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**DEVELOPING, TESTING, EVALUATING AND OPTIMIZING
SOLAR HEATING SYSTEMS**

**PROJECT STATUS REPORT FOR
OCTOBER AND NOVEMBER 1996**

Prepared for:

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Submitted by:

**Solar Energy Applications Laboratory
Colorado State University**

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UNIQUE SOLAR SYSTEM COMPONENTS

INTEGRATED TANK/HEAT EXCHANGER MODELING/EXPERIMENTS

The development of an improved wrap-around heat exchanger/tank model continues. Part of October and November was spent organizing a review of thermal storage tank modeling literature for inclusion in the dissertation.

Work has begun on the fortran code required for a two layer (boundary layer and core region) model of the wrap-around heat exchanger solar thermal storage tank. Both plug-flow (TRNSYS Type 38) and fixed volume (TRNSYS Type 4 or 60) models of the core region of the tank are currently being considered. Several of the approximate solutions methods detailed in the August/September progress report will be employed to model the natural convection boundary layer. The accuracy and the ease of use of each method will be evaluated and compared.

As part of this effort, a Karman-Polhausen integral method analysis (Sparrow, 1955, 1956) of the natural convection boundary layer on a nonisothermal vertical surface in a nonisothermal medium has been developed. Drake (1966, and in Evans et. al. 1968) employed an integral analysis of the boundary layer in her investigation of the uniform heating of the fluid inside a vertical cylinder. The computer code created to implement this solution method has been added to the suit of computer codes that have been developed to predict the velocity and temperature profiles in the natural convection boundary layer on the inside of the vertical walls of the wrap-around heat exchanger tank.

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ADVANCED RESIDENTIAL SOLAR DOMESTIC HOT WATER (SDHW) SYSTEMS

This report is for October and November, 1996.

Experimental Work

The current emphasis of this work is the use of energy draw data from short-term tests for validating system performance. The test protocol to be followed is that of FSEC (Steven Long), and is available via anonymous ftp from [alpha.fsec.ucf.edu](ftp://alpha.fsec.ucf.edu). We have examined FSEC's revised protocols, and totally approve of them.

The short-term test data have been collected, and the raw data (Volts and T/C readings) are being processed into engineering format (flow rates, temperatures, etc.). Soon, the processed data files should be available on our WWW site (WWW.SEAL.ColoState.EDU) as clickable links, together with the paper describing them.

We have adopted a tentative long-term test protocol, consistent with the DST efforts. These are attached for your perusal. Long-term testing should commence in January.

Optimization of Evacuated Tube Collectors

This effort involves an array of evacuated tube collectors, which is being tested experimentally and simulated numerically. The simulations consist of the pre-calculation of IAM's, and subsequent simulation using TRNSYS. This work is nearing completion.

Specific tasks accomplished during these two months include:

- The IAM code has been thoroughly tested. It will be put up on our WWW site in January, for all to access. Both source code (Fortran 90), and an executable code for Intel-based systems will be made available.
- A paper has been written on this topic for the 1997 International Solar Energy Conference, Washington DC. A draft copy of the paper is attached.
- The experimental tests have been completed, using both four- and eight-tube ICS modules. The four-tube module was obtained by removing every other tube from the eight-tube module, to provide a different spacing between tubes (greater influence of the backplane reflector). The backplane reflectance was varied by using different backplane materials. Over the 38 separate days of testing, the energy gain from TRNSYS simulations agrees, on average, to within 3%, with a maximum error of 11%.
- A thesis on this topic is almost complete, and should be available by March 1997.

Proposed Long Term Test Protocol:

1. The NEG and Thermodynamics system will be heated with auxiliary energy until both systems are at approximately 55C. (Note: The temperature of the collector loop of the Thermodynamics system may vary substantially from 55C depending on the ambient weather conditions.)
2. As recommended in the DST test procedures [1,p81], the mixing valve will not be used. This is to avoid saturation of the system at high solar to load ratios.
3. These tests will attempt to cover a range of solar to load ratios from 0.4 to 3.0. In the DST test procedures, solar to load ratios of 0.4 to 4.0 are recommended [1,p35]. However, these same procedures state that saturation is to be avoided [1,p28]. Therefore, solar to load ratios higher than 3.0 will not be attempted, as the Thermodynamics system has a tendency to saturate.
4. To obtain sufficient variability in the solar to load ratio, the draw volume will be altered over the testing period, as described below. Again, this is recommended in the DST procedures [1,p35].
5. Draws will be done every day, and consist of three equal volume draws commencing at 8am, 12pm and 4pm solar time. (Note: Since only one draw on one system may be performed at any one time, the NEG system will be drawn from first, and the Thermodynamics system second.)
6. The flow rate during the draw will be approximately 3gpm.
7. A constant draw volume will be used for three days in a row before changing to a new draw volume. Four separate draw volumes, ranging from 120 gallons to 20 gallons per draw for the Thermodynamics system and 55 to 8 gallons per draw for the NEG system, will be employed over the course of this test.
8. The larger volume draws will be performed earlier in the test sequence in an attempt to minimize problems with saturation of the systems.
9. At the end of the approximately 12 day long test, the systems will undergo an energy purge, until the inlet and outlet temperatures agree within 1 C.

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1. Visser, H. and A.C. de Geus, eds, December 1992. Dynamic Testing of Solar Domestic Hot Water Systems, Final report of the IEA Dynamic Systems Testing Group, International Energy Agency Solar Heating and Cooling Programme.

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INCIDENT ANGLE MODIFIER'S (IAM'S) BY MONTE CARLO

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ABSTRACT

A fast, portable Monte Carlo computer code to compute Incidence Angle Modifiers (IAM's) for cylindrical solar collectors is described. IAM's are used to correct the tau-alpha product for practical effects such as shading, back plane reflectance, inter-reflection, etc. Novel contributions include: (1) extending the material model to more practical outgoing directional distributions for reflectance, (2) including more efficient ways of dealing with refraction, and (3) including more efficient ways of tracing photons. The new code, written in Fortran 90, is portable, is much easier to use (the input deck is much simpler), and runs can be done in less than 3% of the CPU time as for the previous code. Outdoor experiments on an array of eight cylindrical tubes with various back planes are described. Agreement with TRNSYS runs in daily energy gain is excellent: over the 20 data sets, taken on different days, a maximum error of 11.2% is observed, with an average error of 3.3%.

INTRODUCTION

The performance of solar collectors varies throughout the day due to the varying angle at which the solar radiation is incident upon the collector. As a result, accurately predicting the performance of a solar collector requires the knowledge of how the collector performs relative to the solar radiation's angle of incidence. The typical flat plate collector achieves its optimal performance at normal incidence. The reduction in performance of flat plate collectors at off-normal incidence is primarily due to the optical properties of the glazing and collector plate. Incident Angle Modifiers (IAM's) are used to correct a solar collector's performance at normal incidence to off normal directions. IAM's can reliably be predicted for flat plate collectors analytically and experimentally [Duffie & Beckman, 1991]. IAM's are defined by

$$IAM = \frac{(\tau\alpha)}{(\tau\alpha)_n} \quad (1)$$

the ratio of the transmittance-absorptance product ($\tau\alpha$) at a given angle of incidence to that at normal incidence $(\tau\alpha)_n$. The $(\tau\alpha)$ is the ratio of the irradiation absorbed by the solar collector, to that incident upon the collector's aperture plane.

Cylindrical solar collectors pose a more daunting problem. The more complex geometry of these collectors requires three-dimensional consideration. A pair of incident angles, referred to as theta longitudinal (θ_l) and theta transverse (θ_t), shown in Fig. 1, are used to characterize the angle of incidence of the sun's rays. In addition to material properties, the IAM's for cylindrical solar collectors must consider shading effects, inter-tube reflections and back plane reflectance. The $(\tau\alpha)$ is calculated for cylindrical solar collectors as

$$(\tau\alpha) = \frac{\sum n_{tubes}}{\sum n_{ap}} \quad (2)$$

the ratio of photons absorbed by all collector tubes (n_{tubes}) to the number of photons directly incident upon the aperture plane (n_{ap}).

Perez et al. (1995) introduced an analytical algorithm for calculating the radiation received by cylindrical solar collectors. The algorithm considers inter-tube shading and diffuse radiation from the surroundings and the support structure (back plane). The algorithm does not account for specular reflections from the back plane, variation of tube pitch within the collector array or radiation reflected from other cylinders or surfaces within the collector array.

Similar to Knapmiller's (1991) work in calculating IAM's for cylindrical solar collectors, a computer program employing the Monte Carlo method is used here. A sufficient number of particles must be emitted to render the answers stationary, or independent to some small statistical tolerance, of additional emissions. Thus, the Monte Carlo process is to emit particles,

Figure 1. Two incident angles (θ_l , θ_t) used to describe the sun's incident direction.

trace each in an enclosure with possibly many intermediate surface interactions, until each eventually is absorbed.

THEORY

The theoretical formulation of the collector requires modeling of the collector's geometry and material properties.

Geometry

In order to facilitate portability and speed, the geometry of the collector is kept simple with cylinders and planes as the only objects. Each collector tube is modeled as a pair of concentric cylinders, the outer of which is the glazing (Fig. 2). The tubes are aligned longitudinally along the x-axis as shown in Fig. 3. The orientation of the tubes is fixed, while the size and location are not. The size is given by three values: length (l), outside radius of the glazing (r_o), and outside radius of the collector tube (r_i) (Fig. 2). The location of each tube is determined by its origin (x_0, y_0, z_0), as shown in Fig. 3. For a typical array of collector tubes, x_0 and z_0 are constant for all cylinders and the displacement along the y-axis (y_0) varies.

A back plane is provided to model photon interaction behind the collector tubes. The back plane is a rectangle situated in the x-y plane at $z=0$ with edges parallel to the x and y axes (Fig. 3). The back plane is defined by the corner values to which its edges correspond. In addition to the back plane, an aperture plane must be specified. This virtual plane is used as a reference for determining the collector's performance, as $(\tau\alpha)$ is the ratio of energy absorbed by the collector tubes to the energy incident, in the absence of cylinders, upon the aperture plane (Eq. (2)). The area of the aperture plane is often defined as:

$$A_{ap} = n \cdot l \cdot p \quad (3)$$

where n is the number of collector tubes, l is the length of the collector tubes and p is the average tube pitch (on-center spacing of the tubes). Since the aperture plane is simply a reference plane, keeping track of the exact area used for a particular set of IAM data is more important than adhering to a convention. A bottom plane and top plane, both infinite in extent and parallel to the x-y plane, are used to absorb photons which have exited the volume of interest. The perfectly absorbing bottom plane is located at $z=0$, and absorbs photons reaching it and missing the back plane. The top plane is located at a z value just above the highest point on the collector and absorbs reflected photons traveling upwards which have missed the collector tubes.

An emission plane is used to emit the solar radiation incident upon the collector. This plane is rectangular with its upper and lower edges parallel to the bottom plane, shown in Fig. 4. It is oriented such that its surface normal strikes the bottom plane at the corresponding angle of incidence, shown in

Figure 2. Collector tubes are modeled as concentric cylinders centered about the cylinder's origin (y_0, z_0).

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Figure 3. Orientation of the collector tubes, back plane and bottom plane relative to the x, y and z axes.

Fig. 4 as the solar azimuth (ϕ) and solar altitude (α). It's size is just large enough to include all surfaces in its emissions. This is accomplished by projecting its vertices, along the outward normal, into the bottom plane and assuring that all surfaces projected in the same manner are contained within the projected emission plane. Photons are emitted at random locations across the emission plane and normal to its surface.

MATERIAL PROPERTIES

The material properties implemented here are for a tubular solar collector with a semi-transparent cover and an opaque interior cylinder. The next subsection presents models for opaque surfaces, and the subsequent subsection presents material models for the semi-transparent covers.

Radiative Properties for Opaque Surfaces

Radiative surface material properties for use in Monte Carlo algorithms, specifically mixed material models, consisting of specular and diffuse components of reflectance, have been in use for over three decades [Bobco 1964, Sparrow et al 1962, Sarofim & Hottel 1966, Sparrow & Lin 1965]. Detailed investigations by Toor and Viskanta [1968] and Schornhorst and Viskanta [1968] have shown that a mixed model wherein the two components of reflectance are constant (independent of incident angle) may lead to substantial error. Thus, some investigators employ mixed models wherein the two components vary with incident angle. In this work, traditional mixed material models are extended to be more representative

Figure 4. Orientation of the emission plane with its outward normal intersecting the bottom plane at the corresponding incident angles (ϕ , α).

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Figure 5. Three directional distributions models for the reflective flux of materials.

of real materials. Two enhancements are proposed. First, a more sophisticated model for the outgoing directional distribution of "diffuse" reflections and/or emissions is proposed. Secondly, a semi-specular component, which "spreads" the specular reflection in space, is also proposed. The material model proposed here is motivated by that presented in Modest [1993], on page 288.

Figure 5 shows outgoing directional distributions for photons. Three components of reflectance are proposed. The first is a weighted diffuse component, with outgoing flux described as

$$\rho(\theta_o) = \rho_n \cos^{r_d-1}(\theta_o) \quad (4)$$

The traditional Lambertian distribution is obtained for $r_d = 1$, while $r_d = 0$ yields an isotropic outgoing flux. Powers of r_d greater than 1 skew the distribution toward the normal, while powers of r_d less than 1 skew toward the grazing angle (Fig. 5a). The second component of reflectance is the traditional specular component (Fig. 5b), which is a delta function at the outgoing direction of $\{\theta_o, \phi_o\} = \{\theta_i, \phi_i + \pi\}$. The third component is a semi-specular component, which "spreads" the specular distribution in space at an angle which may be offset about the specular angle (Fig. 5c). As this third component is not used in the present work, it will not be discussed further.

Note that the present implementation considers the radiative properties to be independent of incident angle. That is, the fraction of photons reflected diffusely and that reflected specularly both remain constant, independent of incident angle of the incoming photon. Although this may lead to error in some cases, it was judged that insufficient material properties exist to date to warrant more than this level of modeling. Also, the present formulation is for a single wavelength band, requiring the use of "solar" optical properties. The validity of this assumption will be assessed experimentally.

Radiative Properties for Semi-transparent Surfaces

The optical behavior of semi-transparent materials is well understood [Modest 1993], and will not be covered here. Instead, the details of an approximate model, used for the sake of simplicity and performance, which was implemented in the Monte Carlo code will be covered. The approximation made is that the semi-transparent layer can be modeled locally as a flat plate, with no deviation of flight path due to refraction. This

approximation becomes more accurate the thinner the layer. Indeed, the semi-transparent covers on our collectors are of glass 2 mm in thickness, with a nominal diameter of 12.6 cm. Note, however, that the glass properties, α , τ , and ρ , are computed for a flat plate exactly using the index of refraction, thickness and extinction coefficient of the glass. It is felt that this situation will be well modeled subject to these assumptions.

For photons incident upon the glass from either inside or outside, a random number on $[0,1]$ determines, according to the material properties, the disposition of the photon. If absorbed, a photon absorption counter is incremented for the cover. If transmitted, the photon passes straight through the glass, with no change in direction. Otherwise, it is reflected into the specular direction.

Before implementing the above model, some photons were traced by hand through the glass, with no approximation. For the thicknesses and properties of our glass, it was observed that little absolute error exists for each photon, and that the aggregate error is even smaller because there are compensating errors due to the photons coming in over the entire hemisphere. However, it will be important for the experimental data to confirm this.

IMPLEMENTATION

A Fortran 90 computer code employing the Monte Carlo method has been written to calculate the IAM's for cylindrical solar collectors. The program operates by emitting a large number of photons from specified angles of incidence and tracing them until they are absorbed by one of the components of the collector's geometry. Each component can simply be thought of as a logical node for which a counter is incremented every time a photon is absorbed by it. The user supplies an input deck containing all the information the program needs to compute IAM's. This includes collector geometry, material specifications, a series of incident angles (θ_i, θ_t), a maximum number of photons to emit and a desired convergence tolerance (C_{tol}). The incident angles (θ_i, θ_t) constitute the rows and columns, respectively, of the matrix of IAM's. The angle of normal incidence ($\theta_i=0, \theta_t=0$) must be included, since all the IAM's are based on the collector's performance at normal incidence.

Photon Emission

After reading the input deck, the computer program begins the Monte Carlo Ray Tracing procedure. The first angle of

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incidence (generally normal incidence) is chosen from which blocks of photons are emitted and traced (photon loops). Two random numbers are used to locate a random position on the emission plane (x_e, y_e, z_e) from which to emit a photon. The photon is emitted with a path described by a unit vector normal to the emission plane's surface. A user-specified number of photons are emitted for every photon loop after which the optical calculations are made.

Ray Tracing

Photons follow the path of a line in three-space:

$$\frac{x - x_e}{e_x} = \frac{y - y_e}{e_y} = \frac{z - z_e}{e_z} \quad (8)$$

where e_x , e_y , and e_z are the direction cosines of the photon's path along the x, y and z axes, respectively (the emission plane's outward normal for initial emissions). Using this equation for the photon's path, intersection calculations are carried out to determine which surface the photon will hit. It is first determined if the photon will hit the aperture plane. This is done by simply intersecting Eq. (8) with the bottom plane ($z = 0$), and determining if the x and y values of the intersection point lie within the aperture plane. This is the only time the photon's path is intersected with the aperture plane. Next, the photon's path is intersected with each of the glass cylinders. To aid in calculation efficiency, the intersection is first conducted in two dimensions (y-z plane). The equation of a cylinder in the y-z plane is simply the equation of a circle:

$$(y - y_0)^2 + (z - z_0)^2 = r_0^2 \quad (9)$$

Simultaneously solving Eq. (9) and the y-z components of Eq. (8) produces a pair of real solutions, $(y_{i,1}, z_{i,1})$ and $(y_{i,2}, z_{i,2})$, if the photon's path intersects the cylinder in these two dimensions. Only one of these solutions is valid, and it is the one with the smallest positive change of the z component (δz):

$$\delta z = (z_i - z_e)e_z \quad (10)$$

Knowing the y and z values of the intersection point, Eq. (8) is used again to determine the x value of the intersection point in three dimensions. This intersection continues to be valid if it lies within the x limits of the cylinder:

$$x_0 > x_i > x_0 - l \quad (11)$$

Each cylinder in front of the emission point must be checked to see if the photon hits it. The path will often intersect more than one cylinder mathematically. The valid intersection location (x_i, y_i, z_i) is stored each time the path intersects a cylinder, and the cylinder of smallest δz is chosen as the cylinder of intersection.

When a photon intersects a glass cover, a random number is used to determine if the photon is transmitted, reflected or

absorbed, based on the angle of incidence at which the photon strikes the glass.

- If transmitted, the photon leaves from the intersection location without changing its direction and tracing continues to determine if the photon strikes the inner cylinder or the inner surface of the glass cover. Tracing continues inside the annulus until the photon exits the annulus or is absorbed.
- If reflected, the photon leaves from the intersection location in the direction of the specular reflection vector and the intersection calculations begin again.
- If absorbed, the counter for the glass covers is incremented and a new photon is emitted.

If no cylinders are "hit," the photon's path is then intersected with the back plane. If the back plane is also missed, the photon is absorbed by the bottom plane, its counter is incremented and a new photon is emitted. If the photon does hit the back plane, a new random number is drawn to determine if the photon is absorbed or reflected. If absorbed, the back plane counter is incremented and a new photon is emitted. If reflected, a new direction is chosen based on the back plane material specifications, and tracing continues.

Calculations

After each photon loop completes, the current ($\tau\alpha$) is calculated using Eq. (2), and the convergence factor [Maltby, 1990], C, is calculated

$$C = Z \sqrt{\frac{|1 - (\tau\alpha)|}{(\tau\alpha) \cdot n_{ap}}} < C_{tol} \quad (12)$$

where Z is the cumulative normal distribution coefficient. The value of Z for 95% confidence is 1.96, taken from standard normal tables. Photon loops are executed until $C < C_{tol}$, where C_{tol} is the user supplied convergence tolerance. Once the specified convergence tolerance is achieved, the calculations proceed for the next angle of incidence.

VALIDATION

Hundreds of particle traces with "real" material properties were output from the code and followed by hand. All checked exactly. However, on the order of 50,000 photons are emitted before 1% tolerance can be attained for a single incident direction. Manually following every photon trace to verify the validity of the run would be prohibitively time consuming. Two methods have been used to validate the results of the IAM program: (1) analytical and (2) experimental.

Analytical

There are some simple situations for which analytical solutions exist and can be tested. Consider a bank of black cylindrical solar collectors with a black ($p = 0$) back plane and a transparent glazing ($\tau_g = 1.0$). At any angle of incidence for this collector, the value of ($\tau\alpha$) should be equal to the ratio of the area of the cylinders projected into the emission plane to the area of the aperture plane projected into the emission plane. Using four collector tubes ($r_i = 5.5$ cm, $l = 200$ cm) with a

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Figure 6. Comparison of an analytical solution to the solution produced by the Monte Carlo method.

pitch of 30 cm, the calculations and results for $\theta_i = 0^\circ$ and $\theta_t = 0^\circ$ to 85° are given as Fig. 6. Interesting results occur beyond 70° . At approximately 70° inter-tube shading begins, hence the smaller slope. Although inter-tube shading continues beyond 75° , the projected area of the aperture plane approaches zero while the projected area of the cylinders approaches a finite value due to its diameter, hence the very steep slope. The average error for these 19 angles is 0.06% with a maximum error of 1.7%. This lends confidence that the photon tracing is correct.

Experimental

Outdoor tests are also used to validate the IAM's produced by this new code. An eight-tube integral collector-storage (ICS) module with a total volume of 151 liters (40 gal), is used for these tests. The collector is mounted on the testbed (tilt = 45°) at the Solar Energy Applications Laboratory at Colorado State University. The tests consist of filling the collector with isothermal water in the morning, exposing it to ambient conditions for a portion of the day (typically 5-8 hours) and measuring the change in energy at the end of the test by

drawing water through the collector until $T_{out} - T_{in} < 0.5^\circ\text{C}$. Four different back planes (parameters given in Table 1) are used during these tests to verify the back plane modeling. Three of the back planes, polished stainless steel, masonite painted white and masonite painted black, are mounted to the collector's frame approximately 8 cm below the tube centers. The final back plane is the painted plywood surface of the testbed approximately 30 cm below the tube centers. A minimum of four separate data points on four different days are collected for each back plane configuration. The days varied from mostly sunny to very sunny. Two Eppley PSP's are used to measure both the solar radiation on the collector plane and the diffuse radiation (using a shadow band) on the collector plane. Ambient temperature data are also collected using a type T thermocouple, shielded and aspirated.

A TRNSYS model of the collector was built using the Type 46 (ICS) subroutine. Input into TRNSYS includes the ambient conditions for each test and the table of IAM's corresponding to the collector's geometry. TRNSYS is then run to predict the increase in energy of the collector. Comparing the predicted energy change with the measured energy change shows excellent agreement (Fig. 7). The average error for all the data

Table 1. Parameters for the four back planes used in the experiments.

Back plane Description	Size (l x w)	Specular Reflectance	Diffuse Reflectance
Stainless	78" x 51"	0.6	0.0
White	78" x 66"	0.0	0.7
Black	78" x 66"	0.0	0.1
Testbed	78" x 63"	0.0	0.4

Figure 7. Comparison of simulated energy gain to the actual energy gain.

Figure 8. Comparison of $(\tau\alpha)$ for white and black back planes with $\theta_i=0^\circ$.

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points is 3.3% with a maximum error for any single data point of 11.2%. The standard deviation of the errors is 5%. Because of the close spacing of the collector tubes, the effect of the back plane is small yet still evident. Figure 8 shows (α) for black and white back planes, with $\theta_i = 0$. The difference is most evident at near normal incident angles, when the sun "sees" most of the back plane. The difference diminishes at transverse incident angles above 30°. Over all these angles, the average difference is approximately 10%.

CONCLUSIONS

IAM's play a significant role in predicting the performance of cylindrical solar collectors. This new Fortran 90 code is nearly 50 times faster than the previous code. The input deck is short, simple and allows the use of comment lines. Surface material properties can be modeled more accurately with the use of 3 reflectance types. The code has been validated both analytically and experimentally. The code can be compiled with any Fortran 90 compiler and can be run on PC's with a Pentium processor with satisfactory speed. Sample input decks, the code and an executable for UNIX and DOS can be obtained from the Solar Energy Applications Laboratory home page: <http://www.ColoState.EDU/Orgs/SEAL>.

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Management and Coordination of Colorado State/DOE Program

Coordination of research activities continued on the technical research tasks under the DOE grant, and accounts were maintained and updated. Financial and technical reports were submitted as required.