airstream, $W/m^2{\cdot}{}^oC$

6. Convective airstream-to-cover heat transfer

$$QCAC = HC * (TI - TC) * AREA$$

where: QCAC = airstream-to-cover convective heat transfer, W
TC = cover temperature, ^oC

7. Convective cover-to-sky heat transfer

$$QCCS = HW * (TC - TS) * AREA$$

where: QCCS = cover-to-sky convective heat transfer, W
HW = wind heat transfer coefficient, $W/m^2{\cdot}{}^oC$
TS = sky temperature, ^oC

8. Cover-to-sky radiation

$$QRCS = \sigma * \varepsilon_c * (TCA^4 - TSA^4) * AREA$$

where: QRCS = cover-to-sky radiation, W
TSA = absolute sky temperature, ^oK

9. Cover temperature

A trial and error process of incrementing cover temperature is used until:

$$QCAC + QRPC = QCCS + QRCS$$

10. Useful energy collected at the increment

$$QUSE = QCPA - QCAC$$

where: QUSE = useful energy collected at the increment, W

11. Airstream temperature exiting increment

$$TO = QUSE/(CP * M) + TI$$

where: TO = airstream temperature exiting increment, ^oC
CP = specific heat of air, $W{\cdot}hr/(kg{\cdot}{}^oC)$
M = amount of air, kg/hr

Radiation reflected onto the north collector is considered evenly distributed.

2. Plate-to-cover radiation is found using the heat transfer equation for radiation between two infinite parallel plates (Holman, 1976). Terms used to calculate plate-to-cover radiation include the Stefan-Boltzmann constant, absolute plate and cover temperatures, and plate and cover emissivities.[1]
3. Energy convected from the back of the absorber plate to the airstream behind the absorber plate is calculated from the convective heat transfer coefficient for that side, the plate temperature, and the airstream temperature entering the increment. A convection coefficient obtained from Newton's law of cooling is used to express the effect of the back losses due to convection (Holman, 1976).[2]
4. Energy convected from the absorber plate to the airstream in front of the absorber plate is determined from an energy balance at the absorber plate. Other terms in the energy balance are the solar radiation absorbed by the absorber plate, the plate-to-cover radiation and the back losses.
5. Absorber plate temperature is calculated based on the definition

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[1]Net plate-to-cover radiation is assumed for the initial increment on the north side to be 25 percent of the north solar radiation absorbed by the plate, and on the south side to be 10 percent of the absorbed south radiation.

[2]Back losses for the first iteration process are assumed to be negligible. Once through the first iteration, back losses are calculated from the previous iteration.

of convection from the plate to airstream. Nusselt number is used to define the convected heat transfer coefficient of the airstream. This heat transfer coefficient plus the increment area, airstream temperature, and the plate to airstream convected energy determine the absorber plate temperature.

6. Convective heat transfer from the airstream to the cover is determined from basic laws of convection heat transfer. Convected energy from the airstream to cover is a product of the temperature difference of the airstream of cover, the airstream heat transfer coefficient, and increment area.

7. Convective heat loss from the cover plate which is exposed to outside winds is found from a dimensional expression given by Duffie and Beckman (1974) which related the heat transfer coefficient in $W/m^2 \cdot {}^oC$ to the wind speed in m/s. This wind heat transfer coefficient, cover and sky temperatures, and area determine the convective cover-to-sky heat transfer.

8. Cover-to-sky radiation heat transfer is determined by using area, Stefan-Boltzmann constant, cover emissivity, and absolute cover and sky temperatures. Stefan-Boltzmann's law of thermal radiation (Holman, 1976) is used to calculate the cover to sky radiation heat transfer.

9. A trial and error process of incrementing the cover temperature continues until an energy balance between the plate to cover heat transfer and the cover to sky losses is obtained. Convective airstream to cover heat transfer and plate to cover radiation make up the plate-to-cover heat transfer while cover to sky losses are

comprised of convective cover to sky energy transfer and cover-to-sky radiation losses.

10. Useful energy collected for the increment is established by an energy balance. The energy balance also includes convected plate to airstream energy and convected airstream to cover energy.
11. Temperature exiting the increment is defined by rearranging the quantities in the equation for useful energy. The specific heat equation includes the terms of volume of air, specific heat of air, and temperature entering the increment.

The incrementing process is continued until the predicted energy collected approaches within 0.1 kW of the previous iteration value or until the process is repeated ten times. The effect is a simultaneous solution of 11 equations and 11 unknowns. With initial assumptions as indicated in the thesis, this procedure does converge to a solution.

Model Validation

A mathematical model was developed to predict the useful energy collected and temperatures in the solar energy intensifier system. Model predictions were compared with measured temperatures and energy collected in a full scale prototype during corn drying in the fall of 1979. Additionally, the Nusselt number and the south-to-north airflow ratio were varied over a likely range of values based on past research and experimental conditions to determine their effect on collected energy.

Figure 12 compared predicted energy collection with measured energy collection for a representative sunny day during the drying season, December 13, 1979. A comparison of predicted and measured

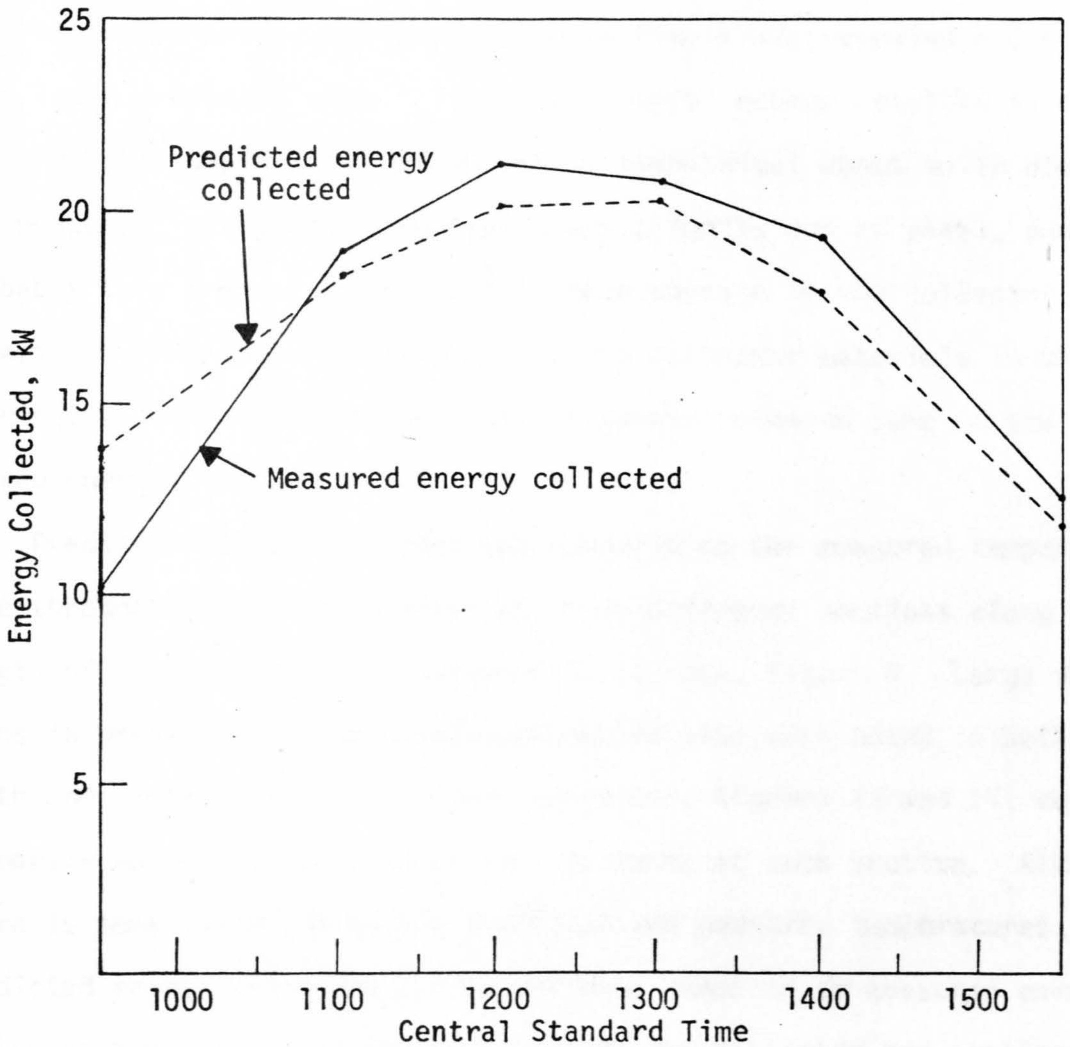

Figure 12 Relationship between predicted and measured energy collected for December 13, 1979.

energy collected for December 13, 1979, using a planimeter to measure the respective areas under each curve in Figure 12, revealed a 2.4 percent lower predicted value. Predicted, useful energy resulted in a uniform bell-shaped curve approximately symmetrical about solar noon. The measured, collected energy curve was slightly out of phase, due probably to a thermal lag created by heat storage in the collector materials. Heat was required to warm the collector materials in the morning, while in the afternoon the materials released some of the stored energy.

Predicted temperature rise was compared to the measured temperature rise through the solar collector at three different sections along the length of the collector for December 13 at noon, Figure 4. Large variations in predicted and measured temperature rise were noted in both the north and south sides of the solar collector, Figures 13 and 14, due primarily to the variability of airflow rates at each section. Although there is some variation in the predicted and measured temperatures, predicted energy collected can be reliably compared to measured energy collected because in the ductwork between the collector and application, where airflow has stabilized, temperatures and airflow were accurately measured.

Nusselt number, varied over a range of values (13.24 to 22.60) reported from previous heated plate research, resulted in differences between the predicted and measured useful energy ranging from -.6 to 4.1 percent (Figure 15). Predicted and measured energy collected differed by 2.6 percent with a Nusselt number of 17.02, which was believed to be the best value based on theoretical conditions.

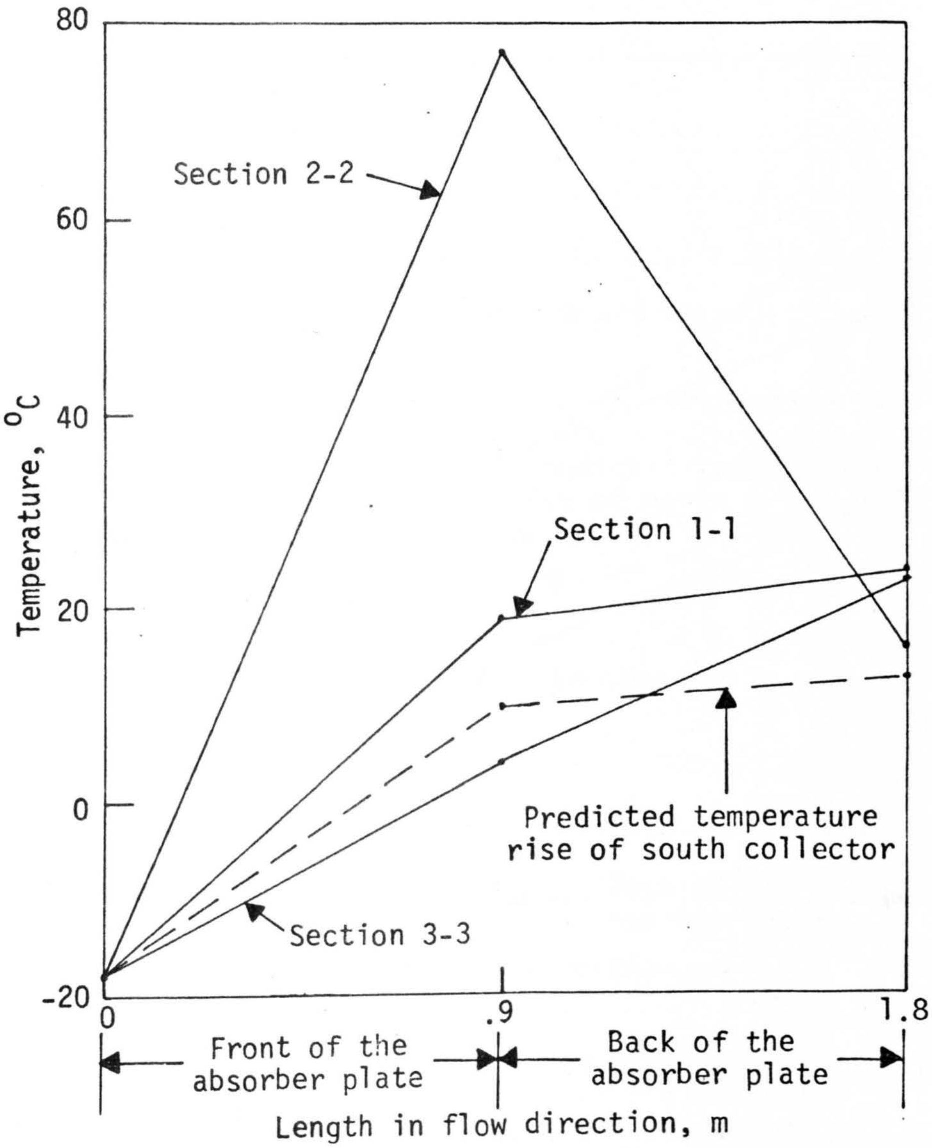

Figure 13 Comparison of predicted with measured temperature rise through the collector at three points along the length of the south facing collector.

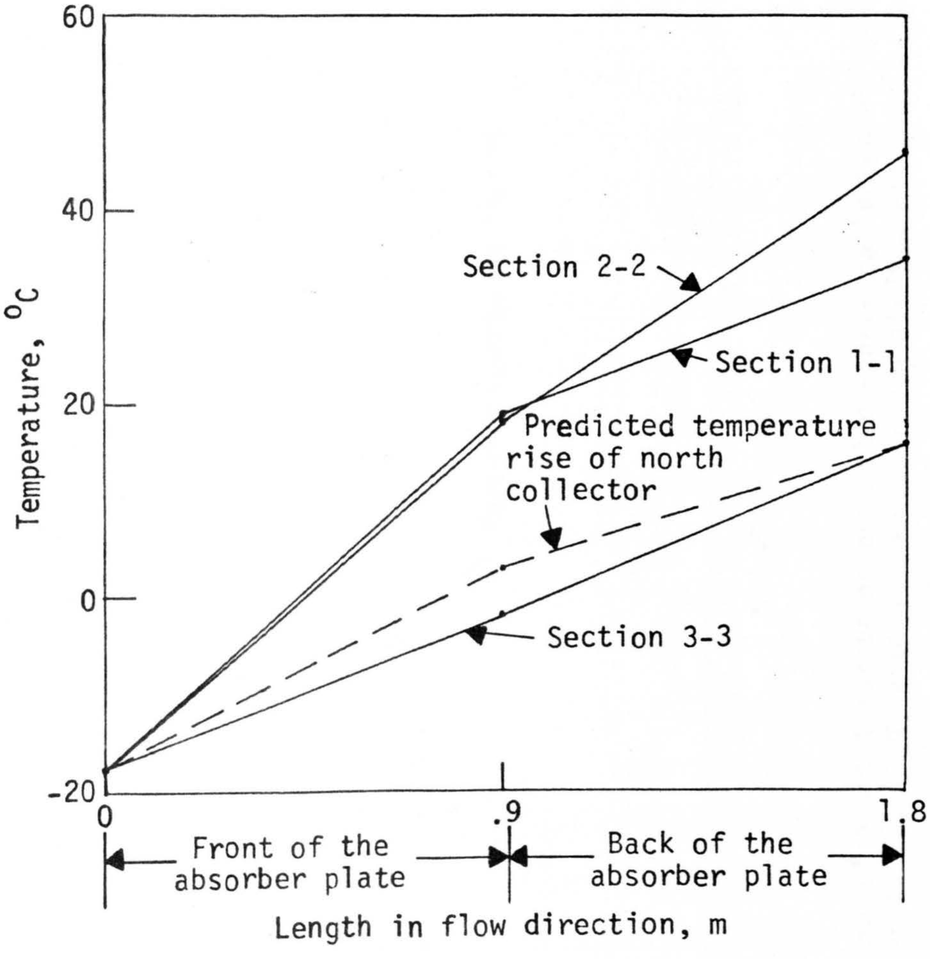

Figure 14 Comparison of predicted with measured temperature rise through the collector at three points along the length of the north facing collector.

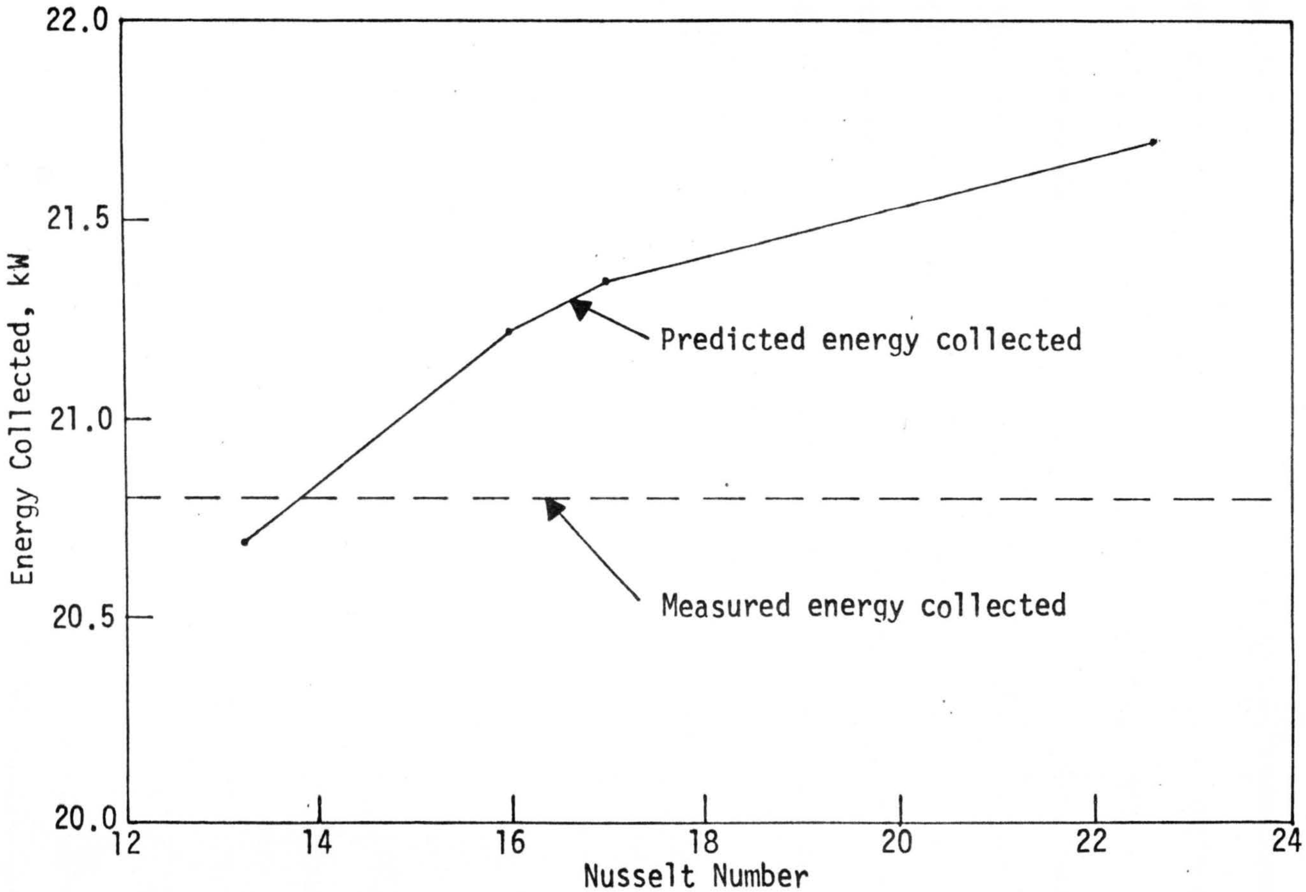

Figure 15 Effect of Nusselt number on predicted energy collected at noon on December 16, 1979, with a south-to-north airflow ratio of 1:3.

Varying south-to-north airflow rates from 0.25 to 0.50, which is the range of values expected based on geometrical considerations, resulted in a 1.1 to 3.7 percent difference between measured and predicted energy, Figure 16. Since the south-to-north plate spacing was 1:3, an airflow ratio of 0.33 was normally used.

The model can be used to predict temperatures entering storage units and to size solar energy intensifier systems for specfic solar applications. Also, extensive field testing can be minimized, because with the model, design alternatives for the system can be evaluated, and only the designs most promising can be selected for testing.

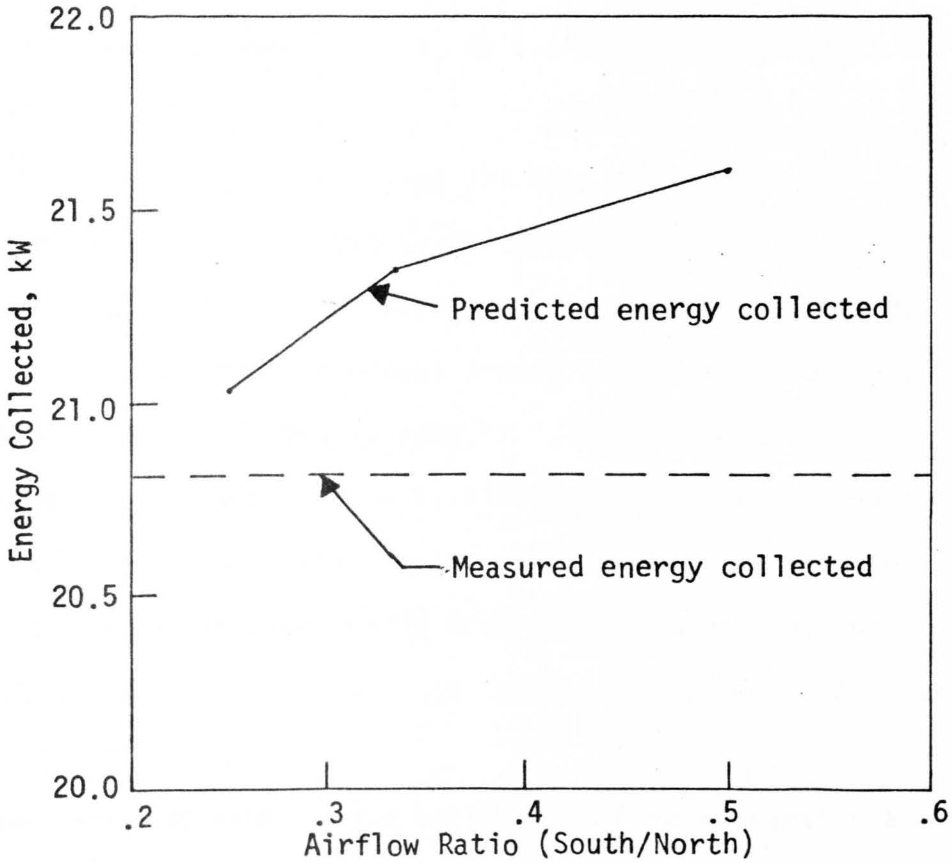

Figure 16 Effect of airflow ratio on predicted energy collected at noon on December 16, 1979, with a Nusselt number of 17.02.

CONCLUSIONS

The following conclusions were reached as a result of this study:

1. Average daily thermal efficiency of the solar energy intensifier system from November 8, 1979, to December 17, 1979, was 50.9 percent.
2. Total energy collected during the test period was 1815.2 kW-hr, while the total available solar radiation was 3567.6 kW-hr.
3. Average daily insolation during testing was 270.6 langleys while the average during the normal drying season at Brookings, South Dakota, was 353.5 langleys/day.
4. A highly significant, direct, linear equation accounted for 82.3 percent of the variation in the measured hourly energy collected.
5. For a 180-day heating period from October to March, the solar system savings would equal the initial investment cost over a five-year period.
6. A mathematical model using basic laws of heat transfer and thermodynamics predicted a 2.4 percent lower value of collected energy than the measured energy collected on December 13, 1979.
8. A -.6 to 4.1 percent difference between the predicted and measured useful energy was noted with Nusselt numbers ranging from 13.24 to 22.60.
9. Varying south-to-north collector side airflow ratio from 0.25 to 0.50 resulted in a 1.1 to 3.7 percent difference between measured and predicted energy collected.
10. Predictions of the model can be used to evaluate design

considerations in the solar energy intensifier system.

11. The model can be used to size solar energy intensifier systems for specific applications.

SUMMARY

Research was conducted at South Dakota State University to evaluate the solar energy intensifier system for corn drying from November 8 to December 17, 1979. Total energy collected during the test period was 1815.2 kW-hr with an average daily efficiency of 50.9 percent. Statistical analysis was used to develop significant equations based on insolation that predict hourly collected energy.

Over the 40-day test period, the energy savings averaged $1.30/day for a propane fired system. If the daily energy savings were adjusted to the average daily direct normal insolation available from October to March, an average of $313.33/year of propane would be saved. Solar system savings would equal the initial investment costs over a five-year period with 13 percent fuel inflation.

A mathematical model developed from basic laws of heat transfer and thermodynamics was used to predict useful energy collected and temperatures for the South Dakota State University solar energy intensifier system. Predicted useful energy for December 13, 1979, resulted in a uniform bell-shaped curve symmetrical about solar noon with 2.4 percent less predicted than measured energy collected. Varying Nusselt numbers between 13.24 and 22.60 and south-to-north airflow ratios from 0.25 to 0.50 resulted in little difference between measured and predicted energy collected. Predictions of this model can be used to evaluate design considerations, to predict temperatures entering storage units, and to size solar energy intensifier systems for solar applications.

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Appendix A

MATERIAL COSTS FOR

THE EXPERIMENTAL SOLAR SYSTEM

Table A.1 Costs of collector materials

Quantity	Description	Unit Cost, $	Total Cost, $
10	Glass, low iron tempered (0.4 x 86.4 x 193.0 cm)	24.98	249.84
20	Steel, sheet (0.61 mm x 1.22 x 2.44 m)	11.20	224.00
1	Steel, sheet (0.76 mm x 1.22 x 3.05 m)	17.50	17.50
57.91 m	Steel, angle (0.32 x 1.91 x 1.91 cm)	.65	37.44
39.01 m	Steel, angle (0.32 x 1.27 x 1.27 cm)	.54	21.16
1.52 m	Steel, channel (0.32 x 0.79 x 1.91 cm)	.69	1.05
13	Lumber, Grade #2 (1.27 cm x 1.22 x 2.44 m)	10.24	133.12
16	Lumber, Grade #2 (5.08 x 15.24 cm x 2.44 m)	3.49	55.84
53.34 m	Insulation, unfaced fiberglass batt (15.24 x 30.48 cm)	.69	36.74
4 liter	Paint, black high absorptive paint	5.00	20.00
	Caulking, silicone		32.00
	Welding rods		10.00
	Miscellaneous (bolts, screws, nails, etc.)		30.00
			$868.69

Table A.2 Costs of reflector materials.

Quantity	Description	Unit Cost, $	Total Cost, $
64.01 m	Reflective material (0.10 mm x 0.61 m)	4.87	311.64
10	Steel, sheet (0.76 mm x 1.22 x 3.05 m)	17.50	175.00
26.82 m	Steel, bar (0.32 x 12.7 cm)	1.96	52.64
12.80 m	Steel, standard thickness pipe (5.08 cm - diam)	4.00	51.24
48.77 m	Steel, angle (0.48 x 3.18 x 3.18 cm)	1.17	56.83
24.38 m	Steel, angle (0.48 x 2.54 x 2.54 cm)	1.10	26.86
18.29 m	Steel, channel (0.32 x 0.95 x 1.91 cm)	0.99	18.10
60.96 m	Steel, channel (0.32 x 1.27 x 3.81 cm)	1.17	71.46
	Mounting brackets		30.12
	Welding rods		20.00
	Miscellaneous (rivets, bolts, nuts, etc.)		25.00
			$838.89

Appendix B

DAILY RADIATION, ENERGY COLLECTED AND EFFICIENCY

Table B.1 Daily radiation, energy collected and efficiency for hours from 800 to 1700.

Day	Incident Radiation (kW)	Energy Collected (kW)	Daily Efficiency (%)
11/ 8/79	56.67	14.56	25.7
11/ 9/79	35.56	14.67	41.3
11/10/79	22.77	3.75	16.5
11/11/79	35.86	18.80	52.4
11/12/79	134.45	85.71	63.7
11/13/79	150.57	87.18	57.9
11/14/79	92.88	31.99	34.4
11/15/79	144.87	83.21	57.4
11/16/79	157.80	85.78	54.4
11/17/79	164.01	84.72	51.7
11/18/79	149.90	70.13	46.8
11/19/79	149.82	82.93	55.4
11/20/79	14.05	1.00	7.1
11/21/79	9.23	0.00	0.0
11/22/79	19.62	2.37	12.1
11/23/79	121.87	40.99	33.6
11/24/79	131.88	69.75	52.9
11/25/79	37.48	5.70	15.2
11/26/79	75.17	17.64	23.5
11/27/79	73.02	34.44	47.2
11/28/79	53.12	14.17	26.7
11/29/79	119.04	64.54	54.2
11/30/79	68.02	15.99	23.5
12/ 1/79	129.41	97.02	75.0
12/ 2/79	112.05	75.06	67.0
12/ 3/79	111.07	53.30	48.0
12/ 4/79	97.88	44.56	45.5
12/ 5/79	82.51	56.55	68.5
12/ 6/79	20.78	3.34	16.1
12/ 7/79	49.30	28.57	58.0
12/ 8/79	52.99	23.09	43.6
12/ 9/79	134.06	84.93	63.4
12/12/79	99.43	52.15	52.5
12/13/79	151.53	103.02	68.0
12/14/79	113.84	57.14	50.2
12/15/79	52.00	17.52	33.7
12/16/79	158.25	97.19	61.4
12/17/79	120.69	74.21	61.5
Total Period	3503.42	1797.66	51.3

Appendix C

RAW DATA

TABLE C.1 RAW DATA DIRECT NORMAL RADIATION STRIKING COLLECTOR (W/M**2) AND AIR TEMPERATURES (C) AT LOCATIONS (FIGURE 4)

MO	DA	YR	HR	RAD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
11	8	1979	800	0.01	-7	-7	-7	-7	-7	1	1	-8	0	-8	-8	-8	-8	2	-8	-8	-2	-7	-7	-7	-7	-7	-7	-7
11	8	1979	930	0.33	-1	-1	-1	-1	-1	5	5	0	5	-1	-1	0	-2	4	-3	-3	0	-3	-3	-3	-3	-4	-4	-5
11	8	1979	1100	0.22	6	2	1	1	1	10	10	1	7	1	1	1	1	8	-1	0	2	1	1	1	1	-2	-2	-2
11	8	1979	1200	0.31	6	3	2	2	2	10	10	2	7	2	2	2	2	7	0	1	4	2	2	2	2	0	0	-2
11	8	1979	1300	0.45	11	6	5	7	6	16	16	4	11	4	4	4	3	10	0	4	8	4	5	5	5	0	0	-2
11	8	1979	1400	0.25	7	4	2	5	5	15	15	3	1	3	3	3	2	10	1	1	6	2	3	3	3	0	0	-1
11	8	1979	1530	0.03	-3	-3	-3	-3	-3	5	5	-3	-3	-3	-3	-3	-3	4	-3	-3	1	-3	-3	-3	-3	-3	-2	-3
11	8	1979	1700	0.01	-3	-3	-3	-3	-3	8	8	-3	-3	-3	-3	-3	-3	8	-3	-3	6	-3	-3	-3	-3	-3	-3	-3
11	9	1979	800	0.0	-3	-3	-3	-3	-3	2	-4	-4	-4	-4	-4	-4	-4	1	-4	-4	-2	-4	-4	-4	-4	-4	-3	-4
11	9	1979	930	0.04	-4	-4	-4	-4	-4	1	-4	-4	-4	-4	-4	-4	-4	1	-4	-4	-2	-3	-3	-3	-3	-4	-4	-4
11	9	1979	1100	0.17	-3	-3	-3	-3	-3	3	1	-3	-3	-3	-3	-3	-3	2	-3	-3	-2	-2	-3	-3	-3	-4	-4	-4
11	9	1979	1200	0.16	0	0	-2	-1	-1	6	-3	-2	-2	-2	-2	-2	-1	4	-2	0	1	0	0	-1	-1	-3	-3	-4
11	9	1979	1300	0.13	-2	-2	-2	-2	-2	7	-3	-2	-2	-2	-2	-2	-1	6	-2	-1	0	0	-1	-1	-1	-3	-3	-4
11	9	1979	1400	0.10	-3	-3	-3	-3	-3	4	4	-3	-3	-3	-3	-3	-3	3	-4	-4	0	-3	-3	-3	-3	-4	-4	-5
11	9	1979	1530	0.39	11	7	-2	4	4	11	3	7	4	12	6	6	6	12	6	16	16	14	5	10	7	-1	-1	-4
11	9	1979	1700	0.01	-6	-6	-6	-6	-6	1	-6	-6	-6	-6	-6	-6	-6	1	-6	-6	-2	-6	-6	-6	-6	-6	-5	-6
11	10	1979	800	0.01	-8	-8	-8	-8	-8	-3	-10	-10	-4	-8	-8	-8	-8	-3	-8	-8	-7	-7	-7	-7	-7	-7	-7	-7
11	10	1979	930	0.06	-3	-3	-3	-3	-3	-2	-5	-5	-5	-5	-5	-5	-5	-2	-5	-5	-4	-5	-5	-5	-5	-5	-5	-5
11	10	1979	1100	0.14	-2	-2	-2	-2	-2	2	0	-3	-3	-3	-3	-3	-3	1	-3	-3	-2	-3	-3	-3	-3	-3	-3	-4
11	10	1979	1200	0.08	-2	-2	-2	-2	-2	4	4	2	-3	-3	-3	-3	-3	2	-3	-3	-1	-2	-2	-2	-2	-3	-3	-4
11	10	1979	1300	0.13	-4	-4	-4	-4	-4	5	-2	-2	-2	-2	-2	-2	-2	2	-3	-3	-1	-2	-2	-2	-2	-3	-3	-4
11	10	1979	1400	0.10	-2	-2	-2	-2	-2	6	-2	-2	-3	-3	-3	-3	-3	0	-3	-3	0	-3	-3	-3	-3	-3	-3	-3
11	10	1979	1530	0.10	-2	-2	-2	-2	-2	4	4	0	-3	-3	-3	-3	-3	3	-3	-3	0	-2	-2	-2	-2	-3	-3	-3
11	10	1979	1700	0.01	-4	-4	-4	-4	-4	5	-3	-3	-4	-4	-4	-4	-4	3	-4	-4	-1	-4	-4	-4	-4	-4	-4	-4
11	11	1979	800	0.01	-5	-5	-5	-5	-5	-2	-5	-5	-5	-5	-5	-5	-5	-2	-5	-5	-5	-5	-5	-5	-5	-5	-5	-5
11	11	1979	930	0.20	-1	-1	-1	-1	-1	4	-2	-2	-2	-2	-2	-2	-2	3	-3	-3	-1	-1	-1	-1	-1	-2	-2	-2
11	11	1979	1100	0.18	25	16	13	25	17	22	22	16	10	21	14	14	11	12	8	15	15	13	14	14	14	4	4	-2
11	11	1979	1200	0.10	3	3	2	2	2	15	6	1	1	1	1	1	1	10	1	1	2	2	2	2	2	1	1	1
11	11	1979	1300	0.28	16	13	12	11	12	20	10	11	10	8	10	10	7	12	5	7	7	10	11	11	11	4	4	2
11	11	1979	1400	0.18	7	6	4	4	4	15	4	4	4	4	4	4	4	10	3	3	3	4	4	4	4	3	3	2
11	11	1979	1530	0.06	5	5	3	4	4	54	54	3	3	3	3	3	3	43	3	3	22	3	3	3	3	3	3	2
11	11	1979	1700	0.01	2	2	2	2	2	45	1	1	1	1	1	1	1	41	1	1	23	1	1	1	1	1	2	1
11	12	1979	800	0.01	-4	-4	-4	-4	-4	35	35	-5	-5	-5	-5	-5	-5	34	-5	-5	21	-5	-5	-5	-5	-5	-5	-5
11	12	1979	930	0.10	-3	-3	-3	-3	-3	46	80	-3	-3	-3	-3	-3	-3	38	-4	-4	24	-3	-3	-3	-3	-4	-4	-4
11	12	1979	1100	0.79	35	34	41	38	34	40	18	30	35	41	34	37	18	22	14	21	18	27	28	27	23	4	3	-2
11	12	1979	1200	0.83	43	41	42	56	41	47	35	30	45	52	37	47	22	31	21	34	31	32	35	35	31	6	5	-1
11	12	1979	1300	0.82	45	43	44	55	41	46	46	35	31	45	38	44	22	25	21	27	25	28	40	37	33	7	6	0
11	12	1979	1400	0.73	43	44	36	58	41	46	20	43	42	54	42	44	18	21	23	30	26	30	38	35	32	10	8	0
11	12	1979	1530	0.48	27	18	8	23	16	55	17	21	16	27	21	23	14	43	11	18	34	16	16	18	16	5	5	1
11	12	1979	1700	0.04	1	3	-2	2	1	36	0	1	-2	-1	0	0	0	40	-2	-1	32	-1	0	0	0	-1	-1	-1
11	13	1979	800	0.20	-5	-5	-5	-5	-5	38	38	-5	-5	-5	-5	-5	-5	37	-5	-5	32	-5	-5	-5	-5	-5	-5	-5
11	13	1979	930	0.57	22	22	22	22	21	78	78	20	15	17	17	18	8	53	5	15	45	11	17	14	13	3	3	-1
11	13	1979	1100	0.75	40	37	46	47	42	44	44	36	37	55	41	44	24	24	21	35	32	33	37	36	31	10	8	2
11	13	1979	1200	0.80	48	45	44	60	46	47	30	37	43	62	43	47	30	28	24	42	36	41	42	42	36	12	11	4
11	13	1979	1300	0.75	53	55	36	56	51	52	43	44	36	53	46	50	31	31	30	41	34	37	42	42	37	13	13	6
11	13	1979	1400	0.70	50	41	42	58	44	44	27	27	32	50	40	43	27	27	27	37	34	35	37	37	33	12	12	5
11	13	1979	1530	0.39	31	20	13	23	18	35	35	28	12	17	18	18	18	35	12	17	23	17	16	16	16	7	7	7
11	13	1979	1700	0.07	2	2	1	2	2	4	5	3	1	2	2	2	2	12	2	2	6	1	2	2	2	1	2	2

TABLE C.1 RAW DATA DIRECT NORMAL RADIATION STRIKING COLLECTOR (W/M**2) AND AIR TEMPERATURES (C) AT LOCATIONS (FIGURE 4)

MO	DA	YR	HR	RAD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
11	14	1979	800	0.01	-2	-2	-2	-2	-2	4	-1	-2	2	-2	-2	-2	-2	2	-2	-2	-1	-2	-2	-2	-2	-2	-2	-2
11	14	1979	930	0.05	-1	-1	-1	-1	-1	17	-1	-1	23	-1	-1	-1	-1	26	-2	-2	13	-3	-3	-3	-3	-3	-3	-4
11	14	1979	1100	0.13	2	2	1	1	1	32	1	1	30	1	1	1	1	32	0	1	22	1	1	1	1	0	0	0
11	14	1979	1200	0.87	8	8	4	4	5	42	5	5	40	4	4	5	5	25	3	5	13	6	6	6	5	3	3	1
11	14	1979	1300	0.71	43	38	26	41	40	43	24	37	37	38	33	34	20	21	15	22	15	24	32	31	27	12	12	4
11	14	1979	1400	0.47	34	32	25	40	31	54	20	24	22	30	22	22	15	40	15	21	25	21	24	24	22	11	11	5
11	14	1979	1530	0.38	26	21	11	15	15	34	23	17	11	13	14	14	14	33	10	11	14	13	13	13	13	8	8	7
11	14	1979	1700	0.01	4	4	4	4	4	6	2	4	4	4	4	4	4	4	4	4	1	3	3	3	3	3	4	4
11	15	1979	800	0.15	-1	-1	-1	-1	-1	4	-1	-1	3	-1	-1	-1	-1	2	-2	-2	0	-1	-1	-1	-1	-1	-1	-1
11	15	1979	930	0.59	23	20	14	17	21	65	15	21	53	16	18	21	17	47	12	23	44	17	16	17	15	5	5	3
11	15	1979	1100	0.63	44	42	45	48	43	54	30	41	38	50	38	43	31	26	24	33	31	35	37	36	33	13	13	6
11	15	1979	1200	0.66	45	43	43	53	44	42	31	45	36	51	40	42	30	24	25	36	26	36	38	37	34	15	14	7
11	15	1979	1300	0.80	56	54	56	63	55	50	50	51	44	57	48	50	34	26	26	41	26	41	50	47	42	18	17	11
11	15	1979	1400	0.71	54	55	58	67	55	56	56	56	48	65	52	53	31	31	31	48	44	41	47	-8	42	20	18	12
11	15	1979	1530	0.45	38	31	24	34	31	33	33	34	32	41	33	35	23	25	24	25	25	26	31	33	31	16	16	15
11	15	1979	1700	0.07	12	10	7	10	10	5	10	12	7	10	10	10	8	4	7	8	2	7	8	8	8	7	7	8
11	16	1979	800	0.22	-2	-2	-3	-3	-3	2	2	-3	1	-3	-3	-3	-3	3	-3	-3	-1	-2	-2	-2	-2	-3	-3	-3
11	16	1979	930	0.56	23	22	22	26	23	66	44	21	54	22	20	23	12	45	11	14	48	15	20	18	15	6	6	2
11	16	1979	1100	0.76	45	44	50	50	44	70	53	44	55	53	37	42	24	38	24	27	36	33	38	38	34	18	16	8
11	16	1979	1200	0.81	54	52	50	66	53	57	35	35	36	77	45	46	31	36	27	46	46	42	48	46	42	22	22	12
11	16	1979	1300	0.80	58	56	60	67	57	52	52	52	44	62	48	51	33	25	35	50	37	42	50	48	44	25	24	14
11	16	1979	1400	0.72	60	60	48	65	56	56	56	60	54	67	54	54	34	34	34	50	47	44	51	48	45	26	26	17
11	16	1979	1530	0.47	44	37	30	40	36	36	36	37	40	46	37	41	28	28	30	35	34	35	36	38	36	24	24	17
11	16	1979	1700	0.06	16	16	12	14	15	8	14	17	12	15	15	14	13	8	11	14	7	13	14	15	15	12	13	13
11	17	1979	800	0.22	-4	-4	-5	-5	-5	0	0	-3	1	-5	-5	-5	-5	0	-6	-6	-3	-2	-2	-2	-2	-2	-2	-2
11	17	1979	930	0.61	24	21	21	27	24	57	57	21	51	21	18	23	8	43	10	10	44	11	20	18	14	4	4	0
11	17	1979	1100	0.80	47	42	35	36	40	65	65	53	75	63	44	51	25	45	25	36	51	34	34	41	34	15	17	10
11	17	1979	1200	0.84	60	56	57	67	55	62	54	65	72	85	54	58	34	47	28	51	58	44	42	48	41	20	20	12
11	17	1979	1300	0.82	63	54	45	58	58	57	57	54	51	55	46	53	36	34	34	46	42	45	47	52	44	24	24	14
11	17	1979	1400	0.74	63	61	47	64	60	65	65	54	52	51	43	46	35	37	40	46	47	44	47	46	43	24	24	16
11	17	1979	1530	0.50	44	34	28	38	34	34	34	38	37	44	38	42	30	30	30	40	40	36	36	38	36	23	23	17
11	17	1979	1700	0.05	14	13	10	12	12	5	5	14	10	12	12	12	11	4	11	12	4	12	12	12	12	11	11	11
11	18	1979	800	0.16	-2	-2	-2	-2	-2	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-2	-2
11	18	1979	930	0.54	23	24	25	26	26	48	15	20	41	21	20	22	13	35	14	14	27	15	21	20	17	8	8	3
11	18	1979	1100	0.77	41	35	30	35	35	46	46	42	53	51	37	41	25	40	23	34	36	32	32	34	31	16	16	8
11	18	1979	1200	0.80	48	46	37	56	46	52	43	46	50	63	40	43	30	31	28	44	35	37	36	40	35	20	21	11
11	18	1979	1300	0.79	53	50	54	61	51	42	42	38	31	41	38	37	31	24	28	40	26	37	40	42	37	22	22	13
11	18	1979	1400	0.69	51	46	41	58	48	52	40	37	48	43	36	40	31	32	32	44	42	38	41	40	37	23	23	14
11	18	1979	1530	0.43	36	30	31	36	31	33	27	33	30	35	32	33	25	28	26	32	32	30	30	31	28	20	20	15
11	18	1979	1700	0.0	12	12	12	13	13	7	7	12	12	12	12	12	12	8	12	12	7	12	12	12	12	12	12	12
11	19	1979	800	0.14	1	1	1	1	1	4	4	1	3	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1
11	19	1979	930	0.55	23	23	27	30	31	46	17	22	36	28	22	27	15	31	16	16	15	31	25	22	20	7	8	3
11	19	1979	1100	0.75	38	32	34	40	40	45	27	44	48	56	40	45	25	34	22	40	42	34	34	36	32	13	14	6
11	19	1979	1200	0.80	45	40	51	62	48	54	54	38	37	71	44	42	27	28	26	41	42	37	37	42	35	16	16	8
11	19	1979	1300	0.79	47	48	46	60	51	45	33	38	32	41	38	40	27	23	28	40	33	36	40	41	36	17	17	10
11	19	1979	1400	0.70	45	40	50	61	50	50	31	34	34	41	35	37	26	27	28	38	40	36	41	38	35	17	17	10
11	19	1979	1530	0.43	32	26	26	35	25	27	24	30	33	34	28	31	21	23	23	30	30	27	27	28	26	13	14	10
11	19	1979	1700	0.01	7	10	6	8	10	5	7	10	5	8	8	7	7	3	6	6	2	6	7	7	7	6	6	5

TABLE C.1 RAW DATA DIRECT NORMAL RADIATION STRIKING COLLECTOR (W/M**2) AND AIR TEMPERATURES (C) AT LOCATIONS (FIGURE 4)

MO	DA	YR	HR	RAD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
11	20	1979	800	0.0	-3	-3	-3	-3	-3	0	3	-3	5	-3	-3	-3	-3	5	-3	-3	1	-3	-3	-3	-3	-3	-3	-3
11	20	1979	930	0.03	0	0	0	0	0	22	22	0	22	0	0	0	0	22	0	0	17	0	0	0	0	0	0	0
11	20	1979	1100	0.07	1	1	1	1	1	21	21	1	22	1	1	1	1	25	1	1	21	1	1	1	1	1	1	0
11	20	1979	1200	0.06	2	2	2	2	2	13	13	2	12	2	2	2	2	13	1	1	11	2	2	2	2	1	1	1
11	20	1979	1300	0.06	2	2	2	2	2	2	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
11	20	1979	1400	0.09	5	4	3	3	3	22	11	8	17	3	3	3	3	23	1	1	17	2	2	2	2	2	2	1
11	20	1979	1530	0.07	2	2	2	2	2	18	18	1	16	1	1	1	1	18	1	1	15	1	1	1	1	1	2	1
11	20	1979	1700	0.0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	1	1	1
11	21	1979	800	0.0	-2	-2	-2	-2	-2	4	-1	-2	1	-2	-2	-2	-2	5	-2	-2	4	-2	-2	-2	-2	-2	-1	-1
11	21	1979	930	0.02	-1	-1	-1	-1	-1	21	-2	-2	16	-2	-2	-2	-2	24	-2	-2	25	-2	-2	-2	-2	-2	-1	-1
11	21	1979	1100	0.08	0	0	0	0	0	21	-1	-1	16	0	0	0	-1	25	-1	-1	22	-1	-1	-1	-1	-1	0	0
11	21	1979	1200	0.07	0	0	0	0	0	10	-1	-1	7	0	0	0	-1	24	-1	-1	21	-1	-1	-1	-1	-1	0	0
11	21	1979	1300	0.06	0	0	0	0	0	2	-1	-1	3	0	0	0	-1	2	0	0	3	0	0	0	0	0	0	0
11	21	1979	1400	0.02	0	0	0	0	0	22	22	-1	16	-1	-1	-1	-1	25	0	0	18	0	0	0	0	0	0	0
11	21	1979	1530	0.01	0	0	0	0	0	18	-1	-1	18	0	0	0	0	24	0	0	20	0	0	0	0	0	1	0
11	21	1979	1700	0.0	0	0	0	0	0	2	-1	-1	1	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0
11	22	1979	800	0.01	-3	-3	-3	-3	-3	5	1	-4	4	-4	-4	-4	-4	2	-3	-3	1	-3	-3	-3	-3	-3	-3	-3
11	22	1979	930	0.07	-2	-2	-2	-2	-2	44	-3	-2	44	-2	-2	-2	-2	44	-2	-2	40	-2	-2	-2	-2	-2	-2	-2
11	22	1979	1100	0.08	-2	-2	-1	-1	-1	41	-2	-2	32	-1	-1	-1	-1	37	-1	-1	30	-1	-1	-1	-1	-2	-1	-2
11	22	1979	1200	0.08	-2	-2	-1	-1	-1	37	-2	-2	33	-1	-1	-1	-1	35	-1	-1	27	-1	-1	-1	-1	-2	-1	-2
11	22	1979	1300	0.11	-1	-1	-1	0	0	7	-1	-1	0	0	0	0	-1	1	0	0	4	0	0	0	0	-1	-1	-1
11	22	1979	1400	0.11	-1	-1	-1	0	0	28	-2	-1	26	-1	-1	-1	-1	27	-1	-1	24	-1	-1	-1	-1	-2	-1	-2
11	22	1979	1530	0.07	-2	-1	-1	-1	-1	17	-2	-1	17	-1	-1	-1	-1	28	-4	-2	21	-2	-2	-2	-2	-2	-1	-2
11	22	1979	1700	0.0	-2	-2	-2	-2	-2	-1	-2	-2	0	-2	-2	-2	-2	0	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
11	23	1979	800	0.02	-6	-6	-7	-7	-7	6	6	-7	5	-7	-7	-7	-7	5	-7	-7	2	-7	-7	-7	-7	-7	-7	-7
11	23	1979	930	0.64	-2	2	16	13	11	55	-3	5	42	10	4	8	-2	40	1	1	42	1	6	5	3	-4	-3	-5
11	23	1979	1100	0.27	-1	0	0	0	0	42	-2	-2	37	0	-1	-1	-2	37	-4	-4	32	-1	-1	-1	-1	-3	-3	-3
11	23	1979	1200	0.42	0	1	1	1	1	42	-1	-1	36	1	1	1	-1	35	0	0	32	0	0	0	0	-4	-4	-4
11	23	1979	1300	0.89	5	16	21	21	23	25	4	7	10	17	13	16	4	7	10	12	13	12	15	14	12	2	2	0
11	23	1979	1400	0.77	23	36	43	46	38	63	13	37	48	41	28	38	16	38	21	21	31	25	27	28	22	8	6	1
11	23	1979	1530	0.36	26	21	13	22	18	47	47	21	20	27	17	27	12	41	12	16	36	17	18	20	17	4	4	1
11	23	1979	1700	0.01	-2	-2	-2	-2	-1	2	2	-2	-2	-2	-2	-2	-2	1	-2	-2	-1	-2	-2	-2	-2	-2	-1	-2
11	24	1979	800	0.02	-15	-15	-15	-15	-15	1	-12	-12	-16	-16	-16	-16	-16	-1	-15	-15	-3	-15	-15	-15	-15	-15	-15	-15
11	24	1979	930	0.17	-6	-6	-10	-10	-8	47	47	-8	-10	-10	-10	-10	-10	44	-10	-10	34	-10	-10	-10	-10	-10	-10	-11
11	24	1979	1100	0.55	24	14	12	15	17	72	5	18	36	18	13	14	3	50	3	16	51	8	10	10	8	-2	-2	-4
11	24	1979	1200	0.81	30	22	15	31	24	76	36	24	41	31	18	23	11	48	10	14	43	16	18	18	15	1	1	-5
11	24	1979	1300	0.86	43	38	31	45	38	43	22	20	31	43	32	34	16	22	11	21	21	23	31	31	26	4	4	-4
11	24	1979	1400	0.77	44	37	41	52	40	65	22	37	31	45	31	38	16	38	17	27	42	24	27	27	24	6	6	-2
11	24	1979	1530	0.47	27	18	13	22	17	50	40	38	21	27	20	22	10	36	11	17	36	16	17	17	16	3	3	-1
11	24	1979	1700	0.01	-4	-4	-5	-4	-4	1	-3	-3	-6	-5	-5	-5	-5	0	-5	-5	-2	-5	-4	-4	-4	-5	-5	-5
11	25	1979	800	0.01	-6	-6	-6	-6	-6	4	-6	-6	-7	-7	-7	-7	-7	4	-7	-7	0	-6	-6	-6	-6	-6	-6	-6
11	25	1979	930	0.08	-3	-3	-3	-3	-3	37	-3	-3	-3	-3	-3	-3	-3	44	-4	-4	34	-3	-3	-3	-3	-4	-4	-4
11	25	1979	1100	0.10	-1	-1	-1	-1	-1	37	-2	-2	-2	-2	-2	-2	-2	40	-3	-3	34	-2	-2	-2	-2	-2	-2	-2
11	25	1979	1200	0.22	5	5	2	2	2	41	18	2	2	2	2	2	2	32	0	1	16	2	2	2	2	-1	0	0
11	25	1979	1300	0.27	10	8	3	4	5	11	4	4	3	5	4	4	3	8	1	2	4	4	4	4	4	1	1	1
11	25	1979	1400	0.24	10	8	4	5	5	38	4	5	3	4	4	4	4	33	2	3	27	4	4	4	2	2	2	2
11	25	1979	1530	0.11	6	6	2	4	4	36	1	4	2	3	3	3	3	32	2	2	26	2	2	2	2	2	2	1
11	25	1979	1700	0.01	0	0	0	0	0	2	4	0	0	0	0	0	0	4	0	0	1	0	0	0	0	0	0	0

TABLE C.1 RAW DATA DIRECT NORMAL RADIATION STRIKING COLLECTOR (W/M**2) AND AIR TEMPERATURES (C) AT LOCATIONS (FIGURE 4)

MO	DA	YR	HR	RAD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
11	26	1979	800	0.01	-3	-3	-3	-3	-3	0	-3	-3	-3	-3	-3	-3	-3	0	-4	-4	-3	-4	-4	-4	-4	-4	-3	-4
11	26	1979	930	0.08	-3	-3	-4	-4	-4	13	-3	-3	-3	-3	-3	-3	-3	15	-4	-4	11	-4	-4	-4	-4	-4	-4	-4
11	26	1979	1100	0.24	-1	-1	-3	-3	-2	18	-2	-2	-2	-2	-2	-2	-2	26	-3	-3	20	-2	-2	-2	-2	-4	-4	-4
11	26	1979	1200	0.70	2	3	5	11	6	20	1	2	2	2	1	3	0	13	0	0	11	1	1	2	2	-2	-2	-2
11	26	1979	1300	0.45	12	16	10	16	12	16	4	14	13	15	11	12	4	7	3	6	6	6	8	8	8	0	0	-2
11	26	1979	1400	0.56	14	12	5	8	8	38	4	8	6	7	7	8	4	28	4	-1	23	3	5	5	4	-1	-1	-2
11	26	1979	1530	0.06	0	1	-2	-1	-1	32	-2	-2	-2	-2	-2	-2	-2	27	-3	-3	24	-2	-2	-2	-2	-3	-3	-3
11	26	1979	1700	0.01	-4	-4	-4	-4	-4	0	-4	-4	-4	-4	-4	-4	-4	0	-4	-4	-2	-4	-4	-4	-3	-4	-4	-4
11	27	1979	800	0.08	-12	-12	-12	-12	-12	1	-6	-12	-12	-12	-12	-12	-12	0	-12	-12	-2	-12	-12	-12	-12	-12	-11	-11
11	27	1979	930	0.40	0	0	-7	-6	-4	50	-6	-6	-7	-7	-7	-7	-6	50	-8	-7	47	-5	-5	-5	-5	-8	-8	-8
11	27	1979	1100	0.32	4	4	-3	1	1	56	25	0	-2	-1	-1	-1	-1	56	-3	-2	48	-2	-1	-1	-1	-4	-4	-4
11	27	1979	1200	0.45	20	12	13	21	14	71	71	11	7	15	8	10	4	40	4	6	26	8	10	10	8	-1	-1	-2
11	27	1979	1300	0.33	37	24	27	43	35	46	20	36	26	42	33	33	16	22	11	17	15	21	27	25	25	3	3	-4
11	27	1979	1400	0.35	7	6	3	4	5	54	2	4	2	2	3	3	2	43	0	0	35	1	2	2	2	-1	-1	-1
11	27	1979	1530	0.08	0	1	-1	1	3	55	-2	-1	-2	-1	-1	-1	-1	42	-2	-2	24	-2	-1	-1	-1	-2	-2	-2
11	27	1979	1700	0.01	-3	-3	-4	-2	-2	15	-3	-3	-4	-3	-3	-3	-3	10	-4	-4	1	-4	-3	-3	-3	-4	-4	-4
11	28	1979	800	0.01	-10	-10	-10	-10	-10	3	3	-11	-11	-11	-11	-11	-11	2	-11	-11	-1	-11	-11	-11	-11	-11	-10	-10
11	28	1979	930	0.08	-8	-8	-8	-8	-8	45	45	-10	-10	-10	-10	-10	-10	46	-10	-10	33	-8	-8	-8	-8	-8	-8	-10
11	28	1979	1100	0.22	-5	-5	-6	-6	-6	51	-7	-6	-6	-6	-6	-6	-4	53	-7	-6	42	-4	-5	-5	-5	-7	-7	-8
11	28	1979	1200	0.45	-4	-4	-5	-4	-4	53	-6	-6	-6	-6	-6	-6	-3	32	-5	-4	27	-2	-4	-4	-4	-7	-7	-7
11	28	1979	1300	0.22	-1	-1	-4	-2	-3	30	-4	-3	-4	-3	-3	-3	0	33	-4	0	25	1	-1	-2	-2	-6	-6	-7
11	28	1979	1400	0.36	1	0	0	0	0	51	-4	0	0	0	0	0	2	55	-1	3	50	4	0	0	0	-6	-6	-7
11	28	1979	1530	0.13	-4	-4	-5	-5	-5	48	-7	-6	-6	-6	-6	-6	-5	42	-6	-5	25	-4	-4	-5	-5	-6	-6	-7
11	28	1979	1700	0.01	-8	-8	-8	-8	-8	7	-8	-8	-8	-8	-8	-8	-8	8	-8	-8	-3	-8	-8	-8	-8	-8	-8	-8
11	29	1979	800	0.01	-12	-12	-12	-12	-12	3	3	-13	-13	-13	-13	-13	-13	1	-13	-13	-2	-12	-12	-12	-12	-12	-12	-12
11	29	1979	930	0.38	-7	-7	-8	-8	-8	47	-8	-10	-10	-10	-10	-10	-10	35	-11	-11	27	-10	-10	-10	-10	-11	-11	-11
11	29	1979	1100	0.46	14	7	10	21	13	64	1	8	2	10	6	6	7	41	3	8	31	7	10	6	5	-6	-6	-10
11	29	1979	1200	0.38	3	-1	-2	0	0	46	-3	-1	-4	-3	-2	-2	0	23	-4	-2	15	0	0	-1	-1	-7	-7	-8
11	29	1979	1300	0.89	26	28	25	33	34	37	8	25	18	27	27	31	16	15	8	20	16	23	28	25	22	-1	-1	-7
11	29	1979	1400	0.80	28	28	30	50	37	61	11	22	27	40	30	36	15	35	14	25	33	23	28	25	23	0	0	-6
11	29	1979	1530	0.36	17	13	16	24	14	45	6	17	21	23	14	18	4	28	5	11	32	8	12	12	11	-2	-2	-5
11	29	1979	1700	0.01	-6	-6	-7	-7	-7	4	-8	-7	-7	-7	-7	-7	-7	-2	-7	-7	-3	-8	-7	-7	-7	-7	-7	-7
11	30	1979	800	0.0	-8	-8	-8	-8	-8	5	-8	-8	-8	-8	-8	-8	-8	5	-8	-8	-1	-8	-8	-8	-8	-8	-8	-8
11	30	1979	930	0.17	-5	-5	-5	-5	-5	46	-5	-5	-5	-5	-5	-5	-5	33	-6	-6	26	-5	-5	-5	-5	-6	-6	-6
11	30	1979	1100	0.30	1	-1	-1	-1	-1	33	-1	-1	-2	-2	-2	-2	-2	32	-3	-3	20	-2	-2	-2	-2	-4	-4	-4
11	30	1979	1200	0.47	10	6	5	5	7	44	41	6	5	5	5	6	4	17	1	3	11	4	5	5	4	-3	-2	-3
11	30	1979	1300	0.47	12	11	3	7	7	12	7	6	2	5	5	5	5	7	1	3	2	4	4	4	4	-2	-2	-2
11	30	1979	1400	0.35	4	5	0	1	1	33	0	1	0	0	0	0	0	25	-1	-1	20	1	1	1	1	-3	-2	-3
11	30	1979	1530	0.11	0	0	-2	-1	-1	28	-2	-1	-2	-2	-2	-2	-2	21	-3	-3	14	-2	-2	-2	-2	-3	-3	-3
11	30	1979	1700	0.0	-6	-5	-6	-5	-5	-1	-2	-3	-6	-5	-5	-5	-5	-2	-6	-6	-5	-6	-6	-6	-6	-6	-6	-6
12	1	1979	800	0.0	-17	-17	-17	-17	-17	-1	-1	-17	-17	-17	-17	-17	-17	-4	-17	-17	-7	-17	-17	-17	-17	-17	-17	-17
12	1	1979	930	0.40	2	2	4	4	4	60	-6	1	-1	-1	-1	1	-7	27	-6	-4	24	-4	0	0	-2	-12	-12	-15
12	1	1979	1100	0.70	33	28	34	36	30	71	5	33	25	37	24	27	6	34	5	22	36	22	22	20	16	-4	-4	-10
12	1	1979	1200	0.79	40	30	22	44	33	45	45	33	27	44	28	37	8	18	7	23	31	18	24	23	21	-2	-2	-8
12	1	1979	1300	0.71	44	36	24	41	33	64	64	35	26	41	30	33	10	14	2	15	15	17	26	26	22	-1	-1	-11
12	1	1979	1400	0.61	40	34	24	43	35	73	11	31	41	48	30	32	8	35	8	16	35	17	25	24	21	0	-1	-10
12	1	1979	1530	0.33	21	13	5	18	12	56	14	18	17	21	12	17	0	35	3	8	35	6	10	11	10	-4	-3	-8
12	1	1979	1700	0.02	-12	-12	-13	-13	-13	2	2	-3	-13	-13	-12	-12	-12	0	-13	-13	-3	-13	-12	-12	-12	-12	-12	-12

TABLE C.1 RAW DATA DIRECT NORMAL RADIATION STRIKING COLLECTOR (W/M**2) AND AIR TEMPERATURES (C) AT LOCATIONS (FIGURE 4)

MO	DA	YR	HR	RAD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
12	2	1979	800	0.0	-13	-13	-13	-13	-13	0	-13	-13	-13	-13	-13	-13	-13	-3	-13	-13	-5	-13	-13	-13	-13	-13	-13	-13
12	2	1979	930	0.29	4	4	7	10	8	54	-3	2	1	1	1	1	-2	31	-2	0	28	0	3	1	1	-6	-6	-10
12	2	1979	1100	0.55	23	22	26	32	24	60	22	21	15	28	18	20	6	32	6	17	32	13	17	14	14	0	0	-7
12	2	1979	1200	0.64	30	25	27	38	30	63	26	26	35	38	21	23	8	37	10	22	36	16	24	20	18	1	2	-5
12	2	1979	1300	0.67	33	25	30	41	30	34	34	22	13	21	21	22	11	14	6	16	15	16	24	21	20	4	4	-4
12	2	1979	1400	0.60	31	26	35	46	34	64	10	20	17	37	24	27	10	35	13	18	35	17	24	20	18	3	4	-3
12	2	1979	1530	0.32	17	13	11	17	13	46	42	31	11	14	12	13	5	33	6	13	32	10	12	12	11	1	2	-3
12	2	1979	1700	0.01	-3	-3	-3	-3	-3	4	4	0	-4	-3	-3	-3	-3	1	-3	-3	-2	-3	-3	-3	-3	-3	-3	-3
12	3	1979	800	0.0	-8	-8	-8	-8	-8	7	7	-10	-10	-10	-10	-10	-10	2	-10	-10	-1	-8	-8	-8	-8	-8	-8	-8
12	3	1979	930	0.15	-2	-2	-2	-2	-2	53	-3	-3	-3	-3	-3	-3	-3	35	-4	-4	34	-3	-3	-3	-3	-4	-4	-4
12	3	1979	1100	0.40	18	14	12	17	14	50	50	13	11	15	13	13	12	45	7	12	32	12	12	12	11	3	3	1
12	3	1979	1200	0.77	35	35	31	40	35	52	20	35	41	43	33	35	22	42	17	25	32	27	32	30	25	7	7	2
12	3	1979	1300	0.73	37	31	23	41	31	34	25	30	18	28	24	24	16	17	12	21	18	18	25	24	22	8	8	3
12	3	1979	1400	0.80	42	41	41	54	41	66	66	57	33	45	33	37	20	41	21	27	30	28	34	32	28	10	10	4
12	3	1979	1530	0.20	22	22	13	22	17	48	13	15	17	21	17	18	11	37	12	15	23	14	16	16	15	7	7	4
12	3	1979	1700	0.01	1	1	0	1	1	4	1	1	0	0	0	0	0	4	0	0	0	0	0	0	0	0	1	1
12	4	1979	800	0.0	-7	-7	-7	-7	-7	-1	-1	-6	-6	-6	-6	-6	-6	-2	-7	-7	-5	-6	-6	-6	-6	-6	-6	-6
12	4	1979	930	0.36	8	3	2	1	2	47	3	3	2	1	2	2	2	40	0	2	32	2	2	1	1	0	0	-2
12	4	1979	1100	0.73	20	21	24	23	24	82	50	21	17	18	20	21	12	50	11	18	34	16	20	18	16	6	6	1
12	4	1979	1200	0.55	32	28	30	37	34	47	47	26	38	37	26	30	17	35	15	24	17	23	26	25	22	8	8	2
12	4	1979	1300	0.58	34	28	25	40	31	33	33	25	20	28	24	24	15	15	13	20	6	18	24	22	21	8	8	3
12	4	1979	1400	0.33	24	22	21	25	24	41	28	20	15	18	16	17	11	27	12	14	15	15	18	17	16	7	7	3
12	4	1979	1530	0.15	6	5	4	6	6	26	26	5	4	4	4	4	4	26	3	4	12	4	4	5	5	3	4	3
12	4	1979	1700	0.0	1	1	1	1	1	2	2	1	1	1	1	1	1	2	1	1	-2	1	1	1	1	1	2	1
12	5	1979	800	0.0	0	0	0	0	0	3	3	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	1
12	5	1979	930	0.49	15	16	24	24	24	46	11	15	15	17	16	17	12	36	10	12	25	13	17	14	14	4	4	1
12	5	1979	1100	0.73	23	27	35	43	35	51	15	23	33	44	34	37	28	36	25	43	42	38	33	33	28	8	8	2
12	5	1979	1200	0.82	25	32	38	54	40	52	51	28	42	58	41	43	31	37	27	50	48	40	37	37	33	10	10	2
12	5	1979	1300	0.13	18	20	16	36	18	20	13	17	8	23	16	14	17	16	12	22	20	23	23	23	23	5	6	2
12	5	1979	1400	0.09	4	4	3	5	4	31	3	4	3	3	4	4	5	32	3	4	23	4	4	4	4	2	2	2
12	5	1979	1530	0.03	1	2	2	2	2	30	1	1	1	1	1	1	1	28	1	1	25	1	2	2	2	1	2	1
12	5	1979	1700	0.0	1	1	1	1	1	5	0	0	0	0	0	0	0	3	0	0	1	0	0	0	0	0	1	0
12	6	1979	800	0.01	-4	-4	-4	-4	-4	5	0	-5	-5	-5	-5	-5	-5	1	-4	-4	0	-4	-4	-4	-4	-4	-4	-4
12	6	1979	930	0.04	-2	-2	-2	-2	-2	31	-3	-3	-2	-2	-2	-2	-2	36	-3	-3	24	-2	-2	-2	-2	-2	-2	-2
12	6	1979	1100	0.15	1	2	2	2	2	34	1	1	1	1	1	1	1	24	0	0	13	1	1	1	1	0	0	0
12	6	1979	1200	0.08	5	5	2	4	4	26	3	3	3	3	3	3	3	24	2	2	10	3	3	3	3	2	2	1
12	6	1979	1300	0.06	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	2	1
12	6	1979	1400	0.21	2	2	2	2	2	14	2	2	2	2	2	2	2	15	1	1	2	2	2	2	2	2	3	1
12	6	1979	1530	0.01	2	2	2	2	2	15	2	2	2	2	2	2	2	16	2	2	1	1	1	1	1	1	2	2
12	6	1979	1700	0.0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	2	2	2	2	2
12	7	1979	800	0.0	-3	-3	-3	-3	-3	-4	-4	-4	-4	-4	-4	-4	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3
12	7	1979	930	0.21	-3	-3	-3	-3	-3	21	-4	-4	-4	-4	-4	-4	-2	21	-3	-3	2	-3	-3	-3	-3	-4	-4	-4
12	7	1979	1100	0.21	18	20	17	26	22	38	7	13	10	22	15	14	21	30	13	31	28	24	13	12	12	0	0	-4
12	7	1979	1200	0.42	3	5	0	7	2	13	2	3	0	5	4	3	5	25	1	8	12	4	4	3	3	-2	-1	-3
12	7	1979	1300	0.20	15	16	16	22	16	16	7	12	12	18	16	16	16	15	11	18	11	16	14	13	12	1	1	-2
12	7	1979	1400	0.14	1	1	-1	2	0	24	0	0	-1	0	0	0	0	23	-1	0	6	0	0	0	0	-2	-2	-3
12	7	1979	1530	0.17	-2	-2	-2	-1	-1	22	-2	-2	-2	-2	-2	-2	-2	22	-2	-2	10	-2	-2	-2	-2	-3	-2	-3
12	7	1979	1700	0.01	-5	-5	-5	-5	-5	-1	-5	-5	-5	-5	-5	-5	-5	-2	-5	-4	-4	-4	-4	-4	-4	-5	-4	-5

TABLE C.1 RAW DATA DIRECT NORMAL RADIATION STRIKING COLLECTOR (W/M**2) AND AIR TEMPERATURES (C) AT LOCATIONS (FIGURE 4)

MO	DA	YR	HR	RAC	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
12	8	1979	800	0.06	-15	-15	-15	-15	-15	2	2	-15	-15	-15	-15	-15	-15	-2	-15	-15	-6	-15	-15	-15	-15	-15	-14	-14
12	8	1979	930	0.03	-11	-11	-11	-11	-11	43	16	-11	-11	-11	-11	-11	-11	35	-8	-8	31	-8	-8	-8	-8	-8	-7	-8
12	8	1979	1100	0.04	-7	-7	-7	-7	-7	46	42	-7	-7	-7	-7	-7	-7	27	-8	-8	27	-7	-7	-7	-7	-7	-7	-8
12	8	1979	1200	0.09	-5	-5	-5	-5	-5	21	-5	-5	-5	-5	-5	-5	-5	37	-6	-6	27	-5	-5	-5	-5	-6	-5	-6
12	8	1979	1300	0.15	-2	-2	-3	-3	-3	3	-3	-3	-3	-3	-3	-3	-3	4	-4	-4	-1	-3	-3	-3	-3	-3	-3	-5
12	8	1979	1400	0.66	25	24	28	35	26	51	51	17	22	25	21	25	10	31	12	17	30	15	20	17	15	3	3	-3
12	8	1979	1530	0.41	17	15	12	20	14	40	8	13	13	18	13	16	6	28	7	13	27	11	13	13	12	2	2	-2
12	8	1979	1700	0.0	-2	-2	-2	-2	-2	1	-2	-2	-2	-2	-2	-2	-2	0	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
12	9	1979	800	0.04	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-3	-4	-4	-5	-5	-5	-5	-5	-5	-3	-4
12	9	1979	930	0.51	16	17	17	20	20	41	10	13	14	15	15	17	7	26	6	10	13	11	15	11	12	3	6	0
12	9	1979	1100	0.71	41	37	37	47	38	52	52	27	38	51	38	42	20	30	16	40	34	27	32	32	27	10	10	2
12	9	1979	1200	0.77	48	48	44	63	50	57	38	40	53	70	48	56	27	35	24	41	30	37	44	43	37	16	14	5
12	9	1979	1300	0.76	54	55	36	66	50	50	34	47	43	58	46	47	28	27	22	36	4	37	45	45	40	17	16	7
12	9	1979	1400	0.68	54	50	40	54	52	66	32	32	44	61	47	52	26	34	28	37	15	34	42	41	36	17	17	8
12	9	1979	1530	0.21	34	27	21	31	26	38	38	27	26	33	26	28	17	30	18	24	24	22	24	25	23	12	12	8
12	9	1979	1700	0.01	6	5	4	5	5	5	5	6	3	4	4	4	4	3	3	4	4	3	4	4	4	3	4	4
12	10	1979	800	0.01	0	0	0	0	0	2	2	0	0	0	0	0	-10	4	0	0	0	-1	0	0	0	0	1	1
12	10	1979	930	0.38	10	10	10	10	10	41	7	8	7	7	7	8	6	33	6	6	8	8	8	8	8	5	5	4
12	10	1979	1100	0.43	27	26	22	28	25	52	26	23	21	24	20	21	16	37	15	18	12	20	20	20	20	12	12	8
12	10	1979	1200	0.25	26	24	18	25	18	44	25	20	17	21	20	21	17	42	16	18	18	18	21	21	20	12	13	10
12	10	1979	1300	0.70	25	24	17	24	21	40	30	20	16	20	18	18	16	16	14	16	16	16	17	17	17	12	13	12
12	12	1979	800	0.06	-17	-17	-17	-17	-17	-2	-17	-17	-4	-17	-17	-17	-17	-4	-17	-17	-8	-17	-17	-17	-17	-17	-17	-17
12	12	1979	930	0.49	-2	-3	-3	-3	-3	51	-6	-5	-5	-5	-5	-4	-7	41	-10	-6	40	-6	-5	-5	-5	-12	-12	-14
12	12	1979	1100	0.73	22	18	25	33	24	85	4	8	8	22	12	14	4	56	1	30	66	8	13	13	11	-2	-2	-11
12	12	1979	1200	0.47	14	8	8	20	13	72	37	4	11	15	10	12	2	24	2	11	28	24	11	10	8	-2	-2	-8
12	12	1979	1300	0.54	20	16	20	22	21	36	23	12	10	11	11	13	4	17	2	7	17	8	13	12	11	0	0	-7
12	12	1979	1400	0.38	14	12	12	16	13	51	3	4	6	13	8	10	2	31	2	5	33	4	8	7	6	-1	-1	-5
12	12	1979	1530	0.04	-3	-3	-3	-3	-3	33	-4	-4	-4	-4	-4	-4	-4	27	-5	-5	24	-4	-4	-4	-4	-4	-4	-5
12	12	1979	1700	0.0	-5	-5	-5	-5	-5	0	0	-5	-5	-5	-5	-5	-5	1	-6	-6	0	-5	-5	-5	-5	-5	-5	-5
12	13	1979	800	0.06	-11	-11	-11	-11	-11	0	-6	-11	-11	-11	-11	-11	-11	-1	-11	-11	-7	-11	-11	-11	-11	-11	-10	-10
12	13	1979	930	0.54	10	11	10	13	12	70	35	5	5	10	10	11	4	43	2	6	34	7	8	6	6	-5	-5	-8
12	13	1979	1100	0.75	28	32	30	50	33	70	40	26	23	42	30	33	20	45	13	42	65	28	28	28	23	0	0	-6
12	13	1979	1200	0.82	37	30	45	56	42	62	21	34	37	53	38	44	18	34	17	30	35	30	37	33	28	3	3	-5
12	13	1979	1300	0.80	41	35	34	56	46	51	51	27	24	43	32	32	16	20	12	23	23	24	36	34	28	4	3	-4
12	13	1979	1400	0.72	41	32	45	52	46	76	53	37	40	55	34	37	16	44	18	25	48	23	35	31	27	4	4	-3
12	13	1979	1530	0.45	27	25	20	34	23	35	35	25	23	27	20	24	8	14	12	16	20	14	18	20	16	2	2	-3
12	13	1979	1700	0.0	-6	-6	-6	-6	-5	2	-6	-5	-6	-6	-6	-6	-6	6	-6	-5	-3	-5	-5	-5	-5	-6	-5	-5
12	14	1979	800	0.03	-5	-5	-5	-5	-5	10	-2	-5	-5	-5	-5	-5	-5	6	-5	-5	2	-5	-5	-5	-5	-5	-5	-5
12	14	1979	930	0.45	10	10	11	12	11	73	3	5	5	6	6	7	2	53	57	4	45	5	10	10	7	0	0	-3
12	14	1979	1100	0.63	27	27	31	34	30	85	14	18	22	31	22	25	12	63	12	23	61	18	22	21	18	6	6	0
12	14	1979	1200	0.60	34	26	21	35	31	72	72	43	35	41	26	30	15	37	14	25	47	23	26	26	23	8	8	1
12	14	1979	1300	0.64	18	18	16	17	20	27	11	13	11	11	12	13	8	15	8	11	11	12	14	14	13	5	5	1
12	14	1979	1400	0.46	31	27	27	37	31	68	68	48	23	27	22	24	14	50	15	20	43	18	23	22	21	8	8	3
12	14	1979	1530	0.31	22	18	15	23	18	51	51	16	15	20	16	17	11	38	12	15	34	14	15	16	15	6	6	3
12	14	1979	1700	0.01	1	1	1	1	1	7	7	1	1	1	1	1	1	8	1	1	4	1	1	1	1	1	2	1

TABLE C.1 RAW DATA DIRECT NORMAL RADIATION STRIKING COLLECTOR (W/M**2) AND AIR TEMPERATURES (C) AT LOCATIONS (FIGURE 4)

MO	DA	YR	HR	RAD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
12	15	1979	800	0.0	-4	-4	-4	-4	-4	1	-1	-4	-4	-4	-4	-4	-4	2	-4	-4	-2	-4	-4	-4	-4	-4	-3	-4
12	15	1979	930	0.10	-2	-2	-2	-2	-2	28	-3	-3	-3	-3	-3	-3	-3	33	-3	-3	21	-2	-2	-2	-2	-2	-2	-2
12	15	1979	1100	0.08	0	0	-2	-1	-1	31	-2	-1	-3	-2	-2	-2	-1	27	-2	1	27	0	0	0	0	-3	-3	-4
12	15	1979	1200	0.46	5	6	2	3	2	37	0	1	1	2	2	3	4	23	3	7	20	7	3	3	3	-3	-3	-5
12	15	1979	1300	0.47	6	8	4	6	6	10	1	3	2	2	2	2	7	13	3	8	13	10	3	3	3	-3	-3	-5
12	15	1979	1400	0.17	-2	0	-5	-3	-3	32	-4	-3	-5	-4	-3	-3	0	28	-4	-2	25	-1	-3	-3	-3	-6	-5	-7
12	15	1979	1530	0.14	-8	-7	-10	-8	-8	24	7	-8	-10	-10	-8	-8	-7	22	-8	-7	17	-7	-8	-8	-8	-10	-10	-11
12	15	1979	1700	0.0	-13	-13	-13	-13	-13	-8	-12	-13	-13	-13	-13	-13	-13	-5	-13	-13	-10	-13	-13	-13	-13	-13	-13	-13
12	16	1979	800	0.07	-17	-17	-17	-17	-17	-5	-17	-17	-17	-17	-17	-8	-17	-17	-10	-17	-17	-10	-17	-17	-17	-17	-17	-17
12	16	1979	930	0.56	-8	-4	-3	0	0	41	50	13	-7	-6	-6	26	-12	23	-14	-12	24	-7	-4	-8	-8	-17	-17	-17
12	16	1979	1100	0.80	11	14	20	30	18	70	70	16	14	35	18	62	-1	36	-5	16	48	8	14	12	8	-15	-15	-17
12	16	1979	1200	0.86	18	23	18	34	27	76	76	15	17	45	22	54	4	23	-2	15	33	13	20	18	14	-12	-12	-17
12	16	1979	1300	0.84	25	21	34	63	32	44	44	21	28	43	24	27	6	15	7	16	20	16	24	21	10	-11	-11	-17
12	16	1979	1400	0.75	27	20	14	35	26	83	83	22	21	36	20	21	3	43	4	13	52	14	24	20	16	-10	-10	-16
12	16	1979	1530	0.45	10	8	0	17	5	73	73	10	11	15	6	15	-6	38	-3	0	46	0	2	4	2	-12	-12	-17
12	16	1979	1700	0.0	-17	-17	-17	-17	-17	1	1	-17	-17	-17	-17	-17	-17	-3	-17	-17	-17	-17	-17	-17	-17	-17	-17	-17
12	17	1979	800	0.0	-14	-14	-14	-14	-14	-3	-14	-14	-14	-14	-14	-14	-14	-7	-14	-14	-10	-14	-14	-14	-14	-14	-14	-14
12	17	1979	930	0.46	4	4	4	4	4	52	-4	2	-5	2	1	2	-5	27	-5	-4	25	-2	2	2	0	-8	-8	-12
12	17	1979	1100	0.75	24	21	22	32	22	64	34	37	23	35	17	23	3	40	2	20	45	11	15	15	12	-2	-2	-10
12	17	1979	1200	0.74	30	17	14	30	22	56	56	17	25	41	21	25	6	33	12	18	26	16	20	20	16	0	0	-7
12	17	1979	1300	0.49	26	16	13	30	21	24	10	15	13	24	15	15	5	7	2	12	12	10	14	14	12	0	0	-6
12	17	1979	1400	0.57	28	21	22	31	25	51	51	37	22	31	22	25	7	28	8	16	34	15	20	20	17	1	1	-5
12	17	1979	1530	0.29	22	17	17	27	20	47	7	14	15	21	14	20	5	28	7	14	31	11	12	13	12	0	1	-3
12	17	1979	1700	0.0	-5	-5	-5	-5	-5	-1	-1	-1	-6	-6	-6	-6	-6	-2	-6	-6	-4	-5	-5	-5	-5	-5	-5	-5

Appendix D

VARIABLES AND EQUATIONS

OF COMPUTER MODEL

Table D.1 List of variables and equations comprising the performance model.

Name	Symbol	Unit	Description
	M	--	Computer array subscript where: M=1 refers to the south facing collector M=2 refers to the north facing collector
	LL	--	Computer array subscript for the increment number of the airflow passage
	LP	--	Computer array subscript with LP = LL + 1
	LX	--	Computer array subscript for the back flow increment number which corresponds to the front absorber plate increment
	KK	--	Computer array subscript for the number of iterations
	N	--	Number of divisions of the absorber plate (N = 30)
	NX	--	Number of divisions of the airflow passage (NX = N + N)
Collector length	l	m	l = 9.7536
Collector width	w	m	w = 0.889
Increment area of collector	AREA	m^2	AREA = l * w/N

Table D.1 (cont.)

Name	Symbol	Unit	Description
Hydraulic diameter	HD(M)	m	HD(1) = 0.0105 HD(2) = 0.0304
Backside hydraulic diameter	HDB	m	HDB = 0.0380
Nusselt number	XNUS	--	XNUS = 17.02
Thermal conductivity	COND	$W/(m \cdot {}^{o}C)$	COND = 0.024255
Heat transfer coefficient	HC(M)	$W/(m^2 \cdot {}^{o}C)$	HC(M) = XNUS * COND/HD(M)
Backside heat transfer coefficient	HCB	$W/(m^2 \cdot {}^{o}C)$	HCB = XNUS * COND/HDB
Airflow rate	AIR(M)	m^3/hr	AIR(1) = 418.381 AIR(2) = 1255.144
Total airflow rate	TAIR	m^3/hr	TAIR = 1673.526
Wind speed	A(67)	m/s	Wind speed from the Agricultural Engineering building
Wind heat transfer coefficient	HW	$W/(m^2 \cdot {}^{o}C)$	HW = 5.7 + 3.8 * A(67)
Solar radiation	A(50)	W/m^2	Radiation available for a collector tilted 60 degrees from the horizontal
Profile angle	A(57)	Rad	Solar angle based on latitude, time of day, and time of year

Table D.1 (cont.)

Name	Symbol	Unit	Description
Intercepted reflector area	A(58)	m^2	A(58) = 29.728 * cos (A(57))
Absorber plate absorptivity	α	--	α = .95
Glass transmissivity	τ	--	τ = .9
Reflector reflectance	ρ	--	ρ = .9
Solar radiation absorbed by an increment of collector	QSOL(M)	W	QSOL(1) = τ * α * A(50) * AREA QSOL(2) = τ * α * ρ * A(50) * A(58)/N
Outside ambient temperature	A(49)	^oC	
Temperature exiting the system	A(46)	^oC	
Temperature rise of the system	A(61)	^oC	A(61) = A(46) - A(49)
Specific volume	A(62)	m^3/kg	A(62) = (273.15 + A(49))/353.09
Mass flow rate for system	A(63)	kg/hr	A(63) = TAIR/A(62)
Specific heat	CP	$W \cdot hr/(kg \cdot {}^oC)$	CP = 0.27912
Energy collected for the system	A(64)	kW	A(64) = A(63) * CP * A(61)/1000.0

Table D.1 (cont.)

Name	Symbol	Unit	Description
Absolute sky temperature	TSA	^{o}K	TSA = A(49) + 273.15
Absolute sky temperature raised to the fourth	TS4	$^{o}K^{4}$	TS4 = TSA^{4}
Mass flow rate for each collector side	FL(M)	kg/hr	FL(M) = AIR(M)/A(62)
Airflow temperature entering increment	B(M,LL)	^{o}C	B(M,1) = A(49) (After the first increment, air exiting the previous increment becomes B(M,LL))
Glass cover temperature	TC(M,LL)	^{o}C	Found by trial and error
Absolute cover temperature	TCA	^{o}K	TCA = TC(M,LL) + 273.15)
Absolute cover temperature raised to the fourth power	TC4	$^{o}K^{4}$	TC4 = TCA^{4}
Plate to airstream convected energy	QCPA	W	QCPA = QSOL(M) - QRP(M,LL) - QBL(M,LL) (QRPC(M,LL) and QBL(M,LL) are initially assumed)
Absorber plate temperature	TP(M,LL)	^{o}C	TP(M,LL) = QCPA/(AREA * HC(M)) + B(M,LL)
Absolute plate temperature	TPA	^{o}K	TPA = TP(M,LL) + 273.15

Table D.1 (cont.)

Name	Symbol	Unit	Description
Absolute plate temperature raised to the fourth power	TP4	$^oK^4$	$TP4 = TPA^4$
Cover to sky convected energy	QCCS	W	QCCS = AREA * HW * (TC(M,LL) - A(49))
Glass cover emissivity	ε_c	--	$\varepsilon_c = .9$
Stefan-Boltzmann constant	σ	$W/(m^2 \cdot {}^oK^4)$	$\sigma = 5.669 \times 10^{-8}$
Cover to sky radiation	QRCS	W	QRCS = ε_c * σ * AREA * (TC4 - TS4)
Airstream to cover convected energy	QCAC	W	QCAC = AREA * HC(M) * (B(M,LL) - TC(M,LL))
Absorber plate emissivity	ε_p	--	$\varepsilon_p = .95$
Plate to cover radiation	QRPC(M,LP)	W	$QRPC(M,LP) = \dfrac{\sigma * AREA * (TP4 - TC4)}{1/\varepsilon_c + 1/\varepsilon_p - 1}$
Useful energy collected	QUSE	W	QUSE = QCPA - QCAC
Airflow temperature exiting the increment	B(M,LP)	W	B(M,LP) = QUSE/(CP * FL(M)) + B(M,LL)
Averaged absorber plate temperature back flow	PLATE(M,LL)	^oC	PLATE(M,LL) = .3 * TP(M,LX) + .5 * TP(M,LX+1) + .2 * TP(M,LX+2)

Table D.1 (cont.)

Name	Symbol	Unit	Description
Convected back loss	QBL(M,LX)	$^{\circ}$C	AREA * HCB * (PLATE(M,LL) - B(M,LL))
Predicted energy collected	QPRE(KK,M)	kW	QPR(KK,M) = FL(M) * CP * (B(M,NX+1) - A(49))/1000.0

Appendix E

PROGRAM LISTING OF THE MODEL

```
C
C   APPENDIX E   PROGRAM LISTING OF THE MODEL
C
C*****************************************************************************
C*****************************************************************************
C  THE MATHEMATICAL MODEL WHICH PREDICTS USEFUL ENERGY COLLECTED AND
C  TEMPERATURES IN THE SDSU SOLAR SYSTEM IS BASED ON FUNDAMENTAL LAWS OF
C  HEAT TRANSFER AND THERMODYNAMICS.  USING THESE LAWS, THE SOLAR SYSTEM
C  GEOMETRY, PHYSICAL PROPERTIES OF THE MATERIALS, AND WEATHER DATA,
C  EIGHT UNKNOWN ENERGY TRANSFERS AND THREE UNKNOWN TEMPERATURES ARE
C  DETERMINED BY SOLVING ELEVEN EQUATIONS AT EACH INCREMENT ALONG THE
C  AIRFLOW PATH IN THE COLLECTOR.  THESE ELEVEN EQUATIONS ARE NOT
C  INDEPENDENT, SO AN ITERATIVE TRIAL AND ERROR PROCESS IS UTILIZED.
C*****************************************************************************
C*****************************************************************************
C
C
      DIMENSION A(80),HC(2),AIR(2),B(2,65),QBL(2,65),QSN(12)
      DIMENSION TP(2,65),QRPC(2,65),FL(2),PSR(2),QSOL(2),TC(2,65),HD(2)
      DIMENSION PLATE(2,65),CPRE(10,2)
      INTEGER HR,DY
C
      WRITE(6,1)
    1 FORMAT('1','TABLE F.1  SAMPLE OUTPUT OF THE MODEL')
C
C  N IS THE NUMBER OF INCREMENTS ALONG ONE SIDE OF THE ABSORBER PLATE.
      N=30
C
C  AREA IS BASED ON A WIDTH OF 32 FT AND INCREMENTED N TIMES ALONG THE
C  88.9 CM PATH LENGTH OF THE ABSORBER PLATE.  (IN M*M)
      AREA=9.7536*0.889/N
C
C  PLATE SPACINGS FOR SOUTH (PS(1)=0.00508 M) AND NORTH (PS(2)=0.01524 M)
C
C**********   NUSSELT NUMBER   ******************************************
C
C  HEAT TRANSFER COEFFIENT FOR SOUTH (HC(1)), NORTH (HC(2)), AND BACK-
C  SIDE OF AIR PASSAGE FOR SOUTH AND NORTH SIDE (HCB).  (IN W/(M*M*C))
C  HD=HYDRAULIC DIAMETER.  HD=2*L*PS(M)/(L+PS(M))
C  L = 32 FT = 9.7536 M
C  HC=NU*K/HD.  K=0.024255 W/(M*C)
C  NU=15.97  HD(1)=0.0105 M  HD(2)=0.0304 M  HDB=0.0380 M
C
      XNUS=17.02
      HD(1)=0.0105
      HD(2)=0.0304
      HDB=0.0380
      COND=0.024255
```

```
C
      HC(1)=XNUS*CCNC/HD(1)
      HC(2)=XNUS*CCNC/HD(2)
      HCB=XNUS*CCNC/HCB
C
C**********    AIR FLOW    **********************************************
C
C  TOTAL AIRFLOW RATE FOR THE SYSTEM  (M*M*M/HR)
      TAIR=1673.526
C
C  AIR FLOW RATE FOR SOUTH (AIR(1)) AND NORTH (AIR(2)).  ASSUME A 3 TO 1
C  RATIO OF AIR FLOW RATE.  THE 985 TOTAL CFM WAS DIDVIDED INTO 246.25
C  CFM FOR SOUTH AND 738.75 CFM FOR NORTH.  THESE AIRFLOWS ARE FOR A 32
C  FT LENGTH.  (M*M*M/HR)
      AIR(1)=418.381
      AIR(2)=1255.144
C
C  SPECIFIC HEAT OF AIR (CP)  (W*HR/(KG*C))
      CP=.27912
C
C**********    RAW DATA    **********************************************
C
C  WIND SPEED MEASURED FROM AG ENGINEERING ROOF  (A(66)=MPH)  (A(67)=M/S)
      A(66)=5.0
      A(67)=A(66)*0.32173
C
C  WIND HEAT TRANSFER COEFFICIENT (W/(M*M*C)
   13 HW=5.7+3.8*A(67)
C
C  RADIATION (A(1)=(CAL/(CM*CM*MIN)) AND THERMOCOUPLE TEMPERATURES
C  (A(2-25)=F)FOR DECEMBER 16, 1979 AT NOON CENTRAL STANDARD TIME
      MC=12
      DA=16.
      HR=1200
      A(1)=1.23
      A(2)= 67.
      A(3)= 75.
      A(4)= 67.
      A(5)= 95.
      A(6)= 82.
      A(7)=171.
      A(8)=171.
      A(9)= 60.
      A(10)= 65.
      A(11)=115.
      A(12)= 73.
      A(13)=131.
      A(14)= 40.
```

```
      A(15)= 74.
      A(16)= 28.
      A(17)= 61.
      A(18)= 92.
      A(19)= 57.
      A(20)= 69.
      A(21)= 67.
      A(22)= 58.
      A(23)= 10.
      A(24)=  9.
      A(25)=  0.
C
C**********   TEMPERATURE CONVERSION  ***********************************
C
C  CONVERT TEMPERATURE FROM FAHRENHEIT TO CELCIUS
   17 DO 22 L=26,49
      A(L)=(A(L-24)-32.)/1.8
   22 CONTINUE
C
C**********   SOLAR TIME   *********************************************
C
C  LOCAL CIVIL TIME WITH BROOKINGS LONGITUDE AT 96 DEG 46 MIN NORTH
C    (TIME IN MINUTES)
      IF(HR.EQ.930) CT=542.93
      IF(HR.EQ.1100) CT=632.93
      IF(HR.EQ.1200) CT=692.93
      IF(HR.EQ.1300) CT=752.93
      IF(HR.EQ.1400) CT=812.93
      IF(HR.EQ.1530) CT=902.93
      D=334.+DA
C
      IF(D-325.) 25,27,30
   25 EQT=13.62+.038*(21.-DA)
      GO TO 35
C
   27 EQT=13.92
      GO TO 35
C
   30 IF(DA.LT.21.) DD=DA+9.
      IF(DA.GT.21.) DD=DA-21.
      EQT=13.92-0.413*DD
C
   35 CONTINUE
C
C  SOLAR TIME (MINUTES)
      A(51)=CT+EQT
C
C**********   SOLAR ANGLES   ********************************************
```

```
C
C   SOLAR DECLINATICN (RADIANS)
       A(52)=23.45*SIN((360.*(284.+D)/365.)*.017453)*.017453
C
C   HOUR ANGLE (RACIANS)
       A(53)=0.25*(ABS(720.-A(51)))*0.017453
C
C   LATITUDE FCR BRCCKINGS IS 44 CEG 19 MIN (0.77346 RACIANS)
C
C   SOLAR ALTITUCE (RADIANS)
       A(54)=ARSIN(0.71549*(COS(A(52)))*(COS(A(53)))+0.69862*SIN(A(52)))
C
C   SOLAR AZIMUTH (RACIANS)
       A(55)=ARSIN((CCS(A(52)))*(SIN(A(53)))/(COS(A(54))))
C
C   INCIDENT ANGLE (RADIANS)
       A(56)=ARCCS((CCS(A(54)))*(COS(A(55)))*0.866+(SIN(A(54)))*0.5)
C
C   PROFILE ANGLE (RACIANS)
       A(57)=ATAN((TAN(A(54)))/(CCS(A(55))))
C
C**********    AVAILABLE SCLAR RACIATION    ********************************
C
C   CCNVERSION CF RACIATICN TC W/(M*M)
       A(50)=A(1)*697.8
C
C   REFLECTCR AREA BASED ON A 10 BY 32 FT REFLECTOR.  (COS(A(57,I,J,K)) IS
C   IS THE REFLECTCR PROJECTICN ANGLE.  (M*M)
       A(58)=29.728*CCS(A(57))
C
C   REFLECTCR AREA PROJECTEC ON A COLLECTCR INCREMENT.  (M*M)
       RAREA=A(58)/N
C
C
C*************************************************************************
C              SOLAR RADIATICN ABSCRBED BY THE ABSORBER PLATE  (QSCL)
C*************************************************************************
C
C   AMCUNT CF SCLAR ENERGY AVAILABLE ON THE SOUTH SIDE OF THE CCLLECTCR
C   FOR A 30 CM BY N INCREMENT AREA.  (.9 IS THE GLASS EMISSIVITY AND .95
C   IS THE PLATE ABSCRPTIVITY)  (WATTS)
       QSOL(1)=.9*.95*A(50)*AREA
C
C   AMCUNT OF SOLAR ENERGY AVAILABLE ON THE NORTH SIDE CF THE CCLLECTCR
C   FOR A 30 CM BY N INCREMENT AREA.  (.9 IS THE GLASS EMISSIVITY AND THE
C   REFLECTCR REFLECTANCE AND .95 IS THE PLATE ABSORPTIVITY)  (WATTS)
       QSCL(2)=.9*.9*.95*A(50)*RAREA
C
```

```
C**********    MEASURED ENERGY COLLECTED    ********************************
C
C  CHANGE IN TEMPERATURE OF THE SOLAR SYSTEM  (DEG C)
      A(61)=A(46)-A(49)
C
C  SPECIFIC VOLUME  (M*M*M/KG)
      A(62)=(273.15+A(49))/353.09
C
C  MASS FLOW RATE IS BASED ON AN AIR FLOW RATE OF (985 CFM = 1673.526
C  M*M*M/HR).  (KG/HR)
      A(63)=1673.526/A(62)
C
C  MEASURED ENERGY COLLECTED    (KW)
      A(64)=A(63)*CP*A(61)/1000.0
C
      WRITE(6,686) N,AREA,RAREA,XNUS,HD(1),HD(2),HDB,AIR(1),AIR(2),
     $TAIR,A(67),A(49),QSCL(1),QSCL(2)
  686 FORMAT('0'//' **********  PRINCIPLE INPUT DATA  **********'//27X,'
     $NUMBER OF ABSORBER'/27X,'PLATE INCREMENTS =',I3//20X,'AREA (M*M) '
     $/24X,'COLLECTOR INCREMENT =',F6.3/24X,'REFLECTOR AREA OF'/24X,'COL
     $LECTOR INCREMENT =',F6.3//29X,'NUSSELT NUMBER =',F6.2//20X,'HYDRAU
     $LIC DIAMETER (M*M) '/28X,'SOUTH COLLECTOR =',F7.4/28X,'NORTH COLLE
     $CTOR =',F7.4/34X,'BACK SIDE =',F7.4//20X,'AIRFLOW (M*M*M/HR) '/28X
     $,'SOUTH COLLECTOR =',F8.2/28X,'NORTH COLLECTOR =',F8.2/31X,'SYSTEM
     $ TOTAL =',F8.2//27X,'WIND SPEED (M/S) =',F7.3//20X,'OUTSIDE TEMPER
     $ATURE (C) =',F7.2//20X,'SOLAR RADIATION STRIKING COLLECTOR INCREME
     $NT (W) '/28X,'SOUTH COLLECTOR =',F7.2/28X,'NORTH COLLECTOR =',F7.2
     $)
C
      WRITE(6,687)HC(1),HC(2),HCB,HW,A(64)
  687 FORMAT('0'//' **********  RESULTS SUMMARY  **********'//20X,'CONVE
     $CTIVE PLATE TO AIR'/20X,'HEAT TRANSFER COEFFICIENT (W/(M*M*C)) '/2
     $8X,'SOUTH COLLECTOR =',F6.2/28X,'NORTH COLLECTOR =',F6.2/34X,'BACK
     $ SIDE =',F6.2//21X,'WIND HEAT TRANSFER'/21X,'COEFFICENT (W/(M*M*C)
     $) =',F6.2//10X,44('*')/13X,'MEASURED ENERGY COLLECTED (KW) =',F6.2
     $/10X,44('*'))
C
C  TSA IS THE ABSOLUTE SKY TEMP
      TSA=A(49)+273.15
      TS4=TSA**4
C
C**********    M FOR NORTH AND SOUTH    **********************************
C
      DO 530 M=1,2
C
      IF(M.EQ.2) GO TO 888
      WRITE(6,755)
  755 FORMAT('1','PREDICTED TEMPERATURES AND HEAT TRANSFER OF THE SOUTH
```

```
     $FACING CCLLECTCR')
      GC TO 985
  888 WRITE(6,889)
  889 FCRMAT('1','PREDICTEC TEMPERATURES ANC HEAT TRANSFER OF THE NCRTH
     $FACING CCLLECTCR')
C
  985 WRITE(6,989)
  989 FCRMAT('0',13X,'******* TEMPERATURE (C) ********',4X,'********* ENE
     $RGY TRANSFERRED (W) ********'/1X,'ITER',2X,'INC',4X,'SKY',3X,'ENTE
     $R',3X,'EXIT',2X,'PLATE',2X,'COVER',4X,'**RADIATICN*',2X,'********C
     $ONVECTICN********',4X,'CCLLECTED'/2X,'NO',4X,'NO',4X,'(S)',18X,'(P
     $)',4X,'(C)',6X,'P-C',4X,'C-S',4X,'P-A',4X,'A-C',4X,'C-S',4X,'BACK'
     $,3X,'ENERGY (KW)')
C  FL(M) IS THE MASS FLOW RATE  (KG/HR)
      FL(M)=AIR(M)/A(62)
C
C  THE TEMPERATURE ENTERING THE SYSTEM IS THE AMBIENT TEMP  (A(49))
      B(M,1)=A(49)
C
C**********    KK IS THE ITERATION PROCESS    ******************************
C
      KK=1
   70 CONTINUE
C
C  ASSUME INITIAL VALUES FOR PLATE TO COVER RADIATION FOR THE FIRST
C  INCREMENT.  AFTER THE PLATE TEMP IS FOUND, USE AN AVERAGE QRPC(LL)
C  FROM THE INCREMENT BEFCRE.
      IF(KK.NE.1) GC TO 67
      QRPC(1,1)=QSCL(1)*0.1
      QRPC(2,1)=QSCL(2)*0.25
C
C  ASSUME THE TEMP CF THE COVER (TC) IS INITIALLY AT AMBIENT TEMPERATURE
   67 TC(M,1)=A(49)
C
      LX=N
      NX=N+N
      LI=NX
C
C**********    LL IS THE INCREMENTS OF THE PLATE    ***********************
C
      DO 120 LL=1,NX
      LP=LL+1
C
C  FOR THE FIRST LOOP, THE BACK LOSS (QBL(LL)) IS ASSUMED ZERO.  AFTER
C  THE FIRST ITERATION, THE BACK LOSS VALUE IS USED FROM CALCULATIONS OF
C  THE ITERATION BEFORE.
C
C  WHEN LL IS GREATER THAN N, THE FLOW IS OVER THE BACK OF THE PLATE.
```

```
      IF(LL.GT.N) GC TO 11C
C
C  CALCULATING PLATE TEMPERATURE.  (TP(M,LL) = DEG C)
C    QCPA IS THE CCNVECTIVE ENERGY OF THE PLATE TC AIRSTREAM  (W)
C    CRPC IS THE RACIATION ENERGY OF THE PLATE TO THE COVER  (W)
C
      IF(KK.GT.1.ANC.LL.EQ.1) CRPC(M,1)=(CRPC(M,1)+QRPC(M,2))/2.0
C
C
C*************************************************************************
C              PLATE TC AIRSTREAM CONVECTIVE HEAT TRANSFER  (CCPA)
C*************************************************************************
C
      CCPA=QSCL(M)-CRPC(M,LL)-CBL(M,LL)
C
C
C*************************************************************************
C              ABSCRBER PLATE TEMPERTURE  (TP)
C*************************************************************************
C
      TP(M,LL)=CCPA/(AREA*HC(M))+B(M,LL)
C
C
C*************************************************************************
C              COVER TEMPERATURE  (TC)
C*************************************************************************
C
C  TPA IS ABSCLUTE PLATE TEMP AND TCA IS ABSOLUTE COVER TEMP  (K)
      TPA=TP(M,LL)+273.15
      TP4=TPA**4
      TCA=TC(M,LL)+273.15
      TC4=TCA**4
C
C
C*************************************************************************
C              COVER TO SKY CCNVECTIVE HEAT TRANSFER  (CCCS)
C*************************************************************************
C
      CCCS=AREA*HW*(TC(M,LL)-A(49))
C
C
C*************************************************************************
C              COVER TO SKY RACIATION  (CRCS)
C*************************************************************************
C
      CRCS=AREA*(TC4-TS4)/19597352.79
C
C  COVER TO SKY HEAT TRANSFER
```

```
      CSLOS=QCCS+QRCS
C
C
C***********************************************************************
C               AIRSTREAM TO COVER CONVECTIVE HEAT TRANSFER   (QCAC)
C***********************************************************************
C
      QCAC=AREA*HC(M)*(B(M,LL)-TC(M,LL))
C
C
C***********************************************************************
C               PLATE TO COVER RADIATION   (QRPC)
C***********************************************************************
C
      QRPC(M,LP)=AREA*(TP4-TC4)/20525648.45
C
C  PLATE TO COVER HEAT TRANSFER
      PCLOS=QCAC+QRPC(M,LP)
C
      IF(PCLOS-CSLOS) 107,127,117
C
  107 TC(M,LL)=TC(M,LL)-.3
      TCA=TC(M,LL)+273.15
      TC4=TCA**4
C
      QCCS=AREA*HW*(TC(M,LL)-A(49))
      QRCS=AREA*(TC4-TS4)/19597352.79
      CSLOS=QCCS+QRCS
C
      QCAC=AREA*HC(M)*(B(M,LL)-TC(M,LL))
      QRPC(M,LP)=AREA*(TP4-TC4)/20525648.45
      PCLOS=QCAC+QRPC(M,LP)
C
      IF(PCLOS-CSLOS) 107,127,127
C
  117 TC(M,LL)=TC(M,LL)+.3
      TCA=TC(M,LL)+273.15
      TC4=TCA**4
C
      QCCS=AREA*HW*(TC(M,LL)-A(49))
      QRCS=AREA*(TC4-TS4)/19597352.79
      CSLOS=QCCS+QRCS
C
      QCAC=AREA*HC(M)*(B(M,LL)-TC(M,LL))
      QRPC(M,LP)=AREA*(TP4-TC4)/20525648.45
      PCLOS=QCAC+QRPC(M,LP)
C
      IF(PCLOS-CSLOS) 127,127,117
```

```
C
C
C*********************************************************************
C              USEFUL ENERGY CCLLECTED AT THE INCREMENT  (QUSE)
C*********************************************************************
C
  127 QUSE=QCPA-CCAC
C
C
C*********************************************************************
C              AIRSTREAM TEMPERATURE EXITING THE INCREMENT  (TO)
C*********************************************************************
C
C  CALCULATE THE TEMP OUT CF THE INCREMENT AND INTO THE NEXT INCREMENT
      B(M,LP)=QUSE/(FL(M)*CP)+B(M,LL)
C
      LI=LI-1
      GO TO 115
C
C  THIS IS FOR THE FLOW ON THE BACK OF THE PLATE
C
  110 IF(LX.GE.N-1) GO TO 144
      PLATE(M,LL)=.3*TP(M,LX)+.5*TP(M,LX+1)+.2*TP(M,LX+2)
      GO TO 158
  144 PLATE(M,LL)=TP(M,LX)
C
C
C*********************************************************************
C              BACK PLATE TC AIRSTREAM CONVECTIVE HEAT TRANSFER  (CBL)
C*********************************************************************
C
  158 CBL(M,LX)=AREA*HCB*(PLATE(M,LL)-B(M,LL))
      B(M,LP)=CBL(M,LX)/(FL(M)*CP)+B(M,LL)
C
      LX=LX-1
      TC(M,LP)=TC(M,LL)
  115 CONTINUE
C
C
C**********   PREDICTED ENERGY COLLECTED   ********************************
C
C  PREDICTED AMCUNT CF ENERGY COLLECTED  (KW)
C
      QPRE(KK,M)=FL(M)*CP*(B(M,LP)-A(49))/1000.0
C
      IF(LL.GT.30) GO TO 302
      IF(LL.EQ.1.OR.LL.EQ.15) GO TO 298
      IF(LL.EQ.30) GO TO 298
```

```
      GO TO 120
C
  298 WRITE(6,301) KK,LL,A(49),B(M,LL),B(M,LP),TP(M,LL),TC(M,LL),QRPC(M,
     *LL),QRCS,QCPA,QCAC,QCCS,QBL(M,LL),QPRE(KK,M)
  301 FORMAT(' ',I3,I5,2X,5F7.1,2X,6F7.1,F10.2)
      GC TO 120
C
  302 IF(LL.EQ.45.OR.LL.EQ.60) GO TO 299
      GC TO 120
C
  299 WRITE(6,303) KK,LL,A(49),B(M,LL),B(M,LP),PLATE(M,LL),QBL(M,LX),QPR
     *E(KK,M)
  303 FORMAT(' ',I3,I5,2X,4F7.1,44X,F7.1,F10.2)
C
  120 CCNTINUE
C
      IF(M.EQ.1) GC TO 387
      IF(ABS(QPRE(KK,M)-QPRE(KK-1,M)).LE.0.1.OR.KK.EQ.9)  GO TO 500
      GO TO 389
  387 IF(ABS(QPRE(KK,M)-QPRE(KK-1,M)).LE.0.05.OR.KK.EQ.9)  GO TO 500
C
  389 KK=KK+1
      WRITE(6,472)
  472 FCRMAT(' ')
      GC TO 70
C
  500 IF(M.EQ.2) GC TO 507
      WRITE(6,503)QPRE(KK,M)
  503 FCRMAT('0',3X,57('*')/3X,' ENERGY PREDICTED FRCM THE SOUTH FACING
     $ CCLLECTCR =',F6.2/4X,57('*'))
      GC TO 530
  507 WRITE(6,511) QPRE(KK,M)
  511 FCRMAT('0',3X,57('*')/3X,' ENERGY PREDICTED FRCM THE NORTH FACING
     $ COLLECTCR =',F6.2/4X,57('*'))
  530 CCNTINUE
      STCP
      END
```

Appendix F

SAMPLE OUTPUT OF THE MODEL

TABLE F.1 SAMPLE OUTPUT OF THE MODEL

```
**********  PRINCIPLE INPUT DATA  **********

                    NUMBER OF ABSORBER
                    PLATE INCREMENTS = 30

              AREA (M*M)
                  COLLECTOR INCREMENT = 0.289
                  REFLECTOR AREA OF
                  COLLECTOR INCREMENT = 0.917

                       NUSSELT NUMBER = 17.02

              HYDRAULIC DIAMETER (M*M)
                      SOUTH COLLECTOR = 0.0105
                      NORTH COLLECTOR = 0.0304
                            BACK SIDE = 0.0380

              AIRFLOW (M*M*M/HR)
                      SOUTH COLLECTOR =  418.38
                      NORTH COLLECTOR = 1255.14
                         SYSTEM TOTAL = 1673.53

                    WIND SPEED (M/S) =  1.609

              OUTSIDE TEMPERATURE (C) = -17.78

              SOLAR RADIATION STRIKING COLLECTOR INCREMENT (W)
                      SOUTH COLLECTOR = 212.10
                      NORTH COLLECTOR = 605.94


**********  RESULTS SUMMARY  **********

              CONVECTIVE PLATE TO AIR
              HEAT TRANSFER COEFFICIENT (W/(M*M*C))
                      SOUTH COLLECTOR = 39.32
                      NORTH COLLECTOR = 13.58
                            BACK SIDE = 10.86

               WIND HEAT TRANSFER
               COEFFICENT (W/(M*M*C)) = 11.81

     ********************************************
        MEASURED ENERGY COLLECTED (KW) = 20.81
     ********************************************
```

PREDICTED TEMPERATURES AND HEAT TRANSFER OF THE SOUTH FACING COLLECTOR

		******* TEMPERATURE (C) ********					******** ENERGY TRANSFERRED (W) ********						
							**RADIATION*		********CONVECTION********				
ITER NO	INC NO	SKY (S)	ENTER	EXIT	PLATE (P)	COVER (C)	P-C	C-S	P-A	A-C	C-S	BACK	COLLECTED ENERGY (KW)
1	1	-17.8	-17.8	-16.5	-1.0	-16.6	21.2	1.2	190.9	-13.6	4.1	0.0	0.20
1	15	-17.8	-2.1	-1.2	14.5	-5.1	23.4	13.4	188.7	33.8	43.3	0.0	2.68
1	30	-17.8	10.4	11.1	26.4	4.5	29.4	24.9	182.7	66.6	76.1	0.0	4.66
1	45	-17.8	13.7	13.7	16.2							0.0	5.09
1	60	-17.8	12.5	12.2	0.4							0.0	4.85
2	1	-17.8	-17.8	-16.2	2.6	-16.3	18.7	1.5	231.2	-17.0	5.1	-37.8	0.25
2	15	-17.8	-0.6	0.3	15.6	-3.9	23.6	14.8	183.6	37.5	47.4	4.9	2.92
2	30	-17.8	9.4	9.8	21.7	3.0	24.6	23.0	139.3	72.8	70.9	48.2	4.46
2	45	-17.8	12.2	12.3	16.7							4.9	4.86
2	60	-17.8	11.9	11.8	3.6							0.0	4.77
3	1	-17.8	-17.8	-16.3	1.5	-16.3	19.4	1.5	218.9	-17.0	5.1	-26.2	0.24
3	15	-17.8	-1.6	-0.8	14.0	-4.8	22.8	13.8	177.4	36.0	44.3	12.0	2.75
3	30	-17.8	8.6	9.1	21.8	2.4	25.1	22.3	149.8	70.2	68.9	37.2	4.33
3	45	-17.8	11.5	11.5	15.2							12.0	4.73
3	60	-17.8	11.0	10.8	2.6							0.0	4.62
4	1	-17.8	-17.8	-16.3	1.5	-16.3	19.1	1.5	219.5	-17.0	5.1	-26.5	0.24
4	15	-17.8	-1.3	-0.3	14.6	-4.2	22.9	14.4	179.6	33.5	46.4	9.6	2.81
4	30	-17.8	9.2	9.7	22.2	3.3	24.7	23.4	147.5	67.1	72.0	39.8	4.44
4	45	-17.8	12.1	12.2	15.8							9.6	4.83
4	60	-17.8	11.5	11.4	2.6							0.0	4.71
5	1	-17.8	-17.8	-16.3	1.7	-16.3	19.0	1.5	221.2	-17.0	5.1	-28.0	0.24
5	15	-17.8	-1.4	-0.6	14.4	-4.8	23.0	13.8	179.6	38.3	44.3	9.5	2.78
5	30	-17.8	8.7	9.2	21.7	2.7	25.2	22.7	147.7	68.5	69.9	39.2	4.36
5	45	-17.8	11.6	11.7	15.6							9.5	4.76
5	60	-17.8	11.2	11.0	2.7							0.0	4.65
6	1	-17.8	-17.8	-16.3	1.5	-16.3	19.0	1.5	219.6	-17.0	5.1	-26.5	0.24
6	15	-17.8	-1.3	-0.4	14.5	-4.2	22.8	14.4	179.1	33.3	46.4	10.2	2.81
6	30	-17.8	9.1	9.6	22.1	3.3	25.1	23.4	147.8	66.4	72.0	39.3	4.43
6	45	-17.8	12.0	12.1	15.8							10.2	4.82
6	60	-17.8	11.5	11.3	2.6							0.0	4.70

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ENERGY PREDICTED FROM THE SOUTH FACING COLLECTOR = 4.70
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PREDICTED TEMPERATURES AND HEAT TRANSFER OF THE NORTH FACING COLLECTOR

ITER NO	INC NO	******* TEMPERATURE (C) ******** SKY (S)	ENTER	EXIT	PLATE (P)	COVER (C)	******** ENERGY TRANSFERRED (W) ******** **RADIATION* P-C	C-S	********CONVECTION******** P-A	A-C	C-S	BACK	COLLECTED ENERGY (KW)
1	1	-17.8	-17.8	-16.7	98.0	4.1	151.5	24.4	454.5	-86.0	74.8	0.0	0.54
1	15	-17.8	-3.4	-2.4	103.0	11.4	188.3	34.0	417.7	-58.0	99.6	0.0	7.45
1	30	-17.8	10.7	11.6	112.5	19.8	206.7	45.9	399.3	-35.6	128.3	0.0	14.25
1	45	-17.8	20.1	20.6	104.3							0.0	18.61
1	60	-17.8	27.5	27.9	94.1							0.0	22.13
2	1	-17.8	-17.8	-17.2	40.5	-9.4	167.7	8.7	228.9	-33.0	28.7	209.3	0.26
2	15	-17.8	-8.9	-8.3	56.0	-3.0	91.1	15.8	254.3	-23.0	50.5	260.5	4.60
2	30	-17.8	-1.3	-0.8	51.9	-0.9	80.7	18.3	208.6	-1.4	57.6	316.6	8.21
2	45	-17.8	3.9	4.2	55.5							260.5	10.67
2	60	-17.8	8.8	9.2	56.0							0.0	13.04
3	1	-17.8	-17.8	-17.0	68.8	-3.7	118.0	15.0	340.0	-55.3	48.1	148.0	0.40
3	15	-17.8	-7.0	-6.2	74.5	2.1	124.3	21.9	319.8	-35.6	67.9	161.8	5.59
3	30	-17.8	3.6	4.3	81.7	8.1	133.7	29.6	306.8	-17.7	88.4	165.5	10.68
3	45	-17.8	10.8	11.2	75.5							161.8	14.03
3	60	-17.8	16.5	16.8	68.1							0.0	16.74
4	1	-17.8	-17.8	-17.0	65.2	-4.3	118.2	14.4	325.6	-53.0	46.1	162.1	0.38
4	15	-17.8	-7.5	-6.9	67.4	-0.0	111.4	19.4	294.2	-29.5	60.7	200.3	5.29
4	30	-17.8	1.6	2.2	66.8	3.6	106.8	23.8	255.8	-7.7	73.0	243.3	9.66
4	45	-17.8	7.8	8.2	67.5							200.3	12.59
4	60	-17.8	13.3	13.7	66.3							0.0	15.24
5	1	-17.8	-17.8	-17.0	65.0	-4.3	114.5	14.4	325.0	-53.0	46.1	166.4	0.38
5	15	-17.8	-7.4	-6.7	70.1	0.9	115.7	20.5	304.2	-32.5	63.8	186.0	5.37
5	30	-17.8	2.5	3.1	74.8	6.0	119.2	26.8	283.8	-13.9	81.2	202.9	10.10
5	45	-17.8	9.1	9.5	70.7							186.0	13.23
5	60	-17.8	14.7	15.0	65.9							0.0	15.87
6	1	-17.8	-17.8	-17.0	66.9	-4.0	112.6	14.7	332.5	-54.2	47.1	160.9	0.39
6	15	-17.8	-7.4	-6.7	69.1	0.6	114.6	20.1	300.3	-31.3	62.7	191.0	5.36
6	30	-17.8	2.1	2.7	70.2	4.5	113.4	24.9	267.4	-9.4	76.1	225.1	9.90
6	45	-17.8	8.5	8.9	69.4							191.0	12.94
6	60	-17.8	14.1	14.4	66.9							0.0	15.60
7	1	-17.8	-17.8	-17.0	65.5	-4.3	113.5	14.4	326.8	-53.0	46.1	165.7	0.38
7	15	-17.8	-7.4	-6.7	69.5	0.9	114.4	20.5	302.0	-32.6	63.8	189.5	5.35
7	30	-17.8	2.3	2.9	73.0	5.4	116.0	26.1	277.8	-12.3	79.1	212.1	9.99
7	45	-17.8	8.8	9.2	69.9							189.5	13.08
7	60	-17.8	14.3	14.7	66.0							0.0	15.72
8	1	-17.8	-17.8	-17.0	66.6	-4.0	112.5	14.7	331.1	-54.2	47.1	162.4	0.39
8	15	-17.8	-7.4	-6.7	69.4	0.6	114.6	20.1	301.4	-31.4	62.7	189.9	5.36
8	30	-17.8	2.2	2.8	71.1	4.8	115.2	25.3	270.4	-10.3	77.1	220.4	9.95
8	45	-17.8	8.7	9.1	69.7							189.9	13.00
8	60	-17.8	14.2	14.6	66.7							0.0	15.66

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ENERGY PREDICTED FROM THE NORTH FACING COLLECTOR = 15.66

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