1

CANADIAN THESES ON MICROFICHE

I.S.B.N.

THESES CANADIENNES SUR MICROFICHE

National Library of Canada
Collections Development Branch

Canadian Theses on
Microfiche Service

Ottawa, Canada
K1A 0N4

Bibliothèque nationale du Canada
Direction du développement des collections

Service des thèses canadiennes
sur microfiche

NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us a poor photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30. Please read the authorization forms which accompany this thesis.

THIS DISSERTATION
HAS BEEN MICROFILMED
EXACTLY AS RECEIVED

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de mauvaise qualité.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30. Veuillez prendre connaissance des formules d'autorisation qui accompagnent cette thèse.

LA THÈSE A ÉTÉ
MICROFILMÉE TELLÉ QUE
NOUS L'AVONS REÇUE

National Library
of Canada

Bibliothèque nationale
du Canada

Canadian Theses Division Division des thèses canadiennes

Ottawa, Canada
K1A 0N4

60012

PERMISSION TO MICROFILM — AUTORISATION DE MICROFILMER

• Please print or type — Écrire en lettres moulées ou dactylographier

Full Name of Author — Nom complet de l'auteur

STEPHEN JAMES HARRISON

Date of Birth — Date de naissance

JAN 21, 1952

Country of Birth — Lieu de naissance

CANADA

Permanent Address — Résidence fixe

18 RUPERT ST.
OTTAWA, ONTARIO
K1S 3S3 CANADA.

Title of Thesis — Titre de la thèse

METEOROLOGICAL EFFECTS ON THERMAL
PERFORMANCE TESTS OF FLAT-PLATE
SOLAR COLLECTOR.

University — Université

CARLETON UNIV.

Degree for which thesis was presented — Grade pour lequel cette thèse fut présentée

M. ENG.

Year this degree conferred — Année d'obtention de ce grade

1982

Name of Supervisor — Nom du directeur de thèse

J. T. ROGERS

Permission is hereby granted to the NATIONAL LIBRARY OF CANADA to microfilm this thesis and to lend or sell copies of the film

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission

L'autorisation est, par la présente, accordée à la BIBLIOTHÈQUE NATIONALE DU CANADA de microfilmer cette thèse et de prêter ou de vendre des exemplaires du film

L'auteur se réserve les autres droits de publication, ni la thèse ni de longs extraits de celle-ci ne doivent être imprimés ou autrement reproduits sans l'autorisation écrite de l'auteur

Date

Oct. 15, 1982

Signature

[Signature]

**METEOROLOGICAL EFFECTS ON THERMAL PERFORMANCE
TESTS OF FLAT-PLATE SOLAR COLLECTORS**

by

© S.J. Harrison

A thesis

presented to the

Faculty of Graduate Studies and Research
in partial fulfillment of the requirements

for the degree of

Master of Engineering

Carleton University
Ottawa, Canada
September, 1982

The undersigned recommend to the
Faculty of Graduate Studies and Research
the acceptance of the thesis:

Meteorological Effects on Thermal Performance Tests
of Flat-Plate Solar Collectors

Submitted by, S.J. Harrison, B.Eng.,
in partial fulfillment of the requirements
for the degree of Master of Engineering

Thesis Supervisor

Chairman, Department of
Mechanical and Aeronautical
Engineering

Carleton University
October 15, 1982

ABSTRACT

A theoretical analysis of the effects of meteorological factors on the thermal performance of flat-plate solar collectors has been conducted. Theoretical results were determined by computer analysis of the optical and thermal performance of a typical flat-plate solar collector. Results are presented for the effects of meteorological and operational factors on component heat transfer and the combined effect on plots of Collector Thermal Efficiency.

An experimental determination of solar collector thermal performance was conducted for a variety of meteorological conditions. The results of the theoretical analysis and experimental data compare favorably. The feasibility of normalizing experimental data to standard meteorological conditions by theoretical analysis was investigated.

Results indicate that standard representations of solar collector thermal performance are not adequate to account for changing meteorological conditions.

II

ACKNOWLEDGEMENT

The author wishes to acknowledge the support and encouragement of the Division of Building Research and the Solar Energy Project Office of the National Research Council of Canada, and to express his appreciation to the people who assisted in this project. These include;

- J.R. Sasaki of NRCC for his encouragement during the project,
- Prof. J.T. Rogers of Carleton University for his guidance and patience during the project,
- L.P. Chabot for his assistance in setting up and conducting the experimental portion of the project,
- M. Bernier for assisting in reduction of the large amount of data collected,
- D. Scott of DBR for preparing the graphics for the final report,
- S. Nussbaumen and B. Gallimore for typing the report, and
- L.L. Hamelin for providing the computer program to calculate fluid properties.

This project would not have been possible without the cooperation of Carleton University and the National Research Council of Canada and the author wishes to thank both parties. Portions of this research were funded under NSERC Grant A6342.

III

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	I
ACKNOWLEDGEMENTS	II
TABLE OF CONTENTS	III
NOMENCLATURE	VI
1. INTRODUCTION	1
2. THERMAL PERFORMANCE OF SOLAR COLLECTORS	4
2.1 Energy Balance for Solar Collectors	4
2.2 The Hottel, Willier, Bliss Model of Thermal Performance	5
2.3 Thermal Performance Ratings	8
3. THERMAL PERFORMANCE TEST METHODS	10
3.1 Review of Test Methods and Procedures	10
3.2 Problems Related to Thermal Performance Testing	11
3.3 Problem Definition and Approach	16
4. HEAT TRANSFER ANALYSIS	19
4.1 Heat Transfer in Solar Collectors	19
4.2 Heat Loss Coefficient, U_L	21
4.2.1 Back Heat Loss Coefficient	24
4.2.2 Edge Heat Loss Coefficient	25
4.2.3 Top Heat Loss Coefficient	26
4.2.3.1 Effective Sky Temperature	32
4.2.3.2 Wind Induced Heat Transfer Coefficient	40
4.2.3.3 Convective Heat Transfer Coefficient, h_{c-p-c}	48
4.3 Transmission of Glazings and Effective Transmission-Absorption Product, $(\tau\alpha)_e$	56
4.3.1 Transmission of Glazings	57
4.3.2 Effective Transmittance-Absorptance Product	63
4.4 Heat Removal From Flat-Plate Solar Collectors	64
4.4.1 Collector Heat Removal Factor, F_R	65
4.4.2 Collector Efficiency Factor, F'	66
4.4.3 Fin Efficiency, F	68
4.4.4 Heat Transfer Coefficient, h_f	68
4.4.5 Calculation of F_R for Chamberlain Collector	70
4.5 Calculation of Theoretical Efficiency	71
5. COMPUTER SIMULATION OF THERMAL PERFORMANCE	74
5.1 COLSM Subroutine	76
5.2 Subroutine TOPL	77
5.3 Subroutine TSKY	79
5.4 Subroutine CHTPC	79
5.5 Subroutine STAEFF	79
5.6 Subroutine OPTCAL	80
5.7 Subroutine APFR	80
5.8 Subroutine FLPROP	80
5.9 Program RCOLSM	80

IV

	Page
6. THEORETICAL RESULTS-EFFECTS OF METEOROLOGICAL AND OPERATIONAL FACTORS	89
6.1 Meteorological Effects on Heat Transfer in Flat-Plate Solar Collectors	90
6.1.1 Top Loss Heat Transfer Coefficient	90
6.1.2 Effective Transmittance X Absorptance Product, ($\tau\alpha$) ^e	97
6.1.3 Heat Removal Factor, F_R	100
6.2 Effect of Meteorological and Operational Factors on Collector Thermal Performance	102
6.2.1 Effects of Collector Slope	102
6.2.2 Effects of Wind Heat Transfer Coefficient	104
6.2.3 Effects of Beam Incident Angle	104
6.2.4 Effects of Insolation Level	104
6.2.5 Effect of Ambient Air Temperature	106
6.2.6 Effect of Ground Reflectance	108
6.2.7 Effects of Diffuse Radiation Fraction	108
6.2.8 Effect of Operational Condition	108
6.2.9 Operational and Meteorological Extremes	112
6.2.10 Meteorological Extremes	112
7. EXPERIMENTAL MEASUREMENTS	114
7.1 Experimental Objectives	114
7.2 Solar Collector Test Facility	114
7.2.1 Temperature Measurements	120
7.2.2 Meteorological Measurements	121
7.2.3 Data acquisition	122
7.3 Experimental Procedure	123
7.4 Data Processing	125
8. EXPERIMENTAL DATA	128
8.1 Test Data	128
8.2 Analysis of Test Data	128
9. DISCUSSION-EFFECT OF METEOROLOGICAL FACTORS ON TEST RESULTS	130
9.1 Discussion of Theoretical Results	130
9.1.1 Significance of the Results for Other Collector Types	134
9.1.2 Significance to Simulator Testing	138
9.2 Discussion of Experimental Results	139
9.3 Comparison of Theoretical and Experimental Results	141
9.4 Normalization of Experimental Results	145
9.5 Recommended Conditions for Thermal Performance Tests	151
10. CONCLUSIONS	152
11. AREAS FOR FUTURE STUDY	154
REFERENCES	155

	<u>Page</u>
APPENDIX A - Physical and Optical Specifications of the Chamberlain Solar Collector	161
B - COLSM simulation, Computer Program Listings	164
C - Energy Balance for Chamberlain Solar Collector	178
D - Data for Runs COLSM	180
E - Experimental Equipment	201
F - Experimental Data	210
G - Frequency Analysis of Experimental Data	214
H - Uncertainty Analysis for Experimental Determination of Thermal Efficiency	219

NOMENCLATURE

A	area of collector surface
A _c	collector reference area, i.e., aperture or gross collector area
c _p	specific heat
C _b	bond conductance
D	diameter of tubes
D _h	hydraulic diameter
D _i	inside diameter
F	fin efficiency factor
F'	collector efficiency factor
F _R	collector heat removal factor
G	transfer fluid mass flow per unit collector area
h	heat transfer coefficient
I	total solar radiation measured in the collector plane
k	thermal conductivity
K	length extinction coefficient
K ₁	parameter eqn.
K ₂	parameter eqn.
L	collector component length, thickness
m	mass flow rate for collector
n	index of refraction
n _t	number of flow tubes
Nu	Nusselt Number

VII

W_{per}	Wetted perimeter around fluid passageway
Pr	Prandtl Number , $\equiv C_p \mu / k$
p	pressure
Q	rate of energy transfer
Q_u	useful energy collected
q	heat transfer rate
Ra	Rayleigh Number
R_A	sky atmospheric longwave radiation on a horizontal surface
$R_A(s)$	sky atmosphere longwave radiation incident on an inclined surface
Re	Reynolds Number based on D_h
R_G	ground source longwave radiation
$R_G(s)$	ground source longwave radiation incident on an inclined surface
$R(s)$	total longwave radiation incident on an inclined surface
S	collector slope
T	temperature
U	thermal conductance
V_w	wind speed
X	parameter eqn. 5.

Greek

α	absorptance
ϵ	emittance
η	thermal efficiency based on reference area

VIII

θ	angle between surface normal and beam radiation
θ_2	refraction angle
λ	wavelength
μ	absolute viscosity
ν	Kinematic viscosity
ρ	reflectance
σ	Stefan-Boltzmann Constant, $(5.67 \times 10^{-8} \text{ W/m}^2 \text{K}^4)$
τ	transmittance
$(\tau\alpha)_e$	effective transmittance absorptance product of the glazing and absorber plate

Subscripts

a	air, ambient
b	back side
c	cover, by convection
c-a	cover-to-ambient
d	diffuse
ds	diffuse from sky
dg	diffuse from ground
dp	dew point
e	effective, edge
f	heat transfer fluid
f_i, f_o	inlet fluid, outlet fluid respectively
g	ground
i	insulation

IX

L overall loss
LW Longwave radiation
o fluid-to-ambient loss
p absorber plate
p-c plate-to-cover
p-s absorber plate to sky
pm mean for absorber plate
m mean
r by radiation
s sky
st stationary
T top
W wind induced
 α considering absorptance only
II,1 two components of polarization, parallel and perpendicular

METEOROLOGICAL EFFECTS ON THERMAL PERFORMANCE

TESTS OF FLAT-PLATE SOLAR COLLECTORS

1. INTRODUCTION

The increase in the use of solar energy for space and service-water heating has resulted in the introduction of a number of solar heating components, notably collectors, to the Canadian market. This has increased the need for solar component performance standards that will provide the users of solar heating systems with some assurance of functional performance, reliability and durability.

One component of these requirements is thermal performance testing. Collector thermal performance data is used (1) by purchasers and certifying agencies to compare the relative worth of competing products (i.e., ranking) and (2) by designers to predict the thermal performance of a system utilizing the evaluated collector. The thermal performance of a solar collector may be derived by analysis (1,2) using the known heat transfer and optical properties of the constituent materials or by experimental means. As many proprietary collectors are fabricated with materials and methods that are inadequately described in terms of their optical and heat transfer properties, it has become common practice to determine the performance characteristic of collectors by testing them with natural or simulated solar radiation.

The representation of thermal performance of flat plate solar collectors which is widely used is of the form originally derived by Hottel and Whillier (2) and later modified by Bliss (3). It is a simplified model of the thermal performance as a number of parameters are not accounted for.

These factors are often thought to represent only second-order effects but as the requirements for accuracy and repeatability increase, their influence becomes more significant. Recently, a test procedure for rating the thermal performance of solar collectors has been developed (4), based on the Hottel, Whillier, Bliss, model and has been widely used throughout North America and Europe. To assess the validity of this test procedure, a number of round-robin test programs have been performed with alarming results (5,6,7). Tests performed at different laboratories on similar test samples produced largely different results. Much of the variation was attributed to instrument error but an analysis of the meteorological conditions encountered during the tests indicated that they influenced the results. Other studies (8,9) have also indicated that environmental factors cause variations in the performance of solar collectors and recently Lumsdaine (10) and Bruck et al (11) have shown their effect on thermal performance test results.

In the light of these findings and realizing the requirements for repeatable and accurate performance ratings, this research was undertaken to determine the effect of meteorological conditions on thermal performance test results for flat plate solar collectors.

It should be noted that it has been shown (10,12) that factors other than those related to environmental conditions, (e.g., collector orientation, heat transfer fluid flow rate and physical properties, etc.), do affect the thermal performance of solar collectors. These factors, though, were considered outside of the scope of this study and as such were only considered in regard to the theoretical and experimental analysis of meteorological influences on collector thermal performance test results.

FIGURE 1

TYPICAL FLAT PLATE SOLAR COLLECTOR

2. THERMAL PERFORMANCE OF SOLAR COLLECTORS

2.1 Energy Balance for Flat-Plate Solar Collectors

A flat-plate solar collector, (figure 1) usually consists of an insulated box enclosing an absorbing surface with a transparent cover on the face to allow the entry of solar radiation. A heat transfer medium, (e.g., air, water, or glycol etc.), is circulated through flow channels attached to or part of the absorber plate.

The thermal performance of a solar collector may be described in terms of an energy balance that relates the solar energy incident on the collector to the energy removed by the heat transfer fluid and the thermal losses from the collector enclosure. This is given by;

$$A_c (I (\tau\alpha)_e) = Q_u + Q_L + Q_s \quad (1)$$

where I = rate of incident solar radiation on the solar collector per unit area

$(\tau\alpha)_e$ = transmittance-absorptance product of the cover

A_c = area of the collector aperture

Q_u = rate of energy extraction from the collector by the heat transfer fluid

Q_L = rate of energy loss from the collector to the surroundings

Q_s = rate of energy storage in the collector

It is important to note that implicit in this simple heat balance is the fact that each of these terms is the sum of complex heat transfer

mechanisms including conduction, convection, and radiation heat transfer.

2.2 The Hottel, Whillier, Bliss Model of Thermal Performance

The theoretical performance of flat-plate solar collectors is described for steady-state conditions (2), where the rate of energy extracted from the collector is equal to the rate of radiative energy absorbed, minus the rate of heat loss to the surroundings, (i.e., $Q_g=0$).

This is expressed as;

$$Q_u/A_c = I (\tau\alpha)_e - U_L (T_p - T_a) \quad (2)$$

where: U_L = heat loss coefficient for the collector, $W/m^2 K$

T_p = average temperature of the collector absorber surface, $^{\circ}C$

T_a = ambient air temperature, $^{\circ}C$

For the purpose of system design, it is convenient to relate the performance of the solar collectors to the temperature of the heat transfer fluid, as the plate temperature is usually not known. Bliss (3) derived two collector efficiency factors, F' and F_R , to allow the use of either the mean or inlet fluid temperature in the collector equation. These are given by:

$$\frac{Q_u}{A_c} = F' [I(\tau\alpha)_e - U_L (T_m - T_a)] \quad (3)$$

$$\frac{Q_u}{A_c} = F_R [I(\tau\alpha)_e - U_L (T_{fi} - T_a)] \quad (4)$$

where F' = collector efficiency factor

F_R = collector heat removal factor

T_m = average temperature of fluid in the collector °C (i.e.,
arithmetic mean of inlet and outlet temperature)

T_{fi} = inlet temperature of the fluid °C

The two relationships are correlated according to reference (3) by:

$$F_R = F' \left(\frac{1 - \exp(-X)}{X} \right) \quad (5)$$

where; $X = F' U_L (G C_p)^{-1}$

G = mass flow rate of the fluid per unit area of collector,
(kg/s)/m²

C_p = specific heat of transfer fluid J/(kg.K)

The ratio of collected useful energy to solar energy incident on the collector is the collection efficiency, η :

$$\eta = \frac{Q_u}{IA_c} = F_R (\tau\alpha)_e - F_R U_L \left(\frac{T_{fi} - T_a}{I} \right) \quad (6)$$

If values of η are plotted versus corresponding values of $(T_{fi} - T_a)/I$, a straight line with an intercept $F_R (\tau\alpha)_e$ and slope $F_R U_L$ will result, figure 2. Values of $F_R (\tau\alpha)_e$ are good indicators of optical efficiency and values of $F_R U_L$ are representative of the heat loss from the collector.

FIGURE 2

IDEALIZED SOLAR COLLECTOR PERFORMANCE CURVE

PLOT OF SOLAR COLLECTOR EFFICIENCY

FIGURE 3

TYPICAL MEASURED COLLECTOR PERFORMANCE CURVE FOR
FLAT-PLATE SOLAR COLLECTOR

2.3 Thermal Performance Ratings

Thermal performance ratings are used by solar system designers and purchasers of solar heating components to compare the performance and cost effectiveness of competing products.

Thermal performance results are utilized to produce "sticker" performance ratings (20). These usually take the form of values of average daily output for specific inlet temperatures. Values are directly derived by multiplying the solar collector thermal efficiency by the incident solar radiation for a standard day. Values of thermal efficiency are determined from the thermal performance test result at a specific inlet fluid temperature, ambient air temperature and hourly average values of solar radiation. Purchasers utilizing this type of rating refer directly to the energy collected on the standard day to compare competing products. The energy output at the required fluid temperature is combined with unit cost to arrive at the most cost effective product.

For large commercial installations, computer simulation programs are utilized to determine collector array output and subsequent system performance. These simulation programs input the solar collector characteristics, i.e. $F_R (r\alpha)_e$ and $F_R U_L$. Solar collector thermal efficiency is determined for hourly data, of solar radiation, ambient air temperature and fluid inlet temperature (1).

Simplified design methods exist which utilize long term average solar radiation and air temperature data for particular locations (73).

All of these procedures assume that a specific thermal performance test result fully characterizes a solar collector's performance, (some simulations include the effect of solar radiation incident angle), but most do not account for the effects of varying meteorological and operational parameters on solar collector thermal performance.

Finally, direct comparisons of the thermal performance shown on a performance curve are often made. In many instances the choice of product used has been determined on the basis of plus or minus a couple of efficiency points.

Contracts to supply solar heating equipment are often awarded on the basis of thermal performance test results. This has prompted solar collector manufacturers to demand a high degree of accuracy in performance ratings.

It is clear that users of solar collector test data should be aware of the factors that affect the test result and their uncertainties.

3. THERMAL PERFORMANCE TEST METHODS

3.1 Review of Test Methods and Procedures

A comprehensive review of existing thermal performance test methods was performed during 1974 by The National Bureau of Standards (8). From this, a formalized collector testing method was recommended including the testing procedure and facility to be used, and the required accuracy of the measurement instruments (13). A second test procedure, ASHRAE Standard 93-77, was introduced by the American Society of Heating, Refrigeration and Air-Conditioning Engineers in 1977 (4). Basically, the ASHRAE standard outlines the same efficiency tests as the NBS procedure, but includes additional tests for determining the transient response of the collector and the variation in performance due to increasing incident angle. (The angle between the direct solar beam and an outward drawn normal to the plane of the collector aperture).

These procedures call for steady-state tests to be performed over a range of collector inlet fluid temperatures under clear sky and steady radiation conditions at times near solar noon. Values of experimental efficiency, " η " are determined by measuring, simultaneously, the mass flow rate, inlet and outlet fluid temperatures and the solar insolation. The instantaneous efficiency is determined by the ratio of energy collected by the heat transfer fluid to the solar energy incident on the collector. This is given by:

$$\eta = \frac{Q_u}{IA_c} = m C_p \frac{(T_{fo} - T_i)}{IA_c} \quad (7)$$

where; m = the mass flow rate of heat transfer fluid through the collector, kg/s

C_p = the specific heat of the heat transfer fluid, J/kg°C

T_{fo} = outlet temperature of the fluid, °C

Experimentally derived values of collection efficiency may then be plotted against the appropriate parameter, i.e., $(T_{fi} - T_a)/I$, and the values of $F_R(\tau\alpha)_e$ and $F_R(U_L)$ determined by the intercept and the slope of the performance curve, figure 3. A complete description of the ASHRAE test procedure and apparatus is given in references (4) and (8).

3.2 Problems Related to Thermal Performance Testing

The performance testing of solar collectors is a relatively complex procedure. ASHRAE Standard 93-77 (4) was intended to provide a standardized test procedure to enable the characterization of the thermal performance of solar collectors in a universal plot. These plots could then be compared in order to rate products and predict solar system performances. This testing procedure and performance representation is based on the simplified Hottel, Whiller, Bliss model of thermal performance described previously. In this representation a number of parameters are not accounted for, such as wind speed and direction, absolute ambient air temperature, ground reflectance, collector tilt, percentage of diffuse radiation, and the effects of the intensity of solar radiation on collector thermal losses. These factors have in the past been considered to account for only second order effects and it was thought satisfactory just to limit the extreme values during data selection. The test procedure sets ranges of acceptable values for

windspeed, solar radiation, and ground reflectance. The ambient air temperature is allowed to vary only 30°C during a single test and the data is limited to clear sky periods when the diffuse solar radiation level is low and the collector performance is at steady state.

This presents two problems; 1. a large number of relatively clear sky periods are required to yield a full set of data and at certain times of the year this may require a long test period during which the variability of the weather conditions can cause a high degree of scatter in the data making interpretation difficult. 2. The requirement for limited environmental conditions during testing further limits the available testing time and causes the time required for a full performance evaluation to be lengthened.

The ASHRAE standard attempts to compromise between available test periods and variability in the test results. The procedure in its existing form would be suitable if all the tests were performed in a climatic region where atmospheric variations from season to season were limited and clear sunny days were abundant. Such is the case for the south western United States where in fact one of the largest test facilities exists. Even at the best locations, variations in atmospheric conditions do occur and cause variability in the test results. The problem is much more severe in the more northern regions of the U.S. and Canada where large seasonal variations occur.

This effect was illustrated in a program organized by the National Bureau of Standards intended to assess the validity of the test procedure. In this "Round-Robin Test Program", thermal performance tests were performed

on two types of solar collectors by 21 test laboratories across the U.S.

(5). The results, (figure 4), showed a large spread in the measured values of collector efficiency. The variation was attributed to systematic errors and the different environmental conditions experienced from facility to facility. A more recent "Round-Robin" test, performed under the organization of the International Energy Agency, (IEA) showed similar results but the variation that occurred was largely attributed to environmental factors experienced during the test and systematic errors

(6).

These test programs indicate the problem with current test procedures and performance representations. Consistent results cannot be achieved when virtually identical test samples are tested to a similar procedure by different test laboratories. The variations that occurred were certainly due to systematic differences between test laboratories, random measurement uncertainty, sample variation and changing meteorological conditions, but it is not clear to what extent each factor has influenced the results.

Theoretical analysis indicates that while random measurement uncertainty and sample variability cannot alone account for the variation in the test results, meteorological conditions could account for the variation as could systematic errors (7).

Lumsdaine (10) has also indicated possible sources of error in the testing of solar collectors. In particular he cites collector tilt angle, wind velocity, and ratio of direct to diffuse solar radiation as factors causing variations in test results. Lumsdaine suggests that test results are a function of a number of factors and that a modified test procedure

FIGURE 4

RESULTS OF "ROUND-ROBIN TEST PROGRAM", CONDUCTED BY
NATIONAL BUREAU OF STANDARDS

should be used where the effects of atmospheric conditions are further controlled. The ASHRAE test procedure implicitly assumes that the value of collector efficiency η is only a function of $(T_{fi} - T_a)/I$ and that $F_R(\tau\alpha)_e$ and $F_{R,L}U_L$ are effectively constant. Bowen (14) and Shewen and Hollands (15) have elaborated on the problems of utilizing a constant value for the heat loss coefficient of solar collectors. Not accounting for environmental and operational conditions, may result in an under- or over-prediction of collector performance. Shewen and Hollands (16) have stated that if parameters $F_{R,L}U_L$ and $F_R(\tau\alpha)_e$ were truly constant, the standard test procedures presented in ASHRAE Standard 93-77 would constitute a complete thermal performance test on the collector. However, many parameters are temperature dependent (particularly $F_{R,L}U_L$) and result in a convex-up plot rather than a straight line when η is plotted versus $(T_{fi} - T_a)/I$ as shown in figure 3. As a result the ASHRAE plot is not a universal plot for a given collector, but dependent on the values of the meteorological conditions experienced during the test. Variations of these quantities over a test period can cause scatter in the data and variation between specific tests can lead to biased results. This makes comparisons between collector types and accurate performance predictions impossible.

To overcome this difficulty it has been argued (7,16) that test data should be referred to conditions of standardized values of T_a and I . If data were not measured under these standard conditions, an agreed procedure should be used to correct the values to standard conditions. It is proposed (16) that these standardized values should be representative of average Canadian conditions, with a weighting toward the winter if the collectors

are to be used for solar heating systems. The following standard values were suggested (16);

$$T_a = 0^\circ\text{C}$$

$$I = 630 \text{ W/m}^2$$

Streed (5) attempted to normalize round-robin test results to standard conditions but the results were confounded by both systematic measurement errors between the participating test facilities and uncertainty in the uniformity of optical and thermal properties of the test sample. Bruck (11) has shown the effects of the various atmospheric conditions experienced during a test by computer analysis but did not verify the results by experimental means.

While normalization of test results to standard test conditions has been suggested as one approach to direct comparison, another possibility is to modify the basic Hottel, Willier, Bliss model to account for more of the environmental parameters experienced during a test. Modifications of this type have been suggested by Shewen and Hollands (15) and Tabor (17,18).

3.3 Problem Definition and Approach

As outlined in the previous section, the ASHRAE representation of thermal performance does not produce a universal plot for a given solar collector. Data indicates that other factors not accounted for in the Hottel, Willer, Bliss Model affect the test results making detailed comparisons impossible. Studies have shown that variations in test results

do occur (5,6), although the influence of any one factor has not been demonstrated. This lack of definitive results was largely due to the possibility of a number of factors influencing the result of previous studies. Possible systematic errors or sample variability introduced major uncertainties into the results of the Round-Robin test programs undertaken in the past. A separate study to determine the effect of meteorological factors on solar collector test results is required. This study should be conducted in a manner that eliminates the effects of sample variability and systematic measurement error. These objectives may be met by two methods;

1. A theoretical analysis of the basic heat transfer properties associated with solar collector thermal performance is performed to determine the relative effects of each of the atmospheric parameters on the thermal performance of solar collectors. The computer analysis may be performed in a systematic manner by varying each parameter separately to determine its effect.
2. The performance of a single solar collector test sample is measured under a variety of atmospheric conditions, utilizing a single test facility for all tests. The use of a single test sample and test facility ensure that systematic errors and sample variability are eliminated when the relative effects of atmospheric conditions on collector thermal performance are evaluated.

The project described herein consists of the experimental testing of a solar collector to determine its thermal performance under a variety of atmospheric conditions spanning the range of values experienced in the Canadian climate. Values of wind velocity, solar radiation intensity and

percent diffuse component, absolute ambient air temperature, and heat transfer fluid temperature were measured for each operational condition. A single glazed flat plate solar collector (see Appendix A) was used for the evaluation as it is described in many studies (5,6,7) and its optical and thermal properties are well known.

Data was recorded for a period of time spanning almost a full calendar year ensuring that a range of atmospheric conditions were experienced. The data was recorded on magnetic tape for subsequent analysis by computer. Only data that met the basic requirements of the ASHRAE test standard (i.e., steady state operation, minimum solar radiation, etc.), were used for the analysis.

A major phase of this project consisted of the writing of a computer program to simulate the thermal performance of the solar collector. The computer program utilizes fundamental heat transfer relationships to simulate the collector's performance at specific atmospheric conditions. The computer model allows the systematic analysis of each of the atmospheric parameters to determine its effect on collector performance. Once the effects of these parameters is determined the analysis may be used to evaluate the feasibility of normalizing the data taken during the experimental portion of this project to standard conditions. The effectiveness of the theoretical analysis in normalizing the experimental data to standard conditions is determined by the agreement of the generated data with the experimental results and the reduction of scatter in the experimental data.

4. HEAT TRANSFER ANALYSIS

4.1 Heat Transfer in Solar Collectors

The theoretical equation for the thermal performance of flat plate solar collectors is given in section 2 as:

$$Q_u = A_c (I(\tau\alpha)_e) - Q_L - Q_s \quad (8)$$

Assuming $Q_s = 0$, then, the rate of energy extracted from the collector is the difference between the rate of solar energy absorbed by the absorber plate, $I(\tau\alpha)_e$, and the rate of thermal energy loss to the surroundings, Q_L where $Q_L = U_L A_c (T_p - T_a)$.

Optical and thermal loss mechanisms are shown diagrammatically in figure (5) for a conventional flat plate solar collector. Optical losses

FIGURE 5

OPTICAL AND THERMAL LOSS MECHANISMS
IN A FLAT-PLATE SOLAR COLLECTOR

include absorption and reflection of the incident solar beam at the glazing of the collector and reflection at the absorber surface. Thermal losses from the collector consist of conduction losses through the back and edge of the collector to the surrounding environment, and conduction, convection and radiation losses through the front of the collector.

In the simplified representation of thermal performance, the values of $(\tau\alpha)_e$ and U_L are considered to be constant for all atmospheric conditions. This is, in fact, not true as both the optical and heat transfer properties of the solar collector are effected by meteorological conditions.

The energy balance on a single glazed flat plate solar collector may be represented in simple terms by the thermal network shown in figure 6.

In actual fact, the resistance networks for the heat transfer in a solar collector are quite complex. To assess the effects of atmospheric factors, we may first investigate the factors that affect the overall heat loss coefficient, U_L and separately those that affect the optical properties, $(\tau\alpha)_e$. To ultimately assess the overall effect on the thermal performance of a solar collector, the interaction of these two effects must be evaluated.

FIGURE 6

SIMPLE THERMAL NETWORK FOR THE
ENERGY BALANCE IN A SINGLE GLAZED
FLAT-PLATE SOLAR COLLECTOR

The following sections will present the analysis of the steady state thermal performance of the Chamberlain flat plate solar collector, described in Appendix A. This collector is of conventional design and construction and is the model used for studies at NRCC. The analysis is derived using conventional heat transfer practice and follows closely the relationships presented by Duffie and Beckman (1, 40) and Kreith and Kreider (19). The general analysis, while specifically derived for the Chamberlain collector, will be applicable to other collectors of similar design. Transient effects, while present in the operation of real systems, are not allowed during thermal performance testing and so will not be considered in this analysis.

4.2 Heat Loss Coefficient U_L

If the following assumptions are applied, the heat loss network for a solar collector may be represented as shown in figure 7.

1. The solar collector is thermally in steady state.
2. The temperature distribution from the top to the bottom of the absorber plate is uniform.
3. Heat flow is one-dimensional through the covers and back insulation.
4. The headers connecting the absorber plate tubes represent only a small percentage of the absorber plate.
5. The sky can be represented as a black-body sink for infrared radiation at an equivalent sky temperature.
6. The irradiation of the collector plate is uniform.

FIGURE 7

THERMAL NETWORK FOR HEAT LOSS FROM THE
ABSORBER PLATE SHOWING EDGE, BACK AND
TOP LOSSES

The heat loss from the absorber plate to the surrounding atmosphere may be refined as shown in figure (7) to show the back and edge heat losses

through the collector casing. For most solar collectors the relative values of these two terms is small compared with the losses through the collector front glass face. The rate of heat loss through the edge and back of the solar collector is relatively insensitive to variations in atmospheric conditions other than those of the temperature difference between T_p and T_a .

The value of Q_L is the rate of energy loss from the collector to the surroundings. These losses will be made up of losses through the back and edges of the collector and losses through the top of the collector;

$$Q_L = q_{\text{back}} + q_{\text{edge}} + q_{\text{top}} \quad (9)$$

Relating each of these losses to the temperature difference between the mean absorber plate temperature, T_{pm} , and the ambient air temperature, T_a , the expression becomes:

$$Q_L = A_{\text{back}} U_{\text{back}} (T_{pm} - T_a) + A_{\text{edge}} U_{\text{edge}} (T_{pm} - T_a) + A_{\text{top}} U_{\text{top}} (T_{pm} - T_a) \quad (10)$$

If we further relate each of these values to the reference area of the solar collector, the heat loss per unit collector reference area, A_c , is;

$$\frac{Q_L}{A_c} = \left\{ \frac{A_{\text{back}}}{A_c} U_{\text{back}} + \frac{A_{\text{edge}}}{A_c} U_{\text{edge}} + \frac{A_{\text{top}}}{A_c} U_{\text{top}} \right\} \cdot (T_{pm} - T_a) \quad (11)$$

If we let

$$U_b = \frac{A_{back}}{A_c} U_{back} ; \quad U_T = \frac{A_{top}}{A_c} U_{top} ; \quad U_e = \frac{A_{edge}}{A_c} U_{edge} \quad (12)$$

then

$$\frac{Q_L}{A_c} = [U_b + U_e + U_T] \cdot (T_{pm} - T_a) \quad (13)$$

The value of $U_b + U_e + U_T$ is usually given the name Heat Loss Coefficient, U_L ,

$$\text{i.e.,} \quad U_b + U_e + U_T = U_L \quad (14)$$

Thus, the relationship for heat loss can then be given as

$$Q_L = A_c U_L (T_{pm} - T_a) \quad (15)$$

4.2.1 Back Heat Loss Coefficient

The energy loss through the back of the collector is determined by the thermal resistance of the back insulation and the collector housing and film coefficients for the outer surface. In most cases, (and the one being considered), the value of heat loss may be accurately predicted using the resistance of the insulation only since the thermal resistance of the insulation constitutes the governing resistance to heat flow from the back.

The effect is even further reduced as edge and back losses are usually a small portion of the total loss from the collector. See results in Appendix C. The back heat loss coefficient is then given by:

$$U_b = \frac{U_{back} A_{back}}{A_c}$$

where $U_{back} = k_i / L_i$

giving $U_b = \frac{k_i A_{back}}{L_i A_c}$

4.2.2 Edge Heat Loss Coefficient

Accurate derivations of the edge losses of solar collectors is quite complicated. Relationships for determining the average values of edge loss are given in references (19) and (22) for specific configurations. The edge Heat loss coefficient is given as:

$$U_e = \frac{k_e A_{edge}}{L_e A_c} \quad (17)$$

where k_e is the thermal conductivity of the edge insulation,

L_e is the thickness of the edge insulation.

Edge losses often vary from collector make to make depending on the details of the design. Consequently combined values of U_{back} and U_e are often determined experimentally.

4.2.3 Top Heat Loss Coefficient

Heat loss through the top of the solar collector is by both convection and radiation heat transfer. Heat is transferred from the absorber plate to the cover plate by convection across an inclined air layer and also by radiative exchange between the plate and the cover glass. Some long-wave radiation is transmitted through the glass from the absorber plate to the atmosphere but since glass is almost totally opaque to long-wave radiation, this accounts for only a small amount of the heat loss. This is not always the case for some thin films and plastics, as they may be effectively transparent to long-wave infrared radiation.

The energy transferred to the cover from the absorber plate is lost to the atmosphere by convection to the ambient air (often enhanced by wind), and by radiation exchange from the cover plate to the sky and the surroundings. The radiation leaving the cover plate is assumed to be radiating to a black-body source for infrared radiation at an effective sky temperature. Relationships for effective sky temperature, T_s , are discussed in section 4.4.2.

A detailed heat transfer network for the top-loss heat transfer coefficient is given in figure 8, showing both the radiative and convective heat loss paths.

FIGURE 8
THERMAL NETWORK FOR HEAT-LOSS FROM THE TOP
OF A SOLAR COLLECTOR SHOWING CONVECTIVE
AND RADIATIVE COMPONENTS

The simplified performance representation described in section 2.0 assumes that U_L (and U_{top}) are constant. It may be seen from figure 8 that, in fact, U_{top} is a function of both T_a , T_p and T_{sky} and the values of $h_{w,c-a}$, $h_{r,c-s}$, $h_{c,p-c}$ and $h_{r,p-c}$. These terms are a function of collector orientation and wind velocity. Gross assumptions that are commonly made are that h_w is constant regardless of wind speed and that T_s is equal to the ambient air temperature T_a . The validity of these assumptions will be described in detail in the subsequent sections.

The relationship for heat transfer from the collector absorber plate to the coverglass is given by;

$$q_{p-c} = q_{rad,p-c} + q_{conv,p-c} \quad (18)$$

The value for the radiative exchange between the plate and cover can be approximated by the relationship for radiative exchange between infinite parallel flat plates (1).

$$q_{rad,p-c} = \frac{A_{top} \sigma (T_{pm}^4 - T_c^4)}{(1/\epsilon_p) + (1/\epsilon_c) - 1} \quad (19)$$

This relationship should be valid for almost all flat plate collectors as the distance between the cover and absorber plate is small relative to the area of the plates. Subsequently edge effects should be minimal.

The heat transfer due to convection is given by:

$$q_{conv,p-c} = A_{top} h_{c,p-c} (T_{pm} - T_c) \quad (20)$$

Converting the relationship for $q_{r,p-c}$ we may derive the radiation heat transfer coefficient $h_{r,p-c}$;

$$h_{r,p-c} = \frac{q_{rad,p-c}}{A_{top} (T_{pm} - T_c)} \quad (21)$$

thus

$$h_{r,p-c} = \frac{\sigma (T_{pm}^4 - T_c^4)}{[(1/\epsilon_p) + (1/\epsilon_c) - 1] (T_{pm} - T_c)} \quad (22)$$

which can be reduced to

$$h_{r,p-c} = \frac{\sigma (T_{pm}^2 + T_c^2) \cdot (T_{pm} + T_c)}{(1/\epsilon_p) + (1/\epsilon_c) - 1} \quad (23)$$

The value of the convective heat transfer coefficient, $h_{c,p-c}$ is determined by the relationship;

$$h_{c,p-c} = Nu (k_a / L_{p-c}) \quad (24)$$

The relationships for the $h_{c,p-c}$, Nu, the Nusselt number and k_a , the thermal conductivity of air are presented in sections 4.2.3.3. The heat transfer from the absorber plate to the cover can now be expressed as;

$$q_{p-c} = A_{top} U_{p-c} (T_{pm} - T_c) \quad (25)$$

where

$$U_{p-c} = h_{c,p-c} + h_{r,p-c} \quad (26)$$

It should be noted that the heat loss from the absorber plate to the cover glass is the same value as the heat transferred from the cover glass to the atmosphere.

$$q_{p-c} = q_{c-a} \quad (27)$$

The heat loss from the cover to the atmosphere is by convection and by radiation to the sky;

$$q_{c-a} = q_{rad,c-s} + q_{conv,c-a} \quad (28)$$

where

$$q_{conv,c-a} = A_{top} h_w (T_c - T_a) \quad (29)$$

where h_w is the wind induced heat transfer coefficient described in section 4.2.3.2.

The radiation loss from the cover to the sky is given by;

$$q_{rad,c-s} = A_{top} \cdot \epsilon_c \sigma (T_c^4 - T_s^4) \quad (30)$$

as expressed as radiation heat transfer coefficient

$$h_{r,c-a} = \frac{\epsilon_c \sigma (T_c^4 - T_s^4)}{(T_c - T_a)} \quad (31)$$

where T_s is given by the expression developed in section 4.2.3.2. The resultant heat loss is given by

$$q_{c-a} = A_{top} (h_w + h_{r,c-s}) \cdot (T_c - T_a) \quad (32)$$

$$= A_{top} (U_{c-a}) \cdot (T_c - T_a)$$

where:

$$U_{c-a} = h_w + h_{r,c-s} \quad (33)$$

Heat transfer by radiative exchange between the absorber plate and the sky is given by;

$$q_{rad,p-s} = A_{top} \tau_{LW} \epsilon_p \sigma (T_{pm}^4 - T_s^4)$$

where τ_{LW} is the transmittance of the cover to long-wave radiation.

This radiation heat transfer coefficient is given as:

$$h_{r,p-s} = \frac{\tau_{LW} \epsilon_p \sigma (T_{pm}^4 - T_s^4)}{(T_{pm} - T_a)} \quad (34)$$

The overall heat transfer coefficient for top heat loss may now be expressed as

$$U_{top} = \left[\frac{1}{U_{p-c}} + \frac{1}{U_{c-a}} \right]^{-1} + h_{r,p-s} \quad (35)$$

The heat loss for the collector top per collector unit area is then:

$$\frac{q_{top}}{A_c} = \frac{A_{top}}{A_c} U_{top} (T_{pm} - T_a) = U_T (T_{pm} - T_a) \quad (36)$$

$$\text{for } A_c = A_{top}$$

4.2.3.1 Effective Sky Temperature

To evaluate the radiation exchange between a surface, of area A, and the sky, the sky can be considered as a blackbody at an effective sky temperature T_s . In this case the net radiation exchange, Q_{rad} between a horizontal flat plate and the sky is given by:

$$\frac{Q_{rad}}{A} = \epsilon_p \sigma (T_p^4 - T_s^4) \quad (37)$$

In the simplified representation of collector thermal performance described in section 2.0 it is usually assumed that the effective sky temperature is equal to the ambient air temperature. Many researchers have shown that this assumption is often not true, (1, 21, 22, 23, 25, 26).

The difference in sky and ambient temperature is a result of radiative exchange between the atmosphere and the radiating surface. Atmospheric radiation originates from constituents within the atmosphere, The intensity of the radiation emitted at any wavelength is dependent upon the partial pressure of the constituents, their temperature and their thickness. Water vapour and carbon dioxide are the principle constituents with respect to atmospheric radiation, the former being the most important. Both show absorptive (and emissive) characteristics at selected wavelengths over the entire spectrum. In the wavelength region 8.5 to 13.0 μm , atmospheric water vapour is largely transparent to longwave radiation, but at all other wavelengths it can be considered practically opaque to longwave radiation (24). Clouds are powerful sources of atmospheric radiation and in

general, the effect of clouds is to close the "atmospheric window" in the 8.5 to 13.0 μm region. Clouds will therefore always increase the amount of atmospheric radiation relative to the clear sky condition. This will result in higher effective sky temperatures as compared to the clear sky case where the net radiative exchange is to the much colder upper atmosphere. Solar collector thermal performance tests are only conducted during relatively clear sky conditions although the amount of moisture in the atmosphere may vary for different tests. In actual system operation large amounts of cloud cover may be present but these periods will usually constitute periods when the available solar radiation is low. During collector testing though, large differences in ambient air temperature and effective sky temperature may be present.

Several relationships have been proposed to relate T_s , for clear skies, to other meteorological variables. This has been undertaken as effective sky temperature has not been routinely measured in the past. Relatively inexpensive instruments for direct measurements have recently been developed but their accuracy is still in question (21).

Swinbank (23), has related sky temperature to local air temperature by the relationship

$$T_s = 0.0552 (T_a)^{1.5} \quad (38)$$

where T_s and the ambient air temperature, T_a are both in degrees Kelvin.

Bliss (24), has related effective sky temperature to the water content of

the air and its temperature. The relation uses dew point temperature, T_{dp} ;

$$T_s = T_a \left[0.8 + T_{dp} - \frac{273}{250} \right]^{\dagger} \quad (39)$$

Willier (22) recommends subtracting 6°C from the air temperature

$$T_s = T_a - 6^{\circ}\text{C} \quad (40)$$

although values significantly lower have been recorded (25).

Unsworth and Monteith (28), have recently derived a relationship for incoming atmospheric radiation, R_A , from the sky during clear sky conditions

$$R_A = p + q \cdot \sigma T_a^4 \quad (41)$$

where p and q were found to be $-119 \pm 16 \text{ W/m}^2$ and 1.06 ± 0.04 respectively from measurements in England. The relationship has an estimated uncertainty in a single estimate R_A of $\pm 30 \text{ W/m}^2$, (or $\pm 6 \text{ K}$ at $T_a = 293 \text{ K}$).

The value of effective sky temperature may be simply determined,
e.g.,:

for the case $T_a = 20^{\circ}\text{C} = 293 \text{ K}$

$$\begin{aligned} R_A &= -119 + 1.06 (5.67 \times 10^{-8}) (293)^4 \\ &= 324 \text{ W/m}^2 \end{aligned}$$

The effective sky temperature is determined by treating this radiation as equivalent to that coming from a black body radiator at a temperature equal to T_s .

$$T_s = \left(\frac{324}{5.67 \times 10^{-8}} \right)^{\frac{1}{4}}$$

$$= 275 \text{ K} = 2^\circ\text{C}$$

Swinbank's relationship gives a value of 3.8°C . Figure (9) compares values derived by the two relationships (21).

- UNSWORTH & MONTEITH EQUATION (1): $R_A = 1.06 \sigma T_a^4 - 119$
- ◊ SWINBANK EQUATION (2): $R_A = 9.37 \times 10^{-6} \sigma T_a^6$

FIGURE 9
CLEAR SKY VALUES OF EFFECTIVE SKY TEMPERATURE
FOR A HORIZONTAL SURFACE

It may be noted that the depression of the T_s relative to T_a is significant and subsequently should be considered in the heat transfer analysis. It should be noted that while this difference may be large, the solar collector is usually tilted at some angle to the horizontal and as such views the ground in front of it as well as the sky. The ground is usually at a temperature very close to the ambient air temperature. The net result is that the collector "sees" two surfaces; one at T_s and one at T_a .

Values of longwave radiation incident upon inclined surfaces have been derived (26). The radiation incident upon a surface inclined at an angle to the horizontal, figure (10) is a combination of atmospheric and ground radiation, i.e.,

$$R(s) = R_A(s) + R_G(s) \quad (42)$$

where: $R(s)$ - is the incident longwave radiation on the surface, W/m^2

$R_A(s)$ - is the incident atmospheric radiation on the inclined surface, W/m^2

$R_G(s)$ - is the longwave radiation incident on the inclined surface from the adjacent ground, buildings, etc., W/m^2 .

Inclined surfaces receive radiation from the atmosphere, the ground and any surrounding buildings, in the ratio of their respective configuration factors. Although it is possible to predict the longwave radiation originating from the atmosphere, there is very little information available regarding the magnitude of the ground radiation (26). The ground radiates in accordance with the temperature attained by its surface and its spectral emissivity. The ground temperature is dependent upon the nature of the surface, the prevailing climatic conditions and the heat gains and losses during the previous day. It is generally assumed that the ground radiation

seen by an inclined surface is equal to that emitted by a black body at ambient air temperature, but if the emissivity of the ground is known then the value of the ground component, $R_G(S)$, incident on a surface inclined at a slope S to the horizontal may be estimated by;

$$R_G(S) = \epsilon_g \sigma T_g^4 \cdot \frac{(1 - \cos S)}{2} \quad (43)$$

The value of $R_A(S)$ is more complex as atmospheric radiation is not isotropic and varies across the sky. Cole (26) has derived a relationship for atmospheric radiation incident on an inclined surface, for clear skies,

$$R_A(S) = R_A \cdot K_1 + K_3 b \sigma T_a^4 \quad (44)$$

where; R_A - is calculated for the horizontal case as before

b - is a constant = 0.09

K_1 and K_2 - are given in table (1) as taken from reference (27).

Considering the previous example for a surface sloped at 60° to the horizontal;

As calculated for the horizontal case $R_A = 324 \text{ W/m}^2$.

$$R(60) = R_A(60) + R_G(60)$$

and

$$R_A(60) = R_A \cdot K_1 + K_3 \cdot 0.09 \sigma T_a^4,$$

FIGURE 10

SURFACE INCLINED AT SLOPE "S"

TABLE 1: Values of factors K_1 and K_3 , (Ref. 27)

Surface inclination	K_1	K_3
0	1.0000	0.0000
10	0.9924	0.0221
20	0.9698	0.0613
30	0.9330	0.1225
40	0.8830	0.1798
50	0.8214	0.2339
60	0.7500	0.2803
70	0.6710	0.3159
80	0.5868	0.3381
90	0.5000	0.3457

from table (1) for 60° inclination, $K_1 = 0.7500$, $K_3 = 0.2803$, and

$$T_a = 20^\circ\text{C} = 293^\circ\text{K}$$

therefore:

$$\begin{aligned} R_A(60) &= 324 (0.7500) + 0.2803 \cdot 0.09 \cdot 5.67 \times 10^{-8} \cdot (293)^4 \\ &= 253.5 \text{ W/m}^2 \end{aligned}$$

The value of $R_G(60)$ is given by;

$$R_G(60) = \epsilon_g \sigma T_g^4 \cdot \frac{(1 - \cos 60)}{2}$$

assuming that the ground is rough concrete with a value of $\epsilon_g = 0.94$, (29)

$$\text{and } T_g = T_a,$$

$$\begin{aligned} \text{then } R_G(60) &= 0.94 \cdot 5.67 \times 10^{-8} \cdot (293)^4 \cdot \frac{(1 - \cos 60)}{2} \\ &= 98.2 \text{ W/m}^2 \end{aligned}$$

The value $R(60)$ is then;

$$\begin{aligned} R(60) &= R_A(60) + R_G(60) \\ &= 253.5 + 98.2 \text{ W/m}^2 \\ &= 351.7 \text{ W/m}^2 \end{aligned}$$

the value of T_s for this case is then,

$$\begin{aligned} T_s &= \left(\frac{351.7}{5.67 \times 10^{-8}} \right)^{\frac{1}{4}} \\ &= 280.6 \text{ K} = 7.6^\circ\text{C} \end{aligned}$$

We see that the value of T_s at 60° tilt is 5.6 °K warmer than the horizontal case due to longwave radiation emitted from the ground and seen by the inclined surface. Theoretical values of longwave radiation incident on an

inclined surface area shown in figure (11) as calculated by the above relations using the TSKY program described in section 4.6, and assuming $\epsilon_g = 0.9$.

FIGURE 11
EFFECTIVE SKY TEMPERATURE FOR
INCLINED SURFACES (CLEAR SKY)

4.2.3.2 Wind Induced Heat Transfer Coefficient

The effect of wind velocity on the thermal performance of flat plate solar collector has been investigated by many researchers (1, 8, 42, 44).

While it is clear that wind considerably influences collector thermal performance through variations in h_w (44), the wind induced surface heat transfer coefficient, the relationship between h_w and atmospheric wind is an area of considerable controversy.

The flow of wind over a solar collector is highly complex in nature due to variations in wind direction and velocity that result in complex 3-dimensional flow patterns. Nearby structures, obstructions and surface roughness affect the atmospheric boundary layer. This introduces considerable uncertainty into the determination of the flow field around real solar collector installations.

Experiments conducted outdoors on real solar collectors are complicated by the transient nature of the wind and solar radiation. The relatively long response time of the solar collector, absorber plate and glazing make the collection of meaningful data difficult if not impossible. For this reason, many recent studies (8,44) to relate wind effects to the thermal performance of solar collectors have relied on computer analysis utilizing empirical relationships derived for surface heat transfer coefficients determined in wind tunnel experiments (32, 33, 37, 38, 39).

Analysts (1,8,22,30) in the past have used the relationship for forced convection heat transfer suggested by Jürges in 1924, (33), which is based on the work done by Nusselt and Jürges in 1922 (32). The relationship as presented by Duffie and Beckman (1), is;

$$h_w = 5.7 + 3.8V \quad (45)$$

where h_w is the wind induced heat transfer coefficient in W/m^2K , and

V is the wind velocity in m/sec.

The original description of this work (32) was presented in German and was introduced into American engineering practice by McAdams in his classical book, "Heat Transmission" (34), in 1933. The relationship was adopted by ASHRAE, (31) for calculating wind induced heat losses from buildings. The fact the original text was in German seems to have limited later investigators' understanding of the original experiment and led to considerable speculation over the last 60 years as to the work's applicability to solar collectors.

Criticisms of the work (33) are summarized below with corresponding references;

1. The data was originally obtained for air flow parallel to a vertical copper plate which is typically not the case found in solar collector installations where wind may pass over the collector at an arbitrary angle, (36, 38, 39, 46).
2. The relationship does not account for the dimensions of the plate used for the experiment although classical heat transfer theory indicates that average heat transfer coefficient depends on the stream-wise length of the plate. Therefore results are only applicable to plates of the same dimension as used in the original experiment (38, 40).
3. The characteristics of the experiment are not defined, in relation to Reynolds number and turbulence intensity of the flow. The exact specification of V is not given (37, 38, 46).
4. Radiation heat transfer was probably not accounted for in the experiment (36, 38, 40).

The work of Nusselt and Jürges (32), has recently been translated into English by Serré, 1979, (35). A review of this translation indicates that the original work was performed with a 0.5 m square copper plate mounted vertically on one side of a wind tunnel. The flow over the plate

was uniform and radiation heat transfer was accounted for, negating criticism no. 4. It is interesting to note that authors state that the relation in wide scale usage (33) is only applicable to velocities below 5 m/sec. A relationship for wind speed above this value is presented in the original work. Reviewing the work of Nusselt and Jürges, Gladstone (47), points out that the turbulence intensity encountered during the tests was about 1.3%, whereas atmospheric wind has values ranged from 10 to 30%.

It may be concluded from the above discussion, that there is good agreement that the relationship widely in use (33), is inappropriate for application to solar collectors.

This seems to be the extent of the agreement of subsequent researchers which will be discussed below.

Many subsequent researchers have conducted investigations to arrive at better relationships for wind induced heat transfer coefficients. The experiments may be divided into four categories;

- 1) classical heat transfer experiments on flat plates of various geometries in wind tunnels.
- 2) Experiments on full sized solar collectors conducted outdoors.
- 3) Experiments on small mock-solar collectors or hot plates mounted outdoors.
- 4) Scaled experiments of solar collectors under the influence of a simulated atmospheric boundary layer in wind tunnels.

The experiments have investigated flow patterns, heat transfer coefficients, and their interactions. A survey of the work does not reveal conclusive results, but the relationships for wind induced heat transfer

coefficient, h_w are reviewed below by author.

Reviewing the translation by Serré (35) of the Nusselt and Jürges original paper, Nusselt and Jürges recommend;

$$h_w = 7.14 V^{0.78} + 5.35e^{-0.6V} \text{ W/m}^2\text{°C} \quad (46)$$

for $0 < V < 25$ m/sec. They suggest that for practical applications the following equations may be used

$$\begin{aligned} \text{for;} \quad V < 5 \text{ m/sec, } h_w &= 5.8 + 3.95V, \text{ W/m}^2\text{°C} & (47) \\ V > 5 \text{ m/sec, } h_w &= 7.14 V^{0.78}, \text{ W/m}^2\text{°C} \end{aligned}$$

Watmuff et al, (36), suggest that if radiation effects are eliminated from Jürges relation (32) then a better relation would be;

$$h_w = 2.8 + 3.0 V \text{ W/m}^2\text{°C} \quad (48)$$

for: $0 < V < 7$ m/sec.

This justification is not valid as radiation effects were accounted for in the Jürges experiment.

The more recent work by Tien and Sparrow, 1977 (37), presents wind tunnel experiments for square plates, situated at various orientations to the flow direction. These experiments were performed by sublimation of naphthalene from the surface of a plate, and using an analogy between heat transfer and mass transfer they determined heat transfer coefficients. They concluded that, due to three-dimensional flow effects that heat transfer was almost independent of flow direction. These results were correlated to:

$$j = 0.931 \text{ Re}^{-\frac{1}{2}} \quad (49)$$

where
$$j = (h_w / \rho C_p V_\infty) Pr^{2/3}$$

where ρ is the density of the air,

C_p is specific heat,

Pr is the Prandtl number,

V_∞ is the free stream velocity of the air flow

Re is Reynolds number based on edge length.

This experiment was conducted on square plates and the authors suggest that it is not applicable to rectangular plates. Reynolds numbers from 20,000 to 100,000 were investigated.

Tien and Sparrow conclude that Jürges' relationship substantially overestimates the value of h_w .

In a later work Tien and Sparrow, 1979 (38), discuss further experiments on the distribution of heat transfer coefficient across a plate. They once again state the insensitivity to wind direction and note that the highest heat-transfer coefficients occur near the edges of the plate. Flow patterns were observed to be highly complex and three dimensional. They note that flow patterns are not very dependent on Reynolds number. In Sparrow and Nelson's work, 1981 (39), the authors investigated wind related heat losses on leeward facing and windward facing collector surfaces using techniques similar to those used in their previous experiments. They concluded that leeward wind losses are slightly smaller, (i.e., 10%), than windward values, when Re is less than 60,000. For Re greater than 60,000 leeward values are higher. Flow visualization showed that eddies formed over the leeward surface and tended to enhance heat transfer. For

rectangular plates Sparrow and Tiens relation (40) is given as;

$$Nu = 0.86 Re^{\frac{1}{2}} Pr^{1/3} \quad (50)$$

where the characteristic length is four times the plate area divided by the plate perimeter.

The conclusions of the work of Sparrow is that eqn. (45) overpredicts h_w by two to three hundred percent and that wind direction has little effect.

Hewitt and Griggs (41) investigated wind effects on solar collectors in a mammoth study employing outdoor tests on real solar collectors, indoor experiments on mini-collectors and wind tunnel experiments on hot plates. The results are neither conclusive nor convincing.

The authors conclude that Jürges' results predict too high a heat loss at high velocities and too low a value at low velocities while Sparrow and Tien (37) uniformly overpredict losses by 10%.

Duffie and Beckman (40) suggest for collectors on buildings, that for h_w , to use the larger of $5 \text{ W/m}^2\text{C}$ or

$$h_w = \frac{8.6 V^{0.6}}{L^{0.4}} \quad (51)$$

where L is the cube root of the house volume. The value of $5 \text{ W/m}^2\text{C}$ is suggested to be representative of the natural convection heat transfer case.

Green (42) suggests, that for velocities parallel to the collector surface

$$h_w = 3.0 + 7.4 v_p^{\frac{1}{2}} \quad (52)$$

These values were determined by tests on full scale collectors in a solar simulator, blowing wind from a "Scroll" fan, along the plate surface. The characteristics of the flow were not stated. They cite the work of Oliphant (43), to conclude that free stream wind velocity is 1.3 to 3 times the velocity parallel to the plate.

A review of the work of Oliphant suggests that his method for measuring velocity parallel to the collector glazing was invalid as the wind velocity was measured parallel to the ground and not parallel to the collector surface.

Hamelin (44) has illustrated the effect of h_w on solar collector performance, and calculates the natural convection heat transfer rate using the results of Fujii (45). Results show that the natural convection coefficient is a function of plate temperature, but values approach $4 \text{ W/m}^2\text{K}$.

In a recent work of Kind et al (46), wind tunnel and full scale experiments were performed, attempting to maintain a turbulence intensity similar to natural wind. It is suggested that the turbulence intensity of wind has a significant effect on h_w . The atmospheric boundary layer was modelled for the wind tunnel portion of the research.

It was concluded that heat transfer coefficient was independent of wind direction except for winds from the sides of the collector array. The wind tunnel results are a strong function of Reynolds number. The results also showed the occurrence of separation for leeward flows. When the wind

tunnel results of Kind et al (46) are extrapolated to full scale results a tentative conclusion is that Jürges' results are high.

None of the relations presented for wind induced heat transfer coefficient are conclusive and it was decided for this study, that for the theoretical evaluation of wind effects on solar collectors, values of h_w would be presented rather than wind velocity. This would ensure that the results would be applicable to future studies of the relationship between h_w and free stream wind velocity. The value of $h_w = 5 \text{ W/m}^2\text{°C}$ was chosen to represent the natural convection case ranging to values of $40 \text{ W/m}^2\text{°C}$ for high V .

One conclusion of the above described studies, is that wind direction does not seem particularly important as the heat transfer rate remains constant in the separation regions formed by leeward flow direction.

The relationship between h_w and free stream velocity is not well established particularly when the flow is influenced by obstructions. This was the case for the experimental portion of this study as the test collector was mounted on top of a building.

4.2.3.3 Convective Heat Transfer Coefficient, $h_{c,p-c}$

Natural or free convective heat transfer in a solar collector occurs between the absorber plate and the cover plate. The rate of heat transfer depends upon many factors, including plate spacing, tilt angle of the collector, air temperature and plate length.

Correlations for predicting convective heat transfer between inclined parallel plates have been presented, (48, 49, 50, 51). Buchberg et al (48)

reviewed the literature on natural convection in 1974. The work of Hollands et al (50, 51, 52, 53) is generally considered the most representative for predicting convective heat transfer coefficients in solar collectors. An excellent discussion of convective heat transfer between inclined air layers, heated from below, is presented in reference (53), and is summarized below.

When a fluid is stationary, (i.e., not undergoing convection), it transfers heat by conduction just as a solid and the heat transfer rate for a parallel, stationary, air layer, q_{st} , between the absorber plate and cover of a solar collector is;

$$q_{st} = \frac{A k_a (T_p - T_c)}{L_{p-c}} \quad (53)$$

where: k_a is the thermal conductivity of the air,

T_p, T_c are the temperatures of the absorber plate and cover plate,

L_{p-c} is the thickness of the fluid layer, referring to figure (12).

FIGURE 12
INCLINED AIR LAYER
BOUNDED BY ABSORBER
PLATE AND COVER GLASS

FIGURE 13
BASE FLOW OCCURRING IN
INCLINED AIR LAYERS HEATED
FROM BELOW

The heat transfer coefficient for the stationary air layer, h_{st} is given:

$$h_{st} = \frac{A q_{p, st}}{T_p - T_c} = \frac{A k_{p, a}}{L_{p-c}} \quad (54)$$

When a temperature difference is applied across the air layer a temperature variation is initially established by conduction, this then results in a density variation in the fluid. The resultant buoyancy force causes an imbalance between the gravity and hydrostatic pressure forces on the fluid resulting in a flow of the fluid. Under this convective flow thermal energy is transported by bulk movement of the fluid as well as conduction. Free convective heat transfer increases the heat flow relative to the stationary case. The Nusselt number, Nu , represents the ratio of the heat transfer across the fluid layer in the convecting case relative to that in the purely

stationary, conducting case.

$$Nu = \frac{h_{c,p-c} L_{p-c}}{k_a} = \frac{h_{c,p-c}}{h_{st}} = \frac{q_{conv,p-c}}{q_{st}} \quad (55)$$

The free convective motion and heat transfer are a function of a number of variables. These include the slope and temperature of the inclined surfaces, the length of the enclosure, L_p , the distance between the plate and cover, L_{p-c} , and the fluid properties which vary with temperature. It can be shown, that for a fixed geometry and orientation, the total effect on free convective heat transfer as represented by Nu can be characterized by the Rayleigh number, Ra , and the Prandtl number Pr .

$$Ra = C p \rho^2 g \beta (T_p - T_c) X_c / (\mu k_a)$$

where g is the local acceleration of gravity, m/s^2 ,

β is the volumetric thermal expansion coefficient of the fluid, K^{-1} ,

X_c is a characteristic dimension, L_{p-c} for the solar collector case, m

$$Pr = C_p \mu / k_a$$

Values for Ra for air are given (53);

$$Ra = 2.737 \left(1 + \frac{200}{T_{alm}}\right)^2 \left(\frac{100}{T_{alm}}\right)^4 (T_p - T_c) (100 L_{p-c})^3 p_{atm}^2 \quad (56)$$

where T_{alm} is the mean temperature of the fluid layer in K, L_{p-c} is in meters and the atmospheric pressure, P_{atm} , is in atmospheres.

For horizontal air layers where the thickness is much less than either lateral dimension, if the Raleigh number is less than a critical value of 1708, the fluid remains stationary due to viscous damping overcoming buoyancy effects. Thus heat transfer is by conduction only. At slightly higher Ra, instability causes a cellular motion to form in the fluid. The value of Nu increased rapidly with Ra from this point.

For horizontal surfaces with aspect ratio, (i.e., length of the plate divided by thickness of the air layer), greater than 10, Nu is only a function of Ra. For inclined surfaces, (slope = s , $s > 0^\circ$), the value of Nu becomes increasingly dependent on aspect ratio with s , but for $s < 70^\circ$ and aspect ratio greater than 25 the dependence on aspect ratio is small. For $s > 0$ and if Ra is less than a critical value of $1708/\cos s$, "base" flow exists. Base flow is shown in figure (13) where a single cell is formed with fluid rising along the hot surface and falling along the cold one. In this case heat transfer is normal to the fluid flow and is subsequently by conduction only, i.e., $Nu = 1$. For $Ra > 1708/\cos s$ convective cells set in and Nu increases.

The relationship of Hollands (50, 52, 53) is most widely used to relate Nu as a function of s , for $s = 0^\circ$ to 75° , and aspect ratios greater than 25. Hollands recommends eqn. 57 for $s = 0^\circ$ to 75° , but indicates that errors of 10% may occur for values of s between 60° and 75° .

$$Nu = 1 + 1.44 \left[1 - \frac{1708}{Ra \cos s} \right]^+ \cdot \left[1 - \frac{(\sin 1.8 s)^{1.6} \cdot 1708}{Ra \cos s} \right] + \left[\left(\frac{Ra \cos s}{5830} \right)^{1/3} - 1 \right]^+ \quad (57)$$

where the meaning of the "+" exponent is that only positive values of the terms in the square brackets are to be used (i.e., use zero if the term is negative). Plots of Nu vs Ra for values of s from 0° to 75° are shown in figure (14) from reference (40). The effects of aspect ratio and geometry for varying values of s have been shown by Hollands (51). His results show that for solar collector applications Nu is dependent on the air layer thickness, L_{p-c} , and that heat transfer may be increased or decreased by small variations in cover to absorber spacing, L_{p-c} .

FIGURE 14
NUSSLETT NUMBER AS A FUNCTION OF RAYLEIGH
NUMBER FOR FREE CONVECTION HEAT TRANSFER
BETWEEN PARALLEL FLAT PLATES AT VARIOUS SLOPES
(REF. 40)

Consider the case for the Chamberlain collector at 45° tilt, plate temperature $T_p = 330$ K, cover temperature $T_c = 300$. $L_{p-c} = 0.019$ m and $\frac{L_p}{L_{p-c}} = \frac{2.09}{0.019} = 110.0$. Thus aspect ratio = 110, i.e., greater than 25 so

eqn. (57) holds. The value of Ra is;

$$Ra = 2737 \cdot \left(1 + \frac{200}{315}\right)^2 \cdot \left(\frac{100}{315}\right)^4 \cdot (330-300) \cdot (100 \cdot 0.019)^3 \cdot 1.0^3$$

$$= 15,290 = 1.53 \times 10^4$$

$$\text{where } T_{alm} = \frac{T_p + T_c}{2} = \frac{330 + 300}{2} = 315K$$

$$\text{and } P_{atm} = 1.0 \text{ atmosphere}$$

From eqn (57)

$$Nu = 1 + 1.44 \left[1 - \frac{1708}{1.53 \times 10^4 \cdot \cos 45^\circ}\right]^+ \cdot \left(1 - \frac{(\sin(1.8 \cdot 45))^{1.6} \cdot 1708}{1.53 \times 10^4 \cos 45^\circ}\right)$$

$$+ \left[\left(\frac{1.53 \times 10^4 \cdot \cos 45^\circ}{5830}\right)^{1/3} - 1\right]^+$$

$$= 1 + 1.44 \cdot [0.842]^+ \cdot 0.845 + [0.229]^+$$

Note: all the terms are positive so all will be used in the calculation

$$Nu = 2.25$$

The value of the convective heat transfer coefficient, $h_{c,p-c}$ is given by

eqn. (55)

$$h_{c,p-c} = \frac{k_a Nu}{L_{p-c}} \quad (24)$$

The value of the thermal conductivity for air is derived by the relationship (53);

$$k_a = 0.002528 \cdot \frac{T_{alm}^{1.5}}{(T_{alm} + 200)} \quad (58)$$

For this example, $T_{alm} = 315K$

$$\begin{aligned} k_a &= 0.002528 \cdot \frac{315^{1.5}}{(315+200)} \\ &= 2.74 \times 10^{-2} \text{ W/m K} \end{aligned}$$

The value for $h_{c,p-c}$ is;

$$\begin{aligned} h_{c,p-c} &= \frac{2.7 \times 10^{-2} (2.25)}{0.019} \\ &= 3.25 \text{ W/m}^2\text{°C} \end{aligned}$$

It should be noted that this value is for convective heat transfer and does not include the radiative heat transfer between the absorber plate and cover. The total heat transfer coefficient for the plate to absorber is given by eqn. (26)

$$U_{p-c} = h_{c,p-c} + h_{r,p-c} \quad (26)$$

where, $h_{r,p-c}$ is given by eqn. (22). For the case of the Chamberlain collector with plate emittance equal to $\epsilon_p = 0.12$ and cover emittance, ϵ_c , equal to 0.88. The value of $h_{r,p-c}$ for the previous example is,

$$\begin{aligned} h_{r,p-c} &= 5.67 \times 10^{-8} \frac{(330^2 + 300^2)(330+300)}{(1/0.12) + (1/0.88) - 1} \\ &= 0.839 \text{ W/m}^2\text{°C} \end{aligned}$$

$$\text{and } U_{p-c} = 3.25 + 0.839 = 4.09 \text{ W/m}^2\text{°C}$$

It is interesting to note that radiative exchange accounts for only 22% of the heat transfer in this case. Radiative exchange is a function of the

difference of the 4th power of absolute temperatures between the cover and absorber, and the emittance of the plate and cover. The Chamberlain collector has a "selective absorber surface". That is its optical properties are wavelength, λ , dependent. It is designed to have a high absorptance, α_p , over the short wavelength regions characteristic of solar radiation and to have a low emittance, ϵ_p , for the longer wavelength associated with low temperature thermal radiation. The low ϵ_p of the Chamberlain collector limits radiation heat transfer. If a non-selective absorber plate coating such as black paint was used ($\epsilon_p = 0.95$) the value of $h_{r,p-c}$ would be:

$$h_{r,p-c} = 5.98 \text{ W/m}^2\text{°C}$$

and

$$U_{p-c} = 5.98 + 3.25 = 9.23 \text{ W/m}^2\text{°C}$$

For the non-selective absorber plate, (i.e., $\epsilon_p = 0.95$) the heat transfer coefficient is increased 125% and now radiative heat transfer represents 65% of the heat transfer.

4.3 Transmission of Glazing and Effective Transmission-Absorption Product

$$(\tau\alpha)_e$$

The relationships for the transmission and absorption of glazing materials have been presented (1, 30, 52, 54).

FIGURE 15
TRANSMISSION OF SOLAR RADIATION IN
COVER GLASS

4.3.1 Transmission of Glazings

For surfaces that are transparent to incident radiation to any degree, the sum of absorptance, α , reflectance, ρ , and transmittance, τ , must be unity; that is the incident radiation is absorbed, reflected and transmitted, figure 15. All three properties, α , ρ and τ are functions of the wavelength and angle of incidence of the incoming radiation as well as the refractive index, n , and the extinction coefficient, K , of the material. The values of n and K are also functions of wavelength, but for the narrow

spectrum of solar radiation they may be treated as being independent of wavelength (40). The expressions for the absorptivity, reflectivity and transmissivity for a glazing cover are presented below.

The refraction angle of incoming radiation is given by Snell's Law:

$$\begin{aligned} \sin \theta &= n \sin \theta_2 \\ \text{or} \quad \theta_2 &= \arcsin \frac{(\sin \theta)}{n} \end{aligned} \quad (59)$$

where n = index of refraction for the cover material

θ = angle of incidence of incoming solar radiation

θ_2 = refraction angle of solar radiation

For an air-glass interface the reflectivity is given by Fresnel's formulae. The reflectance has two components corresponding to the two components of polarization resolved parallel and perpendicular to the plane of incidence. Thus we have:

$$\rho_{\parallel} = \frac{\tan^2(\theta - \theta_2)}{\tan^2(\theta + \theta_2)} \quad (60)$$

$$\rho_{\perp} = \frac{\sin^2(\theta - \theta_2)}{\sin^2(\theta + \theta_2)} \quad (61)$$

The fraction of radiation that is absorbed in a single pass through the cover of thickness L_c is given by Bouger's law, i.e.;

$$\alpha_c = 1 - e^{-KL} \quad (62)$$

where L is the optical path length given by;

$$L = L_c / \cos \theta_2 \quad (63)$$

so,

$$\alpha_c = 1 - \exp \left[\frac{-KL}{\cos \theta_2} \right] \quad (64)$$

The transmission of the glazing due to absorption of the glazing only is then given by;

$$\tau_a = e^{\left(\frac{-KL_c}{\cos \theta_2} \right)} \quad (65)$$

The total values of reflectance for each component of the radiation can be attained by the solution to Stoke's equations for the infinite series of reflections in the cover plate (55). These result in;

$$\rho_{11,c} = \rho_{11} \cdot \left(1 + \frac{\tau_a^2 (1-\rho_{11})^2}{1 - \rho_{11}^2 \tau_a^2} \right) \quad (66)$$

similarly,

$$\rho_{1,c} = \rho_1 \cdot \left(1 + \frac{\tau_a^2 (1-\rho_1)^2}{1 - \rho_1^2 \tau_a^2} \right) \quad (67)$$

The values for transmittance are;

$$\tau_{11,c} = \tau_a \cdot \left(\frac{(1 - \rho_{11})^2}{1 - \rho_{11}^2 \tau_a^2} \right) \quad (68)$$

$$\tau_{1,c} = \tau_a \cdot \left(\frac{(1 - \rho_1)^2}{1 - \rho_1^2 \tau_a^2} \right) \quad (69)$$

The average values of transmittance and reflectance are then given by;

$$\rho_c = [\rho_{11,c} + \rho_{1,c}]/2 \quad (70)$$

$$\tau_c = [\tau_{11,c} + \tau_{1,c}]/2 \quad (71)$$

These relations apply to the single cover case, but relationship for multiple covers are presented in references (19, 30, 40) for covers of the

same material and thickness. Edwards (57) has presented relationships for multiple glazings of different materials and thickness.

FIGURE 16
TRANSMISSION OF GLASS VS BEAM
RADIATION INCIDENT ANGLE

The values of transmittance shown in figure (16) are for beam radiation. Values of transmittance for the cover of the Chamberlain collector at various angles of incidence of beam radiation are shown in figure (16) as calculated by the above relationships utilizing the subroutine OPTCAL described in section 4.6.

The transmittance of diffuse solar radiation, τ_d is usually evaluated by;

$$\tau_d = \int_0^{90^\circ} (\tau_c(\theta) \cdot \sin 2\theta) d\theta \quad (72)$$

assuming a uniform distribution of diffuse radiation across the sky. In the past it has been assumed that diffuse radiation reflected from the ground and different portions of the sky is the same, i.e., independent of tilt angle of the collector, resulting in a value of τ_d equal to the value of τ at 60° incidence angle when eqn. 72 is solved. Recently Brandemuehl and Beckman (56) have showed that diffuse radiation reflected from the ground should be treated differently from that coming from the sky. Figure (17) summarizes the work, where an effective incidence angle, θ_e is given for diffuse radiation from the ground and the sky as a function of collector slope, S .

FIGURE 17
EFFECTIVE INCIDENCE ANGLE OF ISOTROPIC
DIFFUSE SOLAR RADIATION FROM BRANDEMUEHL
AND BECKMAN (1980)

These results are applicable to glazing system of one and two covers with index of refraction, n , between 1.34 and 1.526 and extinction lengths, KL_c less than 0.0524. Relationships for the results are (56),

For ground source diffuse, the effective incidence angle is

$$\theta_{e,dg} = 90 - 0.5788(S) + 0.002693 (s)^2 \quad (73)$$

for sky source diffuse, the effective incidence angle is

$$\theta_{e,ds} = 59.68 - 0.1388(S) + 0.001497(s)^2 \quad (74)$$

If we define;

$\tau_{d,s}$ = the transmission of the glazing at an angle equal to the effective beam radiation incident angle, $\theta_{e,ds}$,

$\tau_{d,g}$ = the transmission of the glazing at an angle equal to the effective beam radiative incidence angle, $\theta_{e,dg}$,

ρ_g = the reflectance of the ground adjacent to the solar collector for solar radiation,

SSF = shape factor from cover surface at slope s to the sky;

$$SSF = \frac{1 + \cos S}{2}$$

GSF = shape factor from cover surface at slope S to the ground:

$$GSF = \frac{1 - \cos S}{2}$$

the effective transmittance of the collector to diffuse radiation, $\tau_{e,d}$ is

then;

$$\tau_{e,d} = \frac{\tau_{d,s}(SSF) + \rho_g (\tau_{d,g}) GSF}{SSF + \rho_g (GSF)} \quad (75)$$

4.3.2 Effective Transmittance-Absorptance Product

Of the radiation passing through the cover and striking the absorber plate of a solar collector, some is reflected back to the cover system. All this reflected radiation is not lost because some is reflected back to the absorber plate from the underside of the cover. In order to evaluate the resultant energy gain to the collector the transmittance-absorptance product, $(\tau\alpha)$ must be evaluated. This is given as (1);

$$(\tau\alpha) = \frac{\tau \cdot \alpha_p}{1 - (1 - \alpha_p) \rho_d} \quad (76)$$

where ρ_d is the diffuse reflectance, and can be estimated by using the beam reflectance of the cover at an incidence angle of 60° . If part of the incoming solar radiation is diffuse then this value should be calculated for the diffuse radiation from the ground and sky, where $\tau_{e,d}$ is the effective transmittance of the cover to diffuse sky and ground source solar radiation, as well as for beam solar radiation giving;

$$(\tau\alpha)_d = \frac{\tau_{e,d} \cdot \alpha_p}{1 - (1 - \alpha_p) \rho_d} \quad (77)$$

$$\text{and} \quad (\tau\alpha)_b = \frac{\tau_c \cdot \alpha_p}{1 - (1 - \alpha_p) \rho_d} \quad (78)$$

The derivation of U_L presented in section 4.2.3 assumed that the cover did not absorb solar radiation. In order to maintain the simplicity of that analysis and account for the reduced losses due to absorption of solar radiation by the glass an effective transmission-absorptance product $(\tau\alpha)_e$ is used. All of the solar radiation absorbed by the cover is not lost

as it tends to increase the cover temperature and hence, reduces losses from the collector. This reduction in collector losses can be considered as an increase in the value of the transmission-absorptance product. This is given for the diffuse and beam components, (40);

$$(\tau\alpha)_{e,d} = (\tau\alpha)_d + \alpha_{c,d} \left(1 - \frac{U_T}{p-c}\right) \quad (79)$$

$$(\tau\alpha)_{e,b} = (\tau\alpha)_b + \alpha_{c,b} \left(1 - \frac{U_T}{p-c}\right) \quad (80)$$

where $\alpha_c = (1 - \tau_d)$ for the diffuse and beam components is determined respectively.

The effective transmittance-absorptance product for both beam and diffuse is given by;

$$(\tau\alpha)_e = [(1-f_d)(\tau\alpha)_{e,b} + f_d (\tau\alpha)_{e,d}] \quad (81)$$

where: f_d is the fraction of the total incident solar radiation on the collector that is diffuse from both the sky and ground.

4.4 Heat Removal from Flat-Plate Solar Collectors

The analysis of heat loss coefficient described in section 4.2 relates the heat loss from the solar collector to the mean absorber plate temperature, T_{pm} .

As fluid entering the collector at a temperature, T_{fi} , moves along the absorber plate, heat is transferred to it, (assuming $\eta > 0$). This results in an increase in the fluid temperature and a subsequent increase in the absorber plate temperature. This increased absorber plate temperature

results in increased heat loss q_L . The distribution of T_f , and subsequent T_{pm} through the collector is usually non-linear. The temperature profile along the length of the absorber plate is a function of the fin efficiency of the collector plate, F , the fluid mass flow rate, m , the fluid to tube wall heat transfer coefficient, h_f , and the local fluid temperature. The resultant value of T_{pm} is therefore difficult to determine. As described in section 2., Bliss (3) developed factors, F' , collector efficiency factor, and F_R , collector heat removal factor, so that collector heat loss could be related to inlet fluid temperature, T_{fi} . In designing solar heating systems, T_{fi} is relatively easy to predict. To maintain the integrity and simplicity of the Hottel, Whiller, Bliss collector model (described in section 2), the concepts of F_R and F' will be utilized for this analysis of collector performance.

4.4.1 Collector Heat Removal Factor F_R

The heat removal factor, F_R is the ratio of actual useful energy gain of the collector to the useful gain if the whole collector absorber plate surface was at the fluid inlet temperature, t_{fi} .

$$F_R = \frac{m C_p (T_{fo} - T_{fi})}{A_c [(\tau\alpha)_e I - U_L (T_{fi} - T_a)]}$$

The concept of F_R is analogous to conventional heat exchanger effectiveness,

and has been shown (1, 3, 22, 40) to be given by;

$$F_R = \frac{G C_p}{U_L} [1 - e^{-F' U_L / (G C_p)}] \quad (83)$$

where G is the specific mass flow rate.

$$G = \frac{\dot{m}}{A_c} \quad (84)$$

The useful energy collected in the solar collector is then;

$$q_u = A_c F_R [(\tau\alpha)_e I - U_L (T_{fi} - T_a)] \quad (85)$$

The factor F_R reduces the calculated useful energy gain from what it would have been had the whole collector been at T_{fi} , to what it actually is for a fluid that increases in temperature along its flow path. As mass flow rate through the collector increases, the temperature rise through the collector decreases, causing lower heat losses since T_{pm} is reduced. As the flow rate becomes very large, the temperature rise from inlet to outlet approaches zero, but the absorber plate surface temperature must still be higher than the fluid temperature for heat transfer. This temperature is accounted for by the collector efficiency factor F' . It may be seen that F_R is dependent on the mass flow rate, heat loss coefficient U_L , F' , and C_p .

4.4.2 Collector Efficiency Factor, F'

The collector efficiency factor, F' , is a measure of the ability of the collector to transfer heat to the fluid. Equations for F' for various collector designs have been derived by numerous authors (2, 3, 22, 40). F' represents the ratio of the actual useful energy gain to the useful energy gain that would result if the collector absorbing surface were at the mean fluid temperature T_{pm} . It may also be thought of as the ratio of the heat transfer resistance from the absorber plate to the ambient air, $1/U_L$, to the heat transfer resistance from the fluid to the ambient air, $1/U_o$. Thus;

$$F' = \frac{\frac{1}{U_L}}{\frac{1}{U_o}} \quad (86)$$

or

$$F' = \frac{U_o}{U_L} \quad (87)$$

the value of U_o can be shown (40) to be given by;

$$U_o = \left[W \left\{ \frac{1}{U_L [D + (W-D)F]} + \frac{1}{C_b} + \frac{1}{\pi D_1 h_f} \right\} \right]^{-1} \quad (88)$$

where W, D - are physical dimensions of the absorber plate referring to figure (18).

F - is the fin efficiency of the absorber plate

C_b - is the bond conductance from the absorber plate to tube.

D_1 - is the inside tube diameter

h_f - is the fluid to tube heat transfer coefficient.

For most modern solar collectors, the tube to plate bond conductance is high so the term $1/C_b$ approaches zero.

FIGURE 18

TUBE IN SHEET ABSORBER PLATE,
DIMENSIONS FOR EQN. 88

4.4.3 Fin Efficiency, F

Most conventional flat plate solar collectors are constructed with a "tube in/on sheet" absorber plate similar to that shown in figure (18). Values of fin efficiency, F , are derived for many absorber plate designs (1, 3, 22) but generally values as high as practically possible are chosen. For the case shown in figure (18), the fin efficiency is given by;

$$F = \frac{\tanh [X(W-D)/2]}{X(W-D)/2} \quad (89)$$

where

$$X = \{U_L / (k_p \delta)\}^{1/2} \quad (90)$$

The value of F is dependent on the heat loss coefficient of the solar collector, U_L , the thermal conductivity of the absorber plate k_p , and δ , the fin thickness.

4.4.4 Heat Transfer Coefficient, h_f

The rate of heat transfer from the tube wall to the fluid is characterized by the heat transfer coefficient, h_f , which is dependent on Reynolds number and Prandtl number for the flow situation. Reynolds number is given by;

$$Re = \frac{V D_h}{\nu} \quad (91)$$

where V is the velocity of the fluid flowing in the tubes, ν is the Kinematic viscosity of the fluid and D_h is the hydraulic diameter of the tubes, i.e.,

$$D_h = \frac{4 \text{ (flow area)}}{\text{Wetted perimeter}} \quad (92)$$

Prandtl number is given by;

$$Pr = \frac{\mu C_p}{k_f} \quad (93)$$

where; μ is the dynamic or absolute viscosity of the fluid, and

k_f is the fluid thermal conductivity.

The above properties should be evaluated at the mean fluid temperature.

The flow in solar collectors is usually low and subsequently is laminar. The tube length is usually short so flow is rarely fully developed.

Many relationships for determining h_f exist (1, 19, 22, 34) but may be separated into two categories; constant heat flux and constant wall temperature cases. Duffie and Beckman (40) have suggested that the heat transfer in solar collectors lies between the two cases. High loss collectors approach the constant wall temperature case and low heat loss collectors approach the constant heat flux condition. Generally, the heat transfer coefficients are very similar under either condition, with constant wall temperature values being slightly lower.

For laminar flow in the entrance region of pipes, (constant wall temperature case), the value of Nu_f , (77) is given;

$$Nu_f = 3.65 + \frac{0.0668 (RePrD_h/L)}{1 + 0.04 (RePrD_h/L)^{2/3}} \quad (94)$$

where;

$$h_f = Nu_f \left(\frac{k_f}{D_h} \right) \quad (95)$$

4.4.5 Calculation of F_R for Chamberlain Collector

The absorber plate of the Chamberlain solar collector is not of conventional tube and sheet construction but consists of two steel sheets, "stitch" welded together then expanded to form flow passages. The header is integral to the absorber plate. This design results in a highly efficient absorber plate as much of the absorber surface is in direct contact with the heat transfer fluid, (except for the regions of the welds). For the purpose of analysis the absorber plate is represented by 19 parallel flow passages with the weld region forming a small fin between the flow passage. The dimensions of the Chamberlain absorber plate is shown in figure (19).

FIGURE 19
CHAMERLAIN FLOW PASSAGE CONFIGURATION

The value of U_o can be estimated from,

$$U_o = \left[W \left\{ \frac{1}{U_L [W \cdot F]} + \frac{1}{W_{per} \cdot h_f} \right\} \right]^{-1} \quad (96)$$

The value of F is determined as 0.99, from manufacturers' data. The value of C_b , bond conductance does not apply as the tubes are integral in the plate. W_{per} is the wetted perimeter of the tubes.

4.5 Calculation of Theoretical Thermal Efficiency

The rate of energy extraction by the solar collector heat transfer fluid is given by eqn (4);

$$Q_u = A_c \cdot F_R [I(\tau\alpha)_e - U_L(T_{fi} - T_a)] \quad (4)$$

The collection efficiency is the ratio of Q_u to the energy incident on the collector reference surface area, A_c .

thus;

$$\eta = \frac{Q_u}{A_c \cdot I} \quad (97)$$

To calculate the theoretical efficiency of a solar collector by the relationships presented in the previous sections, an iterative procedure must be followed. While the value of absorbed solar radiation, $I(\tau\alpha)_e$, can be calculated directly; the value of $(\tau\alpha)_e$ is a function of U_L and U_{pm} which is in turn a function of the mean absorber plate temperature, T_{pm} . The mean absorber plate temperature is a function of the mean fluid temperature T_{fm} , which is a function of F_R . The heat removal factor F_R is a function of U_L .

To calculate theoretical thermal efficiency, first an estimate of the mean plate temperature is made. This value should be close to the inlet fluid temperature. From this estimated values of T_{pm} , U_L and $(\tau\alpha)_e$ are determined. The value of T_{fm} is estimated, (i.e., $T_{fm} = T_{fi}$) and the value of F' and F_R are determined using the previously calculated value of U_L . With these approximate values for F_R and U_L and the value of $I(\tau\alpha)_e$, the value of Q_u is determined by eqn. (4).

The actual value of T_{fm} is determined by integrating the fluid temperature along the flow direction of the absorber plate, i.e.,

$$T_{fm} = \frac{1}{L} \int_0^L T_f(x), dx$$

This integral has been shown to be represented by (1);

$$T_{fm} = T_{fi} + \frac{Q_u/A_c}{U_L F_R} \left[1 - \frac{F_R}{F'} \right] \quad (98)$$

Using this relationship, new values of T_{fm} may be determined and F_R calculated in an iterative manner until convergence is obtained on T_{fm} .

The value of T_{pm} may be estimated by (1);

$$T_{pm} = Q_u \cdot R_{p-f} + T_{fm}$$

where R_{p-f} is the heat transfer resistance between the plate and the fluid.

$$R_{p-f} = \frac{1}{h_f \cdot W_{per} \cdot L \cdot n_t}$$

thus $T_{pm} = T_{fm} + Q_u / (h_f \cdot W_{per} \cdot L \cdot n_t)$ (99)

Using this new value for T_{pm} , the value of U_L and $(\tau\alpha)_e$ may be recalculated and process repeated until the value of T_{pm} converges.

During the calculations of U_L the value of U_{top} must be determined by an iterative calculation for each value of T_{pm} . To do this the cover temperature is estimated (i.e., $T_c = (T_{pm} + T_a)/2$), and U_{top} determined. A new value of T_c is then determined and the value of U_{top} recalculated until T_c converges.

The calculation of collection efficiency is then made by eqn (97) utilizing the calculated values of $(\tau\alpha)_e$, F_R , and U_L for the specific meteorological conditions.

These calculations are lengthy by hand so the calculations are performed by the computer subprogram COLSM, described in Section 5.

5. COMPUTER SIMULATION OF THERMAL PERFORMANCE

As described in section 4.5, the calculation of solar collector theoretical efficiency is an iterative process involving T_{pm} , T_{fm} and T_c . For this reason the calculations are most efficiently made on a computer.

The calculations presented in section 4.5, are performed by the subprogram COLSM. This program and the associated main and subprograms were written in Fortran IV, (59). The routines were written and data analyzed on a Digital Equipment Corp., D.E.C. LSI-11-03 digital computer. The computer system operated in single job monitor under RT-11SJ version 3B, (60). The system was configured with a RX01 dual floppy disk drive, (of 1 mega-byte capacity each), two RL01 rigid disk drives, (of 5 mega-bite capacity each), a Decwriter III hard copy terminal and a VT52 CRT. Data could also be transmitted to a Hewlett Packard 2647A intelligent graphics terminal and serial HP 7225A hard copy plotter, for plotting on the HP terminal screen or hard copy plotter. The HP terminal utilized graphics software issued from the D.E.C. Computer, (61).

While the computer system described above represented a very powerful tool for the analysis of data, the COLSM program will run, (minus the graphics capability), on a conventional LSI-11-03 D.E.C. computer, utilizing only the RX01 floppy disk drives and hard copy terminal.

The simulation program was designed and structured utilizing a number of subroutines to perform each step of the calculations. When these subroutines are compiled, they are "linked" together into a single routine of object code for execution by the computer.

The subroutine structure of the simulation allows for checking of

each portion of the simulation independently with changes made only to the particular subroutine being updated. This is a distinct advantage in large simulation programs as is the case for this program which solves in excess of 50 equations iteratively, for each operational point. An advantage of splitting the calculations into logical sections is that these subroutines can be run independently to evaluate the effect of operational and meteorological factors on each of the major components of the heat transfer analysis.

The analysis of component heat transfer and optical performance was done and is described in section 6.0. This analysis provides an insight into the heat transfer factors that affect the overall performance of the solar collector.

The input data, including collector characteristics, operational and meteorological factors are transferred to the simulation subprogram COLSM by the main driver routine RCOLSM. The main program RCOLSM also sets up the data output on the hard copy terminal and produces plots of thermal performance on the H.P. graphics terminal or H.P. hard copy plotter. The program runs interactively, allowing the user to rapidly see the effects of changing operational and meteorological factors.

The subprogram COLSM simulates the performance of the Chamberlain solar collector. It sets up the calculation of optical and heat transfer factors by the appropriate subroutines and allows the iterative calculations between subroutines. The subroutine COLSM makes calls to the subroutines TOPL, STAEFF and APFR which in turn make calls to the subroutines, TSKY, CHTPC, OPTCAL and FLPROP as required. In all there are three levels of

subroutine calls from the main program RCOLSM.

The subroutine TOPL calculates the values of top heat loss coefficient, U_{top} . TOPL makes calls to the subroutine TSKY to calculate the effective sky temperature for the calculation of $h_{r,-s}$ and $h_{r,c-s}$. TOPL also calls the subroutine CHTPC to calculate the convective heat transfer coefficient between the absorber plate and cover glass, $h_{c,p-c}$.

The subroutine STAEFF when called by the COLSM routine calculates the values of the effective transmittance x absorptance product, $(\tau\alpha)_e$, for specific conditions of collector slope, incident angle and U_L . The subroutine makes calls to the subroutine OPTCAL as required to calculate the optical performance of the cover.

The subroutine APFR when called by the COLSM routine calculates the value of the heat removal factor, F_R for specific operational and meteorological factors. The APFR subroutine calls the subroutine FLPROP to calculate the heat transfer properties of the heat transfer fluid as required in the calculation of F_R by the FLPROP routine. Each of the routines was checked thoroughly and calculated values for standard conditions compared to available literature to confirm their accuracy.

A short description and flow chart for each of the computer routines is provided in the following sections. Listings of the routines are provided in Appendix B. Results produced by RCOLSM and the subroutine TOPL, STAEFF and APFR are presented in Section 6.

5.1 COLSM Subroutine

The subroutine COLSM simulates the performance of the Chamberlain

flat-plate solar collector. The program will simulate other single glazed flat plate collectors if slight modifications are made. The value of U_o as calculated by the subprogram APFR is specific to the Chamberlain solar collector. This can be easily changed for more standard absorber plate configurations. Similarly, simulation of multiple cover collectors can be accomplished by modification to the subroutine TOPL and STAEFF to account for multiple glazings.

A flow chart of the COLSM routine is shown in figure (20) and listing provided in Appendix B. The subprogram COLSM specifies the collector optical and heat transfer characteristics, and the dimensions of the collector. It calls the appropriate subroutine to perform the heat transfer analysis and controls iterations between T_{pm} and T_{fm} . COLSM solves eqn's; 16, 14, 98, 99, 97 and calls subroutine TOPL, STAEFF and APFR.

5.2 Subroutine TOPL

The subroutine TOPL calculates the values of top loss heat transfer coefficient, U_{top} , for a single cover flat plate solar collector inclined at an angle to the horizontal for specific values of h_w , T_{pm} , T_{sky} and T_a .

A flow chart of the routine is shown in figure (21), and a listing in Appendix B. The routine calls subroutines, T_{sky} to calculate an effective sky temperature for the calculation of $h_{r,p-c}$ and $h_{r,p-s}$. The TOPL routine calls the subroutine CHTPC to calculate $h_{c,p-c}$ for specific collector slope, T_{pm} and T_c .

The routine TOPL solves eqn's; 31, 33, 23, 26, 34, 35.

FIGURE 20

FLOW CHART FOR PROGRAM TO SIMULATE THE THERMAL PERFORMANCE OF A FLAT-PLATE SOLAR COLLECTOR AT SPECIFIC OPERATIONAL AND ATMOSPHERIC CONDITIONS

5.3 Subroutine TSKY

The subroutine TSKY calculates the effective sky temperature for a surface inclined at an angle "tilt" for specific values of T_a and ground emissivity. It assumes the ground is at a temperature $T_g = T_a$. The shape factors between the surface and the sky and ground are calculated for a specific inclination angle and accounted for in the calculation. The routine solves eqn's; 41, 44, 43, 42. The flow chart for TSKY is presented in figure (22).

5.4 Subroutine CHTPC

The subroutine CHTPC calculates the convective heat transfer coefficient between the collector absorber plate and cover, $h_{c,p-c}$. The calculation is for specific inclination angle, T_{pm} and T_c . A flow chart of CHTPC is shown in figure (23). The routine solves eqn's; 56, 58, 57, 24.

5.5 Subroutine STAEFF

The subroutine STAEFF calculates the effective transmittance x absorptance product for specific cover/absorber combinations, at inclination angle, incident angle, fraction diffuse radiation, ground reflectance, and U_L . The routine solves eqn's; 73, 74, 75, 77, 78, 79, 80, 81, and makes 4 calls to the subroutine OPTCAL. Figure (24), shows the flow chart for STAEFF.

5.6 Subroutine OPTCAL

The subroutine OPTCAL calculates the optical performance, transmittance, reflectance and absorptance of a single cover using eqn's; 59, 60, 61, 65, 66, 67, 70, 68, 69, 71. The values are calculated for specific beam incident angle, n and KL_c . Figure (25), shows the flow chart for the OPTCAL routine.

5.7 Subroutine APFR

The routine APFR calculates the heat removal factor, F_R for a specific heat transfer, fluid, mass flow rate, and U_L . The routine solves eqn's; 91, 94, 95, 96, 87, 83 and calls the subroutine FLPROP to calculate the heat transfer properties of the heat transfer fluid. Figure (26) shows the flow chart for APFR.

5.8 Subroutine FLPROP

The subroutine FLPROP (44) calculates the heat transfer properties for water or a 50/50% mixture by volume of water and ethylene glycol for a specific T_{fm} . A flow chart for FLPROP is given in figure (27).

5.9 Program RCOLSM

The main program RCOLSM specifies the meteorological conditions for a specific run of COLSM. It runs interactively with the user and calls subroutine PLTSTP to plot the results of a simulation run on either hard copy or graphics screen. This routine is specific to the H.P. equipment, but may only need minor modifications for other computer systems. Figure (28) shows the flow chart for RCOLSM.

FIGURE 21

FLOW CHART FOR SUBROUTINE TO CALCULATE TOP HEAT LOSS COEFFICIENTS

FIGURE 22

FLOW CHART FOR SUBROUTINE TO CALCULATE THE
EFFECTIVE SKY TEMPERATURE

FIGURE 23
FLOW CHART FOR SUBROUTINE TO CALCULATE
CONVECTIVE HEAT TRANSFER COEFFICIENT FROM
THE ABSORBER PLATE TO COVER

FIGURE 24

FLOW CHART FOR SUBROUTINE TO CALCULATE THE EFFECTIVE, TRANSMITTANCE, ABSORPTANCE PRODUCT, $(\tau \alpha)_0$.

2

FIGURE 25

FLOW CHART FOR SUBROUTINE TO CALCULATE THE
TRANSMITTANCE AND ABSORPTION FOR A
SINGLE COVER GLASS

FIGURE 26
SUBROUTINE TO CALCULATE THE HEAT REMOVAL FACTOR FOR A
FLAT-PLATE SOLAR COLLECTOR

FIGURE 27

FLOW CHART FOR PROGRAM TO CALCULATE HEAT
TRANSFER FLUID PROPERTIES

FIGURE 28
FLOW CHART FOR MAIN PROGRAM TO INPUT ATMOSPHERIC CONDITIONS
AND PLOT SOLAR COLLECTOR PERFORMANCE CURVES

6. THEORETICAL RESULTS - EFFECTS OF METEOROLOGICAL AND OPERATIONAL FACTORS

The basic Hottel, Whillier, Bliss model for solar collector thermal performance has been presented in section 2.2. A basic assumption of this representation and associated test procedures (4), is that thermal and optical properties are constant. It is assumed that losses are dependent only on the temperature difference between the absorber plate and ambient air, surrounding the collector.

The problems experienced in ensuring these assumptions are met while performing thermal performance tests has been discussed in section 3. It has become apparent that obtaining repeatable, accurate test results is difficult.

Section 4 presents a detailed heat transfer analysis of the optical and heat transfer characteristics of a flat plate solar collector. Emphasis was placed on the meteorological factors that influence heat transfer and optical parameters.

The results here utilize the analysis described in section 4 and the computer programs described in Section 5. The effects of meteorological factors on the heat transfer of the Chamberlain, single glazed, flat plate, solar collector, (described in Appendix A) are presented. Results are presented for: the effects on U_L through top loss heat transfer coefficient, U_{top} , the optical system through $(\tau\alpha)_e$, and the absorber plate heat transfer through F_R . These three components make up eqn (6) for the thermal performance of a flat plate solar collector.

$$\eta = \frac{Q_u}{I A_c} = F_R (\tau\alpha)_e - F_R U_L \left(\frac{T_{fi} - T_a}{I} \right) \quad (6)$$

6.1 Meteorological Effects on Heat Transfer in Flat-Plate Solar Collectors

Solution of the heat transfer analysis presented in section 4 allows the determination of the effects of meteorological factors on the heat transfer and optical processes in a flat plate collector.

6.1.1 Top Loss Heat Transfer Coefficient

The heat transfer through the cover of a flat plate solar collector is the major source of thermal losses. The analysis presented in section 4.2.3 demonstrates that the loss mechanism is a combination of conduction, convection and radiative heat loss from the absorber plate of the solar collector to the surrounding atmosphere. Eqn. (15) presents this heat loss

as;

$$Q_L = A_c U_L (T_{pm} - T_a)$$

where;

$$U_L = U_e + U_T + U_b$$

The heat loss through the back and sides of most conventional solar collectors (and the Chamberlain collector) are small and relatively insensitive to changing meteorological conditions other than $(T_{pm} - T_a)$. U_T (and U_{top}), are dependent on a variety of operational and meteorological factors.

A common assumption is that U_{top} is constant. Figure (29) shows values of U_{top} vs $(T_{pm} - T_a)$. The value of $(T_{pm} - T_a)$ is increased by effectively increasing the plate temperature, similar to the procedure described in the standard experimental test procedure (4).

It is obvious that U_{top} is in fact not constant but increases with

FIGURE 29
VARIATION IN TOP LOSS
COEFFICIENT, U_{top} , FOR FIXED
METEOROLOGICAL CONDITIONS

FIGURE 30
EFFECT OF COLLECTOR SLOPE
ON U_{top} , FOR $h_w = 5 \text{ W/m}^2 \text{ }^\circ\text{C}$
AND $T_s = T_a$

FIGURE 31
EFFECT OF h_w ON U_{top} , FOR
EFFECTIVE SKY TEMPERATURE = T_a

FIGURE 32
EFFECT OF COLLECTOR SLOPE
AND h_w ON U_{top}

increasing $(T_{pm} - T_a)$. From the analysis presented in section 4 it may be determined that as T_{pm} is increased, the value of $h_{c,p-c}$ increases. The values of $h_{r,p-c}$ and $h_{r,p-s}$ increase as the difference of the fourth power of absolute temperature rather than just linearly with $(T_{pm} - T_a)$. As T_{pm} increases so does the value of T_{alm} , the mean air layer temperature. This results in a variation in the air properties and influences the convective heat transfer through the Ra number. The value of Ra increases as $(T_{pm} - T_a)$ increases and consequently Nu and $h_{c,p-c}$ increase.

The Chamberlain solar collector has a "selective" absorber plate with emissivity to thermal radiation, ϵ_p , equal to 0.12. Many collectors are constructed with "non-selective" absorbers with much higher, ϵ_p , (i.e., $\epsilon_p = 0.95$). In this case the variation in U_{top} becomes even more significant.

As the difference between T_{pm} and T_a becomes very small, heat transfer by convection is reduced until at a value below the critical Ra number, where heat loss is by conduction through the air layer, (i.e., $Nu = 1$). The value of U_L remains relatively constant for smaller values of $(T_{pm} - T_a)$ after this point. This condition rarely occurs for inclined solar collectors. The critical Ra number is given by $Ra/\cos S$, where "S" is the inclination angle of the collector. Thus at high inclination angles a larger value of $(T_{pm} - T_a)$ is required to initiate convection heat transfer.

The effect of collector slope on heat transfer is indicated in figure (30) where U_{top} is presented for inclinations of 0, 45 and 75°, to the horizontal. It may be seen that the value of convective heat transfer

decreases with increasing collector slope. The region indicated as "A" on the 75° tilt curve represents the region below the critical Ra number where heat loss is largely by conduction and convection has not started. These results correspond with the values of Nu vs tilt angle presented in figure (14) of section 4.

While the effect of tilt angle is largely an operational factor, during outdoor thermal performance testing, in order to meet the requirement for normal incidence to beam radiation from season to season, the solar collector must typically be adjusted in tilt through a range from 20 to 75°, (for the Ottawa latitude $\approx 45^\circ \text{N Lat.}$) If the collector being tested is mounted on an altitude/azimuth tracking test frame then the tilt may be steeper to obtain normal incidence in the morning or afternoon periods.

While tilt angle has a significant effect on U_{top} , the value of $U_{\text{p-c}}$ represents only one component of the heat loss from the absorber. Another major resistance to heat transfer is provided by the film coefficient on the outer surface of the glass cover. This is referred to as, wind heat transfer coefficient, h_w , although the heat transfer may be that of natural convection if wind velocity is very low. The discussion in section 4 places a lower limit of $h_w = 4$ or $5 \text{ W/m}^2\text{C}$ for this situation. Increasing wind velocity increases the value of h_w . The effect of increasing h_w on U_{top} is presented in figure (31) for values of h_w ranging from 5 to $30 \text{ W/m}^2\text{C}$.

As h_w increases, it offers less resistance to heat loss from the absorber plate and consequently, U_{top} increases. As h_w becomes larger its net effect on U_{top} reduces. The value of h_w no longer represents the limiting factor in the heat loss and the thermal losses become more

FIGURE 33
VARIATION IN U_{top} WITH T_a
FOR $h_w = 5$ AND $20 \text{ W/m}^2 \text{ } ^\circ\text{C}$

FIGURE 34
 U_{top} VS MEAN ABSORBER PLATE
TEMPERATURE FOR VARYING
AMBIENT AIR TEMPERATURES

FIGURE 35
VARIATION IN U_{top} WITH CHANGING
EFFECTIVE SKY TEMPERATURE FOR
 $h_w = 5 \text{ W/m}^2 \text{ } ^\circ\text{C}$

FIGURE 36
VARIATION IN U_{top} WITH
CHANGING EFFECTIVE SKY
TEMPERATURE FOR $h_w = 20 \text{ W/m}^2 \text{ } ^\circ\text{C}$

dependent on other resistances in the resistance network (see figure (8) section 4.). Specifically the value of $h_{c,p-c}$ limits the heat transfer. Figure (32) shows the effects of varying tilt and subsequently $h_{c,p-c}$ for two ranges of h_w . At high values of h_w it may be seen that varying collector tilt more greatly affects the value of U_{top} .

It may be concluded that while h_w and $h_{c,p-c}$ both significantly affect U_{top} , the effect of tilt will be more significant at higher wind velocities.

As stated, the top heat loss rate is also dependent on radiation heat losses between the absorber plate and cover glass and the cover glass and sky. This is illustrated by figure (33) where values of U_{top} are compared at different values of ambient air temperature, T_a . In this situation to achieve the same value of $(T_{pm} - T_a)$ at higher T_a , the value of T_{pm} must be increased equivalently. As this is done the radiation losses, which are dependent on the absolute absorber plate temperature, increase until a point where the heat transfer becomes dominated by h_w , figure (34). As h_w is increased the temperature profile through the collector increases and T_c reduces, consequently reducing the effect of $h_{c,p-c}$ which reduces the overall effect of the increased radiative heat transfer. The situation illustrated above occurs when experimental measurements are taken in the summer when the inlet fluid temperature must be increased to achieve the same $(T_{pm} - T_a)$ as winter.

To this point it has been assumed that the cover glass radiates energy to the atmosphere at a temperature equivalent to T_a . As described in section 4.2.3.1 this is not the case for clear days. The effective sky

FIGURE 37
VARIATION OF U_{top} WITH T_a
AND CALCULATED EFFECTIVE
SKY TEMPERATURES

FIGURE 38
VARIATION OF U_{top} WITH T_a
FOR CALCULATED T_s AND
 $h_w = 20 \text{ W/m}^2 \text{ °C}$

FIGURE 39
EFFECT OF h_w ON U_{top} ACCOUNTING
FOR REDUCED SKY TEMPERATURE

FIGURE 40
EFFECT OF COLLECTOR SLOPE ON
 U_{top} FOR CALCULATED VALUES OF T_s

temperature may be significantly lower than T_a . The value of T_s depends on the air temperature T_a , and the portion of the sky that the collector sees. At high collector tilt angles, the collector "sees" the ground. The ground is assumed to be at a temperature equal to T_a , with an emissivity to thermal radiation of 0.9. The effect of reduced T_s relative to T_a for values of $h_w = 5$ and $20 \text{ W/m}^2\text{C}$ is shown in figures 34 and 35. At low values of h_w and $(T_{pm} - T_a)$, lower T_s significantly increases the value of U_{top} . This effect is reduced at higher values of h_w and $(T_{pm} - T_a)$, where $h_{r,p-s}$ is less significant in the overall heat transfer. The effects of depressed T_s may be somewhat moderated by the fact that during experimental testing of collectors in the higher latitudes, the collector sees a large portion of the ground adjacent to it.

The program COLSM utilizes the analysis of section 4.2.3.1 to determine an effective sky temperature, T_s for the portions of the sky and ground seen by the collector. Figures (37) through (40) present the results including the effect of T_s as determined by eqn (42) section 4. At low values of h_w corresponding to low wind speed it may be seen that radiative losses to the sky are significant. This significance is reduced at higher $(T_{pm} - T_a)$, and higher wind velocities.

6.1.2 Effective Transmittance X Absorptance Product

The value of the effective, transmittance x absorptance product is dependent on meteorological factors. The analysis leading to the calculation of $(\tau\alpha)_e$ is presented in section 4.3. The optical performance

of the glazing system of the solar collector is dependent on the incident angle of the beam solar radiation, θ , and the fraction of the total incident solar radiation that is diffuse. The diffuse radiation is made up of two components; diffuse radiation reflected from the ground and diffuse radiation emanating from reflection and scattering in the sky.

The model of diffuse radiation presented in section 4.3 and implemented by the computer program OPTCAL, (described in section 5.), assumes that the effective incident angle of the two diffuse components is separate and a function of the collector slope. The slope alters the effective diffuse incident angle, θ_e , but also determines the percentage of longwave radiation received from the sky and ground. The effect of effective incident angle for ground radiation is limited by the fact that when high values of $\theta_{e,dg}$ occur, the collector is at low slope and consequently does not "see" much of the ground. The net effect is that the maximum effect of high ground reflectance occurs at slopes near 45° and is limited to a few percentage points.

The model for diffuse radiation presented in section 4 assumes that diffuse radiation is isotropic, that is, uniform across the sky. While this is a good approximation, its validity reduces for very clear skies where the diffuse radiation may be sun centered, i.e., located near the sun disk. The overall error in this assumption for testing purposes should be small because during clear skies the fraction of diffuse radiation is low, i.e., $f_d < 20\%$. Figure 41 presents the value of $(\tau\alpha)_e$ calculated for ranges of f_d and varying beam radiation, incident angle $0 \leq \theta \leq 90^\circ$. An incident angle of zero corresponds to a direction normal to the cover surface, while 90° ,

corresponds to a direction parallel to the cover surface.

FIGURE 41
EFFECT OF INCIDENT ANGLE ON THE VALUE
OF $(\tau\alpha)_e$ FOR RANGES OF DIFFUSE RADIATION

The net effect of increasing diffuse fraction is to lower the value of $(\tau\alpha)_e$ at incident angles less than approximately 60° . At $\theta > 60^\circ$, it may be seen that increased diffuse radiation increases the value of $(\tau\alpha)_e$. This occurs from the assumption of isotropic diffuse radiation. It is apparent that increased incident angles greater than 60° reduce the value of $(\tau\alpha)_e$. At incident angles less than 30° the effects of θ are negligible. This result does not apply strictly to other collector types, as collectors with multiple glazings show more severe effects of θ (1).

6.1.3 Heat Removal Factor, F_R

The derivation of the heat removal factor for conventional flat-plate solar collectors is presented in section 4.4. F_R is a function of the fin efficiency of the absorber plate, collector efficiency factor, F' , and U_L the heat loss coefficient. F_R is strongly dependent on the collector flow rate. Low flow rates result in an increased T_{pm} , and lower h_f and F' .

As flow rate increases the rate of increase of F_R decreases and the value of F_R approaches the value of F' . This situation corresponds to having the fluid in the absorber plate all at a temperature equivalent to the inlet fluid temperature. The value of F_R is plotted as a function of heat transfer fluid flow rate in figure 42, for the Chamberlain solar collector. The range of flow rate obtained during the experimental portion of this project is shown for reference.

Figure 43 presents plots of F_R vs flow rate for three ranges of U_L . It is apparent that the sensitivity to flow rate increases as U_L increases. Generalizing, it may be concluded that solar collectors with high heat loss, (i.e., non-selective absorber, single glazed) are more sensitive to flow rate changes than collectors with low U_L , (i.e., double glazed or vacuum tube type). It may be concluded from the results of section 6.1.1 that as U_{top} (and U_L) change for varying meteorological conditions so will the value of F_R . It can be concluded from figure 43, that to achieve a high value of F_R in a low loss collector may require a less efficient absorber plate than a high loss collector.

FIGURE 42
EFFECT OF COLLECTOR FLOW RATE ON F_R

FIGURE 43
EFFECT OF U_L ON HEAT REMOVAL FACTOR

6.2 Effect of Meteorological and Operational Factors on Collector Thermal Performance

The thermal performance of the Chamberlain collector as simulated by the COLSM program and presented in a plot of Collection Efficiency vs $(T_{fi} - T_a)/I$, is shown in figure 44. The conditions for test represent those typical for thermal performance tests, e.g.,

$$T_a = 10^\circ\text{C}$$

$$\theta = 0$$

$$I = 1000 \text{ W/m}^2$$

$$S = 45^\circ$$

$$h_w = 15 \text{ W/m}^2\text{C}$$

$$f_d = 0.2$$

$$\rho_g = 0.2$$

The value of effective sky temperature, T_g , was calculated by the methods in section 4.2.3.1 for an inclined surface.

The results of figure 44 show that the result is slightly second order and curves downward with increasing $(T_{fi} - T_a)/I$.

6.2.1 Effects of Collector Slope

The results of section 6.1 show that collector slope significantly affects, U_{top} . This result is consistent with the results shown in figure 45, where theoretical efficiency is shown as a function of collector slope. The results indicate that the large variations occur between tilts ranging from 60 to 75°. Slope effects are heat loss dependent at large values of $(T_{fi} - T_a)/I$ where convective heat loss is dependent on collector slope. The effects are much less evident at low $(T_{fi} - T_a)/I$ where convection heat loss is lower. At $T_{fi} = T_a$ heat loss does occur because T_{pm} is higher than

FIGURE 44
COMPUTER SIMULATED THERMAL PERFORMANCE
OF CHAMBERLAIN FLAT-PLATE SOLAR COLLECTOR

FIGURE 45
EFFECT OF COLLECTOR TILT ON THERMAL
PERFORMANCE

t_a and subsequently the change in U_L that occurs affects the value of F_R as described in Section 6.1.3. This effect is small. A less significant factor is that T_g increases as the collector slope increases and views the ground (-11°C @ 0° and -3.4°C @ 75°). This factor counteracts the effects of convective heat transfer slightly.

6.2.2 Effects of Wind Heat Transfer Coefficient

Figure 46 illustrates the effects of varying h_w . Values of h_w equal to $5 \text{ W/m}^2\text{C}$ represent zero wind (i.e., natural convection), while values greater than $20 \text{ W/m}^2\text{C}$ are representative of high wind speed conditions. The effects of h_w are greater than those of collector slope. The greatest sensitivity to variations in wind speed occur at low values of h_w with ever decreasing effect at high h_w . The effects of h_w are greatest at high heat loss conditions.

6.2.3 Effects of Beam Incident Angle

Figure 47 presents results for increasing θ . The results are considerable and predictable from the results of section 6.1.2 with minimal effects at $\theta < 45^\circ$ and great effects from $\theta = 45^\circ$ to 75° . During solar collector testing incident angles are limited to 30° so effects are minimized. The results presented are for a value of $I = 1000 \text{ W/m}^2$ and $f_d = 0.2$.

6.2.4 Effects of Insolation Level

The effects of varying insolation level, I , are demonstrated in

FIGURE 46
EFFECT OF h_w ON COLLECTOR THERMAL
PERFORMANCE

FIGURE 47,
EFFECT OF BEAM INCIDENT ANGLE

figure 48, for values from I equal to 250 to 1250 W/m^2 . The incident angle is assumed equal to zero in all cases but the ratio of diffuse radiation is assumed to be $f_d = 0.2$. This situation does not occur in normal outdoor operation as at levels of 250 W/m^2 and $\theta = 0$ the sky will be overcast and $f_d = 1$. This more realistic condition is shown in figure 49. The plot shown in figure 47 for varying beam incident angle is also not representative of actual outdoor operation. Beam radiation intensity actually drops as the cosine of θ . Therefore for $I = 1200 \text{ W/m}^2$ and $f_d = .1$ at $\theta = 0$, the corresponding values at varying θ are;

θ	I	f_d
0	1200	10%
60°	720	33%
75°	490	50%

Figure 50 presents these results which correspond to actual outdoor operation. Luckily the experimental derivation of "incident angle modifier" as described in reference 4 should account for these effects. The results shown in figure 47 and 48 could only be achieved in a solar simulator.

6.2.5 Effect of Ambient Air Temperature

Figure 51 presents the effects of varying T_a . This situation occurs during outdoor testing or operation of real flat-plate solar collectors. The results are consistent with those observed in figure 33, section 6.1. As shown in figure 33 this effect will be slightly greater at lower values of h_w .

FIGURE 48
EFFECT OF SOLAR RADIATION LEVEL

FIGURE 49
EFFECT OF LEVEL OF INSOLATION AND f_d

6.2.6 Effect of Ground Reflectance

Figure 52 shows the effect of ground reflectance on collector performance. As discussed in section 6.1 and within the scope of the model, the effect is small even when shown for the case of $f_d = 50\%$ and $h_w = 5 \text{ W/m}^2\text{C}$ as in figure 52. A greater effect of ρ_g would be due to the increased insulation level on the collector surface and the increase in f_d that results from high ground reflectance.

6.2.7 Effects of Diffuse Radiation Fraction

The effects of diffuse radiation have already been implied in the figures 49 and 50 and are shown in figure 53 independent of θ and I . The results correspond to what would be predicted in figure 41, section 6.1. The condition shown rarely occurs outdoors, (i.e., $I = 1000 \text{ W/m}^2$ and $f_d = 100\%$), but may be representative of very hazy bright winter days.

6.2.8 Effect of Operational Conditions

The effect of heat transfer fluid flow rate is presented in figure 54 for flow rates ranging from 1/10 to 10X the value recommended in (4) for collector testing. The results indicate that flowrate significantly affects solar collector thermal performance.

Figure 55 shows the effect of using water as the heat transfer fluid rather than the 50/50% mixture of ethylene glycol as used in the previous examples. The effect is of the order of a few percentage points and can be accounted to the lower specific heat of the mixture of glycol that results

FIGURE 50

EFFECTS OF VARYING INCIDENT ANGLE,
I AND f_d

FIGURE 51

EFFECT OF AMBIENT AIR TEMPERATURE

FIGURE 52

EFFECT OF GROUND REFLECTANCE

FIGURE 53

EFFECT OF INCREASING DIFFUSE SOLAR RADIATION

FIGURE 54
EFFECT OF HEAT TRANSFER FLOW RATE

FIGURE 55
EFFECT OF ETHYLENE GLYCOL OR WATER AS
THE HEAT TRANSFER FLUID

in a higher T_{pm} for the same insolation input.

6.2.9 Operational and Meteorological Extremes

Figure 56 presents the effects on thermal performance of extreme meteorological and operational factors. At $(T_{fi} - T_a)/I = 0$ the net effect is a difference of 6.2 efficiency points. This range increases to a value of 30.1 efficiency points at $(T_{fi} - T_a)/I = 0.1$. The range of flow rates represents values from $\frac{1}{2}$ to 2X the recommended test flow rate (4) although the result would be very close for a range from $\frac{1}{2}$ to 1X the recommended value. These conditions are achievable during thermal performance testing or operation during summer and winter.

6.2.10 Meteorological Extremes

If the effects of flow rate are removed from figure 56 the result is shown as in figure 57.

FIGURE 56

MAXIMUM EXTREMES IN EFFICIENCY FEASIBLE UNDER EXTREME METEOROLOGICAL AND OPERATIONAL FACTORS DURING TESTING

FIGURE 57

MAXIMUM EXTREMES DUE TO METEOROLOGICAL CONDITIONS ONLY

7. EXPERIMENTAL MEASUREMENTS

7.1 Experimental Objectives

The experimental objectives of this project are summarized below:

1. To construct a test apparatus to determine the thermal performance of a typical flat plate solar collector and to monitor the meteorological factors experienced during testing.
2. To measure the thermal performance of a well characterized flat plate solar collector to determine the effect of meteorological factors on the thermal performance test results, independent of test sample variability and systematic errors.

Data should be recorded for a variety of atmospheric conditions which are representative of the range of values that occur during testing performed in the Canadian climate. Only data that meets the requirements of the ASHRAE 93-77 test method (4), should be considered.

7.2 Solar Collector Test Facility

An outdoor test facility was constructed on the roof of building M-24 of the Montreal Road laboratories of the National Research Council to determine the thermal performance of liquid based solar collectors. Test samples are mounted on a fixed frame facing due south and provision was made to adjust the tilt angle of the test collector. Tilt angles ranging from 20° to 70° relative to horizontal may be achieved to maintain the surface of the solar collectors perpendicular to the beam solar radiation at solar noon, (i.e., normal incidence). Heat transfer fluid is pumped to the solar

collectors under test from an equipment room located directly below the test racks.

A schematic drawing of the fluid test loop is shown in figure (58). It consists of a temperature control liquid flow loop and a calorimetry, (i.e., heat-flow measurement), circulation loop. The equipment and instrumentation were designed and selected to conform to the general requirements of the ASHRAE testing procedure (4). The facility has two calorimetry flow loops draining into two interconnected storage tanks of approximately 150 litres total fluid capacity. The heat transfer fluid used for the tests was a 50/50% mixture of ethylene-glycol and water to enable testing to be performed year round.

The temperature control loop circulates liquid from the storage tanks through an electric heater and chilled water heat exchanger to maintain a fixed temperature in the storage tanks. Three power levels are possible on the heater to obtain the best control. Fine control of the tank temperature is accomplished by controlling the flow of chilled water through the heat exchanger. This is accomplished by the use of an electronic proportional control that senses the storage temperature and actuates a proportional pneumatic valve on the chilled water supply to the heat exchanger.

A centrifical pump circulates the heat transfer fluid from the storage tanks through the temperature control loop at approximately 45 litres per minute. The net result is that the storage tanks effectively act as a well mixed constant temperature bath from which the calorimetry test loops draw. The system as constructed maintains a fixed bath temperature within $\pm 0.05^{\circ}\text{C/hr}$ and typically $\pm 0.1^{\circ}\text{C}$ per day. Inlet temperature

FIGURE 58 SCHEMATIC OF DBR/NRC SOLAR CALORIMETER APPARATUS

fluctuations are usually less than 0.02°C over a test interval, (approximately 15 min.).

The heat transfer fluid is drawn (at constant temperature) from the storage tanks by a centrifugal pump and pumped to the roof for circulation through the test solar collector in a closed loop. Flowrate control through the test loop is performed by throttling the flow with a needle valve installed downstream of the pump. This worked well and maintained flow rate effectively constant at a set point for a fixed fluid temperature, but the flow rate did change when the fluid temperature was changed. This was due to the changes in fluid properties with temperature and the subsequent change in the pressure drop through the test loop. This was not a major problem but required that the flow be readjusted after a change in fluid temperature. This condition was later reduced by replacing the needle valve with a Cuno cartridge filter and Kates Automatic Flow Rate Controller. The flow rate through the calorimetry test loops could be set at values ranging from approximately 0.5 to 5 litres per minute.

The flow rate through the test collector was not measured by the method described in the ASHRAE test method (4), which consists of measuring the volume flow rate and multiplying this by the density of the fluid to determine the mass flow rate.

The thermal performance of solar collectors is determined over a wide range of heat transfer fluid temperatures (4), and the thermal properties of the heat transfer fluid are a function of the fluid temperature. Often the physical properties of heat transfer fluids (i.e., glycol-water mixtures) are poorly characterized and the accurate determination of collector thermal

performance requires the measurement of the product of flow rate and absolute specific heat, C_p . Volumetric flow meters must be calibrated to account for variations in fluid density and viscosity with temperature. Considering the duration and accuracy requirements of this experiment, and evidence of the drifting of volumetric flowmeter calibrations with time (Jenkins)(66); a direct comparison reference heat source (RHS) was utilized in the calorimetry loop to determine the rate of energy collection of the test specimen. This technique has been referred to as the "Calorimetric Ratio Technique" as described by Reed and Allen (67). The reference heater is installed in series with the collector under test. Since the mass flow rate through the reference heater and the test solar collector are the same the following holds

$$\frac{Q_u}{C_{pc} \cdot \Delta T_c} = \frac{Q_{RHS}}{C_{pRHS} \Delta T_{RHS}}$$

where

Q_{RHS} is the rate of energy input to the fluid as it passes through the RHS.

C_{pc} , C_{pRHS} are the specific heat of the heat transfer fluid in the solar collector and reference heater, respectively

ΔT_c , ΔT_{RHS} are the temperature rise in the heat transfer fluid as it passes through the solar collector and reference heater respectively.

Equation (4-1) gives:

(100)

$$Q_u = Q_{RHS} \cdot \frac{C_{pc} \Delta T_c}{C_{pRHS} \Delta T_{RHS}}$$

For most test conditions, the difference in fluid temperature between the reference heat source and the test collector can be kept small and the difference in fluid specific heat at the heater and collector can be neglected. The value of Q_{RHS} is equivalent to the electrical energy input to the reference heat source minus any heat losses from the reference heater to the surroundings. Thus:

$$Q_{RHS} = P_{RHS} - Q_{L_{RHS}} \quad (101)$$

The value of P_{RHS} was monitored continuously by an Scientific Columbus Power Transducer. The value of $Q_{L_{RHS}}$ was determined by measuring the heat loss across the heater at a series of mean fluid temperatures above and below the ambient air temperature surrounding the RHS, and applying this correction to the value of P_{RHS} .

The piping of the calorimeter test apparatus was insulated to increase the temperature stability and reduce the temperature difference between the reference heater and solar collector under test. A 750 watt chartridge type heater was used for the reference heater. The calorimetric ratio technique like conventional solar collector testing is subject to errors due to non-steady conditions. The reference heat source has thermal mass and, as such, can store and release energy during transient operating conditions resulting in an over-or under-prediction of collector performance. For this reason, flow rate, inlet temperature, heater power, and subsequent temperature rise must be held constant during each test period. Reference (4) outlines requirements for steady state testing of

solar collectors and these conditions are consistent with those required by the reference heat source. The power input to the reference heater was maintained at a constant value by a Stabiline automatic voltage regulator and the inlet temperature to the RHS was held at fixed temperature (as described) by the temperature control loop.

7.2.1 Temperature Measurements

Temperature difference measurements across the reference heater and the solar collector were made utilizing 8 junction, type T (copper-constantan) differential thermopiles. These devices were reliable and provided a high degree of resolution for the reasonably small temperature rise experienced during testing. Absolute fluid temperature measurements were also made at the inlet and outlet of both the RHS and the test collector using Type "T" thermocouples imbedded in each end of the thermopile devices. Both the thermocouple and the thermopiles were calibrated by the Standards Division of the Physics Division of NRC against primary standards. The accuracy of each of the calorimetric measurements and the subsequent experimental uncertainty is presented in Appendix H. The temperature sensors were inserted in insulated temperature wells inserted parallel to the fluid flow. Fluid mixers were utilized prior to each temperature measurement. Temperature measurements were made as close as possible to the inlet and outlet of both the test collector and the reference heater and the connections insulated to minimize any heat losses.

7.2.2 Meteorological Measurements

The specifications of the meteorological instrumentation are given in Appendix E. Absolute ambient air temperature was measured with a calibrated type "T" thermocouple situated in a well ventilated "Stephenson" screen enclosure installed approximately 1.3 m above the roof of the laboratory adjacent to the test frame. The shelter was installed with the door facing south to ensure that illumination by direct solar radiation could not occur. The wind velocity was measured by a three cup wind anemometer delivering a dc voltage proportional to wind velocity. A directional vane was also incorporated in the device to indicate prevailing wind direction. The wind velocity measurement was located at a point mid height to the collector under test and located approximately 3 meters due south of the test frame. The device was located so as to not shade the collector under test but it was found that the wind speed and direction were highly variable in this location. This is attributed to the fact that the test rack was located approximately 4 meters from the corner of the roof of the building. The wind flow in this location was influenced by the geometry of the building. It was discovered that more consistent data could be achieved by using the wind speed and direction data recorded from a wind anemometer and directional vane located on the top of a 7.6 meter tower located on an adjacent laboratory building located approximately 100 meters to the south of the test facility. It is considered that, while the wind velocity indicated by device was not indicative of the instantaneous local condition at the test collector, it did represent the mean free stream^b condition of the prevailing wind. Mean values obtained from this equipment are representative of the average meteorological conditions.

This wind velocity and direction measurement is made by the Atmospheric Environment Service for the NRC location and mean hourly values of wind speed and direction were combined with the measured collector performance data from AES meteorological summaries for the test periods.

A "black-and-white" Epply model 8-48 pyranometer was used to measure total solar radiation incident on the collector surface. The device was mounted facing due south, tilted at the same tilt as the collector under test. The pyranometer was positioned to minimize reflected and re-radiated energy from the solar collector on to the pyranometer.

Total horizontal solar radiation was measured by a model 10 Epply pyranometer, mounted in a horizontal plane and located where it would not be shaded by surrounding structures. The diffuse component of the incident solar radiation was measured continuously by use of a Shade Ring Diffusograph (68), in conjunction with a model 50 Epply pyranometer mounted horizontally.

7.2.3 Data Acquisition

The specifications of the data acquisition system are given in Appendix E. The data from the calorimetric measurements (i.e., temperature differences, absolute temperatures, heater power) as well as meteorological data (ambient air temperature, total solar radiation incident on collector, total horizontal radiation, diffuse radiation) were monitored continuously during the test intervals and recorded by a central data acquisition system. As discussed previously, wind speed and direction were merged with the data during data processing. The data system was located adjacent to the

calorimeter equipment located directly below the test frames. The data system used was a 60 channel KAYE Model 8000 data logger. Input signals included analog voltage from the pyranometers, thermopile, thermocouple and power transducers. Of these the analog signals from the thermocouples are converted by the data logger to temperature values utilizing an automatic electronic reference junction. The resultant analog voltage and temperature readings were recorded on 9 track 800 BPI, magnetic tape using a Cipher tape unit.

Instantaneous readings of all the calorimetry and meteorological factors were recorded at an interval of once per minute during the testing. The interval is considered to be fast enough, due to the steady state nature of the experiment, and the fact that, as required by the ASHRAE test method, testing was only carried out on clear sunny days. The value of total solar radiation was recorded continuously on a strip chart recorder to ensure that the requirement for steady solar radiation conditions was met during testing

The data recorded on magnetic tape was then processed and combined as discussed in Section 7.4, utilizing the computer system described in section 5.

7.3 Experimental Procedure

Tests were conducted during a period spanning mid-summer through the winter to spring. Data was recorded every day regardless of the weather conditions. On clear sunny days that met the basic requirements of (4), the following steps were taken in preparation of the tests.

1. The collector was checked to ensure that it was not damaged or had ingressed moisture into its housing.
2. The meteorological measurement equipment was checked and any precipitation, snow, or ice was removed. Radiometers were wiped with water or alcohol as the ambient temperature dictated.
3. The shadow band was checked and adjusted as required.
4. The collector inlet fluid temperature was held at the set point temperature during the day and set at a new value in the evening.

The tilt of the collector was adjusted periodically to maintain the incident angle to beam radiation within the ASHRAE requirements (4). Particular attention was paid to the accumulation of moisture in the collector casing. Moisture accumulation occurs as a result of the collector "breathing" during the day. Air drawn into the collector contains moisture which condenses on the cold glass surface during the night. This moisture drains to the bottom of the collector where it is absorbed by the fiberglass insulation in the collector. During the day this water evaporates and condenses on the colder glass surface in a continuous stream. In a very short time, if precautions are not taken the insulation becomes saturated, severely degrading the collector thermal performance.

Most solar collectors are equipped with drain holes at their lower edge to drain off water accumulation. The Chamberlain collector did not use this system but was equipped with a self re-generating desiccant system intended to limit moisture accumulation. The Canadian climate seemed too much for this system and it could not regenerate sufficiently. To

counteract moisture accumulation, the collector was purged with dry air every night. The operation was controlled by a timer and shut off early in the morning so as not to affect the tests.

This process of purging ensured that the collector heat loss characteristics remained fixed and a major source of error in the experiment was reduced.

7.4 Data Processing

At the end of a test period consisting of approximately three and a half days, the full data tape was removed from the Cipher tape unit and replaced with a blank tape. These tapes were stored for processing.

Raw data tapes from the data logger contained digital records of the collector inlet and outlet temperatures, ambient air temperature, horizontal total and diffuse solar radiation, total solar radiation on the collector slope, and the millivolt reading of the differential thermopile output, across the collector inlet and outlet. The input power to the reference heater was also recorded on the tape.

This raw data stored in one minute records also contained a record with the date, (year and julian day of the year, i.e., 1-365), and time for reference.

Data processing was accomplished in the following manner;

1. Data tapes were processed on a monthly basis by computer.
2. Each three day tape was scanned to select only data from between the hours of 10:00 AM to 2:00 PM EST., to ensure that incident angles were low.
3. The calorimeter test data was merged with average wind speed and

direction for the corresponding hour.

4. Each data set was scanned during the test period (i.e., 10:00 AM to 2:00 PM), to locate periods of steady state that met the criteria of (4). Steady state conditions were defined as a period of time equal to 5 collector time constants long, (as measured in (4)), and meeting the following requirements:
 - (i) Solar radiation in collector equal to the average over the period $\pm 20 \text{ W/m}^2$
 - (ii) Collector inlet, outlet and ambient air temperature equal to average over period $\pm 0.1^\circ\text{C}$
 - (iii) Temperature rise in the collector equal to average values over period $\pm 0.05^\circ\text{C}$
5. Only data that met the steady state criteria was selected by the computer and stored on magnetic tape.
6. Data records of "steady" data were stored on "monthly", magnetic tapes.
7. These "monthly" data tapes were then combined into a "yearly" data tape containing only data that met the steady state requirements.
8. The "yearly" data tape was transferred onto rigid disk on the computer system described in section 5.

During the data processing, raw data was converted to engineering values by applying the appropriate conversion factors. The temperature rises across the collector and reference heater were derived from the differential thermopile by utilizing the thermopile's sensitivity at the average of the inlet and outlet temperatures of each. The rate of energy collection was determined utilizing the corrected reference heater power

input, and temperature rise and the collector temperature rise as in equation (100), assuming $C_{p_{RHS}} = C_{pc}$. This assumption should typically introduce errors of less than a $\frac{1}{2}$ percent. The solar energy incident on the collector surface was determined from the pyranometer output voltage signal and the calibration factor supplied during the Atmospheric Environment Service calibration. Collection efficiency was determined by;

$$\eta = \frac{Q_u}{IA_c}$$

where the reference area for the Chamberlain collector was equal to the aperture area = 1.79 m².

Tests were conducted on the Chamberlain collector to determine its time constant as described in reference (4). The value obtained was approximately 1 $\frac{1}{2}$ minutes for one time constant in the classical sense. A steady state interval equal to 8 minutes was chosen to process the data and subsequently 8 minute average values were produced.

The resultant data was processed and analyzed as presented in section 7 by the computer system described in section 5 utilizing a software package described in reference 61.

8. EXPERIMENTAL DATA

Data was collected from June 30, 1978, (Julian day No. 181), to May 19, 1979, (Julian day No. 139). During that time, days that had clear skies and periods that met the steady state criteria between the time slot from 10:00 AM to 2:00 PM were very limited. In all 67 days contained data that was suitable for analysis, consisting of 200 data points.

8.1 Test Data

The test data obtained from the experiment is listed in Appendix F, by file number consisting of the test circuit no., collector test slope, year and Julian day. For example, 1C2278.181 corresponds to test circuit 1, Chamberlain collector, 22° tilt, day 181, 1978.

8.2 Analysis of Data

The total data set is plotted in Figure 59 for collection efficiency vs $(T_{fi} - T_a)/I$.

To determine if a wide range of meteorological conditions had been obtained during testing the data was analyzed in regard to operational and meteorological frequency. The results of this analysis are shown in Appendix G.

The following data ranges were determined;

Windspeed: 0 to 7 m/sec,

Ambient Air Temperature: -20 to 30°C

Total Solar Insolation: 750 to 1100 W/m²

Horizontal Diffuse Solar Radiation; 50 to 200 W/m²

Incident Angle, θ : 0 to 40°

Flow rate; 1.8 to 2.6 L/min.

FIGURE 59
 PLOT OF EXPERIMENTALLY DETERMINED THERMAL EFFICIENCY FOR
 THE CHAMBERLAIN SOLAR COLLECTOR

9. DISCUSSION-EFFECT OF METEOROLOGICAL FACTORS ON TEST RESULTS

9.1 Discussion of Theoretical Results

The theoretical effects of meteorological and operational factors, on the thermal performance of the Chamberlain solar collector have been presented in section 6.

While operational factors significantly affect the thermal performance of flat-plate solar collectors, it is assumed that for the purposes of testing collectors, variations in flow rate may be minimized.

If meteorological factors only are considered in the analysis, as shown in figure 57, the divergence of results is reduced. Collector slope is included in meteorological factors as its value is a consequence of obtaining "normal" incident angles during testing for different seasons of the year.

For the Chamberlain collector, it is apparent that wind speed, h_w , collector slope, ambient air temperature and fraction of diffuse solar radiation significantly affect collector thermal performance. It is interesting to note that the effects of these parameters are all to cause a reduction in the maximum thermal performance achievable in a rating test. That is to say, if an "informed" manufacturer chooses when and where he has his product tested and specifies what he will accept for meteorological factors, he may obtain the maximum values predicted in figure 57. This in fact may not represent the actual performance of the collector in an operating system. Consequently, there is no "margin of safety" designed into the system performance evaluation as in common design practice. A considerable overprediction of system performance may occur.

5

If the results of section 6, for the figure 57, are re-run, limiting the meteorological extremes allowed under the standard thermal performance testing document (4), the result is shown in figure 60.

Figure 60 indicates that at $T_{fi} = T_a$ the deviation in η is reduced to a couple of percentage points. At $(T_{fi} - T_a)/I$ equal to 0.1 the variation is ~ 23 percentage points. The output of a collector at the low range would be half that of the maximum at this operation point. It should be noted that in actual use collectors operate at this end of the performance curve for much of the time.

Reviewing the results of section 6.2 it may be determined that the range of values achievable is largely due to the lack of restriction on collector slope and h_w . Wind speed allowed in (4) ranges from 0 to 4.5 m/sec, corresponding to $h_w = 5$ to approximately 30. The ranges of collector slope shown in figure 57 are from 20° to 70° , which is typical for summer and winter extremes in Canada. If a manufacturer was to have his product tested at lower latitudes, (i.e., 30° N Lat.), representing the southern USA, collector slopes of 0° are possible and the effect would be even greater.

The range of wind velocity specified in (4) represents the range of greatest sensitivity to h_w , and therefore is subject to the maximum changes in η for a change in h_w . This not only results in scatter in the test data but also may bias the performance curve to the extremes shown in figure 57. It has been suggested (44), that for simulator collector testing, the minimum wind speed be increased to that corresponding to a value in the range 2.25 to 4.5 m/sec. This would correspond to the mean value in Canada and reduce scatter in the test result. The same recommendations can be made

FIGURE 60
EFFECT OF METEOROLOGICAL CONDITIONS
ALLOWED WITHIN TEST PROCEDURE (4)

FIGURE 61
EFFECT OF LIMITING METEOROLOGICAL
CONDITIONS DURING TESTING

for outdoor testing. Figure 61 demonstrates this fact, showing that if h_w is held to a range corresponding to 20 to 30 W/m^2C , and limiting the collector tilt to 45° , the result is to reduce the extreme range to 7.5 percentage points. This would "weight" the test result to the most common operational value of h_w . Increasing the upper limit of h_w to a value above 30 W/m^2C has little effect on the results as h_w is no longer a limiting factor in the heat transfer. Specifying a fixed collector slope of 45° will cause the requirement of (4) that $\theta < 30^\circ$ to still be met at this latitude. The slope of 45° is typical of solar installations in Canada. The increased restrictions on h_w should not significantly increase the time required for a specific test as the highest frequencies of wind speed occur near these values. Still air conditions rarely occur as described in Section 8. The fact that low wind speeds are allowed under the present standard encourages the use of specific data points with low h_w to generate a higher performance curve.

A further reduction in the requirements for f_d and θ may achieve better results than figure 61 but at the cost of increased testing time. The requirement for steady state conditions described in (4) virtually eliminates radiation levels between 200 to 900 W/m^2 because the atmospheric conditions are too unstable to produce steady state values. Increasing the minimum allowable insolation level to 900 W/m^2 should have no effect on the required testing time for outdoor tests.

This value is greater than that recommended (16) as representing an average value for Canada of $I = 650 W/m^2$. The increased I causes a small reduction in the thermal performance predicted, but the effect will be conservative from the designer's point of view. Periods when insolation

rate is very low, i.e., 250 W/m^2 , represent times when η is very low and consequently, represent a small portion of the total collected energy. This "weighting" the test to higher radiation levels does not seem unreasonable to achieve steady test conditions.

9.1.1 Significance of the Results for Other Collector Types

The results can be applied to other single-glazed flat plate collectors with selective absorber surfaces, without significant error. The Chamberlain represents a high performing collector, largely due to its good selective surface (i.e., $\epsilon_p = 0.95$, $\epsilon_p = 0.12$) and its very effective absorber plate ($F = 0.99$). The effect of the selective surface is to reduce the value of U_L by reduction of radiation losses, $h_{r,p-c}$ and $h_{r,p-s}$ and to subsequently lower the glass temperature, reducing the effect of h_w . A single glazed collector with non-selective absorber, (i.e., $\alpha_p = \epsilon_p = 0.95$), will increase the effect of all meteorological factors. As an example the COLSM simulation was run for the case of $\epsilon_p = 0.95$ and the same meteorological factors as presented in figure 60. The effect of increasing ϵ_p , is to increase the spread between the extremes due to meteorological factors, figure 62.

If the test conditions were limited as described for figure 61, the result is shown in figure 63 for the non-selective case. The maximum deviation is also decreased. If the glazing was not glass, which has a low transmittance to longwave radiation, and was for example "Teflon" plastic the effect of meteorological factor would be as shown in figure 64.

"Teflon" film has a transmittance to longwave radiation of 0.32, (62). For

FIGURE 62
EFFECT OF ϵ_p ON METEOROLOGICAL EXTREMES

FIGURE 63
EFFECT OF LIMITING METEOROLOGICAL
EXTREMES FOR NON-SELECTIVE ABSORBER

this case the collector is more dependent on effective sky temperature. The range of values is actually reduced but with an associated drop in thermal efficiency. The maximum effect of longwave transmittance to the sky is shown in figure 65, to indicate a worst case for the "Teflon" cover. The effect is significant.

The COLSM routine does not presently have the capability to simulate multiple glazed collectors but a double glazed, non-selective absorber plate, collector should respond similarly to the single glazed, selective absorber plate case as the values of U_L are similar (1). The effect of T_g should be very small and the performance curve will be uniformly reduced indicating the loss in transmittance due to the extra sheet of glass in the cover system.

Unglazed collectors similar to those used for swimming pools will be very sensitive to all the meteorological factors. Luckily, their operation is usually limited to low fluid temperatures relative to air temperature, i.e., swimming pool temperature. The dependence of F_R on U_L dictate that the fluid flow rate must be kept very high to limit T_{pm} . A study to determine the sensitivity of F_R as a function of flow rate on h_w is an area recommended for future study.

Double glazed, selective absorber surface, collectors and vacuum tube collectors (40) are characteristic of low U_L and subsequently should be less sensitive to meteorological factors than the Chamberlain collector. The reduced convection losses between the absorber and cover in a vacuum tube type collector seem to indicate that the governing heat losses will be by radiative exchange between the absorber and cover and subsequently be

FIGURE 64
EFFECT OF ϵ_p AND τ_{LW} ON METEOROLOGICAL
EXTREMES

FIGURE 65
MAXIMUM EFFECT OF T_s FOR $\epsilon_p = 0.95$ AND
 $\tau_{LW} = 0.32$

dependent on h_w and T_{pm} . At low fluid temperature, i.e., $T_f < 100^\circ\text{C}$, losses should be small but this type of collector is usually specified for higher temperature applications such as industrial process heat etc. The effect of meteorological factors may be significant in these applications. These effects require investigation.

The results presented for the Chamberlain collector are representative of the greatest portion of commercially available collectors. For this reason the results should be applicable to a broad range of applications.

9.1.2 Significance to Simulator Testing

Solar collector testing indoors using an artificial source of solar radiation has been suggested as one means of eliminating variation in test results due to meteorological conditions. Solar simulators have been described (63, 64) and while offering the capability to standardize the test condition, the relationship between simulator tests and outdoor operation must be determined. Solar simulators are characterized by all beam solar radiation, i.e., $f_d = 0$ and significant amounts of longwave radiation produced by the hotter than normal atmosphere. Simulator lamps have been known to produce 100 W/m^2 of longwave thermal energy above what would occur in the ambient environment.

It has been shown that the effects of effective sky temperature may be reduced by increasing the value of h_w so that convective heat transfer dominates the collector heat loss. Testing collectors that have covers that are transparent to longwave may present significant problems.

The effect of total beam radiation will tend to overpredict the collector performance slightly as will the increased effective sky temperature.

The incident angle modifier test as described (4), presents problems similar to those described in section 6.2.4. The result is that incident angle effects will be more severe if measured under all beam radiation as opposed to those measured with diffuse sky components. Corrections similar to those applied in 6.2.4 should be possible to adjust simulator results to outdoor conditions.

9.2 Discussion of Experimental Results

The experimental results are presented in section 8. The data is shown plotted in figure 59. A curve fit by the method of "least squares", produces the equation

$$\eta (\%) = 77.1 - 422 (T_{fi} - T_a) / I$$

with a standard error = 5.7, (71)

This represents a value for;

$$F_R (T_a)_e = 0.77$$

$$F_R UL = 4.22$$

These values fall within the values derived by the COLSM Simulation for the range of meteorological extremes, figure 57.

The experimental data shows the same trends as that of the theoretical data but the meteorological extremes are not as severe. This can

be accounted to the lack of data during the most extreme cases. This illustrates one important point that for this location the extreme conditions do not readily occur. The data is consistent with theory in that it is more scattered at operational points corresponding to high thermal loss.

The scatter that is shown, is a result of varying meteorological conditions combined with experimental error associated with performing the experiments. An analysis of experimental error associated with the experiment is presented in Appendix H. The scatter due to meteorological conditions may be determined utilizing the COLSM routine with the appropriate range of meteorological and operational factors (figure 66) experienced during the test. Experimental uncertainty alone cannot account for the scatter in the test results. Meteorological conditions experienced during the test combined with experimental uncertainty do account for the scatter in the test data. The solid lines shown in figure 66 represent the meteorological extremes and it should be noted that actual collector operation occurred between these extremes. With a large data set such as obtained during this testing, a curve fit analysis of the data should be fairly representative of the mean operational condition if the data has uniformly distributed meteorological factors. The analysis in section 8 demonstrates that all the data consisted of periods with high solar insolation levels and relatively low diffuse radiation. This is a consequence of the steady state requirement. In effect only very clear, bright days have sufficiently steady state characteristics to meet the requirements of the test procedure (4). The test result is subsequently

biased toward clear sunny days with very low diffuse radiation levels. The consequence of this is discussed in section 9.1.

While the data is fairly uniformly distributed, the standard test procedure calls for only four sets of data to be obtained, evenly distributed along the $(T_{fi}-T_a)/I$ axis. Subsequently any four data points could be chosen for the curve fit. If the data on particular days was biased then significant differences in the predicted average performance would be obtained.

The limit in the scatter of the data, as stated, is a consequence of the limited extreme meteorological conditions experienced during testing at the Ottawa site. It should not be concluded that further extremes may not be achieved, but only that they were not attained during this experimental period.

It is common practice for solar collector manufacturers to ship their products to different test labs across North America. The difference between results obtained in largely different climates may be significant.

9.3 Comparison of Theoretical and Experimental Results

Figure 66 presents the experimentally derived values of collector thermal efficiency. The range of meteorological extremes as predicted by the COSLM computer simulation as represented by the solid lines shown on the plot.

To determine the accuracy of the COLSM program to calculate the absolute value of theoretical efficiency, direct comparisons of calculated and measured η were compared for identical meteorological and operational

FIGURE 66
PLOT OF EXPERIMENTAL DATA SHOWING THEORETICAL
METEOROLOGICAL EXTREMES AND MEASUREMENT UNCERTAINTY

conditions.

It was observed that at high efficiency values where thermal losses from the collector are minimal, that the COLSM program over-predicted experimental efficiencies by approximately 4 to 5 percentage points.

This may be attributed to a number of effects. The optical and heat transfer properties used in the program are those measured on unweathered collectors. The collector used for experimental testing was well aged before the tests as it was used in other outdoor experiments. Fouling of the inner surface of the flow passages of the absorber plate is not accounted for in the COLSM program. The absorber is constructed of carbon steel and it is possible that this may have slightly influenced the absorber plate characteristics.

Variations in performance between new and weathered solar collectors (specifically the Chamberlain solar collector), have been shown (69). The deviation between the experimental and theoretical results is close to that experienced previously (69). Reference (70) concluded that a significant drop in absorber plate absorptance occurred after weathering of air collectors, but heat loss coefficient did not change appreciably.

Assuming that the optical properties on the test collector may be slightly less than those stated, values of ϵ_p , were adjusted in the COLSM program to produce consistent results. A value of $\epsilon_p = 0.90$ was chosen finally as being representative of the weathered value of ϵ_p . The effect of varying α_p on the value of $(\tau\alpha)_e$ is shown in figure 67.

To compare the experimental data with the simulated values, a value of h_w must be determined for the experimental case. This parameter was

FIGURE 67
EFFECT OF ABSORBER PLATE, ABSORPTANCE
ON $(\tau\alpha)_e$

FIGURE 68
COMPARISON OF SOLAR COLLECTOR THERMAL
EFFICIENCY AS DETERMINED BY THE COLSM
PROGRAM AND EXPERIMENTALLY

not measured directly in the experiment and the difficulties with predicting its value from wind speed data has been discussed in section 4. To resolve this problem, the various relationships for h_w , as described in section 4, were utilized to determine h_w for the experimental data. Experimentally derived values of η were then compared to simulated performance at the predicted h_w . Surprisingly, the best match of the experimental and theoretical data occurred with the relationship originally presented by Jürges, eqn. 46 section 4. The comparison of the resultant experimentally derived efficiency values are plotted against those predicted by COLSM for the same meteorological and operational conditions, figure 68. The dashed lines in figure 68 represent the average experimental uncertainty associated with the experimental measurements.

The data for $\alpha_p = 0.90$, $U_e = 0.1 \text{ W/m}^2 \text{ } ^\circ\text{C}$ and h_w as predicted by eqn. 46 fall within the experimental uncertainty.

The success of eqn. 46 in predicting the value of h_w may be due to the fact that wind speeds were relatively low for the experiments, typically less than 6 m/sec, and the fact that the location of the collectors, free standing on the roof of a building, probably resulted in a highly turbulent flow. The effects of wind direction for this situation would be minimized and this conclusion was supported by the experimental data that showed no correlation to wind direction.

9.4 Normalization of Experimental Results

Normalization of experimental data to standard experimental conditions has been suggested as one method of reducing scatter and biased

test results, (16, 71, 72). The method requires that an accurate model of the collector heat transfer is available. The complexity of the COLSM model for the fairly uncomplicated Chamberlain flat-plate solar collector illustrates part of the problem with a universal application of the theory for all collector types. Models of thermal performance will be required for air and liquid flat plate collectors, vacuum tube type collectors, unglazed collectors and concentrating collectors.

In normalizing theory, it is assumed that a relatively simple collector heat transfer model can predict changes in performance due to varying meteorological conditions better than predicting the absolute collector efficiency at a specific meteorological condition.

Values of experimental efficiency are measured at the experimental meteorological condition. With the meteorological conditions determined during the experiment, values of simulated collector performance are calculated for various values of edge heat loss coefficient, U_e and absorber plate absorptance, α_p , until a match is obtained between the simulated and experimental values of thermal efficiency. Values of α_p and U_e that provide the best fit to all the data obtained during the experiment are used for the normalization. Thus, the computer program is "fit" to the experimental data similar to the analysis given in section 9.3. This fitted collector model is used to predict the performance of the test collector at a standard meteorological condition. The difference between the experimentally determined values of η and those simulated by the collector model at standard conditions are then applied to the experimental data to "correct" it to the standard condition.

This method was applied to the test data derived in this study utilizing the values of α_p , U_e , and h_w determined in section 9.3.

The normalized data is presented in figure 69. Values were normalized to the condition of;

$$h_w = 17 \text{ W/m}^2 \text{ } ^\circ\text{C}$$

$$I = 650 \text{ W/m}^2$$

$$\theta = 0^\circ$$

$$T_a = 0^\circ\text{C}$$

$$\rho_g = 0.2$$

$$S = 45^\circ$$

$$f_d = 0.3$$

It may be seen from figure 69, that the scatter in the data is reduced to a value near the experimental uncertainty of the outdoor tests. Experimental uncertainty represents the limits of accuracy of the normalization procedure assuming the collector model is accurate.

The value of collector performance determined for the standard condition is;

$$\eta = 75.3 - 408 (T_{fi} - T_a)/I$$

with a standard error of 3.2

The normalized data showed a better fit to a second order curve.

$$\eta = 74.7 - 364 (T_{fi} - T_a)/I - 504 \{(T_{fi} - T_a)/I\}^2$$

with standard error equal to 3.1

This better correlation with a second order relationship is consistent with

the theoretical results that also exhibit a second order characteristic.

This characteristic was not apparent in the unnormalized data.

Reviewing figure 69 and the unnormalized data it may be observed that the three data points circled in figure 69 did not move during the normalization process. This fact can be attributed to the fact that these points were at the standard meteorological condition to start with or that the data is in error. A review of the original data showed that they were in fact not taken at the standard condition and that the values of ΔT_c were incorrect, so these points must be assumed to be "in error". If they are eliminated from the data set the resultant curve fit gives;

$$\eta = 74.8 - 622 (T_{fi} - T_a)/I - 528 \{(T_{fi} - T_a)/I\}^2$$

with a standard error = 2.6

These results show that although scatter still exists in the data the values are reduced to within the uncertainty of the experimental values.

An interesting outcome of this analysis has been to indicate errors in data that were not evident in the original data due to meteorological scatter.

An attempt was made to normalize the data to high efficiency values, figure 70. A best fit of the data was given by;

$$\eta = 75.8 - 276 (T_{fi} - T_a)/I - 406 \{(T_{fi} - T_a)/I\}^2$$

with a standard error = 2.6

The standard conditions in this example were;

$$h_w = 5 \text{ w/m } 2^\circ \text{C}$$

$$I = 1100 \text{ w/m}^2$$

$$\theta = 0$$

$$T_a = -20^\circ\text{C}$$

$$\rho_g = 0.7$$

$$S = 45^\circ$$

$$f_d = 0.3$$

In both examples the scatter in the data was not eliminated but has reduced to a value consistent with the experimental measurement uncertainty. The ultimate success of this procedure is dependent on the accuracy of the collector model and the measurement uncertainty of the experimental measurements. The experimental measurement uncertainty is dominated by the uncertainty of the solar radiation measurement, and the collector model is dominated by the uncertainty of the determination of h_w , T_{sky} , and diffuse radiation fraction.

Instruments for more accurately measuring solar radiation are now available and are being improved and characterized. Instruments for measuring T_g are now available (21), but their accuracy is still unknown.

The determination of h_w from wind speed measurements seems to be a major weakness. It is suggested that equipment be developed and utilized to determine the value of h_w present during the particular test. The relationship between h_w and free stream wind velocity should be further investigated so that deviations of solar collector average performance can be made for specific applications.

FIGURE 69

PLOT OF EXPERIMENTAL DATA NORMALIZED TO STANDARD CONDITIONS.

PLOT OF SOLAR COLLECTOR EFFICIENCY

FIGURE 70

PLOT OF DATA NORMALIZED TO STANDARD CONDITIONS
REPRESENTATIVE OF HIGH COLLECTOR PERFORMANCE

9.5 Recommended Conditions for Thermal Performance Tests

Section 9 discusses the results of the theoretical and experimental results. The range of test results achievable within the limits of meteorological factors specified in the standard test procedure (4) are indicated in figure 60. Figure 61 shows that if meteorological extremes are further limited, the range of possible test results may be considerably reduced.

The major contributors to the range of possible test results are h_w and collector slope. If values of h_w are limited to values greater than 20 W/m and collector tilt is held near a value of 45° then consistent test results may be achieved more readily.

As described in section 9, this restriction will result in slightly conservative test results but these would be more representative of average meteorological conditions experienced in Canada. Testing time would not be appreciably lengthened as these conditions readily occur during outdoor testing. The requirement for fixed slope may be harder to achieve during outdoor testing but may be suitable if indoor testing with a solar simulator is utilized.

During outdoor testing, steady state conditions were characterized by solar radiation intensities greater than 900 W/m. Limiting the acceptable range of solar radiation to values above 900 W/m should have little or no effect on testing time but will also reduce the scatter in test data slightly.

10. CONCLUSIONS

1. Theoretical analysis has been performed for a single glazed flat-plate solar collector. Results indicate that thermal efficiency is highly dependent on meteorological and operational conditions.
2. The simple Hottel, Whillier, Bliss model of solar collector performance does not account for these varying conditions.
3. A computer program has been developed that may be used by system designers to evaluate the effect of meteorological conditions. This modified 1-dimensional analysis adequately represents the performance of flat-plate solar collectors.
4. The relative magnitude of different meteorological effects is a function of solar collector optical and thermal properties.
5. Tests results derived within the ASHRAE test procedures (4), allow for a high degree of variation in the results.
6. Tests conducted over an extended period exhibited less extreme meteorological extremes than those allowed in (4) but this may be location dependent.

7. Tests derived in different climatic locations may differ significantly due to the different meteorological factors present.
8. Solar system designers should take care to ensure that the conditions under which their test data was derived are similar to the planned application or they should be modified to represent the conditions present.
9. Work is required to better determine values of wind induced surface heat transfer coefficient and effective sky temperature.
10. The values of predicted effective sky temperature are extreme. Values for overcast skies should be determined. Clear sky and night time values should be verified. The values predicted may not only be significant to solar collectors but also to building heat loss calculations.
11. If values of h_w and T_s can be accurately determined, normalization techniques may prove practical.
12. The experiments presented attempted to limit systematic errors and sample variability. The results show less deviation in the experimentally derived values of thermal efficiency than those measured at different facilities. The results show less scatter than previous "Round-Robin" test programs.

11. AREAS FOR FUTURE STUDY

The effects of meteorological and operational conditions should be determined for other collector types.

Further research is required on techniques to measure and predict wind induced surface heat transfer coefficient and effective sky temperature. Standard techniques for normalization of test results for a variety of collector types should be developed.

A more accurate representation of collector performance than the Hottel, Whillier, Bliss, model should be developed which accounts for the effects of varying operational and meteorological conditions.

REFERENCES

1. Duffie, J.A. and W.A. Beckman, SOLAR ENERGY THERMAL PROCESSES, John Wiley and Sons, 1974.
2. Hottel, H.C., and A. Willier, EVALUATION OF FLAT-PLATE SOLAR COLLECTOR PERFORMANCE, Transactions of The Conference on the Use of Solar Energy, Vol. III, Thermal Processes, Tucson, Arizona, 1955.
3. Bliss, R.W., THE DERIVATION OF SEVERAL PLATE-EFFICIENCY FACTORS USEFUL IN THE DESIGN OF FLAT PLATE SOLAR HEAT COLLECTORS, SOLAR ENERGY, Vol. 3, No. 4, Dec. 1959.
4. METHODS OF TESTING TO DETERMINE THE THERMAL PERFORMANCE OF SOLAR COLLECTORS, ASHRAE STANDARD 93-77, ASHRAE, 345 East 47th St., New York, New York, 10017, 1977.
5. Streed, E.R., et al., RESULTS AND ANALYSIS OF A ROUND-ROBIN TEST PROGRAM FOR LIQUID-HEATING FLAT-PLATE SOLAR COLLECTORS, NBS Technical Note 975, August 1978.
6. RESULTS AND ANALYSES OF IEA ROUND ROBIN TESTING, Report of Task III of The International Energy Agency Program to Develop and Test Solar Heating and Cooling Systems, IKP -Kernforschungsanlage, Julich GmbH, Dec. 1979.
7. Harrison, S.J., PERFORMANCE TESTING OF SOLAR COLLECTORS: RESULTS OF IEA ROUND-ROBIN TESTS, Proceedings of the Solwest 80 Conference, Vancouver, B.C., Aug. 1980.
8. Hill, J.E., et al., DEVELOPMENT OF PROPOSED STANDARDS FOR TESTING SOLAR COLLECTORS AND THERMAL STORAGE DEVICES, NBS Technical Note 899, Feb. 1976.
9. Aranovitch, E., THE JOINT SOLAR COLLECTOR TESTING PROGRAMME OF THE EUROPEAN COMMUNITY, Paper presented at the Meeting of the International Solar Society, U.K. Section, April, 1977.
10. Lumsdaine, E., ON THE TESTING OF SOLAR COLLECTORS TO DETERMINE THERMAL PERFORMANCE, Proceedings of the 1978 Annual Meeting of the American Section of the International Solar Energy Society, Inc., Denver Co., Aug. 1978.
11. Bruck, M., et al, COLLECTOR TEST METHODS, ANALYSIS OF TEST METHODS FOR THE DETERMINATION OF THE THERMAL EFFICIENCY OF FLAT-PLATE COLLECTORS, Austrian Solar and Space Agency, (ASSA), A-1090 Vienna, Sept. 1979.
12. Youngblood, W., W. Schultz, R. Barber, E.R. Streed, AN EVALUATION OF THE HEAT TRANSFER FLUID PROPERTIES AND FLOW RATE ON FLAT-PLATE SOLAR COLLECTOR EFFICIENCY, Sun II, Proceedings of the International Solar Energy Society, Atlanta Georgia, May 1979.

13. Hill, J.E. and T. Kusuda, METHOD OF TESTING FOR RATING SOLAR COLLECTORS BASED ON THERMAL PERFORMANCE. National Bureau of Standards Report NBSIR 74-635, Dec. 1974.
14. Bowen, J.C., THE PROBLEM OF TREATING UL AS A CONSTANT. Proceedings of the 1980 Annual Meeting of the American Section of the International Solar Energy Society Inc., Phoenix, Arizona, June 1980.
15. Shewen, E.C., and K.G.T. Hollands, EQUATIONS FOR REPRESENTING THE UL DEPENDENCE IN COLLECTOR TEST PROCEDURES. Proceedings of the International Solar Energy Society, Atlanta, Georgia, May 1979.
16. Shewen, E.C., and K.G.T. Hollands, A SOLAR COLLECTOR THERMAL PERFORMANCE TEST FOR DEVELOPMENTAL PROGRAMS, Renewable Alternatives, Proceedings of the Fourth Annual Conference of the Solar Energy Society of Canada, London, Ontario, Aug. 1978.
17. Tabor, H., TESTING OF SOLAR COLLECTORS, Solar Energy, Vol. 20, pp. 293-303. Pergamon Press Ltd. 1978.
18. Tabor, H., LETTER TO THE EDITOR, Solar Energy, Vol. 24, pp. 113-115, Pergamon Press Ltd. 1980.
19. Kreith, F., Kreider, J.F., PRINCIPALS OF SOLAR ENGINEERING, Hemisphere Publishing Corp., Washington 1978.
20. Directory of SRCC Certified Solar Collector Ratings, Solar Rating and Certification Corporation, SRCC, Washington, DC. Dec. 1981
21. Green, A.A., Gillet, W.B., THE SIGNIFICANCE OF LONGWAVE RADIATION IN FLAT PLATE SOLAR COLLECTOR TESTING, IEF Conference Proceedings, 'Future Energy Concepts', London, Jan. 1979.
22. Whillier, A., DESIGN FACTORS INFLUENCING SOLAR COLLECTORS, Low Temperature Engineering Applications of Solar Energy, New York, ASHRAE, 1967.
23. Swinbank, W.C., Quart, J., LONGWAVE RADIATION FROM CLEAR SKIES, Royal Meteorological Society, 89, (1963).
24. Bliss, R.W., ATMOSPHERIC RADIATION NEAR THE SURFACE OF THE GROUND, Solar Energy, 5, 103, 1961.
25. Atwater, M.A., Ball, J.T., COMPUTATION OF IR SKY TEMPERATURE AND COMPARISON WITH SURFACED TEMPERATURE, Solar Energy, V21, 1978.
26. Cole, R.J., THE LONGWAVE RADIATIVE ENVIRONMENT AROUND BUILDINGS, Building and Environment, Vol. 11, 1976.
27. Cole, R.J., THE LONGWAVE RADIATION INCIDENT UPON THE EXTERNAL SURFACE OF BUILDINGS, B.S.E., Vol. 44, Dec. 1976.

28. Unsworth, M.J., Monteith, J.L., LONGWAVE RADIATION AT THE GROUND (I) ANGULAR DISTRIBUTION OF INCOMING RADIATION. Q.J. Royal Met. Soc., 101, 1-13, 1971.
29. Sparrow, E.M., Cess, R.D., RADIATION HEAT TRANSFER, Brooks/Cole Publishing Comp. Belmont, California, 1970.
30. Hottel, H.G., Wertz, B.B., THE PERFORMANCE OF FLAT-PLATE SOLAR COLLECTOR, Trans. ASME, pg. 91-104, 1942.
31. ASHRAE HANDBOOK OF FUNDAMENTALS, ASHRAE, 1977.
32. Nusselt, W. and Jürges, W., COOLING A PLANE WALL WITH AN AIR STREAM Gesundheits - Ingenieur, Vol. 52 (45), 1922.
33. Jürges, W., GESUNDHEIT INGENIEUR, 19, 1924.
34. McAdams, W.H., HEAT TRANSMISSION, McGraw-Hill, 1933.
35. Serré, R., TECHNICAL TRANSLATION OF REFERENCE 32. Canadian Institute for Scientific and Technical Information, Ottawa, NRC TT-1939, Canada, 1979.
36. Watmuff, J.H. Charters, W.W.S. and Proctor, D., SOLAR AND WIND INDUCED EXTERNAL COEFFICIENTS, SOLAR COLLECTORS, Comple Int'l Revue d'Helio Technique, p. 56, Sept. 1977.
37. Sparrow, E.M. and Tien, K.K., FORCED CONVECTION ON AN INCLINED AND YAWED FLAT PLATE - APPLICATION TO SOLAR COLLECTORS, J. Heat Transfer 99, 507-512, 1977.
38. Tien, K.K. and Sparrow, E.M., LOCAL HEAT TRANSFER AND FLUID FLOW CHARACTERISTICS FOR AIRFLOW OBLIQUE OR NORMAL TO A FLAT PLATE, International Journal of Heat and Mass Transfer, 22, 349-360, 1979.
39. Sparrow, E.M., Nelson, J.W., WIND-RELATED HEAT TRANSFER COEFFICIENTS FOR LEWARD-FACING SOLAR COLLECTORS, ASHRAE Transactions, V.87, Pt. 1, 1981.
40. Duffie, J.A., Beckman, W.A., SOLAR ENGINEERING OF THERMAL PROCESSES, John Wiley & Sons, N.Y., 1980.
41. Hewitt Jr., H.C., Griggs, E.I., WIND EFFECTS ON COLLECTORS, U.S. Department of Energy Report, D.O.E./CS/35364-T1, Nov. 1979.
42. Green, A.A., Kenna, J.P., Rawcliffe, R.W., THE DIFFERENCE OF WIND SPEED ON FLAT-PLATE SOLAR COLLECTOR PERFORMANCE, IEE Conference, Future Energy Concepts, London, Jan. 1981.
43. Oliphant, M.V., MEASUREMENT OF WIND SPEED DISTRIBUTIONS ACROSS A SOLAR COLLECTOR, SOLAR ENERGY, 24, 403-405, 1980.
44. Hemelin, L.L., WIND SIMULATION REQUIREMENTS FOR INDOOR SOLAR COLLECTOR TESTING, National Research Council, Solar Energy Project, SEP Note No. 4

45. Fujii, T., Imura, H., NATURAL CONVECTION HEAT TRANSFER FROM A PLANE WITH ARBITRARY INCLINATION, Journal of Heat and Mass Transfer, Vol 15, 1972.
46. Kind, R.J., Gladstone, D., Moizer, A.D., WIND-INDUCED HEAT LOSSES FROM SOLAR COLLECTORS, Presented at IVth U.S. National Wind Engineering Research Conference, Seattle, WA. 1981.
47. Gladstone, D., AN INVESTIGATION OF WIND-INDUCED HEAT LOSSES FROM FLAT PLATE SOLAR COLLECTORS, M.Eng. Thesis, Carleton University, Ottawa, 1980.
48. Buchberg, H., Catton, I. and D.K. Edwards, NATURAL CONVECTION IN ENCLOSED SPACES: -A review of Applications to Solar Energy Collection, The American Society of Mechanical Engineers, 74-WA/HT-12, 1974.
49. Randall, K.R., El-Wakil, M.M., and J.W. Mitchell, NATURAL CONVECTION CHARACTERISTICS OF FLAT PLATE COLLECTORS, Proceedings of the 1977 Annual Meeting of American Section of the International Solar Energy Society, Orlando, Fla., V. 4-20, June 1977.
50. Hollands, K.G.T., T.E. Unny, G.D. Raithby and L. Konicek, FREE CONVECTIVE HEAT TRANSFER ACROSS INCLINED AIR LAYERS, Journal of Heat Transfer, Vol. 98, No. 2, 1976.
51. Hollands, K.G.T. DIMENSIONAL RELATIONS FOR FREE CONVECTIVE HEAT TRANSFER IN FLAT-PLATE COLLECTORS, Proceedings of the 1978 Annual Meeting of American Section of the International Solar Energy Society, Inc., Denver Col., Aug. 1978.
52. Hollands, K.G.T., Raithby, G.D. and T.E. Unny, STUDIES ON METHODS OF REDUCING HEAT LOSSES FROM FLAT PLATE SOLAR COLLECTORS, Final Report ERDA Contract No. E(11-1)-2597.
53. SOLAR ENERGY CONVERSION, AN INTRODUCTORY COURSE, Selected Lectures from the 5th Course on Solar Energy Conversion, University of Waterloo, Canada, Aug. 6-19, 1978 edited by A.E. Dixon and J.D. Leslie, Pergamon Press.
54. Mitalas, G.P. and D.G. Stephenson, ABSORPTION AND TRANSMISSION OF THERMAL RADIATION BY SINGLE AND DOUBLE GLAZED WINDOWS, NRC, Division of Building Research, Research Paper No. 173, Ottawa, Dec. 1962.
55. Stokes, G.G., ON THE INTENSITY OF THE LIGHT REFLECTED FROM A TRANSMITTER THROUGH A PILE OF PLATES, Proc. R. Soc. London, Vol. 11, VI860-1962, p. 546-556.
56. Brandemuehl, M.J. and W.A. Beckman TRANSMISSION OF DIFFUSE RADIATION THROUGH CPC AND FLAT PLATE COLLECTOR GLAZINGS, Solar Energy, Vol. 24, pp. 511-513, 1980.
57. Edwards, D.K., SOLAR ABSORPTION BY EACH ELEMENT IN AN ABSORBER-COVER GLASS ARRAY, Solar Energy, Vol. 19, pp. 401-402, 1977.

58. Eckert, E.R.G. and R.M. Drake, HEAT AND MASS TRANSFER, McGraw-Hill Book Company Inc., N.Y., 1959.
59. RT-11/RSTS/E, Fortran IV User's Guide Digital Equipment Cooperation, Maynard, Massachusetts, Sept. 1977.
60. RT-11, USER'S MANUAL, Digital Equipment Corporation, Maynard, Massachusetts, Sept. 1977.
61. Dunn, D.H.K., SYSTEM OPERATORS MANUAL FOR SOLAR CALORIMETER PROJECT, National Research Council, October, 1980.
62. Tabor, H., SELECTIVE SURFACES FOR SOLAR COLLECTORS, Section VI-I, Applications of Solar Energy for Heating and Cooling of Buildings.
63. Norgate, G., CANADA'S NATIONAL SOLAR TEST FACILITY, ISES Solar World Forum, Brighton, England, 23-29 August 1981.
64. Camm, D.M., Richards, S.L.F., Albach, G.G., AN ADVANCED NEW SINGLE LAMP LARGE AREA SOLAR SIMULATOR, Solwest '80, Joint Solar Conference, University of British Columbia, Vancouver, B.C., August 6-10, 1980.
65. Holman, J.P., EXPERIMENTAL METHODS FOR ENGINEERS, McGraw Hill, 1971.
66. Jenkins, J.P., Hill, J.E., A COMPARISON OF TEST RESULTS FOR FLAT-PLATE WATER HEATING SOLAR COLLECTORS USING THE BSE AND ASHRAE PROCEDURES, American Society of Mechanical Engineers, Winter Annual Meeting, New York, NY, Dec. 1979.
67. Reed, K.A., Allen, J.W., SOLAR THERMAL COLLECTOR TESTING : CALORIFIC RATIO TECHNIQUE, Solar Diversification, Proceedings of the International Solar Energy Society; Denver, Co., August, 1978.
68. Latimer, J.R., RADIATION MEASUREMENT, International Field Year for the Great Lakes, Technical Manual Series No. 2, The Secretariat, Canadian National Committee for the International Hydrological Decade, Ottawa.
69. Knoll, R.H., Johnson, S.M., BASELINE PERFORMANCE OF SOLAR COLLECTORS FOR NASA LANGLEY SOLAR BUILDING TEST FACILITY, NASA Technical Memorandum, NASA TM X3505, National Aeronautics and Space Administration, Washington, D.C., May 1977.
70. LONG TERM WEATHERING EFFECTS ON THE THERMAL PERFORMANCE OF THE SOLARON (AIR) SOLAR COLLECTOR, DOE/NASA Report, C.R. -161166.
71. Thomas, W.C., EFFECTS OF TEST FLUID COMPOSITION AND FLOW RATES ON THE THERMAL EFFICIENCY OF SOLAR COLLECTORS, Mechanical Engineering Department, Virginia Polytechnic Institute and State University.
72. CALCULATION OF FLOW RATE AND FLUID PROPERTY CORRECTION FACTOR FOR THE COLLECTOR PERFORMANCE CURVES, Technical Note SR19/A, Public Works Canada, June 1982.

73. Dixon, W.J., Massey, F.J., INTRODUCTION TO STATISTICAL ANALYSIS, McGraw-Hill Book Company, Inc., 1957.
74. Beckman, W.A., et. al. SOLAR HEATING DESIGN² BY THE F-CHART METHOD, John Wiley and Sons, New York, N.Y., 1977
75. Standard Measurement Guide, Engineering Analysis of Experimental Data, ASHRAE Standard 41.5-75, 1975, ASHRAE, 345 E. 47 St., New York, NY.
76. Kline, S.J. and McClintock, F.A., DESCRIBING UNCERTAINTIES IN SINGLE-SAMPLE EXPERIMENTS, Mechanical Engineering, Jan. 1953.

APPENDIX A

Physical and Optical Specifications of the
Chamberlain Solar Collector

FIGURE

CONSTRUCTION DETAILS FOR CHAMBERLAIN
SOLAR COLLECTOR

MANUFACTURER	CHAMBERLAIN MFG. CO. ELMHURST, ILLINOIS U. S. A
GROSS AREA	1.95 m ²
APERTURE AREA	1.79 m ²
COVER PLATE ASSEMBLY	
NUMBER OF GLASS PLATES	1
THICKNESS	3.2 mm
MATERIAL	LOW-IRON, TEMPERED
SOLAR TRANSMITTANCE, τ	0.90
I R EMITTANCE	0.88
ABSORBER PLATE	
MATERIAL	MILD STEEL
FLOW CONFIGURATION	19 PARALLEL PASS
COATING	BLACK CHROME
SOLAR ABSORPTANCE, α	0.94
EMITTANCE, ϵ	0.12
AIR SPACES	
BETWEEN COVER AND ABSORBER	19 mm
INSULATION	
MATERIAL	GLASS-FIBRE
DENSITY	80 kg/m ³
THICKNESS	76 mm
THERMAL CONDUCTIVITY	0.03 W • m ⁻¹ • °C ⁻¹

SCHEMATIC OF FLAT-PLATE COLLECTOR

APPENDIX B

COLSM Simulation

Computer Program Listings

```

C      PROGRAM RCDISM      VERSION 1.0      LAST UPDATE SEPT 8, 1982
C*****
C THIS PROGRAM SIMULATES THE STEADY STATE THERMAL PERFORMANCE OF THE
C A FLAT-PLATE SOLAR COLLECTOR AT SPECIFIC TEST CONDITIONS. THE PROGRAM
C CALLS THE SUBROUTINE COLSM TO PERFORM THE CALCULATIONS. THE SUBROUTINE
C PLISIP IS CALLED TO PLOT OF THE SIMULATED THERMAL PERFORMANCE.
C*****
C
0001      PROGRAM RCDISM
C
0002      DIMENSION FX(500),FY(500),COND(10)
0003      IMPLICIT REAL (A-H,I-J-7)
0004      IMPLICIT LOGICAL (L)
0005      DATA LFTY/'Y',LEIN/'N',LETW/'W',LEIG/'G',LFANS/'W'
0006      DATA COND/45.,0.,1000.,1.,0.36,10.,10.,15.,9.,2/
0007      PI=3.14159265
0008      AG=1.79
0009      INPIS=1
0010      TYP=0.
C
0011      10 CALL CLEAR
0012      DO 11 I=1,500
0013      FX(I)=0.
0014      FY(I)=0.
0015      11 CONTINUE
0016      WRITE(7,12)
0017      12 FORMAT(1H,'THE TEST CONDITIONS FOR THE SIMULATION ARE:')
0018      WRITE(7,150)COND(1)
0019      WRITE(7,14)
0020      WRITE(7,250)COND(2)
0021      WRITE(7,14)
0022      WRITE(7,350)COND(3)
0023      WRITE(7,14)
0024      WRITE(7,450)COND(4)
0025      WRITE(7,14)
0026      WRITE(7,550)COND(5)
0027      WRITE(7,14)
0028      WRITE(7,650)COND(6)
0029      WRITE(7,14)
0030      WRITE(7,850)COND(8)

```

```

0031      WRITE(7,14)
0032      WRITE(7,950)COND(9)
0033      WRITE(7,14)
0034      WRITE(7,1050)COND(10)
0035      WRITE(7,14)
0036      14 FORMAT(' ')
0037      WRITE(7,20)
0038      20 FORMAT(1H,'DO YOU WISH TO CHANGE TEST CONDITIONS, (Y/N)? ')
0039      ACCEPT 25, 1ANS
0040      25 FORMAT(A1)
0041      IF(LANS.NE.LFTY) GO TO 901
0042      CALL CLEAR
0043      75 WRITE(7,80) LFANS
0044      80 FORMAT('FLUID TYPE,(W=WATER, G=GLYCOL)=',A1,' ')
0045      READ(5,75) LFANS
0046      IF(LFANS.EQ.LEIG) TYP=1
0047      IF(LFANS.EQ.LETW.OR.(LFANS.EQ.LEIG)) GO TO 90
0048      GO TO 75
0049      90 CONTINUE
C
0050      C ENTER NEW TEST CONDITIONS
0051      100 WRITE(7,150)COND(1)
0052      READ(5,2000) COND(1)
0053      200 WRITE(7,250)COND(2)
0054      ACCEPT 2000,COND(2)
0055      300 WRITE(7,350)COND(3)
0056      ACCEPT 2000,COND(3)
0057      400 WRITE(7,450)COND(4)
0058      ACCEPT 2000,COND(4)
0059      500 WRITE(7,550)COND(5)
0060      ACCEPT 2000,COND(5)
0061      600 WRITE(7,650)COND(6)
0062      ACCEPT 2000,COND(6)
0063      COND(7)=COND(6)
0064      C 700 WRITE(7,750)COND(7)
0065      C ACCEPT 2000,COND(7)
0066      800 WRITE(7,850)COND(8)
0067      ACCEPT 2000,COND(8)
0068      900 WRITE(7,950)COND(9)
0069      ACCEPT 2000,COND(9)

```

```

0070 1000 WRITE(7,1050)COND(10)
0071 ACCEPT 2000,COND(10)
0072 150 FORMAT(1H,1X, 'COLLECTOR TILT, (deg.) = ',F7.1,' ',',')
0073 250 FORMAT(1X,'RAD, INCIDENT ANGLE, (deg.) = ',F7.1,' ',',')
0074 350 FORMAT(1X,'SOLAR INSOL, LEVEL,(W/sq.M) = ',F7.1,' ',',')
0075 450 FORMAT(1X,'FRACTION OF DIFFUSE RAD. = ',F7.1,' ',',')
0076 550 FORMAT(1X,'FLUID FLOW RATE,(kg./sec) = ',F7.3,' ',',')
0077 650 FORMAT(1X,'AMBIENT AIR TEMP,(deg. C) = ',F7.1,' ',',')
C 750 FORMAT(1X,'INLET FLUID TEMP,(deg. C) = ',F7.1,' ',',')
0078 850 FORMAT(1X,'WIND H.T.COEFF.(W/sq.M C) = ',F7.1,' ',',')
0079 950 FORMAT(1X,'EMITTANCE OF GROUND = ',F7.1,' ',',')
0080 1050 FORMAT(1X,'GROUND REFLECTANCE = ',F7.1,' ',',')
C
0081 GO TO 10
0082 901 CONTINUE
0083 WRITE(4,905)
0084 905 FORMAT('1',3BX,'COI SIM PERFORMANCE SUMMARY')
0085 WRITE(4,910)
0086 910 FORMAT('0', 'OPERATIONAL CONDITIONS FOR SIMULATION')
0087 WRITE(4,925)
0088 925 FORMAT(5X,'TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC.',
' FLOW RATE AIR TEMP. FLUID TEMP. HW')
0089 WRITE(4,935)(COND(I),I=1,8)
0090 935 FORMAT(F7.1,' deg.',F4.1,' deg.',F8.1,' W/sq.M',F11.2,
F9.3,' Kg/sec',F6.1,' deg.C',F6.1,' deg.C',F6.1,' W/(sq.M K)')
0091 WRITE(4,955)COND(9),COND(10)
0092 955 FORMAT('0', ' GROUND EMITTANCE',F4.1,
' GROUND REFLECTIVITY',F4.1)
C WRITE DETAILED HEAT TRANSFER ANALYSIS
0093 WRITE(4,940)
0094 940 FORMAT('0', 'DETAILED HEAT TRANSFER ANALYSIS')
0095 WRITE(4,945)
0096 WRITE(4,946)
0097 945 FORMAT(' TFI TFE REF NUF PR HF ',
' UPC UCA UTOP UL ',
' EPRME FR TAFFE DT/I EFF')
0098 946 FORMAT(' K K # I---',
' W/(sq.M K)--- -- --')
0099 960 CONTINUE
0100 CALL COISM(TYP,COND(1),COND(2),COND(3),COND(4),COND(5),

```

```

COND(6),COND(7),COND(8),COND(9),COND(10),PNITA,TS)
0101 FY(INPTS)=PNITA
C CALCULATE DT/B
0102 FX(INPTS)=(COND(7)-COND(6))/COND(3)
0103 IF(FY(INPTS).LE.0.0) GO TO 1500
0105 IF(FX(INPTS).GE.0.1) GO TO 1500
0107 INPTS=INPTS+1
C
C INCREASE INLET FLUID TEMPERATURE THROUGH RANGE
0108 COND(7)=COND(7)+5.0
0109 GO TO 960
0110 1500 CONTINUE
0111 TSC=TS-273.0
0112 WRITE(4,1700)TSC
0113 1700 FORMAT('0', 'EFFECTIVE SKY TEMP. DURING TEST WAS ',F4.1,
' deg.C')
0114 2000 FORMAT(F9.0)
0115 CALL PTSTUP(FX,FY,INPTS)
0116 WRITE(7,2010)
0117 2010 FORMAT('100 YOU WANT TO RUN AGAIN? ENTER Y TO CONTINUE ',',')
0118 ACCEPT 25, LANS
0119 IF(LANS.NE.1EY) GO TO 2030
0121 COND(7)=COND(6)
0122 INPTS=1
0123 GO TO 10
0124 2030 CONTINUE
0125 STOP
0126 END

```

```

0001      SUBROUTINE COLSM(TYP,TILT,ANGLE,G,FRACD,MFLR,
      TAC,CII,HM,FMG,RELIG,PNITA,TS)
      C      PROGRAM COLSM      VERSION 3.0      LAST UPDATE SEPT 9, 1982
      C***** SUBROUTINE COLSM *****
      C THIS PROGRAM CALCULATES THE THERMAL PERFORMANCE OF THE CHAMBERLAIN *
      C SOLAR COLLECTOR AT DIFFERENT OPERATIONAL AND ATMOSPHERIC CONDITIONS *
      C*****
      C
      C
      C***** SPECIFY SIMULATION PARAMETERS *****
      C
0002      IMPLICIT REAL (A-H,I-J-Z)
0003      KEAL=1,LP=LPC,NU,KLC,LI,N,KR,KI,KP,NT,KF,PNITA,NITA,ST1
0004      SIGMA=5.670E-8
0005      PI=3.14159265
0006      TOL=0.05
      C
      C***** SPECIFY THE COLLECTOR CHARACTERISTICS *****
      C
      C DIMENSIONS (IN MKS UNITS)
0007      AG=1.79
0008      AP=1.79
0009      A=1.79
0010      AB=1.95
0011      DH=0.004357
0012      LI=0.0762
0013      LPC=0.019
0014      D=0.0407
0015      L=7.08
0016      W=0.0437
      C OPTICAL PROPERTIES
0017      N=1.518
0018      KLC=0.035
0019      TRNLW=0.02
      C
      C HEAT TRANSFER PROPERTIES
      C COVER
0020      ENC=0.88
      C ABSORBER PLATE
0021      CSAT=0.000082

```

```

0022      NT=19.0
0023      WPER=0.085
0024      EMP=0.12
0025      ALFAP=0.95
0026      F=0.99
      C COLLECTOR HOUSING
0027      KI=0.03
0028      UE=0.1
      C
      C ***** ENVIRONMENTAL AND OPERATING CONDITIONS *****
      C ENVIRONMENTAL CONDITIONS (TEMPERATURE IN DEGREE K)
0029      TFI=273.0+CII
0030      TA=273.0+TAC
0031      PATH=1.0
      C OPERATIONAL CONDITIONS
0032      SNFR=MFLR/AP
0033      GO CONTINUE
      C
      C ***** HEAT TRANSFER MODEL AND ANALYSIS *****
0034      TPH=TFI+2.0
0035      90 CONTINUE
      C
0036      CALL TOP1(TOL,ENC,EMP,ENG,LPC,ALFAP,TRNLW,TILT,TPH,
      >TA,HM,UTOP,UPC,UCA,TS)
      C
0037      UTOP=(AP/A)*UTOP1
      C ***** DETERMINE THE VALUE OF THE OVERALL HEAT LOSS COEFFICIENT *****
      C BACK HEAT LOSS COEFFICIENT
0038      UB=(KI/LI)*(AB/A)
      C OVERALL HEAT LOSS COEFFICIENT
0039      UL=UB+UE+UTOP
      C
      C ***** CALCULATE OPTICAL PROPERTIES *****
0040      CALL STAEFF(N,KLC,ALFAP,ANGLE,TILT,FRACD,
      >RFFG,UTOP,UPC,STAEFF)
      C
      C ***** DETERMINE THE HEAT REMOVAL FACTOR, FR *****
0041      FRM=TFI
      C
0042      250 CONTINUE

```

FORTRAN IV V02.1-10 Wed 09-Sep-81 17:54:41 PAGE 003

```

0043      CALL APER(TYP,TFM,SHFR,UD,UL,AP,CSA,NT,DH,L,W,
      >WPER,F,HF,KE,NUF,CP,FPRME,PR)
      C
      C ***** CALCULATION OF USEFUL ENERGY COLLECTED *****
      C
0044      QU=AP*FR*(G*TAFF-F-UI*(TFI-TA))
      C
      C ***** CHECK IF ASSUMED PLATE TEMPERATURE IS WITHIN TOLERANCES *****
      C IF NOT, SET ASSUMED COVER TEMPERATURE TO THE CALCULATED VALUE AND
      C IFRATE AGAIN UNTIL VALUE IS WITHIN TOLERANCES.
      C
      C CALCULATE MEAN FLUID TEMPERATURE
0045      TFMN=TFI+(((QU/AP)/(UL*FR))*((1.-(FR/FPRME)))
0046      ERR=ABS(TFMN-TFM)
0047      IF(ERR.LE.TOL) GO TO 350
0049      TFM=TFMN
0050      GO TO 250
      C
      C CALCULATE NEW MEAN PLATE TEMPERATURE
0051      350 TPMN=TFM+(QU/(HF*WPER*L*NT))
      C
0052      ERR=ABS(TPMN-TFM)
0053      IF(ERR.LE.TOL) GO TO 400
0055      TPM=TPMN
0056      GO TO 90
      C
0057      400 CONTINUE
      C ***** CALCULATE COLLECTION EFFICIENCY *****
0058      NITA=(QU/(G*AG))
0059      PNITA=NITA*100.
0060      TFE=TFI+(QU/(SHFR*AP*CP))
      C
      C CALCULATE HEAT LOSS COEFFICIENT
0061      ADELTI=(TFI-TA)/G
      C
      C *****
      C
0062      WRITE(6,240)TFI,TFE,KE,NUF,PR,HF,UPC,UCA,UTOP,UL,FPRME,
      >FR,IAEFF,ADELTI,PNITA
0063      240 FORMAT(2X,2F6.1,F8.1,F6.1,F6.1,F7.1,3X,4F6.2,3X,2F6.3,

```

FORTRAN IV V02.1-10 Wed 09-Sep-81 17:54:41 PAGE 004

```

      >2X,2F6.3,F6.1)
      C
      C WRITE(6,60)TFM,CP,DENR,KE,ABVISC
      C 60 FORMAT(1X,7F3.10X,F9.4,3X,F9.3,3X,F9.5,3X,F10.8)
      C
      C WRITE(6,61)VAVE,RE,NUF,HF,UD
      C 61 FORMAT(2X,'VAVE',F8.6,'RE',F9.1,'NUF',F7.2,'HF',F7.1,'UD',F7.2)
      C
0044      RETURN
0065      END

```

- 169 -

```

FORTRAN IV      V02.1-10   Tue 15-Sep-81 18:38:46      PAGE 001

0001      SUBROUTINE TOP1(TOI,FMC,EMP,FMG,IPC,ALFAP,IRNLW,TILT,TPM,
           >TA,HW,UTOPL,UPC,UCA,TS)
C THIS ROUTINE CALCULATES THE VALUE OF THE TOP LOSS COEFFICIENT
C
C ESTIMATE MEAN ABSORBER TEMPERATURE AND CALCULATE HEAT TRANSFER RATES,
C THEN ITERATE TO REFINES ESTIMATES TO WITHIN SET TOLERANCES.
C
0002      IMPLICIT REAL (A-H,J-Z)
C SET INITIAL VALUES
0003      PATH=1.0
0004      SIGMA=5.670E-8
C WRITE(6,80)TOL,FMC,EMP,FMG,IPC,ALFAP,IRNLW,TILT,TPM,
C >TA,HW
C 80      FORMAT(11F10.4)
0005      90 TC=(TPM+TA)/2.0
0006      CALL TSKY(TA,FMG,TILT,RS,TS)
C TS=TA
C HEAT TRANSFER COEFFICIENT (COVER TO SURROUNDING ENVIRONMENT)
C HW=5.7+(3.8*VM)
C HW=4.55+3.71*(VM**0.63)
0007      DCA=(TC-TA)
0008      IF(DCA.LT.0.0) DCA=0.0
0010      100 HRCA=FMC*SIGMA*((TC**4)-(TS**4))/(DCA)
0011      IF(HRCA.LT.0.0) HRCA=0.0
0013      UCA=HW+HRCA
C HEAT TRANSFER COEFFICIENT (ABSORBER PLATE TO COVER)
C.....1.....2.....3.....4.....5.....6.....7..
C CALCULATE CONVECTIVE HEAT TRANS. COEFF., PLATE TO COVER
0014      CALL CHTPC(TPM,TC,PATH,IPC,ALFAP,TILT,HPC)
0015      HRPC=SIGMA*((TPM**4)+(TC**4))*((TPM+TC))/((1./EMP)+(1./FMC)-1.)
C OVERALL HEAT TRANSFER COEFFICIENT (ABSORBER PLATE TO COVER)
0016      UPC=HPC+HRPC
C LONG WAVE RADIATION HEAT LOSS (ABSORBER PLATE TO SKY)
0017      URPS=IRNLW*EMP*SIGMA*((TPM**4)-(TS**4))/(TPM-TA)
C OVERALL TOP LOSS HEAT TRANSFER COEFFICIENT (PLATE TO ATMOSPHERE)
C.....1.....2.....3.....4.....5.....6.....7..
0018      UTOPL=(1.0/((1.0/UPC)+(1.0/URPS)))+URPS
C
C ***** CHECK IF ASSUMED COVER TEMPERATURE IS WITHIN TOLERANCES *****
C IF NOT, SET ASSUMED COVER TEMPERATURE TO THE CALCULATED VALUE AND

```

```

FORTRAN IV      V02.1-10   Tue 15-Sep-81 18:38:46      PAGE 002

C ITERATE AGAIN UNTIL VALUE IS WITHIN TOLERANCES.
C
0019      TCC=TPM-((UTOPL*(TPM-TA))/UPC)
0020      ERR=ABS(TCC-TC)
0021      I=I+1
0022      IF(ERR.LE.TOL) GO TO 200
0024      TC=TCC
0025      GO TO 100
0026      200 RETURN
0027      END

```


- 170 -

FORTRAN IV V02.1-10 Tue 08-Sep-81 22:46:56 PAGE 001

```

0001 SUBROUTINE TSKY(TA,ENG,TILT,RS,TS)
C SUBROUTINE TO CALCULATE THE EFFECTIVE SKY TEMPERATURE OF THE
C ENVIRONMENT AS SEEN BY A SURFACE INCLINED AT AN ANGLE 'TILT'
C TO THE HORIZONTAL.
C
C TA - AMBIENT AIR TEMPERATURE, (DEG. KELVIN)
C ENG - TOTAL EMITTANCE OF THE GROUND TO LONGWAVE RADIATION
C TILT - TILT ANGLE OF SURFACE TO HORIZONTAL (DEG.)
C SLOPE - TILT ANGLE IN RADIANS
C THETA2 - REFRACTION ANGLE (RADIAN)
C RA - ATMOSPHERIC RADIATION INCIDENT ON A HORIZ. SURFACE
C RAS - ATMOSPHERIC RADIATION INCIDENT ON INCLINED SURFACE
C RGS - LONGWAVE RADIATION ON SURFACE DUE TO THE GROUND
C RS - TOTAL LONGWAVE RADIATION INCIDENT ON SURFACE
C K1 - CONSTANT FOR RAS CALC. FROM COLE
C K3 - CONSTANT FOR RAS CALC. FROM COLE
C SIGMA - STEPHAN-BOLTZMAN CONSTANT
C TS - EFFECTIVE SKY TEMPERATURE, (DEG.K)
C TG - TEMPERATURE OF GROUND, ASSUMED = TA
C
0002 IMPLICIT REAL(A-H,I-Z)
0003 PI=3.14159265
0004 SIGMA=5.670E-08
C
C CALCULATE SLOPE ANGLE (RADIAN)
0005 SLOPE=TILT*PI/180.0
C CALCULATE RA
0006 RA=-119+1.058SIGMA*(TA**4)
C CALCULATE RAS
0007 X=TILT
0008 K1=1.00004-4.46622E-06*X-7.67489E-05*(X**2)+3.42187E-08*(X**3)
>+1.48096E-09*(X**4)
0009 K3=-9.00303E-05+6.1022E-04*X+1.71854E-04*(X**2)
>-2.17531E-06*(X**3)+7.38927E-09*(X**4)
C
0010 RAS=RAS*K1+0.09*K3*SIGMA*(TA**4)
C
C CALCULATE RGS
0011 TG=TA
0012 RGS=ENG*SIGMA*(TG**4)*((1.0-COS(SLOPE))/2.0)

```

FORTRAN IV V02.1-10 Tue 08-Sep-81 22:46:56 PAGE 002

```

C
C CALCULATE RS
0013 RS=RAS+RGS
C
C CALCULATE TS
0014 TS=(RS/SIGMA)**0.25
C
C WRITE(6,100)TA,KA,K1,K3,RAS,RGS,RS,TS
C 100 FORMAT(8F10.3)
0015 RETURN
0016 END

```

```

FORTKAM IV      V02.1-10   Wed 09-Sep-81 11:38:27      PAGE 001

0001      SUBROUTINE CHIPC(TPM,TC,PATH,LPC,ALFAP,TILT,HPC)
C THIS ROUTINE CALCULATES THE VALUE OF THE CONVECTIVE HEAT LOSS
C COEFFICIENT BETWEEN THE ABSORBER PLATE AND COVER.
C
0002      IMPLICIT REAL (A-H,J-Z)
C SET INITIAL VALUES
0003      PI=3.141592654
0004      SIGMA=5.670E-8
0005      SLOPF=TILT*PI/180.0
C CONVECTIVE HEAT TRANSFER COEFFICIENT (ABSORBER PLATE TO COVER)
C.....1.....2.....3.....4.....5.....6.....7..
C AIR LAYER PROPERTIES (ASSUME AT A TEMPERATURE OF TALM)
0006      TALM=(TPM+TC)/2.
0007      DTAL=TPM-TC
0008      XC=LPC
0009      XA=100./TALM
C CALCULATE KAYLEIGH NUMBER
0010      RA=2737.*((1.+2.*XA)**2)*(XA**4)*DTAL*((100./XC)**3)*(PATH**2)
C CALCULATE THERMAL CONDUCTIVITY OF AIR AT THE ASSUMED TEMPERATURE
0011      KA=0.002528*(TALM**1.5)/(TALM+200.)
C CALCULATE THE NUSSELT NUMBER (BY TERMS)
0012      X1=1.-(1708./(RA*COS(SLOPF)))
0013      IF(X1.LT.0.) X1=0.0
0015      X2=1.-((((SIN(1.8*SLOPF))**1.6)*1708.)/(RA*COS(SLOPF)))
0016      X3=((((RA*COS(SLOPF))/5830.))**0.333333)-1.0)
0017      IF(X3.LT.0.) X3=0.0
C      WRITE(3,70) X1,X2,X3
C 70 FORMAT(3F10.5)
0019      NU=1.0+(1.48*X1*X2)*X3
C CONVECTIVE HEAT TRANSFER COEFFICIENT (ABSORBER PLATE TO COVER)
0020      HPC=NU*(KA/LPC)
C.....1.....2.....3.....4.....5.....6.....7..
C      WRITE(6,80)TPM,TC,PATH,LPC,TILT,
C      >TALM,DTAL,RA,KA,NU,HPC
C 80 FORMAT(11F11.4)
0021      200 RETURN
0022      END

```

FORTRAN IV V02.1-10 Sat 12-Sep-81 13:40:59

PAGE 001

- 172 -

```

0001      SUBROUTINE STAFF(N,KLC,ALFAP,ANGLE,TILT,FRACD,
      REFC,UTOP,UPC,TAEFF)
      C SUBROUTINE TO CALCULATE THE OPTICAL PROPERTIES OF THE GLAZING
      C
      C      N - INDEX OF REFRACTION FOR GLAZING
      C      KLC - PRODUCT OF EXTINCTION COEF. & COVER THICKNESS
      C      ANGLE - ANGLE BETWEEN GLAZING SURFACE NORMAL & BEAM RAD. (DEG.)
      C      TILT - SOLAR COLLECTOR TILT IN DEGREES
      C      FRACD - FRACTION OF DIFFUSE RADIATION ON THE COLLECTOR TILT
      C      REFC - GROUND REFLECTANCE TO SOLAR RADIATION
      C      UTOP - HEAT LOSS COEFF., ABSORBER PLATE TO ATMOSPHERE
      C      UPC - HEAT LOSS COEFF., ABSORBER PLATE TO COVER
      C      TRANSC - AVERAGE TRANSMITTANCE OF COVER
      C      TAEFF - EFFECTIVE TRANSMITTANCE ABSORPTANCE PRODUCT
      C      TRG - TRANSMITTANCE OF GLAZING DUE TO ABSORPTION ONLY
      C      REFC - REFLECTANCE OF COVER FOR BOTH COMP. OF POLARIZATION
      C      AGESD - EFFECTIVE INCIDENCE ANGLE FOR SKY DIFFUSE
      C      AGECD - EFFECTIVE INCIDENCE ANGLE FOR GROUND DIFFUSE
      C      TEFFD - EFFECTIVE TRANSMITTANCE TO GROUND AND SKY DIFFUSE
      C
0002      IMPLICIT REAL(A-H,I-Z)
0003      PI=3.14159265
0004      SLOPE=TILT*PI/180.0
0005      GSF=((1.-COS(SLOPE))/2.)
0006      SSF=((1.+COS(SLOPE))/2.)
      C
      C TRANSMISSION OF GLAZING TO BEAM RADIATION
      C *****
0007      CALL OPTCAL(N,KLC,ANGLE,TRANSC,REFC,TRG)
0008      ABSEFB=(1.-TRG)
      C
      C WRITE(4,20)N,KLC,ANGLE,TRANSC,REFC,TRG,ABSEFB
      C 20      FORMAT(7F10.3)
      C
      C CALCULATE TRANS. OF GLAZING TO SKY AND GROUND DIFFUSE RADIATION
      C *****
      C SKY SOURCE DIFFUSE
      C EFFECTIVE INCIDENCE ANGLE FOR SKY DIFFUSE
0009      AGECD=59.48-.1388*TILT+0.001497*(TILT**2.)
      C CALCULATE TRANSMITTANCE TO SKY DIFFUSE
0010      CALL OPTCAL(N,KLC,AGECD,TRCSD,REFCSD,TRGSD)

```

FORTRAN IV V02.1-10 Sat 12-Sep-81 13:40:59

PAGE 002

```

      C GROUND SOURCE REFLECTED DIFFUSE
      C EFFECTIVE INCIDENCE ANGLE FOR GROUND DIFFUSE
0011      AGECD=90.-.5788*TILT+0.002693*(TILT**2.)
      C CALCULATE TRANSMITTANCE TO GROUND SOURCE DIFFUSE
0012      CALL OPTCAL(N,KLC,AGECD,TRCSD,REFCSD,TRGSD)
      C
      C WRITE(4,30)N,KLC,AGECD,TRCSD,REFCSD,TRGSD,AGECD
      C 30      FORMAT(7F10.3)
      C
      C EFFECTIVE TRANSMITTANCE TO GROUND AND SKY DIFFUSE
0013      TEFFD=(TRCSD*SSF+REFC*TRCSD*GSF)/
      >(SSF+REFC*GSF)
      C EFFECTIVE DIFFUSE TRANS. OF GLAZING DUE TO ABSORPTION ONLY
0014      TRGEFD=(TRGSD*SSF+REFC*TRGSD*GSF)/
      >(SSF+REFC*GSF)
0015      ABSEFD=1.-TRGEFD
      C
      C WRITE(4,35)TEFFD,TRGEFD,ABSEFD
      C 35      FORMAT(3F10.3)
      C
      C TRANSMITTANCE X ABSORPTANCE PRODUCT
      C *****
      C HEMISPHERICAL DIFFUSE RADIATION PROPERTIES OF GLAZING
0016      HDANGL=60.0
0017      CALL OPTCAL(N,KLC,HDANGL,HDTRAN,HDREFC,HDTRG)
0018      TRNADD=(TEFFD*ALFAP)/(1.-(1.-ALFAP)*HDREFC)
0019      TRNABD=(TRANSC*ALFAP)/(1.-(1.-ALFAP)*HDREFC)
      C
      C EFFECTIVE TRANSMITTANCE X ABSORPTANCE PRODUCT
      C *****
0020      TAEFFD=TRNADD*ABSEFD*(1.-(UTOP/UPC))
0021      TAEFFB=TRNABD*ABSEFB*(1.-(UTOP/UPC))
      C
0022      TAEFF=((1.-FRACD)*TAEFFD+FRACD*TAEFFB)
      C
      C WRITE(4,25)AGESD,TRCSD,SSF,AGECD,TRCSD,GSF,TEFFD,
      >TRNADD,TAEFF
      C 25      FORMAT(9F10.3)
      C
      C WRITE(4,40)HDREFC,TRNADD,TRNABD,TAEFFD,TAEFFB
      C 40      FORMAT(5F10.3)
0023      RETURN
0024      END

```

- 173 -

FORTRAN IV V02.1-10 Tue 08-Sep-81 22:42:09 PAGE 001

```

0001 SUBROUTINE OPTICAL(N,KLC,ANGLE,TRANSC,REFC,IKG)
C SUBROUTINE TO CALCULATE THE OPTICAL PROPERTIES OF THE GLAZING
C
C N -INDEX OF REFRACTION FOR GLAZING
C KLC -PRODUCT OF EXTINCTION COEF. & COVER THICKNESS
C ANGLE -ANGLE BETWEEN GLAZING SURFACE NORMAL & BEAM RAD. (DEG.)
C THETA1 -INCIDENT ANGLE (ANGLE) EXPRESSED IN RADIANS
C THETA2 -REFRACTION ANGLE (RADIANS)
C ROWPAR -AIR/GLASS INTERFACE REFLECTIVITY,PARALLEL COMP.
C ROWPER -AIR/GLASS INTERFACE REFLECTIVITY,PERPENDICULAR COMP.
C IKG -TRANSMITTANCE OF GLAZING DUE TO ABSORPTION ONLY
C REFC -REFLECTANCE OF COVER FOR BOTH COMP. OF POLARIZATION
C REFFA -REFLECTANCE FOR GLAZING, PARALLEL COMP.
C REFPE -REFLECTANCE FOR GLAZING,PERPENDICULAR COMP.
C TRANPA -TRANS. OF GLAZING DUE TO ABSORP. AND REFLECTION
C TRANPF -TRANS. OF GLAZING DUE TO ABSORP. AND REFLECTION
C TRANSC -AVERAGE TRANSMITTANCE OF COVER
C
0002 IMPLICIT REAL(A-H,J-Z)
0003 PI=3.14159265
C
C CALCULATE INCIDENT ANGLE (RADIANS)
0004 IF(ANGLE.GT.90.) THETA1=PI/2.
0006 THETA1=ANGLE*PI/180.0
0007 IF(THETA1) 30,40,30
C CALCULATE REFRACTION ANGLE (SNELL'S LAW)
0008 30 THE(A2=SIN(THETA1)/N
0009 TEMP=SQRT(1.-THETA2*THETA2)
0010 THETA2=ATAN(THETA2/TEMP)
C CALCULATE REFLECTIVITY AT AIR-GLAZING INTERFACE FOR PARALLEL
C AND PERPENDICULAR COMPONENTS (FRESNEL'S FORMULA)
0011 RPE=SIN(THETA1-THETA2)/SIN(THETA1+THETA2)
0012 RPA=RPE*(COS(THETA1+THETA2)/COS(THETA1-THETA2))
0013 ROWPAR=RPA*RPA
0014 ROWPER=RPE*RPE
0015 GO TO 50
C FOR THE CASE THETA1=0, THEN THETA2=0 AND ROWPAR=ROWPER GIVEN BY:
0016 40 ROWPAR=((N-1.)/(N+1.))**2
0017 ROWPER=ROWPAR
0018 50 CONTINUE

```

FORTRAN IV V02.1-10 Tue 08-Sep-81 22:42:09 PAGE 002

```

C CALCULATE TRANSMITTANCE OF GLAZING DUE TO ABSORPTION OF GLAZING
0019 TRG=EXP(-1.*KLC/COS(THETA2))
0020 STRG=TRG*TRG
C REFLECTANCE VALUES (SOL'N OF STOKES EGNS FOR MULTIPLE REFLECTIONS)
C FOR THE COVER.
0021 REFFA=ROWPAR*(1.+(STRG*(1.-ROWPAR)**2)/((1.-(ROWPAR)**2)*STRG))
0022 REFPE=ROWPER*(1.+(STRG*(1.-ROWPER)**2)/((1.-(ROWPER)**2)*STRG))
C AVERAGE VALUES OF REFLECTANCE FOR THE COVER
0023 REFC=(REFFA+REFPE)/2.
C TRANSMITTANCE OF GLAZING DUE TO ABSORPTION & REFLECTION
0024 TRANPA=TRG*((1.-ROWPAR)**2)/(1.-(ROWPAR)**2)*STRG)
0025 TRANPF=TRG*((1.-ROWPER)**2)/(1.-(ROWPER)**2)*STRG)
C AVERAGE TRANSMITTANCE FOR THE COVER
0026 TRANSC=(TRANPA+TRANPF)/2.
0027 RETURN
0028 END

```

- 174 -

FORTRAN IV V02.1-10 Wed 09-Sep-81 11:41:28 PAGE 001

```

0001 SUBROUTINE APPR(TYP,TFM,SMFR,UO,UL,AP,CHAT,NT,DM,L,W,
      WPER,F,HF,RE,NUF,CP,FPRME,FR,PR)
C THIS ROUTINE CALCULATES THE VALUE OF FR FOR THE CHAMBERLAIN
C COLLECTOR, THE RELATIONSHIP FOR UO SHOULD BE CHANGED TO SUIT,
C OTHER COLLECTOR TYPES IF THEY ARE TO BE EVALUATED.
C
C TYP -FLUID TYPE, .EQ.1>50/50% GLYCOL, .NE.1>WATER
C TFM -MEAN FLUID TEMPERATURE, K
C SMFR -SPECIFIC MASS FLOW RATE, kg/sec sq.m of collector
C UO -FLUID TO ATMOSPHERE HEAT LOSS COEFF., W/sq.m C
C UL -COLLECTOR HEAT LOSS COEFF., W/sq.m C
C AP -ABSORBER PLATE AREA, sq.m
C CSAT -CROSS-SECTIONAL AREA OF FLOW TUBES, sq.m
C NT -NUMBER OF FLOW TUBES
C DM -HYDRAULIC DIAMETER OF FLOW TUBES, m
C L -ABSORBER PLATE EFFECTIVE LENGTH, m
C W -WIDTH OF FIN AND TUBE, m
C WPER -WETTED PERIMETER LENGTH OF FLOW TUBES, m
C HF -HEAT TRANSFER COEFF., FLUID TO TUBE WALL, W/sq.m
C RE -REYNOLD NUMBER OF FLUID
C NUF -NUSSELT NUMBER FOR FLUID
C CP -SPECIFIC HEAT OF FLUID, J/kg.K
C FPRME -COLLECTOR EFFICIENCY FACTOR
C FR -HEAT REMOVAL FACTOR FOR COLLECTOR
C F -FIN EFFICIENCY OF ABSORBER PLATE
C PR -PRANDTL NUMBER
0002 IMPLICIT REAL(A-H,J-Z)
C
C SUBROUTINE TO CALCULATE THE HEAT REMOVAL FACTOR, FR
C
C ***** DETERMINE COLLECTOR EFFICIENCY FACTOR, F *****
C
C CALCULATE HEAT TRANSFER FLUID PROPERTIES
C
0003 CALL FLPROP(TYP,TFM,CP,PR,DENS,ABVISC,KF,KVISC)
0004 VAVE=(SMFR*AP)/(DENS*CSAT*NT)
C WRITE(6,10)PR
C 10 FORMAT (F4.2)
C CALCULATE THE REYNOLDS NUMBER FOR THE HEAT TRANSFER FLUID
0005 RE=(DENS*VAVE*DM)/ABVISC

```

FORTRAN IV V02.1-10 Wed 09-Sep-81 11:41:28 PAGE 002

```

C CALCULATE THE NUSSELT NUMBER FOR THE HEAT TRANSFER FLUID
0006 NUF=3.66+(.0468*(RE*PR*DM/L)/
      >(1+.048*((RE*PR*DM/L)**.666666)))
C CALCULATE HEAT TRANSFER COEFFICIENT (LIQUID TO ABSORBER TUBE)
0007 HF=NUF*(KF/DM)
C CALCULATE HEAT LOSS COEFFICIENT (FLUID TO AMBIENT AIR)
0008 UO=1./((1./(UL*W*F))+1./(WPER*HF)))
C THE COLLECTOR EFFICIENCY FACTOR, F' IS GIVEN BY
0009 FPRME=UO/UL
C THE HEAT REMOVAL FACTOR, FR IS GIVEN BY:
0010 A1=SMFR*CP/UL
0011 A2=(-1.*FPRME*UO)/(SMFR*CP)
0012 FR=A1*(1.-EXP(A2))
0013 RETURN
0014 END

```

- 175 -

```

FORTRAN IV      V02.1-10      Tue 08-Sep-81 23:52:54      PAGE 001

0001      SUBROUTINE FPROP(TYP,TFM,CP,PR,DENS,ABVISC,KF,KVISC)
C ***** THIS SUBROUTINE CALCULATES THE HEAT TRANSFER FLUID *****
C          PROPERTIES BASED ON THE FLUID TEMPERATURE
C
C          TYP -FLUID TYPE,.EQ.1>GLYCOL 50/50 MIX,.NE.1>WATER
C          TFM -MEAN FLUID TMP IN K
C          TFM -MEAN FLUID TMP IN DEG. C
C          CP -FLUID SPECIFIC HEAT,J/kg C
C          KF -FLUID THERMAL CONDUCTIVITY,W/m C
C          DENS -FLUID DENSITY,kg/cubic m
C          KVISC -FLUID KINIMATIC VISCOSITY,cm.2/sec
C          ABVISC -FLUID ABSOLUTE VISCOSITY,kg/m sec
C          PR -FLUID PRANDAL NUMBER
C
0002      IMPLICIT REAL(A-H,I-Z)
0003      TFM=TFM-273.0
0004      IF (TYP.EQ.1.) GO TO 100
C
C      THE FOLLOWING EQUATIONS ARE FOR THE PROPERTIES OF WATER
C      BASED ON THE FLUID TEMPERATURE IN DEGREE CELCIUS
0006      CP=.0149689*TFM**2 - 1.37808*TFM + 4210.02
0007      KF = -7.3946E-6*TFM**2 + 1.8537E-4*TFM + .571494
0008      DENS = -.0035868*TFM**2 - .0670346*TFM + 1000.31
0009      VISC = 7.7628E-10*TFM**5 + 1.2175E-7*TFM**4 - 7.19655E-5*TFM**3
          + 9.1386E-3*TFM**2 - .54136*TFM + 17.7615
0010      KVISC = VISC*1E-7
0011      ABVISC = KVISC*DENS
0012      PR = CP*ABVISC/KF
C
0013      GO TO 101
C
C      THE FOLLOWING EQUATIONS ARE FOR THE PROPERTIES OF UCAR THERMOFLUID 17
C      (50/50 X MIXTURE WITH WATER BY VOLUME) BASED ON THE FLUID
C      TEMPERATURE IN DEGREE CELCIUS
C
0014      100 CP = -.0137147*TFM**2 + 5.99361*TFM + 3148.08
0015      KF = -1.28505E-6*TFM**2 - 6.3741E-6*TFM + .41369
0016      DENS = -.001863*TFM**2 - .465281*TFM + 1077.76
0017      Y=-1.98631E-8*TFM**4+5.22061E-6*TFM**3-5.28159E-4*TFM**2
          +.0448045*TFM+12.4476

```

```

FORTRAN IV      V02.1-10      Tue 08-Sep-81 23:52:54      PAGE 002

0018      KVISC = 2.0/(EXP(Y))
0019      ABVISC = KVISC*DENS
0020      PR = CP*ABVISC/KF
C
0021      101 RETURN
0022      END

```

- 176 -

FORTRAN IV V02.1-10 Wed 09-Sep-81 17:55:17 PAGE 001

```

0001      SUBROUTINE PTSTUP(FX,FY,INPTS)
C SUBROUTINE TO SET UP PLOT PARAMETERS
0002      DIMENSION FX(500),FY(500)
0003      IMPLICIT LOGICAL I1(I)
0004      DATA IETH/'H'//,IFTS/'S'//,IFTY/'Y'//
0005      10  CALL CLEAR
0006          TYPE 20
0007      20  FORMAT('HARD COPY (H) OR SCREEN (S) PLOT? ',8)
0008      ACCEPT 300, IANS
0009      IF(IANS.NE.IETH) GO TO 30
0010      ISCREEN=.FALSE.
0011      XPAGE=10.0
0012      YPAGE=7.0
0013      XAXIS=5.0
0014      YAXIS=5.0
0015      XAXORG=0.75
0016      XORGIN=0.0
0017      YORGIN=0.0
0018      YAXORG=0.5
0019      GO TO 40
0020      30  IF(IANS.NE.IFTS) GO TO 10
0021      ISCREEN=.TRUE.
0022      XPAGE=9.5
0023      YPAGE=4.75
0024      XAXIS=5.0
0025      YAXIS=3.75
0026      XAXORG=0.75
0027      XORGIN=0.0
0028      YORGIN=0.0
0029      YAXORG=0.5
0030      GO TO 40
0031      40  CONTINUE
0032      CALL CLEAR
0033      TYPE 50
0034      50  FORMAT('DO YOU WISH TO PLOT THE AXIS (Y/N)? ',8)
0035      ACCEPT 300, IANS
0036      IF(IANS.NE.IFTY) GO TO 4000
0037      300  FORMAT(A1)
0038      IF(IANS.NE.IFTY) GO TO 4000
0039      40  CONTINUE
0040      XSTP=0.02
0041      YSTP=20.0
0042

```

FORTRAN IV V02.1-10 Wed 09-Sep-81 17:55:17 PAGE 002

```

0043      XMI=0.10
0044      XLO=0.0
0045      YMI=100.0
0046      YLO=0.0
0047      IF(ISCREEN) GO TO 540
0048      CALL BEDSTR(XORGIN,YORGIN,XPAGE,YPAGE)
0049      GO TO 540
0050      540  CONTINUE
0051      CALL SCRSTR(XORGIN,YORGIN,XPAGE,YPAGE)
0052      560  CONTINUE
0053      CALL BGNPL(0)
0054      CALL SETFMT('F4.2','I3')
0055      CALL PARF(XPAGE,YPAGE)
0056      IF(ISCREEN) CALL PHYSOR(XORGIN+XAXORG,YORGIN+YAXORG)
0057      CALL XLABEL('Tf-Ts/ I ',12)
0058      CALL YLABEL('THEORETICAL EFFICIENCY, (X) ',28)
0059      CALL AREA2D(XAXIS,YAXIS)
0060      C CALL HEADIN('THEORETICAL COLLECTOR EFFICIENCY')
0061      CALL GRAF(XLO,XSTP,XMI,YLO,YSTP,YMI)
0062      CALL HEIGHT(0.056)
0063      CALL MARKER(3)
0064      4000  CONTINUE
0065      CALL CURVE(FX,FY,INPTS,0)
0066      4030  CALL PLTCOM
0067      CALL CLEAR
0068      RETURN
0069      END
0070

```

COPY/PRE F.COM RCOLSM.SAV
COPY/PRE F.COM RCOLSM.MAP
R LINK
RCOLSM.SAV,RCOLSM.MAP=RCOLSM.HPI.COM.MOVE//
COLSM
TOPL
TSKY
CHTPO
STAFF
OPTCAL
APFR
FIRKUP
ANGLE/0:1
AKFA2D
BGNPL
LHAI FV
CHAMAR
LLFAR
CONNPT
CURVE
DXTICK
DYTICK
ENDPL
GRAF
HEADIN
HEIGHT
MARKER
AFSSAB
NOMLNK
NUCHAR
PAGE
PHYSOR
PI.COM
RESET
KEVERS
SETAX
SETFMT
SETWIN
STRPT
SYMBOL
WAIT
WIDTH
XINTAX
XLABEL
YTICK
YINTAX
YLABEL
YTICKS
BANGLE/0:2
BCOMP
BOUT
BEDCOM
BEDSTR
BENDPL
BMSG
BPI.COM
BRESET
BSCALE
BSIZE
BSTRPT
BUPRT
BXTICK
BYTICK
SANGLE/0:2
SCOMP
SPOT
SCRCOM
SCRSTR
SMG
SRFSET
SSIZE
SSTRPT
SMIDTH
SXTICK
SYTICK
//
C

- 178 -

APPENDIX C

Energy Balance for Chamberlain Solar Collector

Run of COLSM with:

$$h_w = 5 \text{ and } 30 \text{ W/m}^2\text{C}$$

$$U_e = 0.1 \text{ W/m}^2\text{C}$$

where: $q_e = \frac{F U A}{R_{e c}} (T_{fi} - T_a)$

Output variable description

EFF - Collector Thermal Efficiency

$$DT/I = (T_{fi} - T_a)/I$$

QA - Rate of Energy Absorbed by Absorber Plate

QU - Rate of Energy Collection by Collector

QL - Rate of Thermal Energy Loss From Collector Case

PTL - Percent of Total QL Due To Top Losses

PBL - Percent of Total QL Due to Back Losses

PEL - Percent of Total QL Due to Edge Losses

- 179 -

COI SIM PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
75.0 deg. 0.0 deg. 1000.0 W/cm² 0.20 0.036 kg/sec -30.0 deg.C -30.0 deg.C 5.0 W/cm²

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFO	TA	UL	FR	TAFF	DT/I	EFF	QA	QU	QL	PTI	PBL	PFL
K	K	K											
243.0	256.4	243.0	2.44	0.97	0.835	0.000	80.7	1444.7	1444.7	0.0	0.0	0.0	0.0
248.0	261.0	243.0	2.62	0.97	0.837	0.005	79.5	1446.1	1423.5	22.7	79.8	16.4	3.8
253.0	265.7	243.0	2.70	0.97	0.838	0.010	78.3	1447.8	1401.1	46.7	80.4	15.9	3.7
258.0	270.4	243.0	2.78	0.96	0.839	0.015	76.9	1449.1	1377.1	72.0	81.0	15.4	3.6
263.0	275.0	243.0	2.84	0.96	0.840	0.020	75.5	1450.1	1352.1	98.0	81.4	15.1	3.5
268.0	279.7	243.0	2.89	0.96	0.841	0.025	74.1	1451.0	1326.5	124.5	81.7	14.9	3.5
273.0	284.4	243.0	2.92	0.96	0.841	0.030	72.6	1451.8	1300.3	151.4	81.9	14.7	3.4
278.0	289.0	243.0	2.96	0.96	0.842	0.035	71.2	1452.4	1273.7	178.7	82.1	14.5	3.4
283.0	293.7	243.0	2.99	0.96	0.842	0.040	69.6	1453.0	1246.5	206.5	82.3	14.3	3.3
288.0	298.4	243.0	3.02	0.96	0.843	0.045	68.1	1453.5	1218.9	234.6	82.5	14.2	3.3
293.0	303.1	243.0	3.05	0.96	0.843	0.050	66.5	1453.9	1190.9	263.0	82.7	14.1	3.3
298.0	307.7	243.0	3.08	0.96	0.843	0.055	64.9	1454.3	1162.5	291.8	82.8	13.9	3.3
303.0	312.4	243.0	3.10	0.96	0.843	0.060	63.3	1454.6	1133.8	320.9	82.9	13.8	3.2
308.0	317.1	243.0	3.13	0.96	0.844	0.065	61.7	1455.0	1104.6	350.4	83.1	13.7	3.2
313.0	321.8	243.0	3.15	0.96	0.844	0.070	60.1	1455.2	1075.1	380.2	83.2	13.6	3.2
318.0	326.5	243.0	3.17	0.96	0.844	0.075	58.4	1455.5	1045.2	410.3	83.3	13.5	3.2
323.0	331.2	243.0	3.19	0.96	0.844	0.080	56.7	1455.7	1014.9	440.7	83.4	13.4	3.1
328.0	335.9	243.0	3.22	0.96	0.844	0.085	55.0	1455.9	984.3	471.5	83.6	13.3	3.1
333.0	340.6	243.0	3.24	0.96	0.844	0.090	53.3	1456.0	953.3	502.7	83.7	13.2	3.1
338.0	345.3	243.0	3.26	0.96	0.845	0.095	51.5	1456.1	922.0	534.1	83.8	13.2	3.1
343.0	350.0	243.0	3.28	0.96	0.845	0.100	49.7	1456.3	890.4	565.9	83.9	13.1	3.0

EFFECTIVE SKY TEMP. DURING TEST WAS : -54.7 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
0.0 deg. 0.0 deg. 1000.0 W/cm² 0.20 0.036 kg/sec 30.0 deg.C 30.0 deg.C 30.0 W/cm²

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFO	TA	UL	FR	TAFF	DT/I	EFF	QA	QU	QL	PTI	PBL	PEL
K	K	K											
303.0	314.8	303.0	3.71	0.96	0.831	0.000	79.7	1426.3	1426.3	0.0	0.0	0.0	0.0
308.0	319.5	303.0	4.00	0.96	0.832	0.005	77.7	1424.8	1390.5	34.2	86.8	10.7	2.5
313.0	324.1	303.0	4.24	0.95	0.833	0.010	75.5	1423.2	1350.7	72.4	87.5	10.1	2.4
318.0	328.6	303.0	4.41	0.95	0.833	0.015	73.1	1422.1	1309.2	112.9	88.0	9.7	2.3
323.0	333.2	303.0	4.55	0.95	0.834	0.020	70.7	1421.3	1266.3	155.0	88.4	9.4	2.2
328.0	337.8	303.0	4.66	0.95	0.834	0.025	68.3	1420.6	1222.1	198.5	88.7	9.2	2.1
333.0	342.4	303.0	4.76	0.95	0.834	0.030	65.7	1420.1	1176.9	243.2	88.9	9.0	2.1
338.0	347.0	303.0	4.85	0.95	0.834	0.035	63.2	1419.6	1130.5	289.0	89.1	8.8	2.1
343.0	351.6	303.0	4.94	0.95	0.834	0.040	60.5	1419.1	1083.3	335.8	89.3	8.7	2.0
348.0	356.1	303.0	5.01	0.95	0.835	0.045	57.8	1418.7	1035.2	383.5	89.4	8.6	2.0
353.0	360.7	303.0	5.09	0.95	0.835	0.050	55.1	1418.3	986.3	432.0	89.6	8.4	2.0
358.0	365.3	303.0	5.15	0.95	0.835	0.055	52.3	1417.9	936.5	481.4	89.7	8.3	1.9
363.0	369.9	303.0	5.22	0.95	0.835	0.060	49.5	1417.5	886.0	531.6	89.9	8.2	1.9
368.0	374.4	303.0	5.28	0.95	0.835	0.065	46.6	1417.2	834.7	582.5	90.0	8.1	1.9
373.0	379.0	303.0	5.34	0.95	0.835	0.070	43.7	1416.8	782.7	634.2	90.1	8.0	1.9
378.0	383.6	303.0	5.40	0.95	0.835	0.075	40.8	1416.5	729.9	686.6	90.2	7.9	1.9
383.0	388.1	303.0	5.45	0.95	0.835	0.080	37.8	1416.2	676.5	739.7	90.3	7.9	1.8
388.0	392.7	303.0	5.51	0.95	0.835	0.085	34.8	1415.8	622.4	793.5	90.4	7.8	1.8
393.0	397.3	303.0	5.56	0.95	0.836	0.090	31.7	1415.5	567.6	847.9	90.5	7.7	1.8
398.0	401.9	303.0	5.61	0.95	0.836	0.095	28.6	1415.2	512.1	903.1	90.6	7.6	1.8
403.0	406.4	303.0	5.66	0.95	0.836	0.100	25.5	1414.9	456.0	958.9	90.7	7.6	1.8

EFFECTIVE SKY TEMP. DURING TEST WAS : 14.5 deg.C

- 180 -

APPENDIX D

Data for Runs of COLSM
To Determine the Effect
of Meteorological Factors on
Thermal Performance

- 181 -

COLSIM PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT	INCID. ANGLE	SOLAR INSDL.	DIFF. FRAC.	FLOW RATE	AIR TEMP.	FLUID TEMP.	WIND
45.0 deg.	0.0 deg.	1000.0 W/cm ²	0.20	0.036 Kg/sec	10.0 deg.C	10.0 deg.C	15.0

GROUND EMITTANCE 0.9; GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI K	TFE K	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRHE	FR	TAEFF	DT/I	EFF
-----W/(sq.M K)-----														
293.0	295.3	22.0	3.8	35.9	357.1	2.59	34.84	2.45	2.98	0.986	0.964	0.835	0.000	80.5
288.0	300.0	25.5	3.8	31.2	356.9	3.00	27.54	2.73	3.26	0.985	0.962	0.836	0.005	78.8
293.0	304.4	29.2	3.8	27.5	356.7	3.35	24.45	2.97	3.50	0.985	0.960	0.837	0.010	77.0
298.0	309.2	33.2	3.8	24.4	356.5	3.60	22.74	3.13	3.66	0.985	0.959	0.838	0.015	75.1
303.0	313.9	37.4	3.8	21.9	356.2	3.80	21.70	3.25	3.78	0.985	0.958	0.838	0.020	73.1
308.0	318.5	41.9	3.8	19.7	355.8	3.96	20.98	3.35	3.88	0.985	0.957	0.839	0.025	71.0
313.0	323.1	46.7	3.8	17.8	355.4	4.10	20.47	3.44	3.97	0.984	0.957	0.839	0.030	68.9
318.0	327.7	51.9	3.8	16.1	355.0	4.23	20.08	3.51	4.04	0.984	0.956	0.839	0.035	66.7
323.0	332.3	57.4	3.8	14.7	354.5	4.34	19.78	3.58	4.11	0.984	0.956	0.840	0.040	64.4
328.0	337.0	63.8	3.8	13.3	353.9	4.45	19.55	3.64	4.17	0.984	0.956	0.840	0.045	62.3
333.0	341.6	70.7	3.8	12.1	353.3	4.54	19.36	3.70	4.23	0.984	0.955	0.840	0.050	60.1
338.0	346.2	78.3	3.8	11.1	352.6	4.64	19.21	3.75	4.28	0.984	0.955	0.840	0.055	57.8
343.0	350.8	86.6	3.8	10.1	351.9	4.72	19.09	3.80	4.33	0.984	0.955	0.840	0.060	55.4
348.0	355.5	95.7	3.8	9.2	351.2	4.80	18.98	3.85	4.38	0.984	0.955	0.841	0.065	53.1
353.0	360.1	105.6	3.8	8.4	350.4	4.88	18.90	3.90	4.43	0.984	0.954	0.841	0.070	50.7
358.0	364.7	116.3	3.8	7.7	349.5	4.96	18.82	3.94	4.47	0.984	0.954	0.841	0.075	48.2
363.0	369.3	127.6	3.8	7.0	348.6	5.03	18.76	3.99	4.52	0.984	0.954	0.841	0.080	45.8
368.0	374.0	139.4	3.8	6.5	347.6	5.10	18.71	4.03	4.56	0.983	0.954	0.841	0.085	43.3
373.0	378.6	151.2	3.8	6.0	346.6	5.17	18.67	4.07	4.60	0.983	0.953	0.841	0.090	40.8
378.0	383.2	162.8	3.8	5.6	345.5	5.23	18.63	4.11	4.64	0.983	0.953	0.841	0.095	38.2
383.0	387.9	173.5	3.8	5.3	344.4	5.30	18.61	4.15	4.68	0.983	0.953	0.841	0.100	35.6

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

3 3

OF / DE

- 182 -

COLSIM PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. WIND
0.0 deg. 0.0 deg. 1000.0 W/cm² 0.20 0.036 Kt/sec 10.0 deg.C 10.0 deg.C 15.0

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
K	K				W/(sq.M K)									
283.0	293.2	22.0	3.8	35.9	357.1	3.28	38.79	3.07	3.60	0.985	0.959	0.832	0.000	79.8
288.0	299.9	25.3	3.8	31.3	356.9	3.49	30.00	3.32	3.85	0.985	0.957	0.834	0.005	77.9
293.0	304.5	29.2	3.8	27.5	356.7	3.97	26.26	3.47	4.00	0.984	0.956	0.835	0.010	75.9
298.0	309.1	33.1	3.8	24.5	356.5	4.18	24.16	3.58	4.11	0.984	0.955	0.835	0.015	73.9
303.0	313.7	37.3	3.8	21.9	356.2	4.34	22.87	3.67	4.20	0.984	0.954	0.836	0.020	71.8
308.0	318.3	41.8	3.8	19.7	355.8	4.49	21.99	3.75	4.28	0.984	0.954	0.836	0.025	69.6
313.0	322.9	46.6	3.8	17.8	355.4	4.62	21.36	3.82	4.35	0.984	0.954	0.837	0.030	67.4
318.0	327.5	51.8	3.8	16.2	355.0	4.73	20.88	3.88	4.41	0.984	0.953	0.837	0.035	65.1
323.0	332.1	57.4	3.8	14.7	354.5	4.84	20.51	3.94	4.47	0.984	0.953	0.837	0.040	62.8
328.0	336.7	63.6	3.8	13.4	353.9	4.94	20.22	3.99	4.52	0.984	0.953	0.837	0.045	60.4
333.0	341.3	70.5	3.8	12.2	353.3	5.04	19.99	4.04	4.57	0.984	0.953	0.838	0.050	58.0
338.0	345.9	78.0	3.8	11.1	352.7	5.13	19.80	4.09	4.62	0.983	0.952	0.838	0.055	55.6
343.0	350.5	86.3	3.8	10.1	352.0	5.21	19.44	4.14	4.67	0.983	0.952	0.838	0.060	53.1
348.0	355.1	95.3	3.8	9.2	351.2	5.30	19.51	4.19	4.71	0.983	0.952	0.838	0.065	50.6
353.0	359.7	105.2	3.8	8.4	350.4	5.37	19.39	4.23	4.76	0.983	0.952	0.838	0.070	48.1
358.0	364.3	115.8	3.8	7.7	349.5	5.45	19.31	4.27	4.80	0.983	0.952	0.838	0.075	45.5
363.0	368.9	127.1	3.8	7.1	348.6	5.53	19.23	4.31	4.84	0.983	0.951	0.839	0.080	42.9
368.0	373.6	138.8	3.8	6.5	347.6	5.60	19.16	4.36	4.88	0.983	0.951	0.839	0.085	40.3
373.0	378.2	150.7	3.8	6.1	346.6	5.67	19.11	4.40	4.92	0.983	0.951	0.839	0.090	37.6
378.0	382.8	162.3	3.8	5.7	345.5	5.74	19.06	4.43	4.96	0.983	0.951	0.839	0.095	34.9
383.0	387.4	173.0	3.8	5.4	344.4	5.81	19.02	4.47	5.00	0.983	0.951	0.839	0.100	32.2

EFFECTIVE SKY TEMP. DURING TEST WAS : -11.2 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. WIND
45.0 deg. 0.0 deg. 1000.0 W/cm² 0.20 0.036 Kt/sec 10.0 deg.C 10.0 deg.C 15.0

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
K	K				W/(sq.M K)									
283.0	295.3	22.0	3.8	35.9	357.1	2.59	34.86	2.45	2.98	0.986	0.944	0.835	0.000	80.5
288.0	300.0	25.5	3.8	31.2	356.9	3.00	27.54	2.73	3.26	0.985	0.962	0.836	0.005	78.8
293.0	304.6	29.2	3.8	27.5	356.7	3.35	24.45	2.97	3.50	0.985	0.960	0.837	0.010	77.0
298.0	309.2	33.2	3.8	24.4	356.5	3.60	22.74	3.13	3.64	0.985	0.959	0.838	0.015	75.1
303.0	313.9	37.4	3.8	21.9	356.2	3.80	21.70	3.25	3.78	0.985	0.958	0.838	0.020	73.1
308.0	318.5	41.9	3.8	19.7	355.8	3.96	20.98	3.35	3.88	0.985	0.957	0.839	0.025	71.0
313.0	323.1	46.7	3.8	17.8	355.4	4.10	20.47	3.44	3.97	0.984	0.957	0.839	0.030	68.9
318.0	327.7	51.9	3.8	16.1	355.0	4.23	20.08	3.51	4.04	0.984	0.956	0.839	0.035	66.7
323.0	332.3	57.4	3.8	14.7	354.5	4.34	19.78	3.58	4.11	0.984	0.956	0.840	0.040	64.6
328.0	337.0	63.8	3.8	13.3	353.9	4.45	19.55	3.64	4.17	0.984	0.956	0.840	0.045	62.3
333.0	341.6	70.7	3.8	12.1	353.3	4.54	19.36	3.70	4.23	0.984	0.955	0.840	0.050	60.1
338.0	346.2	78.3	3.8	11.1	352.6	4.64	19.21	3.75	4.28	0.984	0.955	0.840	0.055	57.8
343.0	350.8	84.4	3.8	10.1	351.9	4.72	19.09	3.80	4.33	0.984	0.955	0.840	0.060	55.4
348.0	355.5	95.7	3.8	9.2	351.2	4.80	18.98	3.85	4.38	0.984	0.955	0.841	0.065	53.1
353.0	360.1	105.6	3.8	8.4	350.4	4.88	18.90	3.90	4.43	0.984	0.954	0.841	0.070	50.7
358.0	364.7	116.3	3.8	7.7	349.5	4.96	18.82	3.94	4.47	0.984	0.954	0.841	0.075	48.2
363.0	369.3	127.6	3.8	7.0	348.6	5.03	18.74	3.99	4.52	0.984	0.954	0.841	0.080	45.8
368.0	374.0	139.4	3.8	6.5	347.6	5.10	18.71	4.03	4.56	0.983	0.954	0.841	0.085	43.3
373.0	378.6	151.2	3.8	6.0	346.6	5.17	18.67	4.07	4.60	0.983	0.953	0.841	0.090	40.8
378.0	383.2	162.8	3.8	5.6	345.5	5.23	18.63	4.11	4.64	0.983	0.953	0.841	0.095	38.2
383.0	387.9	173.5	3.8	5.3	344.4	5.30	18.61	4.15	4.68	0.983	0.953	0.841	0.100	35.6

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

- 183 -

COLSIM PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. WIND
60.0 deg. 0.0 deg. 1000.0 W/m² 0.20 0.036 K/s 10.0 deg.C 10.0 deg.C 15.0

GROUND EMISSANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
K	K				W/(m ² K)									
283.0	295.4	22.0	3.8	35.9	357.1	2.29	32.74	2.18	2.70	0.984	0.964	0.834	0.000	80.6
288.0	300.0	25.5	3.8	31.2	356.9	2.72	26.23	2.49	3.02	0.984	0.964	0.836	0.005	79.1
293.0	304.7	29.3	3.8	27.5	356.7	2.98	23.48	2.67	3.20	0.985	0.962	0.837	0.010	77.4
298.0	309.3	33.2	3.8	24.4	356.5	3.23	21.97	2.84	3.37	0.985	0.961	0.837	0.015	75.6
303.0	314.0	37.4	3.8	21.8	356.2	3.44	21.03	2.98	3.51	0.985	0.960	0.838	0.020	73.7
308.0	318.6	41.9	3.8	19.7	355.8	3.61	20.40	3.09	3.62	0.985	0.959	0.838	0.025	71.7
313.0	323.2	46.7	3.8	17.8	355.4	3.75	19.95	3.18	3.71	0.985	0.959	0.839	0.030	69.7
318.0	327.9	52.0	3.8	16.1	355.0	3.88	19.61	3.26	3.79	0.985	0.958	0.839	0.035	67.7
323.0	332.5	57.7	3.8	14.6	354.5	3.99	19.35	3.33	3.86	0.985	0.958	0.839	0.040	65.6
328.0	337.1	63.9	3.8	13.3	353.9	4.10	19.15	3.40	3.92	0.984	0.958	0.839	0.045	63.5
333.0	341.8	70.8	3.8	12.1	353.3	4.19	18.98	3.46	3.98	0.984	0.957	0.839	0.050	61.3
338.0	346.4	78.4	3.8	11.0	352.6	4.28	18.86	3.51	4.04	0.984	0.957	0.840	0.055	59.1
343.0	351.0	86.8	3.8	10.0	351.9	4.37	18.75	3.56	4.09	0.984	0.957	0.840	0.060	56.9
348.0	355.7	95.9	3.8	9.2	351.2	4.45	18.66	3.61	4.14	0.984	0.956	0.840	0.065	54.6
353.0	360.3	105.8	3.8	8.4	350.3	4.52	18.58	3.66	4.19	0.984	0.956	0.840	0.070	52.3
358.0	365.0	116.5	3.8	7.7	349.5	4.60	18.52	3.70	4.23	0.984	0.956	0.840	0.075	50.0
363.0	369.6	127.9	3.8	7.0	348.5	4.67	18.47	3.75	4.28	0.984	0.956	0.840	0.080	47.6
368.0	374.2	139.7	3.8	6.5	347.6	4.73	18.43	3.79	4.32	0.984	0.956	0.840	0.085	45.2
373.0	378.9	151.6	3.8	6.0	346.5	4.80	18.39	3.83	4.36	0.984	0.955	0.841	0.090	42.8
378.0	383.5	163.2	3.8	5.6	345.5	4.86	18.36	3.87	4.40	0.984	0.955	0.841	0.095	40.4
383.0	388.2	173.8	3.8	5.3	344.3	4.93	18.34	3.91	4.43	0.984	0.955	0.841	0.100	37.9

EFFECTIVE SKY TEMP. DURING TEST WAS : -3.4 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. WIND
75.0 deg. 0.0 deg. 1000.0 W/m² 0.20 0.036 K/s 10.0 deg.C 10.0 deg.C 15.0

GROUND EMISSANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
K	K				W/(m ² K)									
283.0	295.4	22.0	3.8	35.9	357.1	1.96	30.53	1.88	2.40	0.987	0.969	0.833	0.000	80.7
288.0	300.1	25.5	3.8	31.2	356.9	2.25	24.83	2.09	2.62	0.986	0.967	0.834	0.005	79.4
293.0	304.8	29.3	3.8	27.5	356.7	2.56	22.46	2.32	2.85	0.986	0.965	0.835	0.010	77.9
298.0	309.4	33.2	3.8	24.4	356.5	2.78	21.13	2.48	3.01	0.986	0.964	0.836	0.015	76.2
303.0	314.1	37.5	3.8	21.8	356.2	2.95	20.31	2.60	3.13	0.986	0.963	0.836	0.020	74.5
308.0	318.7	42.0	3.8	19.6	355.8	3.09	19.75	2.69	3.22	0.985	0.963	0.837	0.025	72.8
313.0	323.4	46.8	3.8	17.7	355.4	3.21	19.35	2.77	3.30	0.985	0.962	0.837	0.030	71.0
318.0	328.1	52.1	3.8	16.1	355.0	3.31	19.05	2.84	3.37	0.985	0.962	0.837	0.035	69.2
323.0	332.7	57.8	3.8	14.6	354.5	3.40	18.82	2.90	3.43	0.985	0.961	0.837	0.040	67.3
328.0	337.4	64.1	3.8	13.3	353.9	3.49	18.64	2.96	3.49	0.985	0.961	0.838	0.045	65.4
333.0	342.1	71.1	3.8	12.1	353.3	3.58	18.50	3.02	3.55	0.985	0.961	0.838	0.050	63.4
338.0	346.7	78.7	3.8	11.0	352.6	3.67	18.40	3.08	3.61	0.985	0.960	0.838	0.055	61.4
343.0	351.4	87.1	3.8	10.0	351.9	3.75	18.31	3.13	3.66	0.985	0.960	0.838	0.060	59.4
348.0	356.1	96.3	3.8	9.1	351.1	3.83	18.23	3.18	3.71	0.985	0.960	0.838	0.065	57.3
353.0	360.7	106.3	3.8	8.3	350.3	3.90	18.17	3.23	3.76	0.985	0.960	0.838	0.070	55.2
358.0	365.4	117.0	3.8	7.6	349.4	3.97	18.12	3.28	3.81	0.985	0.959	0.839	0.075	53.1
363.0	370.1	128.4	3.8	7.0	348.5	4.04	18.07	3.32	3.85	0.984	0.959	0.839	0.080	50.9
368.0	374.7	140.3	3.8	6.5	347.5	4.10	18.04	3.36	3.89	0.984	0.959	0.839	0.085	48.7
373.0	379.4	152.7	3.8	6.0	346.5	4.16	18.01	3.40	3.93	0.984	0.959	0.839	0.090	46.5
378.0	384.1	163.8	3.8	5.6	345.4	4.22	17.98	3.44	3.97	0.984	0.958	0.839	0.095	44.3
383.0	388.7	174.4	3.8	5.3	344.3	4.28	17.96	3.48	4.01	0.984	0.958	0.839	0.100	42.0

EFFECTIVE SKY TEMP. DURING TEST WAS : -3.4 deg.C

- 184 -

COLSIM PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. WIND
45.0 deg. 0.0 deg. 1000.0 W/cm² 0.20 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 3.0

GROUND EMISSANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI K	TFE K	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRMF	FR	TAEFF	DT/I	FFF
-----W/(sq.M K)-----														
283.0	295.4	22.0	3.8	35.9	357.1	2.56	25.08	2.36	2.89	0.986	0.963	0.836	0.000	80.6
288.0	300.1	25.5	3.8	31.2	356.9	2.95	17.90	2.56	3.09	0.986	0.963	0.838	0.005	79.2
293.0	304.7	29.3	3.8	27.5	356.7	3.27	14.96	2.71	3.24	0.985	0.962	0.840	0.010	77.7
298.0	309.4	33.2	3.8	24.4	356.5	3.51	13.39	2.80	3.33	0.985	0.961	0.841	0.015	76.0
303.0	314.1	37.5	3.8	21.8	356.2	3.69	12.45	2.87	3.40	0.985	0.961	0.842	0.020	74.4
308.0	318.7	42.0	3.8	19.6	355.8	3.85	11.87	2.92	3.45	0.985	0.961	0.842	0.025	72.6
313.0	323.4	46.8	3.8	17.8	355.4	3.98	11.37	2.97	3.50	0.985	0.961	0.843	0.030	70.9
318.0	328.1	52.1	3.8	16.1	355.0	4.10	11.03	3.01	3.54	0.985	0.960	0.843	0.035	69.1
323.0	332.7	57.8	3.8	14.6	354.5	4.21	10.79	3.05	3.58	0.985	0.960	0.844	0.040	67.3
328.0	337.4	64.1	3.8	13.3	353.9	4.31	10.60	3.08	3.61	0.985	0.960	0.844	0.045	65.4
333.0	342.1	71.1	3.8	12.1	353.3	4.40	10.45	3.12	3.65	0.985	0.960	0.845	0.050	63.6
338.0	346.8	78.7	3.8	11.0	352.6	4.49	10.34	3.15	3.68	0.985	0.960	0.845	0.055	61.7
343.0	351.4	87.1	3.8	10.0	351.9	4.57	10.25	3.18	3.71	0.985	0.960	0.845	0.060	59.7
348.0	356.1	96.3	3.8	9.1	351.1	4.65	10.19	3.21	3.74	0.985	0.960	0.845	0.065	57.8
353.0	360.8	106.4	3.8	8.3	350.3	4.73	10.13	3.24	3.77	0.985	0.959	0.845	0.070	55.8
358.0	365.5	117.2	3.8	7.6	349.4	4.80	10.09	3.27	3.80	0.985	0.959	0.846	0.075	53.8
363.0	370.2	128.6	3.8	7.0	348.5	4.87	10.06	3.30	3.83	0.984	0.959	0.846	0.080	51.7
368.0	374.8	140.4	3.8	6.5	347.5	4.94	10.04	3.33	3.86	0.984	0.959	0.846	0.085	49.6
373.0	379.5	152.4	3.8	6.0	346.5	5.01	10.03	3.36	3.89	0.984	0.959	0.846	0.090	47.6
378.0	384.2	164.0	3.8	5.6	345.4	5.07	10.02	3.39	3.92	0.984	0.959	0.846	0.095	45.4
383.0	388.9	174.6	3.8	5.3	344.2	5.14	10.02	3.42	3.95	0.984	0.959	0.846	0.100	43.3

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. WIND
45.0 deg. 0.0 deg. 1000.0 W/cm² 0.20 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 10.0

GROUND EMISSANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI K	TFE K	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	FFF
-----W/(sq.M K)-----														
283.0	295.4	22.0	3.8	35.9	357.1	2.57	29.95	2.41	2.94	0.986	0.964	0.835	0.000	80.5
288.0	300.0	25.5	3.8	31.2	356.9	2.97	22.71	2.66	3.19	0.986	0.962	0.837	0.005	79.0
293.0	304.7	29.2	3.8	27.5	356.7	3.32	19.66	2.86	3.39	0.985	0.961	0.838	0.010	77.3
298.0	309.3	33.2	3.8	24.4	356.5	3.56	18.02	3.00	3.53	0.985	0.960	0.839	0.015	75.5
303.0	313.9	37.4	3.8	21.8	356.2	3.76	16.99	3.10	3.63	0.985	0.959	0.840	0.020	73.6
308.0	318.6	41.9	3.8	19.7	355.8	3.92	16.30	3.18	3.71	0.985	0.959	0.840	0.025	71.7
313.0	323.2	46.7	3.8	17.8	355.4	4.06	15.81	3.25	3.78	0.985	0.958	0.841	0.030	69.7
318.0	327.9	52.0	3.8	16.1	355.0	4.18	15.46	3.31	3.84	0.985	0.958	0.841	0.035	67.7
323.0	332.5	57.7	3.8	14.6	354.5	4.29	15.09	3.37	3.89	0.984	0.958	0.841	0.040	65.7
328.0	337.1	64.0	3.8	13.3	353.9	4.39	14.97	3.42	3.95	0.984	0.957	0.842	0.045	63.6
333.0	341.8	70.8	3.8	12.1	353.3	4.49	14.80	3.46	3.99	0.984	0.957	0.842	0.050	61.5
338.0	346.4	78.4	3.8	11.0	352.6	4.58	14.66	3.51	4.04	0.984	0.957	0.842	0.055	59.3
343.0	351.1	86.8	3.8	10.0	351.9	4.66	14.53	3.55	4.08	0.984	0.957	0.842	0.060	57.2
348.0	355.7	95.9	3.8	9.2	351.1	4.74	14.46	3.59	4.12	0.984	0.957	0.843	0.065	55.0
353.0	360.4	105.9	3.8	8.4	350.3	4.82	14.39	3.63	4.16	0.984	0.956	0.843	0.070	52.7
358.0	365.0	116.6	3.8	7.6	349.5	4.90	14.33	3.67	4.20	0.984	0.956	0.843	0.075	50.5
363.0	369.7	128.0	3.8	7.0	348.5	4.97	14.28	3.71	4.24	0.984	0.956	0.843	0.080	48.2
368.0	374.3	139.8	3.8	6.5	347.6	5.04	14.23	3.74	4.27	0.984	0.956	0.843	0.085	45.9
373.0	379.0	151.7	3.8	6.0	346.5	5.11	14.20	3.78	4.31	0.984	0.956	0.843	0.090	43.5
378.0	383.6	163.3	3.8	5.6	345.4	5.17	14.18	3.81	4.34	0.984	0.956	0.843	0.095	41.2
383.0	388.3	173.9	3.8	5.3	344.3	5.24	14.16	3.85	4.38	0.984	0.955	0.843	0.100	38.8

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

- 185 -

COLSIN PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID. ANGLE SOLAR INSOL. DIFF. FRAC. FLOW RATE AIR TEMP. FLUID TEMP. WIND
45.0 deg. 0.0 deg. 1000.0 W/sqM 0.20 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 15.0

GROUND EMISSANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI K	TFE K	REF	NUF	PR	HF W/(sq.M K)	IPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	FFF
283.0	295.3	22.0	3.8	35.9	357.1	2.59	34.86	2.45	2.98	0.986	0.964	0.835	0.000	80.5
288.0	300.0	25.5	3.8	31.2	356.9	3.00	27.54	2.73	3.26	0.985	0.962	0.836	0.005	78.8
293.0	304.6	29.2	3.8	27.5	356.7	3.35	24.45	2.97	3.50	0.985	0.960	0.837	0.010	77.0
298.0	309.2	33.2	3.8	24.4	356.5	3.60	22.76	3.13	3.66	0.985	0.959	0.838	0.015	75.1
303.0	313.9	37.4	3.8	21.9	356.2	3.80	21.70	3.25	3.78	0.985	0.958	0.838	0.020	73.1
308.0	318.5	41.9	3.8	19.7	355.8	3.96	20.98	3.35	3.88	0.985	0.957	0.839	0.025	71.0
313.0	323.1	46.7	3.8	17.8	355.4	4.10	20.47	3.44	3.97	0.984	0.957	0.839	0.030	68.9
318.0	327.7	51.9	3.8	16.1	355.0	4.23	20.08	3.51	4.04	0.984	0.956	0.839	0.035	66.7
323.0	332.3	57.6	3.8	14.7	354.5	4.34	19.78	3.58	4.11	0.984	0.956	0.840	0.040	64.6
328.0	337.0	63.8	3.8	13.3	353.9	4.45	19.55	3.64	4.17	0.984	0.956	0.840	0.045	62.3
333.0	341.6	70.7	3.8	12.1	353.3	4.54	19.36	3.70	4.23	0.984	0.955	0.840	0.050	60.1
338.0	346.2	78.3	3.8	11.1	352.6	4.64	19.21	3.75	4.28	0.984	0.955	0.840	0.055	57.8
343.0	350.8	86.4	3.8	10.1	351.9	4.72	19.09	3.80	4.33	0.984	0.955	0.840	0.060	55.4
348.0	355.5	95.7	3.8	9.2	351.2	4.80	18.98	3.85	4.38	0.984	0.955	0.841	0.065	53.1
353.0	360.1	105.6	3.8	8.4	350.4	4.88	18.90	3.90	4.43	0.984	0.954	0.841	0.070	50.7
358.0	364.7	116.3	3.8	7.7	349.5	4.96	18.82	3.94	4.47	0.984	0.954	0.841	0.075	48.2
363.0	369.3	127.6	3.8	7.0	348.6	5.03	18.76	3.99	4.52	0.984	0.954	0.841	0.080	45.8
368.0	374.0	139.4	3.8	6.5	347.6	5.10	18.71	4.03	4.56	0.983	0.954	0.841	0.085	43.3
373.0	378.6	151.2	3.8	6.0	346.6	5.17	18.67	4.07	4.60	0.983	0.953	0.841	0.090	40.8
378.0	383.2	162.8	3.8	5.6	345.5	5.23	18.63	4.11	4.64	0.983	0.953	0.841	0.095	38.2
383.0	387.9	173.5	3.8	5.3	344.4	5.30	18.61	4.15	4.68	0.983	0.953	0.841	0.100	35.6

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID. ANGLE SOLAR INSOL. DIFF. FRAC. FLOW RATE AIR TEMP. FLUID TEMP. WIND
45.0 deg. 0.0 deg. 1000.0 W/sqM 0.20 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 20.0

GROUND EMISSANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI K	TFE K	REF	NUF	PR	HF W/(sq.M K)	IPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	FFF
283.0	295.3	22.0	3.8	35.9	357.1	2.59	39.79	2.47	3.00	0.986	0.964	0.834	0.000	80.4
288.0	300.0	25.5	3.8	31.2	356.9	3.02	32.42	2.79	3.32	0.985	0.961	0.836	0.005	78.7
293.0	304.6	29.2	3.8	27.5	356.7	3.37	29.31	3.05	3.58	0.985	0.959	0.836	0.010	76.8
298.0	309.2	33.1	3.8	24.5	356.5	3.62	27.58	3.23	3.74	0.985	0.958	0.837	0.015	74.8
303.0	313.8	37.4	3.8	21.9	356.2	3.83	26.49	3.36	3.89	0.985	0.957	0.837	0.020	72.7
308.0	318.4	41.8	3.8	19.7	355.8	3.99	25.76	3.48	4.01	0.984	0.956	0.838	0.025	70.5
313.0	323.0	46.6	3.8	17.8	355.4	4.13	25.23	3.57	4.10	0.984	0.956	0.838	0.030	68.3
318.0	327.6	51.8	3.8	16.2	355.0	4.26	24.83	3.66	4.19	0.984	0.955	0.838	0.035	66.1
323.0	332.2	57.5	3.8	14.7	354.5	4.38	24.61	3.73	4.26	0.984	0.955	0.839	0.040	63.8
328.0	336.8	63.7	3.8	13.4	353.9	4.48	24.27	3.80	4.33	0.984	0.954	0.839	0.045	61.4
333.0	341.4	70.6	3.8	12.2	353.3	4.58	24.07	3.87	4.40	0.984	0.954	0.839	0.050	59.1
338.0	346.1	78.1	3.8	11.1	352.7	4.67	23.90	3.93	4.46	0.984	0.954	0.839	0.055	56.6
343.0	350.7	86.4	3.8	10.1	351.9	4.76	23.77	3.98	4.51	0.984	0.953	0.839	0.060	54.2
348.0	355.3	95.5	3.8	9.2	351.2	4.84	23.65	4.04	4.57	0.983	0.953	0.839	0.065	51.7
353.0	359.9	105.4	3.8	8.4	350.4	4.92	23.56	4.09	4.62	0.983	0.953	0.839	0.070	49.2
358.0	364.5	116.0	3.8	7.7	349.5	4.99	23.47	4.14	4.67	0.983	0.953	0.840	0.075	46.6
363.0	369.1	127.3	3.8	7.1	348.6	5.07	23.40	4.19	4.72	0.983	0.952	0.840	0.080	44.0
368.0	373.7	139.0	3.8	6.5	347.6	5.14	23.35	4.23	4.76	0.983	0.952	0.840	0.085	41.4
373.0	378.3	150.9	3.8	6.0	346.6	5.21	23.29	4.28	4.81	0.983	0.952	0.840	0.090	38.8
378.0	382.9	162.5	3.8	5.7	345.5	5.27	23.25	4.32	4.85	0.983	0.952	0.840	0.095	36.1
383.0	387.5	173.2	3.8	5.3	344.4	5.34	23.21	4.36	4.89	0.983	0.951	0.840	0.100	33.4

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

- 186 -

COLSIM PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION
TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. WIND
45.0 deg. 0.0 deg. 1000.0 W/sqM 0.20 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 30.0

GROUND EMISSANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRHE	FR	TAEFF	DT/I	EFF
K	K				W/(sq.M K)									
283.0	295.3	22.0	3.8	35.9	357.1	2.40	49.69	2.51	3.04	0.986	0.963	0.834	0.000	80.3
288.0	300.0	25.3	3.8	31.2	356.9	3.04	42.26	2.87	3.39	0.985	0.961	0.835	0.005	78.6
293.0	304.6	29.2	3.8	27.5	356.7	3.40	39.10	3.15	3.68	0.985	0.958	0.835	0.010	76.5
298.0	309.1	33.1	3.8	24.5	356.5	3.66	37.35	3.35	3.88	0.985	0.957	0.836	0.015	74.4
303.0	313.7	37.3	3.8	21.9	356.2	3.86	36.24	3.51	4.04	0.984	0.956	0.836	0.020	72.2
308.0	318.3	41.8	3.8	19.7	355.8	4.03	35.48	3.64	4.17	0.984	0.955	0.836	0.025	69.9
313.0	322.9	46.6	3.8	17.8	355.4	4.17	34.91	3.75	4.28	0.984	0.954	0.837	0.030	67.6
318.0	327.5	51.8	3.8	16.2	355.0	4.30	34.49	3.84	4.37	0.984	0.954	0.837	0.035	65.2
323.0	332.1	57.4	3.8	14.7	354.5	4.42	34.17	3.93	4.46	0.984	0.953	0.837	0.040	62.8
328.0	336.7	63.6	3.8	13.4	353.9	4.52	33.90	4.01	4.54	0.984	0.953	0.837	0.045	60.3
333.0	341.3	70.4	3.8	12.2	353.3	4.62	33.69	4.08	4.61	0.983	0.952	0.837	0.050	57.8
338.0	345.8	78.0	3.8	11.1	352.7	4.71	33.51	4.15	4.68	0.983	0.952	0.837	0.055	55.2
343.0	350.4	86.2	3.8	10.1	352.0	4.80	33.37	4.22	4.75	0.983	0.951	0.837	0.060	52.6
348.0	355.0	95.3	3.8	9.2	351.2	4.88	33.24	4.28	4.81	0.983	0.951	0.838	0.065	49.9
353.0	359.6	105.1	3.8	8.4	350.4	4.96	33.13	4.34	4.87	0.983	0.951	0.838	0.070	47.3
358.0	364.2	115.7	3.8	7.7	349.5	5.04	33.04	4.39	4.92	0.983	0.951	0.838	0.075	44.5
363.0	368.8	126.9	3.8	7.1	348.6	5.11	32.96	4.45	4.98	0.983	0.950	0.838	0.080	41.8
368.0	373.4	138.6	3.8	6.5	347.7	5.18	32.89	4.50	5.03	0.983	0.950	0.838	0.085	39.0
373.0	378.0	150.5	3.8	6.1	346.6	5.25	32.83	4.55	5.08	0.983	0.950	0.838	0.090	36.2
378.0	382.6	162.0	3.8	5.7	345.6	5.32	32.78	4.60	5.13	0.983	0.949	0.838	0.095	33.3
383.0	387.1	172.7	3.8	5.4	344.4	5.39	32.73	4.65	5.18	0.982	0.949	0.838	0.100	30.4

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION
TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. WIND
45.0 deg. 0.0 deg. 1000.0 W/sqM 0.20 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 40.0

GROUND EMISSANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRHE	FR	TAEFF	DT/I	EFF
K	K				W/(sq.M K)									
283.0	295.3	22.0	3.8	35.9	357.1	2.61	59.61	2.54	3.07	0.986	0.963	0.834	0.000	80.3
288.0	299.9	25.3	3.8	31.2	356.9	3.06	52.15	2.92	3.44	0.985	0.960	0.834	0.005	78.5
293.0	304.5	29.2	3.8	27.5	356.7	3.42	48.97	3.22	3.75	0.985	0.958	0.835	0.010	76.4
298.0	309.1	33.2	3.8	24.4	356.5	3.68	47.20	3.43	3.96	0.984	0.956	0.835	0.015	74.2
303.0	313.7	37.3	3.8	21.9	356.2	3.88	46.07	3.60	4.13	0.984	0.955	0.835	0.020	71.9
308.0	318.3	41.8	3.8	19.7	355.8	4.05	45.29	3.74	4.27	0.984	0.954	0.836	0.025	69.5
313.0	322.8	46.5	3.8	17.9	355.4	4.19	44.73	3.86	4.38	0.984	0.953	0.836	0.030	67.1
318.0	327.4	51.7	3.8	16.2	355.0	4.32	44.30	3.96	4.49	0.984	0.953	0.836	0.035	64.7
323.0	332.0	57.4	3.8	14.7	354.5	4.44	43.96	4.05	4.58	0.984	0.952	0.836	0.040	62.2
328.0	336.6	63.6	3.8	13.4	353.9	4.55	43.69	4.14	4.67	0.983	0.952	0.836	0.045	59.6
333.0	341.1	70.4	3.8	12.2	353.3	4.65	43.47	4.22	4.75	0.983	0.951	0.836	0.050	57.0
338.0	345.7	77.9	3.8	11.1	352.7	4.74	43.28	4.29	4.82	0.983	0.951	0.836	0.055	54.3
343.0	350.3	86.1	3.8	10.1	352.0	4.83	43.12	4.36	4.89	0.983	0.950	0.836	0.060	51.6
348.0	354.9	95.1	3.8	9.2	351.2	4.91	42.99	4.43	4.96	0.983	0.950	0.836	0.065	48.9
353.0	359.4	104.9	3.8	8.4	350.4	4.99	42.88	4.49	5.02	0.983	0.950	0.837	0.070	46.1
358.0	364.0	115.5	3.8	7.7	349.6	5.07	42.78	4.55	5.08	0.983	0.949	0.837	0.075	43.3
363.0	368.6	126.7	3.8	7.1	348.6	5.14	42.70	4.61	5.14	0.983	0.949	0.837	0.080	40.4
368.0	373.2	138.4	3.8	6.5	347.7	5.21	42.62	4.67	5.19	0.983	0.949	0.837	0.085	37.5
373.0	377.7	150.2	3.8	6.1	346.7	5.28	42.55	4.72	5.25	0.982	0.948			
378.0	382.3	161.7	3.8	5.7	345.6	5.35	42.50	4.77	5.30	0.982	0.948			
383.0	386.9	172.5	3.8	5.4	344.5	5.41	42.44	4.82	5.35	0.982	0.948			

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

- 187 -

COLBIM PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION
 TILT INCID. ANGLE SOLAR INSOL. DIFF. FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
 45.0 deg. 60.0 deg. 1000.0 W/cm² 0.20 0.036 K/s 10.0 deg.C 10.0 deg.C 15.0 W/(cm² K)
 GROUND EMISSANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS					HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
TFI	TFF	REF	NUF	PR	-----W/(cm ² K)-----									
K	K													
283.0	294.5	21.7	3.8	36.3	357.1	2.53	36.19	2.40	2.93	0.984	0.944	0.779	0.000	75.1
288.0	299.2	25.2	3.8	31.6	356.9	2.96	28.00	2.70	3.23	0.985	0.942	0.780	0.005	73.5
293.0	303.8	29.0	3.8	27.7	356.7	3.32	24.68	2.95	3.48	0.985	0.940	0.781	0.010	71.7
298.0	308.5	32.9	3.8	24.6	356.5	3.58	22.89	3.12	3.65	0.985	0.939	0.782	0.015	69.8
303.0	313.1	37.0	3.8	22.1	356.2	3.78	21.79	3.24	3.77	0.985	0.938	0.783	0.020	67.8
308.0	317.7	41.5	3.8	19.9	355.9	3.95	21.05	3.34	3.87	0.985	0.937	0.783	0.025	65.7
313.0	322.3	46.3	3.8	18.0	355.5	4.09	20.51	3.43	3.96	0.984	0.937	0.784	0.030	63.6
318.0	327.0	51.5	3.8	16.3	355.0	4.22	20.12	3.51	4.04	0.984	0.936	0.784	0.035	61.5
323.0	331.6	57.1	3.8	14.8	354.5	4.33	19.81	3.57	4.10	0.984	0.936	0.784	0.040	59.3
328.0	336.2	63.3	3.8	13.4	354.0	4.44	19.57	3.64	4.17	0.984	0.936	0.784	0.045	57.0
333.0	340.8	70.1	3.8	12.2	353.4	4.54	19.38	3.70	4.22	0.984	0.935	0.785	0.050	54.8
338.0	345.5	77.6	3.8	11.1	352.7	4.63	19.22	3.75	4.28	0.984	0.935	0.785	0.055	52.5
343.0	350.1	85.9	3.8	10.1	352.0	4.71	19.10	3.80	4.33	0.984	0.935	0.785	0.060	50.1
348.0	354.7	94.9	3.8	9.2	351.2	4.79	18.99	3.85	4.38	0.984	0.935	0.785	0.065	47.8
353.0	359.4	104.8	3.8	8.4	350.4	4.87	18.90	3.89	4.42	0.984	0.934	0.785	0.070	45.4
358.0	364.0	115.4	3.8	7.7	349.6	4.95	18.83	3.94	4.47	0.984	0.934	0.785	0.075	43.0
363.0	368.6	126.7	3.8	7.1	348.6	5.02	18.77	3.98	4.51	0.984	0.934	0.785	0.080	40.5
368.0	373.2	138.4	3.8	6.5	347.7	5.09	18.72	4.02	4.55	0.983	0.934	0.786	0.085	38.0
373.0	377.9	150.3	3.8	6.1	346.6	5.16	18.67	4.06	4.59	0.983	0.933	0.786	0.090	35.5
378.0	382.5	162.0	3.8	5.7	345.6	5.23	18.64	4.10	4.63	0.983	0.933	0.786	0.095	32.9
383.0	387.1	172.7	3.8	5.4	344.4	5.29	18.61	4.14	4.67	0.983	0.933	0.786	0.100	30.4

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION
 TILT INCID. ANGLE SOLAR INSOL. DIFF. FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
 45.0 deg. 75.0 deg. 1000.0 W/cm² 0.20 0.036 K/s 10.0 deg.C 10.0 deg.C 15.0 W/(cm² K)
 GROUND EMISSANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS					HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
TFI	TFF	REF	NUF	PR	-----W/(cm ² K)-----									
K	K													
283.0	292.0	20.9	3.8	37.7	357.1	2.32	41.69	2.24	2.77	0.986	0.944	0.607	0.000	58.6
288.0	296.7	24.3	3.8	32.7	357.0	2.85	29.66	2.64	3.16	0.986	0.942	0.609	0.005	57.1
293.0	301.4	28.0	3.8	28.7	356.8	3.22	25.48	2.88	3.41	0.985	0.941	0.610	0.010	55.3
298.0	306.0	31.8	3.8	25.4	356.6	3.51	23.34	3.07	3.60	0.985	0.939	0.611	0.015	53.4
303.0	310.7	35.9	3.8	22.7	356.3	3.72	22.08	3.21	3.74	0.985	0.938	0.612	0.020	51.4
308.0	315.3	40.3	3.8	20.4	356.0	3.90	21.25	3.32	3.84	0.985	0.938	0.612	0.025	49.4
313.0	320.0	45.0	3.8	18.4	355.6	4.05	20.66	3.41	3.93	0.984	0.937	0.612	0.030	47.3
318.0	324.6	50.1	3.8	16.7	355.1	4.18	20.23	3.48	4.01	0.984	0.936	0.613	0.035	45.2
323.0	329.2	55.7	3.8	15.1	354.6	4.30	19.90	3.55	4.08	0.984	0.936	0.613	0.040	43.0
328.0	333.9	61.7	3.8	13.8	354.1	4.41	19.64	3.62	4.15	0.984	0.936	0.613	0.045	40.8
333.0	338.5	68.4	3.8	12.5	353.5	4.51	19.43	3.68	4.21	0.984	0.935	0.613	0.050	38.5
338.0	343.2	75.7	3.8	11.4	352.9	4.60	19.26	3.73	4.26	0.984	0.935	0.614	0.055	36.2
343.0	347.8	83.8	3.8	10.4	352.2	4.69	19.13	3.79	4.31	0.984	0.935	0.614	0.060	33.9
348.0	352.4	92.7	3.8	9.5	351.4	4.77	19.02	3.83	4.36	0.984	0.935	0.614	0.065	31.5
353.0	357.1	102.4	3.8	8.6	350.6	4.85	18.93	3.88	4.41	0.984	0.934	0.614	0.070	29.2
358.0	361.7	112.8	3.8	7.9	349.8	4.93	18.85	3.93	4.46	0.984	0.934	0.614	0.075	26.7
363.0	366.4	124.0	3.8	7.2	348.9	5.00	18.79	3.97	4.50	0.984	0.934	0.614	0.080	24.3
368.0	371.0	135.7	3.8	6.7	347.9	5.07	18.73	4.01	4.54	0.983	0.934	0.615	0.085	21.8
373.0	375.7	147.4	3.8	6.2	346.9	5.14	18.69	4.05	4.58	0.983	0.934	0.615	0.090	19.3
378.0	380.3	159.3	3.8	5.8	345.8	5.21	18.65	4.09	4.62	0.983	0.933	0.615	0.095	16.8
383.0	384.9	170.3	3.8	5.4	344.7	5.27	18.62	4.13	4.66	0.983	0.933	0.615	0.100	14.2

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

- 188 -

COLSIN PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID. ANGLE SOLAR INSOL. DIFF. FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 0.0 deg. 1000.0 W/sm 0.20 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 15.0 W/(sq.M K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
K	K				W/(sq.M K)									
283.0	295.3	22.0	3.8	35.9	357.1	2.59	34.74	2.45	2.98	0.986	0.964	0.835	0.000	80.5
288.0	300.0	25.5	3.8	31.2	356.9	3.00	27.54	2.73	3.26	0.985	0.962	0.836	0.005	78.8
293.0	304.6	29.2	3.8	27.5	356.7	3.35	24.45	2.97	3.50	0.985	0.960	0.837	0.010	77.0
298.0	309.2	33.2	3.8	24.4	356.5	3.60	22.76	3.13	3.66	0.985	0.959	0.838	0.015	75.1
303.0	313.9	37.4	3.8	21.9	356.2	3.80	21.70	3.25	3.78	0.985	0.958	0.838	0.020	73.1
308.0	318.5	41.9	3.8	19.7	355.8	3.94	20.98	3.35	3.88	0.985	0.957	0.839	0.025	71.0
313.0	323.1	46.7	3.8	17.8	355.4	4.10	20.47	3.44	3.97	0.984	0.957	0.839	0.030	68.9
318.0	327.7	51.9	3.8	16.1	355.0	4.23	20.08	3.51	4.04	0.984	0.956	0.839	0.035	66.7
323.0	332.3	57.6	3.8	14.7	354.5	4.34	19.78	3.58	4.11	0.984	0.956	0.840	0.040	64.6
328.0	337.0	63.8	3.8	13.3	353.9	4.45	19.55	3.64	4.17	0.984	0.956	0.840	0.045	62.3
333.0	341.6	70.7	3.8	12.1	353.3	4.54	19.36	3.70	4.23	0.984	0.955	0.840	0.050	60.1
338.0	346.2	78.3	3.8	11.1	352.6	4.64	19.21	3.75	4.28	0.984	0.955	0.840	0.055	57.8
343.0	350.8	86.6	3.8	10.1	351.9	4.72	19.09	3.80	4.33	0.984	0.955	0.840	0.060	55.4
348.0	355.5	95.7	3.8	9.2	351.2	4.80	18.98	3.85	4.38	0.984	0.955	0.841	0.065	53.1
353.0	360.1	105.6	3.8	8.4	350.4	4.88	18.90	3.90	4.43	0.984	0.954	0.841	0.070	50.7
358.0	364.7	116.3	3.8	7.7	349.5	4.96	18.82	3.94	4.47	0.984	0.954	0.841	0.075	48.2
363.0	369.3	127.6	3.8	7.0	348.6	5.03	18.76	3.99	4.52	0.984	0.954	0.841	0.080	45.8
368.0	374.0	139.4	3.8	6.5	347.6	5.10	18.71	4.03	4.56	0.983	0.954	0.841	0.085	43.3
373.0	378.6	151.2	3.8	6.0	346.6	5.17	18.67	4.07	4.60	0.983	0.953	0.841	0.090	40.8
378.0	383.2	162.8	3.8	5.6	345.5	5.23	18.63	4.11	4.64	0.983	0.953	0.841	0.095	38.2
383.0	387.9	173.5	3.8	5.3	344.4	5.30	18.61	4.15	4.68	0.983	0.953	0.841	0.100	35.6

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID. ANGLE SOLAR INSOL. DIFF. FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 45.0 deg. 1000.0 W/sm 0.20 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 15.0 W/(sq.M K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
K	K				W/(sq.M K)									
283.0	295.2	22.0	3.8	35.9	357.1	2.58	35.08	2.44	2.97	0.986	0.964	0.825	0.000	79.5
288.0	299.9	25.5	3.8	31.3	356.9	2.99	27.67	2.73	3.26	0.985	0.962	0.826	0.005	77.9
293.0	304.5	29.2	3.8	27.5	356.7	3.34	24.49	2.97	3.50	0.985	0.960	0.827	0.010	76.0
298.0	309.1	33.1	3.8	24.5	356.5	3.60	22.77	3.13	3.66	0.985	0.959	0.828	0.015	74.1
303.0	313.7	37.3	3.8	21.9	356.2	3.80	21.72	3.25	3.78	0.985	0.958	0.828	0.020	72.1
308.0	318.3	41.8	3.8	19.7	355.8	3.94	21.00	3.35	3.88	0.985	0.957	0.829	0.025	70.0
313.0	323.0	46.6	3.8	17.8	355.4	4.10	20.48	3.44	3.97	0.984	0.957	0.829	0.030	67.9
318.0	327.6	51.8	3.8	16.2	355.0	4.23	20.09	3.51	4.04	0.984	0.956	0.829	0.035	65.8
323.0	332.2	57.5	3.8	14.7	354.5	4.34	19.79	3.58	4.11	0.984	0.956	0.830	0.040	63.6
328.0	336.8	63.7	3.8	13.4	353.9	4.45	19.55	3.64	4.17	0.984	0.956	0.830	0.045	61.4
333.0	341.5	70.6	3.8	12.2	353.3	4.54	19.36	3.70	4.23	0.984	0.955	0.830	0.050	59.1
338.0	346.1	78.1	3.8	11.1	352.7	4.63	19.21	3.75	4.28	0.984	0.955	0.830	0.055	56.8
343.0	350.7	86.4	3.8	10.1	351.9	4.72	19.09	3.80	4.33	0.984	0.955	0.830	0.060	54.5
348.0	355.3	95.5	3.8	9.2	351.2	4.80	18.99	3.85	4.38	0.984	0.955	0.830	0.065	52.1
353.0	360.0	105.5	3.8	8.4	350.4	4.88	18.90	3.90	4.43	0.984	0.954	0.831	0.070	49.7
358.0	364.6	116.1	3.8	7.7	349.5	4.95	18.83	3.94	4.47	0.984	0.954	0.831	0.075	47.3
363.0	369.2	127.4	3.8	7.1	348.6	5.03	18.76	3.99	4.51	0.984	0.954	0.831	0.080	44.8
368.0	373.8	139.2	3.8	6.5	347.6	5.10	18.71	4.03	4.56	0.983	0.954	0.831	0.085	42.3
373.0	378.5	151.1	3.8	6.0	346.6	5.16	18.67	4.07	4.60	0.983	0.953	0.831	0.090	39.8
378.0	383.1	162.7	3.8	5.6	345.5	5.23	18.64	4.11	4.64	0.983	0.953	0.831	0.095	37.2
383.0	387.7	173.3	3.8	5.3	344.4	5.30	18.61	4.15	4.67	0.983	0.953	0.831	0.100	34.7

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

- 189 -

COLSIN PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 0.0 deg. 250.0 W/cm² 0.20 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 15.0 W/(cm² K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI K	TFE K	REF	MUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
283.0	284.1	18.9	3.8	41.3	357.2	1.93	91.37	2.01	2.53	0.986	0.948	0.831	0.000	80.4
288.0	290.9	22.2	3.8	35.6	357.1	2.50	36.75	2.39	2.91	0.986	0.965	0.834	0.020	74.9
293.0	295.6	25.7	3.8	31.0	356.9	2.94	28.19	2.69	3.22	0.985	0.962	0.836	0.040	68.0
298.0	300.3	29.5	3.8	27.3	356.7	3.30	24.79	2.94	3.42	0.985	0.960	0.837	0.060	60.4
303.0	305.0	33.4	3.8	24.3	356.5	3.57	22.94	3.11	3.64	0.985	0.959	0.838	0.080	52.4
308.0	309.6	37.7	3.8	21.7	356.2	3.77	21.82	3.24	3.77	0.985	0.958	0.838	0.100	44.2

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 0.0 deg. 300.0 W/cm² 0.20 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 15.0 W/(cm² K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI K	TFE K	REF	MUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
283.0	289.2	19.9	3.8	39.5	357.1	2.03	53.36	2.03	2.55	0.986	0.967	0.833	0.000	80.6
288.0	293.9	23.3	3.8	34.0	357.0	2.71	32.30	2.54	3.06	0.986	0.963	0.835	0.010	77.5
293.0	298.6	26.9	3.8	29.7	356.9	3.09	26.59	2.80	3.33	0.985	0.961	0.836	0.020	74.0
298.0	303.3	30.7	3.8	26.3	356.6	3.42	23.95	3.01	3.54	0.985	0.960	0.837	0.030	70.1
303.0	307.9	34.7	3.8	23.4	356.4	3.65	22.46	3.16	3.69	0.985	0.959	0.838	0.040	66.2
308.0	312.6	39.0	3.8	21.0	356.1	3.84	21.50	3.28	3.81	0.985	0.958	0.838	0.050	62.1
313.0	317.3	43.6	3.8	18.9	355.7	4.00	20.84	3.38	3.90	0.984	0.957	0.839	0.060	57.9
318.0	321.9	48.6	3.8	17.1	355.3	4.14	20.36	3.46	3.99	0.984	0.957	0.839	0.070	53.6
323.0	326.6	54.0	3.8	15.5	354.8	4.26	20.00	3.53	4.06	0.984	0.956	0.840	0.080	49.2
328.0	331.2	60.0	3.8	14.1	354.3	4.37	19.72	3.60	4.13	0.984	0.956	0.840	0.090	44.8
333.0	335.9	66.5	3.8	12.8	353.7	4.47	19.50	3.66	4.19	0.984	0.956	0.840	0.100	40.3

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 0.0 deg. 1250.0 W/cm² 0.20 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 15.0 W/(cm² K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI K	TFE K	REF	MUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
283.0	298.4	23.1	3.8	34.3	357.0	2.77	31.16	2.58	3.11	0.986	0.963	0.835	0.000	80.4
288.0	303.0	26.7	3.8	30.0	356.9	3.15	26.12	2.83	3.36	0.985	0.961	0.837	0.004	79.1
293.0	307.6	30.4	3.8	26.5	356.7	3.45	23.71	3.04	3.57	0.985	0.959	0.837	0.008	77.6
298.0	312.2	34.4	3.8	23.6	356.4	3.68	22.31	3.18	3.71	0.985	0.958	0.838	0.012	76.1
303.0	316.8	38.7	3.8	21.2	356.1	3.86	21.41	3.29	3.82	0.985	0.958	0.839	0.016	74.4
308.0	321.4	43.3	3.8	19.1	355.7	4.02	20.78	3.39	3.92	0.984	0.957	0.839	0.020	72.8
313.0	326.0	48.2	3.8	17.3	355.3	4.15	20.32	3.47	4.00	0.984	0.957	0.839	0.024	71.1
318.0	330.6	53.5	3.8	15.7	354.8	4.27	19.97	3.54	4.07	0.984	0.956	0.840	0.028	69.4
323.0	335.2	59.4	3.8	14.2	354.3	4.38	19.67	3.60	4.13	0.984	0.956	0.840	0.032	67.6
328.0	339.8	65.8	3.8	13.0	353.7	4.48	19.47	3.66	4.19	0.984	0.955	0.840	0.036	65.8
333.0	344.4	72.9	3.8	11.8	353.1	4.58	19.30	3.72	4.25	0.984	0.955	0.840	0.040	64.0
338.0	349.0	80.7	3.8	10.7	352.4	4.67	19.16	3.77	4.30	0.984	0.955	0.840	0.044	62.2
343.0	353.6	89.2	3.8	9.8	351.7	4.75	19.05	3.82	4.35	0.984	0.955	0.841	0.048	60.3
348.0	358.3	98.5	3.8	8.9	350.9	4.83	18.95	3.87	4.40	0.984	0.954	0.841	0.052	58.4
353.0	362.9	108.7	3.8	8.2	350.1	4.91	18.87	3.92	4.44	0.984	0.954	0.841	0.056	56.5
358.0	367.5	119.5	3.8	7.5	349.2	4.98	18.80	3.96	4.49	0.984	0.954	0.841	0.060	54.5
363.0	372.1	131.0	3.8	6.9	348.3	5.05	18.74	4.00	4.53	0.983	0.954	0.841	0.064	52.6
368.0	376.7	142.8	3.8	6.4	347.3	5.12	18.70	4.04	4.57	0.983	0.954	0.841	0.068	50.6
373.0	381.3	154.6	3.8	5.9	346.3	5.19	18.66	4.08	4.61	0.983	0.953	0.841	0.072	48.6
378.0	385.9	166.0	3.8	5.5	345.2	5.26	18.62	4.12	4.65	0.983	0.953	0.841	0.076	46.5
383.0	390.6	178.3	3.8	5.3	344.0	5.32	18.60	4.16	4.69	0.983	0.953	0.841	0.080	44.4
388.0	395.2	184.7	3.8	5.1	342.8	5.38	18.58	4.20	4.73	0.983	0.953	0.842	0.084	42.4
393.0	399.8	190.5	3.8	4.9	341.6	5.45	18.56	4.23	4.76	0.983	0.953	0.842	0.088	40.2
398.0	404.4	192.8	3.8	4.9	340.3	5.51	18.55	4.27	4.80	0.983	0.952	0.842	0.092	38.1
403.0	409.0	190.8	3.8	5.0	338.9	5.57	18.54	4.31	4.83	0.983	0.952	0.842	0.096	36.0
408.0	413.7	184.1	3.8	5.2	337.5	5.63	18.53	4.34	4.87	0.983	0.952	0.842	0.100	33.8

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

- 190 -

COLSIN PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 0.0 deg. 1200.0 W/cm² 0.10 0.036 K4/sec 10.0 deg.C 10.0 deg.C 15.0 W/(cm² K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
K	K				W/(cm ² K)									
283.0	297.9	22.9	3.8	34.5	357.0	2.74	31.66	2.56	3.09	0.984	0.963	0.840	0.000	80.9
288.0	302.8	26.5	3.8	30.2	356.9	3.12	26.34	2.82	3.33	0.985	0.961	0.842	0.004	79.5
293.0	307.1	30.2	3.8	26.4	356.7	3.44	23.82	3.03	3.54	0.985	0.959	0.843	0.008	78.0
298.0	311.7	34.2	3.8	23.7	356.4	3.67	22.39	3.17	3.70	0.985	0.958	0.843	0.013	76.4
303.0	316.3	38.5	3.8	21.3	356.1	3.85	21.44	3.29	3.82	0.985	0.958	0.844	0.017	74.7
308.0	320.9	43.0	3.8	19.2	355.7	4.01	20.81	3.38	3.91	0.984	0.957	0.844	0.021	73.0
313.0	325.5	47.9	3.8	17.4	355.3	4.14	20.34	3.46	3.99	0.984	0.957	0.844	0.025	71.2
318.0	330.1	53.2	3.8	15.8	354.9	4.24	19.99	3.53	4.06	0.984	0.956	0.845	0.029	69.4
323.0	334.7	59.1	3.8	14.3	354.3	4.38	19.71	3.60	4.13	0.984	0.956	0.845	0.033	67.6
328.0	339.3	65.5	3.8	13.0	353.8	4.48	19.49	3.66	4.19	0.984	0.955	0.845	0.038	65.7
333.0	343.9	72.5	3.8	11.9	353.1	4.57	19.31	3.72	4.25	0.984	0.955	0.845	0.042	63.9
338.0	348.6	80.2	3.8	10.8	352.5	4.66	19.17	3.77	4.30	0.984	0.955	0.846	0.046	61.9
343.0	353.2	88.7	3.8	9.8	351.8	4.75	19.05	3.82	4.35	0.984	0.955	0.846	0.050	60.0
348.0	357.8	98.0	3.8	9.0	351.0	4.83	18.96	3.87	4.40	0.984	0.954	0.846	0.054	58.0
353.0	362.4	108.1	3.8	8.2	350.1	4.90	18.87	3.91	4.44	0.984	0.954	0.846	0.058	56.0
358.0	367.0	119.0	3.8	7.5	349.3	4.98	18.80	3.96	4.49	0.984	0.954	0.846	0.062	54.0
363.0	371.6	130.4	3.8	6.9	348.3	5.05	18.75	4.00	4.53	0.983	0.954	0.846	0.067	51.9
368.0	376.2	142.2	3.8	6.4	347.4	5.12	18.70	4.04	4.57	0.983	0.954	0.846	0.071	49.9
373.0	380.9	154.1	3.8	5.9	346.3	5.19	18.66	4.08	4.61	0.983	0.953	0.847	0.075	47.8
378.0	385.5	165.5	3.8	5.6	345.2	5.25	18.63	4.12	4.65	0.983	0.953	0.847	0.079	45.6
383.0	390.1	175.8	3.8	5.3	344.1	5.32	18.60	4.16	4.69	0.983	0.953	0.847	0.083	43.5
388.0	394.7	184.3	3.8	5.1	342.9	5.38	18.58	4.20	4.72	0.983	0.953	0.847	0.087	41.3
393.0	399.3	190.3	3.8	4.9	341.7	5.44	18.56	4.23	4.76	0.983	0.953	0.847	0.092	39.1
398.0	404.0	192.7	3.8	4.9	340.4	5.50	18.55	4.27	4.80	0.983	0.952	0.847	0.096	36.7
403.0	408.6	191.0	3.8	5.0	339.0	5.56	18.54	4.30	4.83	0.983	0.952	0.847	0.100	34.6

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 0.0 deg. 250.0 W/cm² 1.00 0.036 K4/sec 10.0 deg.C 10.0 deg.C 15.0 W/(cm² K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
K	K				W/(cm ² K)									
283.0	286.0	18.8	3.8	41.6	357.2	1.93	95.42	2.01	2.54	0.984	0.968	0.789	0.000	76.3
288.0	290.7	22.1	3.8	35.7	357.1	2.49	37.04	2.38	2.90	0.984	0.965	0.792	0.020	70.8
293.0	295.4	25.7	3.8	31.1	356.9	2.94	28.28	2.69	3.22	0.985	0.962	0.794	0.040	64.7
298.0	300.1	29.4	3.8	27.3	356.7	3.30	24.83	2.94	3.47	0.985	0.960	0.795	0.060	58.6
303.0	304.8	33.4	3.8	24.3	356.5	3.57	22.97	3.11	3.64	0.985	0.959	0.796	0.080	48.4
308.0	309.5	37.6	3.8	21.8	356.2	3.77	21.84	3.24	3.77	0.985	0.958	0.796	0.100	40.2

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

- 191 -

COLSIM PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 0.0 deg. 1200.0 W/cm² 0.20 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 15.0 W/(sq.M K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	FFF
K	K				W/(sq.M K)									
283.0	277.8	22.9	3.8	34.4	357.0	2.74	31.68	2.56	3.09	0.986	0.943	0.835	0.000	80.4
288.0	302.4	26.4	3.8	30.2	356.9	3.12	26.37	2.82	3.34	0.985	0.941	0.836	0.004	79.0
293.0	307.0	30.2	3.8	26.7	356.7	3.43	23.84	3.02	3.55	0.985	0.939	0.837	0.008	77.5
298.0	311.6	34.2	3.8	23.8	356.4	3.66	22.40	3.17	3.70	0.985	0.938	0.838	0.013	75.9
303.0	316.2	38.4	3.8	21.3	356.1	3.85	21.47	3.29	3.81	0.985	0.938	0.839	0.017	74.2
308.0	320.8	43.0	3.8	19.2	355.7	4.01	20.82	3.38	3.91	0.984	0.937	0.839	0.021	72.5
313.0	325.4	47.9	3.8	17.4	355.3	4.14	20.35	3.46	3.99	0.984	0.937	0.839	0.025	70.7
318.0	330.0	53.2	3.8	15.8	354.9	4.26	19.99	3.53	4.06	0.984	0.936	0.840	0.029	68.9
323.0	334.6	59.1	3.8	14.3	354.3	4.38	19.71	3.60	4.13	0.984	0.936	0.840	0.033	67.1
328.0	339.2	65.4	3.8	13.0	353.8	4.48	19.49	3.66	4.19	0.984	0.935	0.840	0.038	65.2
333.0	343.9	72.5	3.8	11.9	353.2	4.57	19.31	3.72	4.25	0.984	0.935	0.840	0.042	63.4
338.0	348.5	80.2	3.8	10.8	352.5	4.66	19.17	3.77	4.30	0.984	0.935	0.840	0.046	61.4
343.0	353.1	88.7	3.8	9.8	351.8	4.74	19.04	3.82	4.35	0.984	0.935	0.841	0.050	59.5
348.0	357.7	98.0	3.8	9.0	351.0	4.82	18.96	3.87	4.40	0.984	0.934	0.841	0.054	57.5
353.0	362.3	108.0	3.8	8.2	350.2	4.90	18.87	3.91	4.44	0.984	0.934	0.841	0.058	55.5
358.0	366.9	118.9	3.8	7.5	349.3	4.98	18.81	3.96	4.48	0.984	0.934	0.841	0.062	53.5
363.0	371.5	130.3	3.8	6.9	348.3	5.05	18.75	4.00	4.53	0.983	0.934	0.841	0.067	51.4
368.0	376.2	142.1	3.8	6.4	347.4	5.12	18.70	4.04	4.57	0.983	0.934	0.841	0.071	49.4
373.0	380.8	154.0	3.8	5.9	346.3	5.19	18.66	4.08	4.61	0.983	0.933	0.841	0.075	47.3
378.0	385.4	165.4	3.8	5.6	345.2	5.25	18.63	4.12	4.65	0.983	0.933	0.841	0.079	45.1
383.0	390.0	175.7	3.8	5.3	344.1	5.32	18.60	4.16	4.69	0.983	0.933	0.841	0.083	43.0
388.0	394.6	184.3	3.8	5.1	342.9	5.38	18.58	4.19	4.72	0.983	0.933	0.842	0.087	40.8
393.0	399.3	190.2	3.8	4.9	341.7	5.44	18.56	4.23	4.76	0.983	0.933	0.842	0.092	38.6
398.0	403.9	192.7	3.8	4.9	340.4	5.50	18.55	4.27	4.80	0.983	0.932	0.842	0.096	36.4
403.0	408.5	191.0	3.8	5.0	339.0	5.56	18.54	4.30	4.83	0.983	0.932	0.842	0.100	34.1

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 40.0 deg. 720.0 W/cm² 0.33 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 15.0 W/(sq.M K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	FFF
K	K				W/(sq.M K)									
283.0	291.4	20.6	3.8	38.1	357.1	2.25	43.72	2.19	2.72	0.986	0.946	0.780	0.000	75.4
288.0	296.0	24.1	3.8	33.0	357.0	2.82	30.20	2.41	3.14	0.986	0.945	0.782	0.007	73.2
293.0	300.7	27.7	3.8	28.9	356.8	3.19	25.72	2.87	3.39	0.985	0.941	0.783	0.014	70.7
298.0	305.4	31.5	3.8	25.6	356.6	3.49	23.48	3.06	3.59	0.985	0.939	0.784	0.021	68.0
303.0	310.0	35.6	3.8	22.9	356.3	3.71	22.17	3.20	3.73	0.985	0.938	0.785	0.028	65.3
308.0	314.7	40.0	3.8	20.5	356.0	3.88	21.31	3.31	3.84	0.985	0.938	0.785	0.035	62.4
313.0	319.3	44.7	3.8	18.5	355.6	4.04	20.70	3.40	3.93	0.984	0.937	0.786	0.042	59.5
318.0	323.9	49.7	3.8	16.8	355.2	4.17	20.26	3.48	4.01	0.984	0.937	0.786	0.049	56.5
323.0	328.6	55.3	3.8	15.2	354.7	4.29	19.97	3.55	4.08	0.984	0.936	0.786	0.056	53.5
328.0	333.2	61.3	3.8	13.8	354.1	4.40	19.66	3.61	4.14	0.984	0.936	0.786	0.062	50.4
333.0	337.9	67.9	3.8	12.6	353.4	4.50	19.45	3.67	4.20	0.984	0.935	0.787	0.069	47.3
338.0	342.5	75.2	3.8	11.5	352.9	4.59	19.28	3.73	4.26	0.984	0.935	0.787	0.076	44.1
343.0	347.2	83.3	3.8	10.4	352.2	4.68	19.14	3.78	4.31	0.984	0.935	0.787	0.083	40.9
348.0	351.8	92.1	3.8	9.5	351.5	4.76	19.03	3.83	4.36	0.984	0.935	0.787	0.090	37.4
353.0	356.5	101.7	3.8	8.7	350.7	4.84	18.94	3.88	4.41	0.984	0.934	0.787	0.097	34.3
358.0	361.1	112.1	3.8	7.9	349.8	4.92	18.86	3.92	4.45	0.984	0.934	0.787	0.104	30.9

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 75.0 deg. 490.0 W/cm² 0.50 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 15.0 W/(sq.M K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	FFF
K	K				W/(sq.M K)									
283.0	287.9	19.5	3.8	40.3	357.1	1.94	63.21	1.96	2.49	0.987	0.948	0.674	0.000	65.3
288.0	292.7	22.8	3.8	34.7	357.0	2.63	33.86	2.48	3.01	0.986	0.946	0.677	0.010	62.3
293.0	297.4	26.4	3.8	30.2	356.9	3.03	27.19	2.76	3.29	0.985	0.942	0.679	0.020	58.8
298.0	302.1	30.2	3.8	26.7	356.7	3.37	24.26	2.99	3.52	0.985	0.940	0.680	0.031	54.9
303.0	306.7	34.2	3.8	23.8	356.4	3.62	22.65	3.14	3.67	0.985	0.939	0.680	0.041	50.9
308.0	311.4	38.5	3.8	21.3	356.1	3.81	21.43	3.24	3.79	0.985	0.938	0.681	0.051	46.7
313.0	316.1	43.0	3.8	19.2	355.7	3.98	20.93	3.36	3.89	0.985	0.937	0.681	0.061	42.4
318.0	320.7	48.0	3.8	17.4	355.3	4.12	20.43	3.45	3.98	0.984	0.937	0.682	0.071	38.1
323.0	325.4	53.3	3.8	15.7	354.9	4.24	20.05	3.52	4.05	0.984	0.936	0.682	0.082	33.6
328.0	330.1	59.7	3.8	14.3	354.3	4.35	19.76	3.59	4.12	0.984	0.936	0.682	0.092	29.1
333.0	334.7	65.6	3.8	13.0	353.8	4.46	19.53	3.65	4.18	0.984	0.936	0.683	0.102	24.5

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

COLSIM PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 0.0 deg. 1000.0 W/sm² 0.20 0.036 Kg/sec -30.0 deg.C -30.0 deg.C 15.0 W/(sq.M K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRHE	FR	TAEFF	DT/I	EFF
K	K													
243.0	256.3	2.9	3.8	252.3	356.3	2.80	33.54	2.63	3.16	0.986	0.941	0.835	0.000	80.2
248.0	260.9	4.2	3.8	178.0	356.5	3.19	28.13	2.89	3.42	0.985	0.958	0.836	0.005	78.5
253.0	265.5	5.7	3.8	130.4	356.8	3.45	24.83	3.05	3.58	0.985	0.957	0.837	0.010	76.7
258.0	270.0	7.4	3.8	99.2	357.0	3.64	22.94	3.16	3.69	0.985	0.957	0.838	0.015	74.9
263.0	274.6	9.8	3.8	77.8	357.1	3.80	21.74	3.26	3.78	0.985	0.956	0.838	0.020	72.9
268.0	279.2	12.2	3.8	62.6	357.2	3.94	20.94	3.33	3.86	0.985	0.956	0.839	0.025	70.9
273.0	283.8	15.0	3.8	51.4	357.2	4.06	20.34	3.40	3.93	0.984	0.955	0.839	0.030	68.9
278.0	288.4	18.0	3.8	43.4	357.2	4.17	19.88	3.46	3.99	0.984	0.955	0.839	0.035	66.8
283.0	292.9	21.2	3.8	37.1	357.1	4.27	19.52	3.52	4.05	0.984	0.955	0.840	0.040	64.7
288.0	297.5	24.6	3.8	32.3	357.0	4.36	19.24	3.57	4.10	0.984	0.955	0.840	0.045	62.6
293.0	302.1	28.3	3.8	28.4	356.8	4.45	19.01	3.62	4.15	0.984	0.954	0.840	0.050	60.4
298.0	306.7	32.1	3.8	25.2	356.6	4.53	18.81	3.66	4.19	0.984	0.954	0.840	0.055	58.2
303.0	311.3	36.2	3.8	22.5	356.3	4.60	18.65	3.71	4.24	0.984	0.954	0.841	0.060	55.9
308.0	315.9	40.6	3.8	20.2	355.9	4.68	18.52	3.75	4.28	0.984	0.954	0.841	0.065	53.7
313.0	320.5	45.3	3.8	18.3	355.5	4.75	18.40	3.79	4.32	0.984	0.954	0.841	0.070	51.4
318.0	325.2	50.4	3.8	16.6	355.1	4.82	18.31	3.83	4.36	0.984	0.954	0.841	0.075	49.0
323.0	329.8	56.0	3.8	15.1	354.6	4.88	18.22	3.87	4.39	0.984	0.954	0.841	0.080	46.7
328.0	334.4	62.1	3.8	13.7	354.1	4.94	18.15	3.90	4.43	0.984	0.953	0.841	0.085	44.3
333.0	339.0	68.7	3.8	12.5	353.5	5.01	18.08	3.94	4.47	0.984	0.953	0.841	0.090	41.9
338.0	343.6	76.1	3.8	11.3	352.8	5.07	18.03	3.97	4.50	0.984	0.953	0.841	0.095	39.5
343.0	348.2	84.2	3.8	10.3	352.1	5.13	17.98	4.01	4.53	0.984	0.953	0.841	0.100	37.0

EFFECTIVE SKY TEMP. DURING TEST WAS 1 -64.5 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 0.0 deg. 1000.0 W/sm² 0.20 0.036 Kg/sec 30.0 deg.C 30.0 deg.C 15.0 W/(sq.M K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRHE	FR	TAEFF	DT/I	EFF
K	K													
303.0	315.0	37.8	3.8	21.6	356.1	2.50	33.93	2.37	2.90	0.986	0.965	0.835	0.000	80.4
308.0	319.6	42.4	3.8	19.5	355.8	2.97	26.98	2.71	3.23	0.985	0.963	0.836	0.005	78.9
313.0	324.3	47.3	3.8	17.6	355.4	3.26	24.06	2.90	3.43	0.985	0.961	0.837	0.010	77.2
318.0	328.9	52.4	3.8	15.9	354.9	3.54	22.53	3.08	3.61	0.985	0.960	0.838	0.015	75.2
323.0	333.6	58.4	3.8	14.5	354.4	3.76	21.59	3.23	3.75	0.985	0.959	0.838	0.020	73.2
328.0	338.2	64.7	3.8	13.2	353.8	3.94	20.95	3.34	3.87	0.985	0.958	0.839	0.025	71.1
333.0	342.9	71.7	3.8	12.0	353.2	4.10	20.50	3.44	3.97	0.984	0.957	0.839	0.030	68.9
338.0	347.5	79.3	3.8	10.9	352.6	4.24	20.16	3.53	4.06	0.984	0.957	0.839	0.035	66.7
343.0	352.1	87.8	3.8	9.9	351.8	4.36	19.90	3.60	4.13	0.984	0.956	0.840	0.040	64.5
348.0	356.7	97.0	3.8	9.1	351.1	4.48	19.72	3.67	4.20	0.984	0.956	0.840	0.045	62.2
353.0	361.4	107.0	3.8	8.3	350.2	4.58	19.56	3.73	4.26	0.984	0.956	0.840	0.050	59.9
358.0	366.0	117.8	3.8	7.6	349.4	4.68	19.43	3.79	4.32	0.984	0.955	0.840	0.055	57.6
363.0	370.6	129.2	3.8	7.0	348.4	4.77	19.33	3.85	4.38	0.984	0.955	0.840	0.060	55.2
368.0	375.3	141.0	3.8	6.4	347.5	4.86	19.24	3.90	4.43	0.984	0.955	0.841	0.065	52.7
373.0	379.9	152.9	3.8	6.0	346.4	4.94	19.17	3.95	4.48	0.984	0.954	0.841	0.070	50.3
378.0	384.5	164.4	3.8	5.6	345.3	5.02	19.12	4.00	4.53	0.983	0.954	0.841	0.075	47.8
383.0	389.2	174.8	3.8	5.3	344.2	5.10	19.07	4.05	4.58	0.983	0.954	0.841	0.080	45.3
388.0	393.8	183.6	3.8	5.1	343.0	5.17	19.04	4.09	4.62	0.983	0.954	0.841	0.085	42.7
393.0	398.4	189.8	3.8	5.0	341.8	5.25	19.01	4.14	4.67	0.983	0.953	0.841	0.090	40.2
398.0	403.1	192.7	3.8	4.9	340.5	5.32	18.99	4.18	4.71	0.983	0.953	0.841	0.095	37.5
403.0	407.7	191.4	3.8	5.0	339.1	5.39	18.97	4.22	4.75	0.983	0.953	0.841	0.100	34.9

EFFECTIVE SKY TEMP. DURING TEST WAS 17.3 deg.C

- 193 -

COLSIM PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 0.0 deg. 1000.0 W/cm² 0.50 0.036 K/s² 10.0 deg.C 10.0 deg.C 5.0 W/(cm² K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
K	K				W/(cm ² K)									
283.0	295.1	21.9	3.8	34.0	357.1	2.54	25.43	2.35	2.88	0.984	0.945	0.820	0.000	79.1
288.0	299.8	25.5	3.8	31.3	356.9	2.94	18.02	2.56	3.09	0.986	0.943	0.822	0.005	77.7
293.0	304.5	29.2	3.8	27.5	356.7	3.26	15.02	2.71	3.23	0.985	0.942	0.824	0.010	76.1
298.0	309.2	33.1	3.8	24.5	356.5	3.50	13.43	2.80	3.33	0.985	0.941	0.825	0.015	74.5
303.0	313.8	37.4	3.8	21.9	356.2	3.69	12.47	2.87	3.40	0.985	0.941	0.826	0.020	72.8
308.0	318.3	41.9	3.8	19.7	355.8	3.84	11.83	2.92	3.45	0.985	0.941	0.827	0.025	71.1
313.0	323.2	46.7	3.8	17.8	355.4	3.98	11.38	2.97	3.50	0.985	0.941	0.827	0.030	69.4
318.0	327.8	52.0	3.8	16.1	355.0	4.10	11.04	3.01	3.54	0.985	0.940	0.828	0.035	67.6
323.0	332.5	57.7	3.8	14.4	354.5	4.21	10.79	3.05	3.58	0.985	0.940	0.828	0.040	65.8
328.0	337.2	64.0	3.8	13.3	353.9	4.31	10.60	3.08	3.61	0.985	0.940	0.828	0.045	63.9
333.0	341.9	70.9	3.8	12.1	353.3	4.40	10.45	3.12	3.65	0.985	0.940	0.829	0.050	62.1
338.0	346.4	78.5	3.8	11.0	352.6	4.49	10.34	3.15	3.68	0.985	0.940	0.829	0.055	60.2
343.0	351.2	86.9	3.8	10.0	351.9	4.57	10.25	3.18	3.71	0.985	0.940	0.829	0.060	58.2
348.0	355.9	96.1	3.8	9.1	351.1	4.65	10.19	3.21	3.74	0.985	0.940	0.829	0.065	56.3
353.0	360.6	106.1	3.8	8.3	350.3	4.73	10.13	3.24	3.77	0.985	0.939	0.830	0.070	54.3
358.0	365.3	116.9	3.8	7.6	349.4	4.80	10.09	3.27	3.80	0.985	0.939	0.830	0.075	52.3
363.0	370.0	128.3	3.8	7.0	348.5	4.87	10.06	3.30	3.83	0.984	0.939	0.830	0.080	50.2
368.0	374.6	140.2	3.8	6.5	347.5	4.94	10.04	3.33	3.86	0.984	0.939	0.830	0.085	48.1
373.0	379.3	152.1	3.8	6.0	346.5	5.01	10.03	3.36	3.89	0.984	0.939	0.830	0.090	46.0
378.0	384.0	163.7	3.8	5.6	345.4	5.07	10.02	3.39	3.92	0.984	0.939	0.830	0.095	43.9
383.0	388.7	174.3	3.8	5.3	344.3	5.14	10.02	3.42	3.95	0.984	0.939	0.831	0.100	41.8

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 0.0 deg. 1000.0 W/cm² 0.50 0.036 K/s² 10.0 deg.C 10.0 deg.C 5.0 W/(cm² K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.7

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
K	K				W/(cm ² K)									
283.0	295.1	21.9	3.8	34.0	357.1	2.54	25.54	2.35	2.88	0.984	0.945	0.815	0.000	78.7
288.0	299.8	25.4	3.8	31.3	356.9	2.94	18.06	2.56	3.09	0.986	0.943	0.818	0.005	77.3
293.0	304.4	29.2	3.8	27.6	356.7	3.26	15.04	2.70	3.23	0.985	0.942	0.819	0.010	75.7
298.0	309.1	33.1	3.8	24.5	356.5	3.50	13.42	2.80	3.33	0.985	0.941	0.820	0.015	74.1
303.0	313.8	37.3	3.8	21.9	356.2	3.69	12.48	2.87	3.40	0.985	0.941	0.821	0.020	72.4
308.0	318.4	41.8	3.8	19.7	355.8	3.84	11.83	2.92	3.45	0.985	0.941	0.822	0.025	70.7
313.0	323.1	46.7	3.8	17.8	355.4	3.98	11.38	2.97	3.50	0.985	0.941	0.823	0.030	69.0
318.0	327.8	51.9	3.8	16.1	355.0	4.10	11.04	3.01	3.54	0.985	0.940	0.823	0.035	67.2
323.0	332.5	57.7	3.8	14.7	354.5	4.21	10.79	3.05	3.58	0.985	0.940	0.824	0.040	65.3
328.0	337.1	63.9	3.8	13.3	353.9	4.31	10.60	3.08	3.61	0.985	0.940	0.824	0.045	63.5
333.0	341.8	70.9	3.8	12.1	353.3	4.40	10.46	3.12	3.65	0.985	0.940	0.824	0.050	61.6
338.0	346.5	78.5	3.8	11.0	352.6	4.49	10.34	3.15	3.68	0.985	0.940	0.824	0.055	59.7
343.0	351.2	86.9	3.8	10.0	351.9	4.57	10.25	3.18	3.71	0.985	0.940	0.825	0.060	57.8
348.0	355.8	96.1	3.8	9.1	351.1	4.65	10.19	3.21	3.74	0.985	0.940	0.825	0.065	55.8
353.0	360.5	106.1	3.8	8.3	350.3	4.73	10.13	3.24	3.77	0.985	0.939	0.825	0.070	53.8
358.0	365.2	116.8	3.8	7.6	349.4	4.80	10.09	3.27	3.80	0.985	0.939	0.825	0.075	51.9
363.0	369.9	128.3	3.8	7.0	348.5	4.87	10.06	3.30	3.83	0.984	0.939	0.825	0.080	49.8
368.0	374.6	140.1	3.8	6.5	347.5	4.94	10.04	3.33	3.86	0.984	0.939	0.826	0.085	47.7
373.0	379.3	152.1	3.8	6.0	346.5	5.01	10.03	3.36	3.89	0.984	0.939	0.826	0.090	45.6
378.0	383.9	163.7	3.8	5.6	345.4	5.07	10.02	3.39	3.92	0.984	0.939	0.826	0.095	43.5
383.0	388.8	174.3	3.8	5.3	344.3	5.14	10.02	3.42	3.95	0.984	0.939	0.826	0.100	41.3

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

- 194 -

COLBIN PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION
TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 0.0 deg. 1000.0 W/cm² 0.00 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 15.0 W/(cm² K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRHE	FR	TAEFF	DT/I	EFF
K	K													
283.0	295.5	22.1	3.8	35.8	357.1	2.60	34.63	2.45	2.98	0.984	0.944	0.845	0.000	81.3
288.0	300.1	25.6	3.8	31.1	356.9	3.01	27.46	2.74	3.27	0.985	0.962	0.847	0.005	79.8
293.0	304.8	29.3	3.8	27.4	356.7	3.35	24.41	2.97	3.50	0.985	0.960	0.848	0.010	78.0
298.0	309.4	33.2	3.8	24.4	356.5	3.60	22.74	3.13	3.66	0.985	0.959	0.848	0.015	76.1
303.0	314.0	37.5	3.8	21.8	356.2	3.80	21.68	3.26	3.79	0.985	0.958	0.849	0.020	74.1
308.0	318.6	41.9	3.8	19.7	355.8	3.97	20.97	3.36	3.88	0.985	0.957	0.849	0.025	72.0
313.0	323.2	46.8	3.8	17.8	355.4	4.11	20.46	3.44	3.97	0.984	0.957	0.850	0.030	69.9
318.0	327.9	52.0	3.8	16.1	355.0	4.23	20.08	3.52	4.04	0.984	0.956	0.850	0.035	67.7
323.0	332.5	57.7	3.8	14.6	354.5	4.35	19.78	3.58	4.11	0.984	0.956	0.850	0.040	65.6
328.0	337.1	63.9	3.8	13.3	353.9	4.45	19.55	3.64	4.17	0.984	0.956	0.850	0.045	63.3
333.0	341.7	70.8	3.8	12.1	353.3	4.55	19.36	3.70	4.23	0.984	0.955	0.851	0.050	61.1
338.0	346.4	78.4	3.8	11.0	352.6	4.64	19.20	3.76	4.28	0.984	0.955	0.851	0.055	58.8
343.0	351.0	86.7	3.8	10.1	351.9	4.72	19.09	3.81	4.33	0.984	0.955	0.851	0.060	56.4
348.0	355.4	95.8	3.8	9.2	351.2	4.80	18.98	3.85	4.38	0.984	0.955	0.851	0.065	54.1
353.0	360.2	105.7	3.8	8.4	350.3	4.88	18.90	3.90	4.43	0.984	0.954	0.851	0.070	51.7
358.0	364.9	116.4	3.8	7.7	349.5	4.96	18.82	3.94	4.47	0.984	0.954	0.851	0.075	49.2
363.0	369.5	127.8	3.8	7.0	348.6	5.03	18.76	3.99	4.52	0.984	0.954	0.852	0.080	46.8
368.0	374.1	139.5	3.8	6.5	347.6	5.10	18.71	4.03	4.56	0.983	0.954	0.852	0.085	44.3
373.0	378.7	151.4	3.8	6.0	346.6	5.17	18.67	4.07	4.60	0.983	0.953	0.852	0.090	41.8
378.0	383.4	163.0	3.8	5.6	345.5	5.23	18.63	4.11	4.64	0.983	0.953	0.852	0.095	39.2
383.0	388.0	173.6	3.8	5.3	344.3	5.30	18.61	4.15	4.68	0.983	0.953	0.852	0.100	36.6

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION
TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 0.0 deg. 1000.0 W/cm² 0.50 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 15.0 W/(cm² K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRHE	FR	TAEFF	DT/I	EFF
K	K													
283.0	295.1	21.9	3.8	36.0	357.1	2.57	35.22	2.43	2.96	0.984	0.944	0.819	0.000	78.9
288.0	299.8	25.4	3.8	31.3	356.9	2.99	27.67	2.72	3.25	0.985	0.962	0.820	0.005	77.3
293.0	304.4	29.1	3.8	27.6	356.7	3.34	24.51	2.97	3.49	0.985	0.960	0.821	0.010	75.5
298.0	309.0	33.1	3.8	24.5	356.5	3.60	22.79	3.13	3.66	0.985	0.959	0.822	0.015	73.6
303.0	313.6	37.3	3.8	21.9	356.2	3.79	21.73	3.25	3.78	0.985	0.958	0.823	0.020	71.6
308.0	318.3	41.7	3.8	19.7	355.8	3.96	21.00	3.35	3.88	0.985	0.957	0.823	0.025	69.5
313.0	322.9	46.6	3.8	17.8	355.4	4.10	20.48	3.44	3.97	0.984	0.957	0.823	0.030	67.4
318.0	327.5	51.8	3.8	16.2	355.0	4.23	20.09	3.51	4.04	0.984	0.956	0.824	0.035	65.2
323.0	332.1	57.5	3.8	14.7	354.5	4.34	19.79	3.58	4.11	0.984	0.956	0.824	0.040	63.1
328.0	336.8	63.7	3.8	13.4	353.9	4.44	19.56	3.64	4.17	0.984	0.956	0.824	0.045	60.8
333.0	341.4	70.5	3.8	12.2	353.3	4.54	19.36	3.70	4.23	0.984	0.955	0.824	0.050	58.6
338.0	346.0	78.1	3.8	11.1	352.7	4.63	19.21	3.75	4.28	0.984	0.955	0.825	0.055	56.3
343.0	350.6	86.4	3.8	10.1	352.0	4.72	19.09	3.80	4.33	0.984	0.955	0.825	0.060	53.9
348.0	355.3	95.3	3.8	9.2	351.2	4.80	18.99	3.85	4.38	0.984	0.955	0.825	0.065	51.6
353.0	359.9	105.4	3.8	8.4	350.4	4.88	18.90	3.90	4.43	0.984	0.954	0.825	0.070	49.2
358.0	364.5	116.0	3.8	7.7	349.5	4.95	18.83	3.94	4.47	0.984	0.954	0.825	0.075	46.7
363.0	369.1	127.3	3.8	7.1	348.6	5.03	18.76	3.99	4.51	0.984	0.954	0.825	0.080	44.3
368.0	373.8	139.1	3.8	6.5	347.6	5.10	18.71	4.03	4.56	0.983	0.954	0.825	0.085	41.8
373.0	378.4	151.0	3.8	6.0	346.6	5.16	18.67	4.07	4.60	0.983	0.953	0.825	0.090	39.3
378.0	383.0	162.6	3.8	5.7	345.5	5.23	18.64	4.11	4.64	0.983	0.953	0.826	0.095	36.7
383.0	387.7	173.3	3.8	5.3	344.4	5.30	18.61	4.15	4.67	0.983	0.953	0.826	0.100	34.1

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

- 195 -

COLSIN PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION
 TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
 45.0 deg. 0,0 deg. 1000.0 W/cm² 1.00 0.034 Kg/sec 10.0 deg.C 10.0 deg.C 15.0 W/(cm² K)

GROUND ENITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TPE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
K	K													
283.0	294.7	21.8	3.8	34.2	357.1	2.54	35.84	2.41	2.94	0.984	0.944	0.793	0.000	74.4
288.0	299.4	25.3	3.8	31.5	356.9	2.94	27.88	2.71	3.24	0.985	0.942	0.794	0.005	74.8
293.0	304.0	29.0	3.8	27.7	356.7	3.33	24.62	2.94	3.48	0.985	0.940	0.795	0.010	73.0
298.0	308.6	32.9	3.8	24.4	356.5	3.59	22.85	3.12	3.65	0.985	0.939	0.796	0.015	71.0
303.0	313.3	37.1	3.8	22.0	356.2	3.78	21.77	3.25	3.77	0.985	0.938	0.796	0.020	69.1
308.0	317.9	41.6	3.8	19.8	355.9	3.95	21.03	3.35	3.88	0.985	0.937	0.797	0.025	67.0
313.0	322.5	46.4	3.8	17.9	355.5	4.09	20.50	3.43	3.96	0.984	0.937	0.797	0.030	64.9
318.0	327.1	51.6	3.8	16.2	355.0	4.22	20.11	3.51	4.04	0.984	0.936	0.797	0.035	62.7
323.0	331.8	57.2	3.8	14.8	354.5	4.34	19.60	3.58	4.11	0.984	0.936	0.798	0.040	60.6
328.0	336.4	63.4	3.8	13.4	354.0	4.44	19.56	3.64	4.17	0.984	0.936	0.798	0.045	58.3
333.0	341.0	70.3	3.8	12.2	353.3	4.54	19.37	3.70	4.23	0.984	0.935	0.798	0.050	56.1
338.0	345.6	77.8	3.8	11.1	352.7	4.63	19.22	3.75	4.28	0.984	0.935	0.798	0.055	53.8
343.0	350.3	86.1	3.8	10.1	352.0	4.71	19.10	3.80	4.33	0.984	0.935	0.798	0.060	51.4
348.0	354.9	95.1	3.8	9.2	351.2	4.80	18.99	3.85	4.38	0.984	0.935	0.799	0.065	49.1
353.0	359.5	105.0	3.8	8.4	350.4	4.87	18.90	3.90	4.42	0.984	0.934	0.799	0.070	46.7
358.0	364.2	115.6	3.8	7.7	349.5	4.95	18.83	3.94	4.47	0.984	0.934	0.799	0.075	44.2
363.0	368.8	126.9	3.8	7.1	348.6	5.02	18.77	3.98	4.51	0.984	0.934	0.799	0.080	41.8
368.0	373.4	138.7	3.8	6.5	347.7	5.09	18.72	4.03	4.55	0.983	0.934	0.799	0.085	39.3
373.0	378.1	150.6	3.8	6.1	346.4	5.16	18.67	4.07	4.59	0.983	0.933	0.799	0.090	36.8
378.0	382.7	162.2	3.8	5.7	345.6	5.23	18.64	4.11	4.63	0.983	0.933	0.799	0.095	34.2
383.0	387.3	172.9	3.8	5.4	344.4	5.29	18.61	4.14	4.67	0.983	0.933	0.799	0.100	31.7

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

- 196 -

COLSIM PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. MW
45.0 deg. 0.0 deg. 1000.0 W/cm² 0.20 0.360 Kg/sec 10.0 deg.C 10.0 deg.C 15.0 W/(sq.M K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
K	K													
283.0	284.3	182.4	4.5	42.9	429.8	1.931	101.49	2.02	2.55	0.987	0.985	0.830	0.000	81.8
288.0	289.2	216.0	4.5	34.5	430.3	2.49	37.10	2.37	2.90	0.987	0.984	0.834	0.005	80.7
293.0	294.2	251.9	4.5	31.6	430.7	2.94	28.17	2.70	3.22	0.986	0.984	0.836	0.010	79.1
298.0	299.2	290.1	4.6	27.7	431.0	3.31	24.71	2.95	3.48	0.986	0.983	0.837	0.015	77.2
303.0	304.1	330.7	4.6	24.5	431.2	3.58	22.85	3.12	3.65	0.986	0.983	0.838	0.020	75.2
308.0	309.1	374.0	4.6	21.9	431.4	3.79	21.74	3.25	3.78	0.986	0.983	0.838	0.025	73.1
313.0	314.0	420.4	4.6	19.6	431.5	3.96	20.99	3.35	3.88	0.985	0.983	0.839	0.030	71.0
318.0	319.0	470.6	4.6	17.7	431.5	4.11	20.45	3.44	3.97	0.985	0.983	0.839	0.035	68.8
323.0	324.0	525.1	4.6	16.0	431.4	4.24	20.06	3.52	4.05	0.985	0.982	0.839	0.040	66.6
328.0	328.9	584.8	4.6	14.5	431.3	4.36	19.76	3.59	4.12	0.985	0.982	0.840	0.045	64.3
333.0	333.9	650.5	4.6	13.1	431.1	4.46	19.57	3.65	4.18	0.985	0.982	0.840	0.050	62.0
338.0	338.9	723.1	4.6	11.9	430.8	4.56	19.33	3.71	4.24	0.985	0.982	0.840	0.055	59.6
343.0	343.8	803.2	4.6	10.8	430.5	4.65	19.18	3.77	4.29	0.985	0.982	0.840	0.060	57.2
348.0	348.8	891.6	4.6	9.8	430.1	4.74	19.06	3.82	4.35	0.985	0.982	0.841	0.065	54.8
353.0	353.7	988.6	4.6	8.9	429.6	4.83	18.96	3.87	4.40	0.985	0.982	0.841	0.070	52.3
358.0	358.7	1094.0	4.6	8.1	429.1	4.91	18.87	3.91	4.44	0.985	0.982	0.841	0.075	49.8
363.0	363.7	1207.3	4.6	7.4	428.4	4.98	18.80	3.96	4.49	0.985	0.982	0.841	0.080	47.3
368.0	368.6	1326.7	4.6	6.8	427.7	5.06	18.74	4.00	4.53	0.985	0.982	0.841	0.085	44.7
373.0	373.6	1449.6	4.6	6.3	427.0	5.13	18.69	4.05	4.57	0.985	0.982	0.841	0.090	42.2
378.0	378.5	1571.7	4.7	5.8	426.1	5.20	18.65	4.09	4.62	0.985	0.982	0.841	0.095	39.5
383.0	383.5	1687.4	4.7	5.5	425.2	5.27	18.62	4.13	4.66	0.985	0.981	0.841	0.100	36.9

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. MW
45.0 deg. 0.0 deg. 1000.0 W/cm² 0.20 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 15.0 W/(sq.M K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
K	K													
283.0	295.3	22.0	3.8	35.9	357.1	2.59	34.86	2.45	2.98	0.986	0.964	0.835	0.000	80.5
288.0	300.0	25.5	3.8	31.2	356.9	3.00	27.54	2.73	3.26	0.985	0.962	0.836	0.005	78.8
293.0	304.6	29.2	3.8	27.5	356.7	3.35	24.45	2.97	3.50	0.985	0.960	0.837	0.010	77.0
298.0	309.2	33.2	3.8	24.4	356.5	3.60	22.76	3.13	3.66	0.985	0.959	0.838	0.015	75.1
303.0	313.9	37.4	3.8	21.9	356.2	3.80	21.70	3.25	3.78	0.985	0.958	0.838	0.020	73.1
308.0	318.5	41.9	3.8	19.7	355.8	3.96	20.98	3.35	3.88	0.985	0.957	0.839	0.025	71.0
313.0	323.1	46.7	3.8	17.8	355.4	4.10	20.47	3.44	3.97	0.984	0.957	0.839	0.030	68.9
318.0	327.7	51.9	3.8	16.1	355.0	4.23	20.08	3.51	4.04	0.984	0.956	0.839	0.035	66.7
323.0	332.3	57.6	3.8	14.7	354.5	4.34	19.78	3.58	4.11	0.984	0.956	0.840	0.040	64.6
328.0	337.0	63.8	3.8	13.3	353.9	4.45	19.55	3.64	4.17	0.984	0.956	0.840	0.045	62.3
333.0	341.6	70.7	3.8	12.1	353.3	4.54	19.36	3.70	4.23	0.984	0.955	0.840	0.050	60.1
338.0	346.2	78.3	3.8	11.1	352.6	4.64	19.21	3.75	4.28	0.984	0.955	0.840	0.055	57.8
343.0	350.8	86.6	3.8	10.1	351.9	4.72	19.09	3.80	4.33	0.984	0.955	0.840	0.060	55.4
348.0	355.5	95.7	3.8	9.2	351.2	4.80	18.98	3.85	4.38	0.984	0.955	0.841	0.065	53.1
353.0	360.1	105.6	3.8	8.4	350.4	4.88	18.90	3.90	4.43	0.984	0.954	0.841	0.070	50.7
358.0	364.7	116.3	3.8	7.7	349.5	4.96	18.82	3.94	4.47	0.984	0.954	0.841	0.075	48.2
363.0	369.3	127.6	3.8	7.0	348.6	5.03	18.76	3.99	4.52	0.984	0.954	0.841	0.080	45.8
368.0	374.0	139.4	3.8	6.5	347.6	5.10	18.71	4.03	4.56	0.983	0.954	0.841	0.085	43.3
373.0	378.6	151.2	3.8	6.0	346.6	5.17	18.67	4.07	4.60	0.983	0.953	0.841	0.090	40.8
378.0	383.2	162.8	3.8	5.6	345.5	5.23	18.63	4.11	4.64	0.983	0.953	0.841	0.095	38.2
383.0	387.9	173.5	3.8	5.3	344.4	5.30	18.61	4.15	4.68	0.983	0.953	0.841	0.100	35.6

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

- 197 -

COLSIN PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 0.0 deg. 1000.0 W/cm² 0.20 0.009 K/s² 10.0 deg.C 10.0 deg.C 15.0 W/(sq.M K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI K	TFE K	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
283.0	327.3	8.8	3.7	23.2	348.8	3.70	22.22	3.19	3.72	0.985	0.884	0.838	0.000	74.1
288.0	330.9	9.7	3.7	21.1	348.5	3.86	21.42	3.29	3.82	0.985	0.882	0.839	0.005	72.3
293.0	334.5	10.8	3.7	19.2	348.1	4.00	20.84	3.38	3.91	0.984	0.881	0.839	0.010	70.4
298.0	338.2	11.9	3.7	17.5	347.7	4.12	20.41	3.45	3.98	0.984	0.879	0.839	0.015	68.6
303.0	341.8	13.0	3.7	16.1	347.2	4.23	20.07	3.52	4.05	0.984	0.878	0.839	0.020	66.6
308.0	345.5	14.3	3.7	14.8	346.7	4.34	19.80	3.58	4.11	0.984	0.877	0.840	0.025	64.7
313.0	349.1	15.7	3.7	13.5	346.2	4.43	19.58	3.63	4.16	0.984	0.877	0.840	0.030	62.7
318.0	352.8	17.2	3.7	12.5	345.6	4.52	19.41	3.69	4.21	0.984	0.876	0.840	0.035	60.7
323.0	356.4	18.8	3.7	11.4	345.0	4.60	19.26	3.73	4.26	0.984	0.875	0.840	0.040	58.6
328.0	360.1	20.6	3.7	10.5	344.4	4.68	19.14	3.78	4.31	0.984	0.874	0.840	0.045	56.5
333.0	363.7	22.6	3.7	9.7	343.7	4.75	19.04	3.82	4.35	0.984	0.874	0.841	0.050	54.4
338.0	367.4	24.7	3.7	8.9	342.9	4.83	18.95	3.87	4.40	0.984	0.873	0.841	0.055	52.3
343.0	371.0	26.9	3.7	8.2	342.1	4.90	18.88	3.91	4.44	0.984	0.873	0.841	0.060	50.1
348.0	374.7	29.3	3.7	7.6	341.3	4.96	18.82	3.95	4.48	0.983	0.872	0.841	0.065	48.0
353.0	378.4	31.9	3.7	7.0	340.5	5.03	18.74	3.98	4.52	0.983	0.872	0.841	0.070	45.8
358.0	382.0	34.5	3.7	6.6	339.6	5.09	18.72	4.02	4.55	0.983	0.871	0.841	0.075	43.5
363.0	385.7	37.2	3.7	6.1	338.6	5.15	18.68	4.06	4.59	0.983	0.871	0.841	0.080	41.3
368.0	389.4	39.8	3.7	5.8	337.6	5.21	18.65	4.10	4.62	0.983	0.870	0.841	0.085	39.0
373.0	393.0	42.3	3.7	5.5	336.6	5.27	18.62	4.13	4.66	0.983	0.870	0.841	0.090	36.7
378.0	396.7	44.5	3.7	5.2	335.6	5.33	18.59	4.16	4.69	0.983	0.869	0.841	0.095	34.4
383.0	400.4	46.3	3.7	5.0	334.5	5.38	18.57	4.20	4.73	0.983	0.869	0.842	0.100	32.1

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 0.0 deg. 1000.0 W/cm² 0.20 0.004 K/s² 10.0 deg.C 10.0 deg.C 15.0 W/(sq.M K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI K	TFE K	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
283.0	372.8	6.4	3.7	13.4	344.5	4.44	19.56	3.64	4.17	0.984	0.743	0.840	0.000	62.4
288.0	375.1	6.8	3.7	12.5	344.0	4.51	19.42	3.68	4.21	0.984	0.742	0.840	0.005	60.8
293.0	377.3	7.4	3.7	11.7	343.5	4.58	19.29	3.72	4.25	0.984	0.741	0.840	0.010	59.1
298.0	379.6	7.9	3.7	10.9	343.0	4.65	19.19	3.76	4.29	0.984	0.740	0.840	0.015	57.4
303.0	381.8	8.5	3.7	10.2	342.4	4.71	19.10	3.80	4.33	0.984	0.739	0.840	0.020	55.7
308.0	384.1	9.2	3.7	9.5	341.8	4.77	19.02	3.83	4.36	0.984	0.738	0.841	0.025	54.0
313.0	386.4	9.9	3.7	8.9	341.2	4.83	18.95	3.87	4.40	0.984	0.737	0.841	0.030	52.2
318.0	388.6	10.6	3.7	8.3	340.6	4.88	18.89	3.90	4.43	0.983	0.736	0.841	0.035	50.5
323.0	390.9	11.4	3.7	7.8	339.9	4.94	18.84	3.93	4.46	0.983	0.736	0.841	0.040	48.7
328.0	393.2	12.2	3.7	7.3	339.3	4.99	18.79	3.97	4.49	0.983	0.735	0.841	0.045	46.7
333.0	395.5	13.0	3.7	6.9	338.5	5.05	18.75	4.00	4.53	0.983	0.734	0.841	0.050	45.1
338.0	397.8	13.9	3.7	6.5	337.8	5.10	18.71	4.03	4.56	0.983	0.733	0.841	0.055	43.3
343.0	400.0	14.8	3.7	6.2	337.0	5.15	18.68	4.06	4.59	0.983	0.733	0.841	0.060	41.5
348.0	402.3	15.6	3.7	5.9	336.2	5.20	18.65	4.09	4.61	0.983	0.732	0.841	0.065	39.6
353.0	404.6	16.5	3.7	5.6	335.4	5.24	18.63	4.11	4.64	0.983	0.731	0.841	0.070	37.8
358.0	406.9	17.2	3.7	5.4	334.5	5.29	18.61	4.14	4.67	0.983	0.731	0.841	0.075	35.9
363.0	409.2	17.9	3.7	5.2	333.7	5.34	18.59	4.17	4.70	0.983	0.730	0.842	0.080	34.0
368.0	411.5	18.5	3.7	5.0	332.8	5.38	18.58	4.20	4.73	0.983	0.729	0.842	0.085	32.1
373.0	413.8	19.0	3.7	5.0	331.8	5.43	18.56	4.22	4.75	0.983	0.729	0.842	0.090	30.2
378.0	416.1	19.2	3.7	4.9	330.9	5.47	18.55	4.25	4.78	0.983	0.728	0.842	0.095	28.2
383.0	418.4	19.3	3.7	4.9	329.9	5.52	18.54	4.28	4.81	0.983	0.727	0.842	0.100	26.3

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

- 198 -

COLSIM PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
45.0 deg. 0.0 deg. 1000.0 W/cm² 0.20 0.036 Kg/sec 10.0 deg.C 10.0 deg.C 15.0 W/(cm² K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI K	TFE K	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/T	EFF
-----W/(cm ² K)-----														
283.0	292.4	87.3	3.8	8.1	514.7	2.34	40.54	2.27	7.80	0.987	0.971	0.834	0.000	81.0
288.0	297.4	99.9	3.8	7.0	521.3	2.87	29.31	2.65	3.18	0.987	0.969	0.836	0.005	79.4
293.0	302.2	112.9	3.8	6.1	527.5	3.24	25.28	2.90	3.43	0.987	0.967	0.837	0.010	77.6
298.0	307.0	126.4	3.8	5.4	533.5	3.53	23.21	3.09	3.61	0.987	0.966	0.838	0.015	75.7
303.0	311.8	140.1	3.7	4.8	539.2	3.74	21.98	3.22	3.75	0.987	0.965	0.838	0.020	73.7
308.0	316.5	153.8	3.7	4.3	544.5	3.92	21.17	3.33	3.86	0.986	0.964	0.839	0.025	71.6
313.0	321.3	167.4	3.7	3.9	549.6	4.07	20.60	3.42	3.95	0.986	0.964	0.839	0.030	69.5
318.0	326.0	181.0	3.7	3.6	554.4	4.20	20.18	3.49	4.02	0.986	0.963	0.839	0.035	67.3
323.0	330.7	194.7	3.7	3.3	558.8	4.32	19.85	3.56	4.09	0.986	0.963	0.840	0.040	65.1
328.0	335.5	208.9	3.7	3.1	563.0	4.42	19.60	3.63	4.16	0.986	0.963	0.840	0.045	62.8
333.0	340.2	223.9	3.7	2.9	566.9	4.52	19.40	3.69	4.22	0.986	0.962	0.840	0.050	60.6
338.0	344.9	240.3	3.7	2.6	570.5	4.62	19.24	3.74	4.27	0.986	0.962	0.840	0.055	58.2
343.0	349.6	258.3	3.7	2.4	573.8	4.70	19.11	3.79	4.32	0.986	0.962	0.840	0.060	55.9
348.0	354.3	278.1	3.7	2.3	576.8	4.79	19.00	3.84	4.37	0.986	0.961	0.841	0.065	53.5
353.0	359.0	299.2	3.7	2.1	579.5	4.87	18.91	3.89	4.42	0.986	0.961	0.841	0.070	51.1
358.0	363.7	320.4	3.7	2.0	581.9	4.94	18.84	3.94	4.47	0.986	0.961	0.841	0.075	48.6
363.0	368.4	338.9	3.7	1.8	584.1	5.02	18.77	3.98	4.51	0.986	0.961	0.841	0.080	46.1
368.0	373.1	350.4	3.7	1.8	585.9	5.09	18.72	4.02	4.55	0.986	0.960	0.841	0.085	43.6
373.0	377.8	350.4	3.7	1.8	587.5	5.16	18.68	4.06	4.59	0.986	0.960	0.841	0.090	41.1
378.0	382.5	334.3	3.7	1.9	588.7	5.22	18.64	4.10	4.63	0.986	0.960	0.841	0.095	38.5
383.0	387.2	302.9	3.7	2.1	589.7	5.29	18.61	4.14	4.67	0.986	0.960	0.841	0.100	35.9

EFFECTIVE SKY TEMP. DURING TEST WAS : -7.4 deg.C

- 199 -

COLSIM PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT	INCID. ANGLE	SOLAR INSOL.	DIFF. FRAC.	FLOW RATE	AIR TEMP.	FLUID TEMP.	HW
75.0 deg.	0.0 deg.	900.0 W/cm ²	0.10	0.072 K/s	-35.0 deg.C	-35.0 deg.C	5.0 W/(sq.M K)

* GROUND EMISSANCE 0.9, GROUND REFLECTIVITY 0.7

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
K	K				W/(sq.M K)									
238.0	242.3	41.9	3.9	40.8	447.5	1.49	45.00	1.50	2.03	0.988	0.982	0.836	0.000	82.1
243.0	247.3	48.5	3.9	34.4	457.1	2.10	20.75	1.94	2.47	0.987	0.980	0.840	0.006	81.0
248.0	252.2	56.2	3.9	29.0	466.3	2.41	15.17	2.10	2.63	0.987	0.980	0.842	0.011	79.6
253.0	257.1	65.3	3.9	24.4	475.3	2.62	12.74	2.19	2.72	0.987	0.979	0.843	0.017	78.2
258.0	262.1	76.0	3.9	20.5	484.0	2.81	11.41	2.27	2.80	0.987	0.979	0.845	0.022	76.6
263.0	267.0	88.6	3.9	17.3	492.3	2.95	10.59	2.32	2.85	0.987	0.979	0.845	0.028	75.0
268.0	271.9	103.2	3.9	14.5	500.4	3.07	10.04	2.37	2.89	0.987	0.979	0.846	0.033	73.4
273.0	276.8	120.1	3.9	12.3	508.1	3.18	9.64	2.40	2.93	0.987	0.979	0.847	0.039	71.7
278.0	281.7	139.4	3.8	10.4	515.5	3.27	9.35	2.44	2.94	0.987	0.979	0.847	0.044	70.0
283.0	286.6	161.0	3.8	8.9	522.7	3.35	9.12	2.47	2.99	0.987	0.979	0.848	0.050	68.3
288.0	291.6	184.7	3.8	7.6	529.5	3.43	8.95	2.49	3.02	0.987	0.978	0.848	0.056	66.5
293.0	296.5	210.2	3.8	6.6	536.0	3.50	8.81	2.52	3.05	0.987	0.978	0.848	0.061	64.8
298.0	301.4	237.1	3.8	5.8	542.2	3.57	8.69	2.55	3.07	0.987	0.978	0.849	0.067	63.0
303.0	306.3	264.7	3.8	5.1	548.2	3.64	8.60	2.57	3.10	0.987	0.978	0.849	0.072	61.1
308.0	311.2	292.5	3.8	4.6	553.8	3.70	8.53	2.59	3.12	0.987	0.978	0.849	0.078	59.3
313.0	316.1	320.2	3.8	4.1	559.1	3.76	8.47	2.62	3.15	0.987	0.978	0.849	0.083	57.4
318.0	321.0	347.8	3.8	3.8	564.1	3.81	8.43	2.64	3.17	0.987	0.978	0.849	0.089	55.5
323.0	325.9	375.4	3.8	3.5	568.8	3.87	8.39	2.66	3.19	0.987	0.978	0.850	0.094	53.6
328.0	330.8	403.7	3.8	3.2	573.2	3.92	8.36	2.68	3.21	0.987	0.978	0.850	0.100	51.7

EFFECTIVE SKY TEMP. DURING TEST WAS : -61.9 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT	INCID. ANGLE	SOLAR INSOL.	DIFF. FRAC.	FLOW RATE	AIR TEMP.	FLUID TEMP.	HW
20.0 deg.	45.0 deg.	1000.0 W/cm ²	0.40	0.018 K/s	35.0 deg.C	35.0 deg.C	40.0 W/(sq.M K)

GROUND EMISSANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/I	EFF
K	K				W/(sq.M K)									
308.0	330.2	24.0	3.7	17.4	350.2	3.54	52.53	3.35	3.88	0.984	0.931	0.815	0.000	75.9
313.0	334.5	26.5	3.7	15.8	349.8	3.88	49.47	3.62	4.15	0.984	0.928	0.816	0.005	73.8
318.0	338.7	29.3	3.7	14.4	349.2	4.13	47.73	3.83	4.36	0.984	0.925	0.816	0.010	71.5
323.0	342.9	32.3	3.7	13.2	348.7	4.33	46.61	3.99	4.57	0.984	0.923	0.816	0.015	69.1
328.0	347.1	35.6	3.7	12.0	348.1	4.50	45.83	4.12	4.65	0.983	0.922	0.817	0.020	66.7
333.0	351.3	39.3	3.7	11.0	347.4	4.64	45.25	4.24	4.77	0.983	0.920	0.817	0.025	64.2
338.0	355.4	43.2	3.7	10.1	346.7	4.77	44.82	4.34	4.87	0.983	0.919	0.817	0.030	61.7
343.0	359.6	47.6	3.7	9.2	345.9	4.89	44.47	4.43	4.96	0.983	0.918	0.817	0.035	59.1
348.0	363.8	52.3	3.7	8.5	345.1	5.00	44.20	4.52	5.05	0.983	0.917	0.817	0.040	56.4
353.0	368.0	57.3	3.7	7.8	344.3	5.11	43.96	4.60	5.13	0.983	0.917	0.817	0.045	53.8
358.0	372.2	62.6	3.7	7.2	343.4	5.20	43.78	4.67	5.20	0.982	0.916	0.817	0.050	51.0
363.0	376.3	68.2	3.7	6.6	342.5	5.29	43.62	4.75	5.27	0.982	0.915	0.817	0.055	48.3
368.0	380.5	73.9	3.7	6.2	341.5	5.38	43.48	4.81	5.34	0.982	0.915	0.817	0.060	45.4
373.0	384.7	79.5	3.7	5.8	340.5	5.46	43.37	4.88	5.41	0.982	0.914	0.817	0.065	42.6
378.0	388.8	84.7	3.7	5.4	339.4	5.54	43.27	4.94	5.47	0.982	0.913	0.818	0.070	39.7
383.0	393.0	89.4	3.7	5.2	338.3	5.62	43.18	5.00	5.53	0.982	0.913	0.818	0.075	36.8
388.0	397.2	93.1	3.7	5.0	337.1	5.70	43.11	5.06	5.59	0.982	0.912	0.818	0.080	33.8
393.0	401.3	95.6	3.7	4.9	335.9	5.77	43.04	5.11	5.64	0.982	0.912	0.818	0.085	30.8
398.0	405.5	96.4	3.7	4.9	334.6	5.84	42.99	5.17	5.70	0.981	0.911	0.818	0.090	27.8
403.0	409.6	95.2	3.7	5.0	333.3	5.91	42.94	5.22	5.75	0.981	0.911	0.818	0.095	24.7
408.0	413.8	91.9	3.7	5.2	332.0	5.98	42.89	5.28	5.80	0.981	0.910	0.818	0.100	21.6

EFFECTIVE SKY TEMP. DURING TEST WAS : 21.4 deg.C

- 200 -

COLSIN PERFORMANCE SUMMARY

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
20.0 deg. 45.0 deg. 1000.0 W/cm² 0.40 0.036 Kt/sec 33.0 deg.C 33.0 deg.C 40.0 W/(sq.M K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.2

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/T	EFF
K	K													
308.0	319.5	42.3	3.8	19.5	355.8	3.05	61.59	2.95	3.48	0.985	0.961	0.814	0.000	78.2
313.0	324.2	47.2	3.8	17.6	355.4	3.51	53.14	3.32	3.85	0.985	0.958	0.815	0.005	74.2
318.0	328.8	52.5	3.8	16.0	354.9	3.85	49.49	3.60	4.13	0.984	0.954	0.816	0.010	74.0
323.0	333.4	58.2	3.8	14.5	354.4	4.12	47.81	3.82	4.35	0.984	0.954	0.816	0.015	71.6
328.0	337.9	64.3	3.8	13.2	353.9	4.33	46.62	3.98	4.51	0.984	0.953	0.816	0.020	69.2
333.0	342.5	71.4	3.8	12.0	353.2	4.50	45.81	4.12	4.65	0.983	0.952	0.817	0.025	66.7
338.0	347.1	79.0	3.8	11.0	352.6	4.65	45.22	4.24	4.77	0.983	0.951	0.817	0.030	64.1
343.0	351.7	87.4	3.8	10.0	351.9	4.79	44.78	4.35	4.88	0.983	0.950	0.817	0.035	61.4
348.0	356.3	96.5	3.8	9.1	351.1	4.91	44.43	4.45	4.98	0.983	0.950	0.817	0.040	58.7
353.0	360.8	106.4	3.8	8.3	350.3	5.02	44.15	4.53	5.06	0.983	0.949	0.817	0.045	55.9
358.0	365.4	117.1	3.8	7.6	349.4	5.13	43.91	4.62	5.15	0.983	0.949	0.817	0.050	53.1
363.0	370.0	128.4	3.8	7.0	348.5	5.23	43.73	4.69	5.22	0.983	0.948	0.817	0.055	50.3
368.0	374.5	140.1	3.8	6.5	347.5	5.32	43.57	4.77	5.30	0.982	0.948	0.817	0.060	47.4
373.0	379.1	151.9	3.8	6.0	346.5	5.41	43.44	4.84	5.37	0.982	0.948	0.817	0.065	44.4
378.0	383.7	163.3	3.8	5.6	345.4	5.50	43.33	4.90	5.43	0.982	0.947	0.817	0.070	41.4
383.0	388.2	173.9	3.8	5.3	344.3	5.58	43.23	4.97	5.50	0.982	0.947	0.818	0.075	38.4
388.0	392.8	182.8	3.8	5.1	343.1	5.66	43.15	5.03	5.56	0.982	0.946	0.818	0.080	35.3
393.0	397.4	189.3	3.8	5.0	341.9	5.74	43.07	5.09	5.62	0.982	0.946	0.818	0.085	32.2
398.0	401.9	192.5	3.8	4.9	340.6	5.81	43.01	5.15	5.68	0.982	0.946	0.818	0.090	29.0
403.0	406.5	191.8	3.8	5.0	339.3	5.89	42.95	5.20	5.73	0.982	0.945	0.818	0.095	25.8
408.0	411.0	186.4	3.8	5.2	337.9	5.96	42.91	5.26	5.79	0.981	0.945	0.818	0.100	22.6

EFFECTIVE SKY TEMP. DURING TEST WAS : 21.4 deg.C

OPERATIONAL CONDITIONS FOR SIMULATION

TILT INCID.ANGLE SOLAR INSOL. DIFF.FRAC. FLOW RATE AIR TEMP. FLUID TEMP. HW
75.0 deg. 0.0 deg. 900.0 W/cm² 0.10 0.036 Kt/sec -33.0 deg.C -33.0 deg.C 5.0 W/(sq.M K)

GROUND EMITTANCE 0.9, GROUND REFLECTIVITY 0.7

DETAILED HEAT TRANSFER ANALYSIS

TFI	TFE	REF	NUF	PR	HF	UPC	UCA	UTOP	UL	FPRME	FR	TAEFF	DT/T	EFF
K	K													
238.0	250.3	1.8	3.8	398.6	355.9	2.04	22.25	1.90	2.42	0.987	0.967	0.839	0.000	81.2
243.0	254.9	2.7	3.8	266.3	356.2	2.37	15.79	2.08	2.61	0.986	0.966	0.842	0.006	79.9
248.0	259.6	4.0	3.8	186.2	356.3	2.58	13.09	2.17	2.70	0.986	0.965	0.843	0.011	78.5
253.0	264.3	5.5	3.8	135.6	356.8	2.77	11.65	2.25	2.78	0.986	0.964	0.844	0.017	77.0
258.0	268.9	7.3	3.8	102.4	356.9	2.92	10.76	2.31	2.84	0.986	0.964	0.845	0.022	75.4
263.0	273.6	9.5	3.8	79.8	357.1	3.04	10.12	2.35	2.88	0.986	0.964	0.846	0.028	73.8
268.0	278.3	12.0	3.8	63.9	357.2	3.15	9.74	2.39	2.92	0.986	0.964	0.847	0.033	72.2
273.0	282.9	14.8	3.8	52.4	357.2	3.24	9.43	2.43	2.96	0.986	0.964	0.847	0.039	70.6
278.0	287.6	17.8	3.8	44.0	357.2	3.33	9.19	2.46	2.99	0.986	0.964	0.848	0.044	68.9
283.0	292.3	21.0	3.8	37.5	357.1	3.41	9.00	2.48	3.01	0.986	0.964	0.848	0.050	67.2
288.0	297.0	24.4	3.8	32.5	357.0	3.48	8.86	2.51	3.04	0.986	0.964	0.848	0.056	65.5
293.0	301.7	28.1	3.8	28.5	356.8	3.55	8.73	2.54	3.06	0.986	0.964	0.848	0.061	63.7
298.0	306.4	32.0	3.8	25.3	356.6	3.61	8.64	2.56	3.09	0.986	0.963	0.849	0.067	61.9
303.0	311.1	36.1	3.8	22.6	356.3	3.67	8.56	2.58	3.11	0.986	0.963	0.849	0.072	60.1
308.0	315.8	40.5	3.8	20.3	355.9	3.73	8.50	2.61	3.14	0.986	0.963	0.849	0.078	58.3
313.0	320.5	45.3	3.8	18.3	355.6	3.79	8.45	2.63	3.16	0.986	0.963	0.849	0.083	56.5
318.0	325.2	50.4	3.8	16.6	355.1	3.84	8.41	2.65	3.18	0.986	0.963	0.850	0.089	54.6
323.0	329.9	56.0	3.8	15.0	354.6	3.89	8.38	2.67	3.20	0.985	0.963	0.850	0.094	52.7
328.0	334.6	62.2	3.8	13.7	354.1	3.94	8.35	2.69	3.22	0.985	0.963	0.850	0.100	50.8

EFFECTIVE SKY TEMP. DURING TEST WAS : -61.9 deg.C

- 201 -

APPENDIX E

Experimental Equipment

Plate 1 - Photo of NRC/DBR Solar Calorimeter Facility

2 - NRC/DBR Rooftop Test Site

3 - EPPLY Model 8-48 Pyranometer used for determination of incident
total solar radiation on the collector surface

4 - Calibration Certificate for pyranometer used to determine incident
solar radiation

5 - Kaye Data System General Description

6 - Kaye Data System Specifications

7 - Cipher 9-Track Tape Unit, Specifications
(used for raw data storage)

8 - Shade ring used for determination of diffuse radiation incident on
horizontal surface

9 - Epply Model 50 - pyranometer used to determine horizontal diffuse
and total solar radiation

- 204 -

Eppley black and white pyranometer.

PLATE 17. Eppley black and white pyranometer, model 8-48.

This pyranometer has a radial wirewound-plated (copper-constantan) thermopile enclosed in a glass hemisphere 50 mm in diameter. The thermopile is a differential type with the hot-junction receivers coated with Parsons' black, and the cold-junction receivers coated with barium sulphate. This whitening agent is nonhygroscopic. The spectral response is similar to the 10- and 50-junction models of the 180° pyrheliometer, which this model replaces. The chromed brass case carries a circular spirit level and adjustable levelling screws.

(a) Response:	0.11	mV/W m ⁻²
(b) Linearity of response:	±1	per cent
(c) Temperature dependence:		
- compensated	±1.5	per cent
(-20 to +40°C)		
(d) Cosine response:	±5	per cent
(at 10° elevation)		
(e) Impedance:	300	Ω
(f) Response time:		
63.2%	3	s
95%	10	s

- 205 -

①

Environment Canada
Atmosphère/Environnement

Environnement Canada
Environnement Atmosphérique

NATIONAL ATMOSPHERIC RADIATION CENTRE

Calibration Certificate No. 76-132

Type of Radiometer Pyranometer
Manufacturer Eppley
Model Number 8-48
Serial Number 15374
Calibration Factor, Short-Wave 7.94 MV/CAL CM⁻² MIN⁻¹
Calibration Factor, Long-Wave _____
Temperature of Calibration 80° F
Temperature Coefficient Temperature Compensated
Internal Resistance _____
Remarks Owner - NRC, OTTAWA. Certificate expires 1 March 1979.
In Charge of Test _____

Approved _____

Assistant Deputy Minister

Date of Approval 3 Mar 77

NOTES: a. Short-Wave calibration factors are based on the International Pyrothermometric Scale 1956.
(Smithsonian Scale of 1913 reduced by 2.0 per cent.)
b. 1 langley min⁻¹ = 1 Calorie cm⁻² min⁻¹
= 68.8 m W cm⁻²
= 221 BTU ft⁻² hr⁻¹

GENERAL DESCRIPTION

The analog "front-end" of the System 8000 is unmatched for reliability, accuracy and flexibility. Greatest emphasis has been placed on reliable operation with ambient conditions and common mode voltage levels typically found in industrial environments. The hermetically-sealed scanning units will operate safely at common mode voltages in excess of 400 volts while introducing less than $\pm 1 \mu\text{V}$ of thermal error. A unique electronic reference matches both slope and curvature of the output of a thermocouple to give reference accuracy of $\pm 0.1^\circ\text{F}$ over a wide range of ambient temperature.

Sensors connected to the System 8000 may be grounded or ungrounded. The use of three-wire, shielded analog circuits and a triple-shielded transformer in the analog power supply provide a fully guarded system with maximum isolation from line noise and a common mode rejection in excess of 140 db.

Analog voltages are converted to digital values by means of a dual-slope integrating DVM having a chopper-stabilized, low-level amplifier and a high-level A/D converter with automatic correction for zero offset. The full-scale value of standard voltage ranges is 20,000 counts, but the internal full-scale count is 200,000. Dividing the basic count by ten on standard voltage ranges eliminates small counting errors.

The greater number of internal counts and a new digital computing circuit, our voltage-to-function converter, provide unusual accuracy and flexibility in conversion of transducer outputs to corresponding values of engineering parameters. For example, thermocouple voltages are converted to temperature units with a conformity of $\pm 0.1^\circ\text{F}$ to the 1971 revised National Bureau of Standards thermocouple tables over the entire normal range of the common thermocouple types. Any system may contain up to three independent conversion circuits simultaneously, and the PROM's controlling each circuit are field changeable to allow even greater flexibility.

All system controls are operated by easily accessible front-panel switches; awkward hidden switches and diode pins are not used. The time, channel identification and data are displayed visually and may be recorded simultaneously on the built-in line printer or an optional serial recorder.

- 207 -

NUMBER OF CHANNELS:	10 to 990 in 10 channel increments.
MAXIMUM SCAN RATE:	3 readings/sec.
COMMON MODE VOLTAGE:	400 VDC or AC.
STABILITY WITH TIME:	<p>20 mv, 200 mv and 2 V ranges:</p> <p>30 days</p> <p>$\pm 1 \mu\text{V} \pm 0.005\%$ full scale $\pm 0.01\%$ reading.</p> <p>1 year</p> <p>$\pm 2 \mu\text{V} \pm 0.005\%$ full scale $\pm 0.02\%$ reading.</p> <p>20 V and 200 V ranges:</p> <p>30 days</p> <p>$\pm 2 \text{ mv} \pm 0.005\%$ full scale $\pm 0.01\%$ reading.</p> <p>1 year</p> <p>$\pm 3 \text{ mv} \pm 0.005\%$ full scale $\pm 0.02\%$ reading.</p> <p>Thermocouple Types E, J, K and T:</p> <p>30 days</p> <p>$\pm 0.1^\circ\text{C} \pm 0.01\%$ reading.</p> <p>1 year</p> <p>$\pm 0.2^\circ\text{C} \pm 0.02\%$ reading.</p> <p>Thermocouple Types R and S:</p> <p>30 days</p> <p>$\pm 0.4^\circ\text{C} \pm 0.01\%$ reading.</p> <p>1 year</p> <p>$\pm 0.8^\circ\text{C} \pm 0.02\%$ reading.</p>
STABILITY WITH AMBIENT TEMPERATURE:	<p>20 mv, 200 mv and 2 V ranges:</p> <p>$\pm 0.1 \mu\text{V}/^\circ\text{C} \pm 0.001\%$ reading/$^\circ\text{C}$.</p> <p>20 V and 200 V ranges:</p> <p>$\pm 0.2 \text{ mv}/^\circ\text{C} \pm 0.001\%$ reading/$^\circ\text{C}$.</p> <p>Thermocouple Types E, J, K and T:</p> <p>$\pm 0.01^\circ\text{C}/^\circ\text{C} \pm 0.001\%$ reading/$^\circ\text{C}$.</p> <p>Thermocouple Types R & S:</p> <p>$\pm 0.04^\circ\text{C}/^\circ\text{C} \pm 0.001\%$ reading/$^\circ\text{C}$.</p>
INPUT IMPEDANCE:	<p>20 mv, 200 mv, 2 V and thermocouple ranges:</p> <p>Greater than 1000 Megohms.</p> <p>20 V and 200 V ranges:</p> <p>1 Megohm.</p>
OPERATING TEMPERATURE:	20° F to 110° F.
POWER:	<p>105 VAC to 125 VAC 50/60 Hz.</p> <p>180 watts to 250 watts for typical systems.</p> <p>220 VAC operation is optional.</p>
THERMOCOUPLE CONFORMITY:	<p>The conversion of thermocouple voltage to temperature units is done by a digital computing circuit. The maximum difference between that conversion and the 1971 revised National Bureau of Standards thermocouple tables is given for the standard thermocouple circuits.</p>

Standard Thermocouple Conversion Circuits				
Model No.	Material	Type	Range	Conformity
8011F or C	Chromel-Constantan	E	-200°F to 1850°F (-130°C to 1010°C)	0.1°F
8012F or C	Iron-Constantan	J	-250°F to 1600°F (-155°C to 870°C)	0.1°F
8013F or C	Chromel-Alumel	K	-150°F to 2500°F (-100°C to 1370°C)	0.1°F
8014F or C	Plat.-Plat.-13% Rh.	R	500°F to 3200°F (260°C to 1760°C)	0.1°F
8024F or C	Plat.-Plat.-13% Rh.	R	32°F to 3200°F (0°C to 1760°C)	0.2°F
8015F or C	Plat.-Plat.-10% Rh.	S	500°F to 3200°F (260°C to 1760°C)	0.1°F
8025F or C	Plat.-Plat.-10% Rh.	S	32°F to 3200°F (0°C to 1760°C)	0.2°F
8016F or C	Copper-Constantan	T	-250°F to 800°F (-155°C to 425°C)	0.1°F

- 208 -

Tape Width & Thickness	1/2 in. wide, 1.5 mil thick	
Reel Drive	Dc motor and position servo	
Capstan Drive	Dc motor with velocity and position servos	
Power	115 Vac, 50-60 Hz	
	STANDARD	OPTIONAL
Incremental Write (cps)	0-1000	800, (200, Model 100M only)
Density (bpi)	556	
Bit Spacing Accuracy (using internal optical encoder)	$\pm 2\%$; $\pm 4\%$ worst case	
Continuous Tape Speed (ips)	12-1/2	
Speed Accuracy	$\pm 1\%$, long-term $\pm 4\%$, instantaneous	
Inter-Record Gap Time	50 ms $\pm$ 10%	1 to 25
File Gap Time	200 ms	

Table 1-1. Specifications

- 209

SHADE RING TYPE I (DIFFUSOGRAPH)

Eppler pyranometer (180° pyrheliometer)

Eppler (180° pyrheliometer) pyranometer.

- 210 -

APPENDIX F

Experimental Data

Data Output Table Explanation

i.e., IC6078.307 - corresponds to test circuit no. 1

- Chamberlain collector
- collector tilt = 60°
- Year = 1978
- Julian Day No. 307

10:12:00 - 10:12:00 - starting time of data record in E.S.T.

Nomenclature

INT - Test interval - seconds

IT2 - Total solar radiation on collector surface, W/m²

· IH2 - Total solar radiation on horizontal surface

IDF - Diffuse solar radiation on horizontal surface

TAM - Ambient air temperature °C

CII - Solar collector inlet fluid temperature

COI - Solar collector outlet fluid temperature

WSP - Average wind speed m/sec.

WDR - Wind Direction

FLR - Heat transfer fluid flowrate L/min.

$$(T_I - T_A)/I = (T_{fi} - T_a)/I$$

EFF - Experimentally determined collector thermal
efficiency

- 211 -

SOLAR COLLECTOR TYPE "C"

20-SEP-82 22:16:47 PAGE 2

FILE DATE	TIME	INT	IT2	IT7	IDF	IDM	IDP	TAM	C11	C01	ST1	WSP	WDR	FLR	(TI-TA)/I	EFF
		Sec	W/M882	W/M882	W/M882	W/M882	Des C	Des C	Des C	Des C	Des C	M/Sec	from	L/Min	(M882/W	%
102278.181	10:42:00	480	904.7	925.3	77.1	0.0	0.00	17.80	18.20	28.10	25.40	6.22	NW	2.12	0.000	75.5
102278.181	10:43:00	480	913.0	931.8	79.0	0.0	0.00	17.80	18.30	28.40	25.70	6.22	NW	2.12	0.001	76.0
102278.181	11:40:00	480	1005.3	1011.3	67.7	0.0	0.00	19.60	19.90	31.00	27.90	6.67	N	2.16	0.000	76.7
102278.181	13:20:00	480	965.7	946.7	81.5	0.0	0.00	23.20	23.40	33.70	30.90	8.44	NW	2.22	0.000	76.6
102278.183	10:15:00	480	906.8	927.6	81.2	0.0	0.00	19.80	23.40	32.70	30.10	4.00	NW	2.21	0.004	73.2
102278.183	12:05:00	480	1009.6	1007.6	87.2	0.0	0.00	21.30	23.20	34.10	31.10	4.89	NW	2.21	0.002	77.1
102278.183	13:47:00	480	921.4	911.0	87.4	0.0	0.00	22.60	23.10	33.10	30.30	4.89	NW	2.21	0.001	77.2
102278.184	10:12:00	480	898.4	912.3	80.8	0.0	0.00	21.10	22.90	32.20	29.50	1.78	NW	2.19	0.002	73.4
102278.184	10:58:00	480	956.2	967.9	90.0	0.0	0.00	21.80	23.20	33.30	30.40	1.78	NW	2.20	0.001	75.6
102278.184	11:06:00	480	971.8	979.5	88.2	0.0	0.00	21.70	23.20	33.60	30.50	2.22	N	2.19	0.002	75.5
102278.184	11:54:00	480	1004.6	999.8	86.4	0.0	0.00	22.90	23.20	34.20	31.00	2.22	N	2.20	0.000	77.1
102278.198	10:48:00	480	945.9	934.0	124.0	0.0	0.00	24.50	27.70	47.00	45.10	1.78	N	2.26	0.014	71.8
102278.199	12:14:00	480	962.0	958.7	65.7	0.0	0.00	22.90	26.70	36.60	35.40	2.22	SW	2.43	0.063	47.2
102278.199	12:58:00	480	971.6	926.0	76.4	0.0	0.00	28.40	30.70	36.40	35.30	2.22	SW	2.43	0.064	46.8
102278.206	10:46:00	480	919.4	900.0	73.7	0.0	0.00	25.60	29.10	38.40	35.30	1.56	SE	2.30	0.004	75.1
102278.209	10:30:00	480	916.5	900.5	56.2	0.0	0.00	18.80	19.40	28.40	25.50	4.89	NW	2.43	0.001	76.4
102278.211	10:08:00	480	908.0	883.1	81.3	0.0	0.00	15.90	18.40	27.40	24.50	3.11	NW	2.34	0.003	74.5
102278.211	11:57:00	480	1002.3	959.6	52.8	0.0	0.00	18.30	19.20	29.40	26.10	3.11	NW	2.37	0.001	78.2
102278.211	12:05:00	480	1003.2	957.7	53.2	0.0	0.00	18.90	19.20	29.50	26.20	3.56	NW	2.36	0.000	78.0
102278.211	12:23:00	480	1009.0	955.7	50.9	0.0	0.00	18.20	19.30	29.70	26.30	3.56	NW	2.37	0.001	78.6
102278.211	12:58:00	480	985.4	935.6	53.2	0.0	0.00	18.10	19.20	29.40	26.10	3.56	NW	2.37	0.001	78.9
102278.230	10:24:00	480	891.7	821.1	57.6	0.0	0.00	21.10	22.80	31.80	28.80	1.78	NW	2.23	0.002	72.9
102278.230	10:57:00	480	941.4	863.9	49.9	0.0	0.00	22.70	23.10	33.20	29.70	1.78	NW	2.19	0.000	75.5
102278.230	11:20:00	480	963.0	879.7	51.1	0.0	0.00	22.00	23.20	33.60	30.00	1.33	NW	2.19	0.001	76.2
102278.230	11:28:00	480	967.4	880.6	53.7	0.0	0.00	23.20	23.30	33.70	30.30	1.33	NW	2.20	0.000	76.8
102278.230	12:58:00	480	957.0	870.1	51.4	0.0	0.00	23.20	23.30	33.80	30.20	2.67	SW	2.21	0.000	77.5
102278.232	12:21:00	480	983.2	889.3	44.4	0.0	0.00	21.20	22.70	33.10	29.80	4.44	NW	2.22	0.002	75.9
102278.232	13:11:00	480	945.1	858.9	55.4	0.0	0.00	20.30	23.00	33.20	29.80	4.00	NW	2.18	0.003	75.9
102278.232	13:39:00	480	909.6	826.7	52.3	0.0	0.00	21.60	22.90	32.80	29.40	4.00	NW	2.15	0.001	75.7
102278.255	12:21:00	480	953.8	818.4	55.0	0.0	0.00	15.20	18.70	28.50	25.30	4.89	NW	2.28	0.004	75.5
102278.255	12:46:00	480	937.4	803.3	54.9	0.0	0.00	15.70	18.70	28.50	25.10	4.89	NW	2.28	0.003	76.1
102278.255	13:00:00	480	921.5	786.2	55.2	0.0	0.00	15.70	18.60	28.20	25.00	5.33	NW	2.29	0.003	76.2
102278.255	13:14:00	480	903.7	770.5	54.1	0.0	0.00	15.90	18.60	27.80	24.60	5.33	NW	2.29	0.003	75.9
102278.256	10:25:00	480	875.5	746.8	49.6	0.0	0.00	12.80	17.90	26.80	23.90	2.67	NE	2.27	0.006	74.0
102278.256	12:38:00	480	936.4	800.9	50.8	0.0	0.00	16.10	19.10	29.10	25.70	2.22	NE	2.24	0.003	76.8
102278.256	12:54:00	480	925.5	769.4	50.8	0.0	0.00	16.70	19.00	28.80	25.50	2.22	NE	2.27	0.002	77.6
102278.256	13:44:00	480	850.6	722.0	51.7	0.0	0.00	16.30	18.70	27.60	24.80	1.11	NE	2.28	0.003	76.6
102278.257	11:33:00	480	940.0	797.8	64.6	0.0	0.00	17.40	18.40	27.80	24.80	4.00	SE	2.34	0.001	76.4

SOLAR COLLECTOR TYPE "C"

20-SEP-82 22:16:47 PAGE 3

FILE	DATE	TIME	INT	IT2	IT7	IDF	IDM	IDP	TAM	C11	C01	ST1	WSP	WDR	FLR	(TI-TA)/I	EFF
			Sec	W/M882	W/M882	W/M882	W/M882		Des C	Des C	Des C	Des C	M/Sec	from	L/Min	(M882/W	%
102278.262		10:29:00	480	861.9	713.5	43.8	0.0	0.00	14.00	35.20	42.80	40.20	3.11	NE	2.30	0.025	66.5
102278.262		10:47:00	480	884.2	735.7	37.6	0.0	0.00	14.70	35.20	43.30	40.60	3.11	NE	2.25	0.023	66.9
102278.262		11:45:00	480	928.7	771.2	31.9	0.0	0.00	16.90	35.30	44.10	40.90	2.22	N	2.27	0.020	69.2
102278.262		13:21:00	480	860.5	711.4	45.6	0.0	0.00	18.30	35.30	43.60	40.60	2.22	N	2.26	0.020	70.4
102278.262		13:57:00	480	788.0	645.4	49.1	0.0	0.00	18.50	35.20	42.60	39.80	2.22	N	2.28	0.021	68.8
102278.268		12:09:00	480	925.0	757.7	63.0	0.0	0.00	9.10	26.30	35.70	32.30	6.22	NW	2.10	0.019	69.1
102278.268		12:35:00	480	914.6	749.2	61.2	0.0	0.00	9.70	26.10	35.60	32.30	6.22	NW	2.09	0.018	69.1
102278.284		10:35:00	480	822.0	544.2	136.0	0.0	0.00	14.70	54.50	61.20	59.30	1.33	E	2.22	0.048	59.2
102278.284		11:01:00	480	853.6	565.7	131.7	0.0	0.00	14.20	54.60	61.80	59.70	2.22	NE	2.21	0.047	61.5
102278.284		12:16:00	480	856.9	568.2	137.6	0.0	0.00	17.20	54.70	62.50	60.20	1.78	NE	2.14	0.044	63.5
102278.289		10:21:00	480	929.8	582.0	64.0	0.0	0.00	3.00	54.00	60.90	59.00	2.67	NW	2.36	0.055	57.4
102278.289		10:57:00	480	969.2	615.2	62.2	0.0	0.00	3.70	53.80	61.30	59.20	2.67	NW	2.35	0.052	59.8
102278.289		11:05:00	480	975.5	621.3	62.1	0.0	0.00	4.20	53.80	61.50	59.30	3.11	N	2.34	0.051	60.2
102278.289		11:13:00	480	988.0	638.1	74.0	0.0	0.00	3.30	53.80	61.70	59.40	3.11	N	2.34	0.051	60.4
102278.290		12:11:00	480	1004.0	639.3	86.4	0.0	0.00	5.50	53.90	62.00	59.70	3.11	SW	2.33	0.048	61.2
102278.290		12:50:00	480	946.8	590.6	68.7	0.0	0.00	6.30	53.90	61.50	59.30	3.11	SW	2.31	0.050	60.4
102278.300		10:37:00	480	906.6	513.2	68.4	0.0	0.00	7.50	78.60	83.20	82.10	4.44	W	2.54	0.078	43.5
102278.300		10:52:00	480	940.2	534.3	74.3	0.0	0.00	7.70	78.50	83.60	82.30	4.44	W	2.54	0.075	45.5
102278.302		10:34:00	480	931.0	518.2	58.8	0.0	0.00	3.40	64.50	70.60	69.10	2.22	NE	2.49	0.066	52.4
102278.302		12:23:00	480	982.6	546.7	67.4	0.0	0.00	5.40	64.60	71.60	69.70	2.22	NW	2.50	0.060	56.9
102278.302		13:06:00	480	915.8	493.5	63.3	0.0	0.00	6.50	64.60	70.90	69.20	0.00	N	2.49	0.063	55.0
102278.302		13:21:00	480	885.5	471.9	72.5	0.0	0.00	6.70	64.50	70.60	68.90	0.00	N	2.49	0.063	54.8
102278.303		11:51:00	480	920.9	519.8	79.9	0.0	0.00	7.00	90.40	94.60	93.60	3.56	S	2.56	0.091	38.4
102278.303		12:03:00	480	925.0	519.7	77.4	0.0	0.00	6.50	90.40	94.60	93.60	4.44	S	2.57	0.091	38.6
102278.303		13:08:00	480	836.7	454.3	79.8	0.0	0.00	8.50	90.00	93.60	92.70	4.89	S	2.56	0.097	35.7
102278.304		12:10:00	480	849.7	473.6	107.6	0.0	0.00	12.60	73.10	78.10	76.80	3.11	SW	2.48	0.071	48.0
102278.304		13:03:00	480	807.7	438.8	102.7	0.0	0.00	14.40	73.10	77.70	76.60	5.33	SW	2.48	0.073	47.0
102278.305		11:39:00	480	944.1	518.1	54.4	0.0	0.00	8.40	98.90	102.90	101.60	1.78	SW	2.74	0.096	38.7
102278.305		12:06:00	480	940.0	514.1	55.7	0.0	0.00	7.90	99.00	102.90	101.60	2.67	SW	2.73	0.097	38.1
102278.306		11:37:00	480	946.9	507.6	71.7	0.0	0.00	11.70	98.40	102.20	101.10	7.11	W	2.70	0.092	36.5
102278.306		11:47:00	480	943.0	505.6	70.3	0.0	0.00	11.60	98.40	102.20	101.10	7.11	W	2.70	0.092	35.8
102278.306		11:55:00	480	942.3	503.9	70.2	0.0	0.00	12.30	98.40	102.20	101.10	7.11	W	2.69	0.091	36.3
102278.306		12:11:00	480	954.9	507.1	69.1	0.0	0.00	12.70	98.40	102.20	101.20	5.33	W	2.69	0.090	36.2
102278.306		12:42:00	480	924.4	483.4	64.1	0.0	0.00	13.10	98.70	102.40	101.20	5.33	W	2.70	0.093	36.6
102278.306		13:21:00	480	856.8	430.7	64.1	0.0	0.00	13.90	98.60	101.70	100.80	5.78	W	2.70	0.099	33.1
102278.307		10:44:00	480	900.2	472.6	52.4	0.0	0.00	11.50	78.30	83.60	81.90	1.78	SE	2.61	0.074	50.6
102278.307		11:02:00	480	921.5	487.3	53.3	0.0	0.00	12.30	78.20	83.70	82.00	1.78	SE	2.61	0.072	50.9
102278.307		11:24:00	480	932.3	496.6	53.2	0.0	0.00	12.80	78.30	83.90	82.20	1.78	SE	2.61	0.070	52.0

- 212 -

SOLAR COLLECTOR TYPE 'C'														20-SEP-82	22:16:47	PAGE	4
FILE DATE	TIME	INT	I12	I1Z	IDF	IDN	IDP	IAM	C11	CO1	ST1	WSP	WDR	FLR	(TI-TA)/I	EFF	
Sec		W/MH22	W/MH22	W/MH22	W/MH22		Deg C	Deg C	Deg C	Deg C	Deg C	M/Sec	from	L/Min	C/MH22/W	Z	
1C6078.307	11:47:00	480	944.4	497.2	53.2	0.0	0.00	15.60	78.40	84.20	82.40	1.78	SW	2.61	0.069	52.7	
1C6078.307	12:19:00	480	912.4	481.4	55.9	0.0	0.00	14.10	78.60	84.20	82.40	1.78	SW	2.61	0.071	52.4	
1C6078.307	12:57:00	480	867.4	444.7	55.4	0.0	0.00	15.20	78.60	83.80	82.10	1.78	SW	2.60	0.073	51.7	
1C6078.307	13:26:00	480	813.7	402.2	55.1	0.0	0.00	15.60	78.30	82.90	81.40	1.78	S	2.60	0.077	48.9	
1C6078.316	10:22:00	480	896.2	437.0	60.9	0.0	0.00	-1.20	45.90	53.10	50.90	3.11	NE	2.20	0.053	57.0	
1C6078.316	10:44:00	480	927.5	456.9	54.7	0.0	0.00	-1.40	45.90	53.60	51.30	3.11	NE	2.20	0.051	58.6	
1C6078.316	10:52:00	480	938.1	463.9	54.2	0.0	0.00	-0.80	45.90	53.70	51.40	3.11	NE	2.20	0.050	58.9	
1C6078.316	11:06:00	480	945.0	472.0	54.9	0.0	0.00	-0.20	46.00	54.10	51.60	1.78	NE	2.20	0.049	60.5	
1C6078.316	11:57:00	480	958.6	483.6	57.2	0.0	0.00	0.20	45.80	54.20	51.60	1.78	NE	2.20	0.048	62.1	
1C6078.316	12:05:00	480	955.7	479.5	56.4	0.0	0.00	0.40	45.80	54.20	51.60	1.78	NE	2.20	0.048	62.0	
1C6078.316	12:18:00	480	944.2	477.4	67.5	0.0	0.00	0.70	45.90	54.20	51.60	1.78	NE	2.20	0.048	62.1	
1C6078.317	10:26:00	480	850.5	416.9	71.4	0.0	0.00	-1.80	45.80	52.20	50.40	4.89	E	2.19	0.056	52.9	
1C6078.317	10:34:00	480	858.7	422.9	71.4	0.0	0.00	-1.20	45.80	52.30	50.50	4.89	E	2.19	0.055	53.4	
1C6078.319	10:17:00	480	850.2	391.7	53.3	0.0	0.00	4.10	45.80	52.30	50.40	5.33	W	2.34	0.049	57.8	
1C6078.319	13:09:00	480	877.1	397.9	59.6	0.0	0.00	5.30	45.80	52.80	50.70	5.78	W	2.34	0.046	60.1	
1C6078.343	11:07:00	480	924.8	370.6	94.9	0.0	0.00	-6.10	16.20	24.90	21.40	2.67	NW	2.02	0.024	61.5	
1C6078.343	11:15:00	480	914.3	377.4	97.2	0.0	0.00	-5.80	16.30	25.20	21.70	2.67	NW	2.03	0.024	62.0	
1C6078.343	12:15:00	480	928.9	379.0	92.5	0.0	0.00	-4.40	16.80	26.20	22.60	2.22	NE	2.04	0.023	66.7	
1C6078.343	12:23:00	480	928.7	378.1	93.4	0.0	0.00	-3.40	16.80	26.20	22.60	2.22	NE	2.04	0.022	66.5	
1C6078.343	12:31:00	480	927.4	376.8	95.5	0.0	0.00	-2.70	16.80	26.20	22.60	2.22	NE	2.04	0.021	66.4	
1C6078.344	10:31:00	480	894.8	343.5	75.8	0.0	0.00	-12.30	15.40	23.50	20.80	5.78	W	2.01	0.037	58.3	
1C6078.344	10:47:00	480	909.8	358.4	77.4	0.0	0.00	-16.90	15.70	23.90	21.20	5.78	W	2.01	0.036	58.7	
1C6078.344	11:50:00	480	989.4	396.4	78.8	0.0	0.00	-16.60	16.10	25.50	22.30	4.89	NW	2.02	0.033	61.7	
1C6078.344	12:06:00	480	989.0	397.4	78.5	0.0	0.00	-16.60	16.20	25.50	22.40	4.89	W	2.03	0.033	61.3	
1C6078.348	10:43:00	480	891.3	353.8	87.6	0.0	0.00	-9.40	16.00	23.90	21.30	7.56	W	2.21	0.028	63.1	
1C6078.348	11:34:00	480	962.4	384.4	69.1	0.0	0.00	-9.50	16.30	24.90	22.20	6.22	W	2.23	0.027	64.2	
1C6078.348	12:07:00	480	959.5	381.9	65.8	0.0	0.00	-9.10	16.50	25.10	22.30	5.33	SW	2.21	0.027	64.4	
1C6078.348	12:15:00	480	957.0	379.6	65.0	0.0	0.00	-9.20	16.50	25.10	22.30	5.33	SW	2.21	0.027	64.5	
1C6078.348	12:47:00	480	931.4	361.4	62.8	0.0	0.00	-8.70	16.50	24.90	22.20	5.33	SW	2.22	0.027	64.1	
1C6078.348	13:01:00	480	910.7	347.9	61.2	0.0	0.00	-8.50	16.40	24.60	21.90	4.89	SW	2.22	0.027	64.2	
1C6078.350	10:50:00	480	870.3	351.7	105.6	0.0	0.00	2.60	16.30	24.60	21.80	4.89	SW	2.22	0.016	68.3	
1C6078.350	12:04:00	480	928.6	364.0	78.5	0.0	0.00	4.20	16.20	25.40	22.30	3.56	SW	2.21	0.013	70.5	
1C6078.350	12:20:00	480	917.4	357.6	77.1	0.0	0.00	4.10	16.40	25.60	22.40	3.56	SW	2.22	0.013	71.3	
1C6078.353	10:55:00	480	912.7	356.2	70.4	0.0	0.00	-12.10	15.60	23.70	21.10	5.33	W	2.20	0.030	63.0	
1C6078.353	11:03:00	480	924.6	364.1	71.7	0.0	0.00	-12.30	15.70	24.00	21.30	4.89	SW	2.20	0.030	63.5	
1C6078.353	12:07:00	480	958.0	386.0	72.3	0.0	0.00	-10.60	16.10	24.80	21.90	5.33	W	2.19	0.028	64.8	
1C6078.362	10:40:00	480	866.2	332.3	70.5	0.0	0.00	-13.60	15.50	22.80	20.40	6.22	W	2.21	0.034	59.9	
1C6078.362	11:11:00	480	921.0	365.0	72.4	0.0	0.00	-12.30	15.70	23.80	21.20	5.78	W	2.23	0.030	62.6	

SOLAR COLLECTOR TYPE 'C'														20-SEP-82	22:16:47	PAGE	5
FILE DATE	TIME	INT	I12	I1Z	IDF	IDN	IDP	IAM	C11	CO1	ST1	WSP	WDR	FLR	(TI-TA)/I	EFF	
Sec	W/MH22	W/MH22	W/MH22	W/MH22	W/MH22	W/MH22	W/MH22	W/MH22	W/MH22	W/MH22	W/MH22	W/MH22	W/MH22	W/MH22	W/MH22	W/MH22	
1C6078.362	12:15:00	480	948.7	382.8	72.9	0.0	0.00	-11.60	16.10	24.50	21.70	4.44	W	2.24	0.029	63.8	
1C6078.362	13:45:00	480	815.9	300.7	62.0	0.0	0.00	-10.40	15.90	23.10	20.70	4.00	W	2.23	0.032	62.4	
1C6079.005	11:25:00	480	945.1	387.3	75.5	0.0	0.00	-10.20	-4.70	5.00	1.90	4.44	SW	2.19	0.006	70.0	
1C6079.005	12:00:00	480	957.8	394.9	75.9	0.0	0.00	-9.20	-3.80	5.70	2.40	3.56	SW	2.20	0.006	71.4	
1C6079.005	12:14:00	480	952.7	394.6	76.1	0.0	0.00	-8.90	-3.70	5.80	2.60	3.56	SW	2.21	0.005	71.6	
1C6079.008	12:08:00	480	943.2	395.4	94.9	0.0	0.00	-7.30	-2.90	6.80	3.30	5.33	W	2.19	0.005	73.5	
1C6079.008	12:23:00	480	941.4	393.2	94.9	0.0	0.00	-6.70	-2.80	7.10	3.60	5.33	W	2.20	0.004	74.4	
1C6079.008	12:45:00	480	917.4	383.3	95.1	0.0	0.00	-6.60	-2.60	7.10	3.60	5.33	W	2.20	0.004	75.1	
1C6079.037	11:50:00	480	1082.3	568.3	86.5	0.0	0.00	-17.70	-8.40	3.10	-0.70	5.33	W	2.10	0.009	73.3	
1C6079.037	12:26:00	480	1087.1	570.7	85.9	0.0	0.00	-16.70	-8.10	3.60	-0.30	4.89	SW	2.10	0.008	73.1	
1C6079.037	12:54:00	480	1072.6	555.4	85.0	0.0	0.00	-16.40	-8.10	3.20	0.60	4.89	SW	2.10	0.008	72.8	
1C6079.037	13:02:00	480	1064.3	549.3	83.6	0.0	0.00	-17.00	-7.90	3.20	-0.50	5.33	SW	2.10	0.009	72.2	
1C6079.037	13:24:00	480	1030.4	522.1	82.1	0.0	0.00	-16.40	-7.90	2.90	-0.80	5.33	SW	2.09	0.008	72.1	
1C6079.037	13:49:00	480	981.5	482.9	79.5	0.0	0.00	-16.40	-7.90	2.20	-1.20	5.33	SW	2.10	0.009	70.8	
1C6079.040	10:55:00	480	1004.2	532.5	107.2	0.0	0.00	-20.90	15.70	24.30	21.60	5.33	W	2.13	0.036	59.2	
1C6079.040	12:24:00	480	1087.0	587.8	109.5	0.0	0.00	-18.90	16.20	26.00	22.80	6.67	W	2.14	0.032	62.0	
1C6079.040	12:48:00	480	1074.3	574.7	106.4	0.0	0.00	-18.80	16.30	25.90	22.70	6.67	W	2.15	0.033	62.0	
1C6079.040	13:54:00	480	986.6	494.3	84.7	0.0	0.00	-16.60	16.30	25.10	22.20	6.22	W	2.14	0.033	61.6	
1C6079.042	11:50:00	480	1115.9	612.2	93.2	0.0	0.00	-21.30	15.40	24.50	21.60	4.44	NW	2.32	0.033	61.1	
1C6079.042	12:06:00	480	1122.0	615.7	93.1	0.0	0.00	-20.70	15.40	24.70	21.70	4.44	W	2.32	0.032	61.6	
1C6079.042	12:30:00	480	1120.9	614.0	93.6	0.0	0.00	-20.80	15.60	24.80	21.90	4.44	W	2.33	0.032	62.0	
1C6079.042	13:36:00	480	1039.9	545.8	87.8	0.0	0.00	-19.90	15.60	24.00	21.30	4.44	W	2.32	0.034	60.9	
1C6079.042	13:46:00	480	1017.8	528.0	86.6	0.0	0.00	-19.40	15.60	23.80	21.20	4.44	W	2.32	0.034	60.4	
1C6079.042	13:54:00	480	1002.6	515.2	85.2	0.0	0.00	-19.40	15.40	23.60	20.90	4.44	W	2.32	0.035	60.4	
1C6079.108	10:30:00	480	864.3	347.0	88.0	0.0	0.00	6.80	68.40	73.20	71.50	5.33	NW	2.42	0.071	42.5	
1C6079.108	11:13:00	480	931.9	391.9	80.8	0.0	0.00	7.50	70.10	76.40	74.10	6.22	NW	2.24	0.067	47.9	
1C6079.108	11:41:00	480	958.7	407.8	79.2	0.0	0.00	8.10	70.10	76.60	74.20	6.22	NW	2.34	0.065	50.1	
1C6079.108	12:05:00	480	960.9	410.1	79.7	0.0	0.00	8.70	70.30	76.80	74.30	5.33	NW	2.33	0.064	49.8	
1C6079.108	12:29:00	480	951.0	399.3	81.6	0.0	0.00	9.10	70.60	77.10	74.60	5.33	NW	2.27	0.065	49.6	
1C6079.108	13:01:00	480	921.6	378.4	82.4	0.0	0.00	10.80	70.40	77.20	74.60	5.33	NW	2.17	0.065	50.0	
1C6079.108	13:34:00	480	863.5	331.9	81.1	0.0	0.00	10.30	70.20	75.80	73.70	5.33	NW	2.34	0.069	47.5	
1C6079.109	10:52:00	480	910.1	386.3	81.0	0.0	0.00	9.60	69.80	75.50	73.20	5.78	NW	2.43	0.066	48.2	
1C6079.109	12:03:00	480	960.6	412.0	84.4	0.0	0.00	10.50	69.90	76.70	73.90	5.78	NW	2.28	0.062	50.1	
1C6079.109	13:55:00	480	819.9	278.9	88.4	0.0	0.00	11.40	70.20	75.20	73.20	5.33	NW	2.37	0.072	45.6	
1C6079.110	12:05:00	480	949.8	402.4	97.4	0.0	0.00	14.40	95.80	100.60	98.90	3.56	W	2.47	0.086	39.4	
1C6079.110	12:29:00	480	942.3	396.9	95.2	0.0	0.00	13.60	95.90	100.60	98.80	3.56	W	2.47	0.087	38.9	
1C6079.110	12:53:00	480	923.3	385.3	96.7	0.0	0.00	14.20	96.20	100.50	98.80	3.56	W	2.47	0.089	36.3	
1C6079.110	13:18:00	480	883.8	353.4	95.8	0.0	0.00	14.80	96.40	100.30	98.80	4.00	NW	2.46	0.092	34.3	

- 213 -

SOLAR COLLECTOR TYPE 'C'

20-SEP-82 22:16:47 PAGE 6

FILE	DATE	TIME	INT	I12	I17	IDF	IDM	IDP	IAM	CI1	CD1	ST1	WSP	WDR	FKR	(I1-IAM)/I	EFF
			Sec	M/H82	M/H82	M/H82	M/H82	Deg C	Deg C	Deg C	Deg C	Deg C	M/Sec	From	L/Min	C/M82/W	Z
1CA079.110	13:50:00	480	826.7	806.5	96.1	0.0	0.00	15.80	96.30	99.70	98.30	4.00	NW	2.46	0.097	32.0	
1CA079.110	13:59:00	480	802.4	781.4	93.8	0.0	0.00	16.20	96.30	99.70	98.30	4.00	NW	2.47	0.100	33.0	
1CA079.113	11:41:00	480	942.1	911.8	105.9	0.0	0.00	15.20	76.70	82.40	80.10	4.89	W	2.37	0.065	45.2	
1CA079.113	11:58:00	480	940.0	907.5	105.2	0.0	0.00	14.70	77.20	83.10	80.70	4.89	W	2.37	0.066	47.0	
1CA079.113	12:16:00	480	936.3	905.5	103.7	0.0	0.00	15.20	76.80	82.70	80.30	6.22	W	2.37	0.066	47.1	
1CA079.113	12:32:00	480	930.4	900.4	105.0	0.0	0.00	15.30	76.70	82.50	80.20	6.22	W	2.35	0.066	46.4	
1CA079.113	12:40:00	480	919.1	895.1	107.1	0.0	0.00	15.30	76.70	82.50	80.10	6.22	W	2.37	0.067	47.2	
1CA079.113	13:12:00	480	883.4	872.7	107.5	0.0	0.00	15.60	76.90	82.40	80.20	5.78	W	2.35	0.069	46.2	
1CA079.113	13:49:00	480	815.7	813.1	100.8	0.0	0.00	16.20	76.70	81.40	79.40	5.78	W	2.35	0.074	42.7	
1CA079.120	11:27:00	480	956.9	947.6	214.2	0.0	0.00	13.70	35.10	46.20	41.90	2.22	SE	2.04	0.022	74.8	
1CA079.122	11:04:00	480	906.8	946.3	116.5	0.0	0.00	9.60	43.50	50.80	48.00	4.89	W	2.38	0.037	60.6	
1CA079.122	11:12:00	480	913.2	945.3	102.5	0.0	0.00	10.20	43.60	50.90	48.10	4.89	W	2.39	0.037	60.3	
1CA079.122	12:00:00	480	926.4	942.9	101.4	0.0	0.00	10.50	43.30	51.00	48.00	4.44	W	2.39	0.035	62.7	
1CA079.122	12:08:00	480	921.2	936.7	103.3	0.0	0.00	10.80	43.20	50.90	47.90	4.44	W	2.38	0.035	62.9	
1CA079.122	12:40:00	480	901.1	919.6	110.8	0.0	0.00	12.10	43.00	50.60	47.60	4.44	W	2.39	0.034	63.6	
1CA079.122	12:48:00	480	890.9	913.9	110.2	0.0	0.00	11.80	42.90	50.40	47.50	4.44	W	2.39	0.035	63.6	
1CA079.122	13:52:00	480	794.0	836.9	103.9	0.0	0.00	13.70	43.40	49.80	47.40	4.44	SW	2.37	0.038	60.3	
1CA079.126	10:10:00	480	804.4	874.7	90.6	0.0	0.00	11.80	34.90	42.50	39.30	1.78	NE	2.16	0.029	64.4	
1CA079.126	12:19:00	480	910.0	943.9	86.0	0.0	0.00	12.90	35.00	44.20	40.10	0.89	S	2.15	0.024	68.6	
1CA079.126	13:16:00	480	855.9	908.9	86.6	0.0	0.00	12.50	34.80	43.20	39.60	2.67	SW	2.15	0.026	66.6	
1CA079.128	10:33:00	480	803.8	861.9	185.4	0.0	0.00	20.50	97.90	101.30	99.90	3.11	SE	2.47	0.096	33.0	
1CA079.129	11:12:00	480	814.2	850.5	188.3	0.0	0.00	29.70	91.60	96.00	94.70	5.78	SW	2.44	0.076	41.6	
1CA079.129	11:27:00	480	816.6	847.3	192.8	0.0	0.00	29.70	91.40	95.90	94.10	5.78	SW	2.43	0.076	42.3	
1CA079.129	11:53:00	480	830.4	850.0	186.6	0.0	0.00	31.00	92.10	96.60	94.80	5.78	SW	2.44	0.074	41.7	
1CA079.130	11:53:00	480	851.7	893.3	219.7	0.0	0.00	21.00	52.80	60.10	56.90	1.78	NW	2.30	0.037	62.4	
1CA079.130	12:09:00	480	847.4	882.8	226.0	0.0	0.00	21.90	52.90	60.20	57.10	1.78	NW	2.30	0.037	62.6	
1CA079.130	12:39:00	480	818.8	851.5	225.2	0.0	0.00	23.10	52.40	59.60	56.40	1.78	NW	2.31	0.036	64.2	
1CA079.131	13:26:00	480	778.5	840.3	204.6	0.0	0.00	20.80	41.90	48.90	46.00	5.33	F	2.30	0.027	65.4	
1CA079.131	13:34:00	480	765.7	827.9	195.5	0.0	0.00	21.20	41.90	48.90	46.10	5.33	F	2.29	0.027	66.1	
1CA079.131	13:42:00	480	750.1	817.4	196.5	0.0	0.00	21.30	41.90	48.80	45.90	5.33	F	2.29	0.027	66.6	
1CA079.131	13:55:00	480	717.7	783.3	210.8	0.0	0.00	21.60	42.00	48.40	45.80	5.33	E	2.28	0.028	64.2	
1CA079.134	10:09:00	480	797.4	876.0	101.8	0.0	0.00	16.00	41.60	48.60	45.90	2.67	SW	2.23	0.032	61.8	
1CA079.134	11:59:00	480	897.6	958.5	122.0	0.0	0.00	19.10	41.60	50.30	46.70	3.11	SW	2.17	0.025	66.5	
1CA079.137	10:17:00	480	792.0	897.8	76.8	0.0	0.00	16.40	43.20	50.30	47.40	1.78	SE	2.25	0.034	63.6	
1CA079.137	12:04:00	480	884.8	962.7	75.7	0.0	0.00	18.30	32.10	41.70	37.70	1.78	S	2.10	0.016	71.9	
1CA079.137	12:25:00	480	876.2	953.7	79.3	0.0	0.00	18.10	31.90	40.50	37.00	1.78	S	2.32	0.016	71.8	
1CA079.137	13:06:00	480	835.7	924.8	76.6	0.0	0.00	18.80	31.90	40.20	36.80	2.22	S	2.29	0.016	71.9	
1CA079.138	10:11:00	480	770.3	868.9	89.3	0.0	0.00	20.40	71.10	75.90	74.20	3.56	S	2.43	0.066	47.8	

SOLAR COLLECTOR TYPE 'C'

20-SEP-82 22:16:47 PAGE 7

FILE	DATE	TIME	INT	I12	I17	IDF	IDM	IDP	IAM	CI1	CD1	ST1	WSP	WDR	FKR	(I1-IAM)/I	EFF
			Sec	M/H82	M/H82	M/H82	M/H82	Deg C	Deg C	Deg C	Deg C	Deg C	M/Sec		From L/Min	C/M82/M	Z
1CA079.138		10:19:00	480	784.4	885.2	88.5	0.0	0.00	20.40	71.10	76.00	74.20	3.56	S	2.43	0.065	47.9
1CA079.138		10:35:00	480	813.6	909.0	89.4	0.0	0.00	21.40	71.20	76.40	74.40	3.56	S	2.42	0.061	48.9
1CA079.138		10:54:00	480	845.5	942.3	93.7	0.0	0.00	21.70	71.40	76.90	74.90	3.56	S	2.43	0.059	49.9
1CA079.138		11:10:00	480	856.3	948.9	88.7	0.0	0.00	21.60	71.70	77.30	75.20	3.56	SE	2.44	0.059	50.4
1CA079.138		11:26:00	480	868.5	949.8	87.5	0.0	0.00	22.70	71.80	77.70	75.40	3.56	SE	2.43	0.057	52.2
1CA079.138		11:42:00	480	871.9	952.5	89.7	0.0	0.00	22.70	71.60	77.70	75.30	3.56	SE	2.42	0.056	53.4
1CA079.138		11:58:00	480	876.7	948.9	87.9	0.0	0.00	22.70	71.40	77.60	75.20	3.56	SE	2.43	0.056	54.3
1CA079.138		12:14:00	480	873.7	939.5	90.6	0.0	0.00	23.70	71.30	77.40	75.10	3.56	SE	2.42	0.054	53.4
1CA079.139		10:54:00	480	834.4	933.7	105.9	0.0	0.00	22.90	36.20	44.70	40.90	4.44	SE	2.29	0.016	69.3

APPENDIX G

Frequency Analysis of Experimental Data

AXIS Label Description

$$DT1/I = (T1-TA)/I \equiv (T_{fi} - T_a)/I$$

WSP $\equiv$ wind speed in m/sec

FLR $\equiv$ heat transfer fluid flowrate, L/min

TAM $\equiv$ ambient air temperature,

IT2 $\equiv$ Total Incident Solar Radiation on Collector Surface,
W/m²

IDF $\equiv$ Horizontal Diffuse Radiation

DNN $\equiv$ Incident Angle of Beam Solar Radiation

APPENDIX H

Uncertainty Analysis for Experimental Determination
of Thermal Efficiency

APPENDIX H

Uncertainty Analysis for Experimental Determination of Thermal Efficiency

A formalized procedure for testing the thermal performance of solar collectors has been produced (4). This standard outlines the facility to be used, the accuracy and precision of the test instrumentation and the procedures required during testing.

The experimental equipment for this study was designed and chosen to meet the general requirements of this standard test procedure. In analyzing the test data an estimate of the uncertainty of the experimentally derived values of the collector thermal efficiency is required.

In performing any experiment an attempt is made to minimize the error associated with the experimental measurements. Unfortunately every measurement is subject to error and the degree to which this error is minimized is a compromise between the accuracy required in the derived value and the cost in money and time required to reduce the error in the component measurements to an acceptable value.

As a worst case, the error in a derived result is equal to sum of the errors of the component measurements. Implicit with this assumption is that the worst case errors will occur simultaneously and in the most detrimental fashion.

This condition is unlikely and consequently, usually overpredicts the error in a derived result. The odds of this condition occurring are small.

The concept of uncertainty implies random deviation about a mean value and subsequently some errors would be positive while others would be negative. Therefore, a series of measurements with relatively large uncertainties could produce a result with an uncertainty not much larger than the uncertainty of the most uncertain measurement (75).

The uncertainty in each component measurement may be described by the best estimate of the value for the variable, followed by the uncertainty interval at the desired confidence level (75) i.e.;

$$V = M \pm W; P \text{ percent}$$

where V is the viable

M is the best value

W is the uncertainty

P is the confidence level

Errors which introduce uncertainty into a derived result may be classified into two categories.

Systematic error - errors which persist and cannot be considered as due entirely to chance. Systematic errors may be due to incorrect instrument calibrations and relate to instrument accuracy, (the ability of the instrument to indicate the true value).

Random Error - errors which cause readings to take random values on either side of some mean value. An instrument which can reproduce subsequent readings

closely is said to have high precision and less random error.

1) Measurements may be highly precise but be inaccurate. During the commissioning of the experimental apparatus used for this study, the measurement equipment was calibrated against traceable standard instruments to minimize systematic errors. The basis of this thesis is that random errors that result in scatter in the experimental data are of major consideration.

In reviewing the uncertainty in an experimentally derived result, Kline and McClintock (76) have presented the following analysis.

Experiments fall into two overlapping categories - single-sample and multiple-sample experiments. Experiments in which uncertainties are evaluated by many repetitions and many diverse instruments are termed multiple-sample. Such experiments can be analyzed by classical statistical means.

The nature of the experiment described in section 7 is such that experimental conditions are subject to weather conditions that often occur infrequently during the year. This makes repetition of specific data virtually impossible.

The requirement to use fixed instrumentation to reduce scatter in the result due to systematic errors, precludes the second requirement of a multiple-sample experiment.

Experiments of the type described in section (7) which are characterized by small data sample sizes are termed single-sample experiments (76).

Since for single-sample experiments classical statistics cannot be used, an estimate of the reliability of the data must be based on estimates. The term "uncertainty" is defined as meaning a possible value the error might have (76). The propagation of uncertainty is defined as the way in which uncertainties in the variables affect the uncertainty in the results.

Kline and McClintock (76) have presented a technique for determining the propagation of errors in a derived result for single-sample experiments. In this technique a best estimate of the uncertainty in each variable is made by the researcher assuming odds (i.e., 20 to 1) that a measured value will fall within the uncertainty interval. If the same uncertainty estimate is used for all the component variables used in the analysis, the uncertainty in the result with the same uncertainty estimate will be given by;

$$W_R = \left[\left(\frac{\partial R}{\partial V_1} W_1 \right)^2 + \left(\frac{\partial R}{\partial V_2} W_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial V_n} W_n \right)^2 \right]^{\frac{1}{2}}$$

which may be reduced to;

$$\frac{W_R}{R} \left[\left(\frac{WV_1}{V_1} \right)^2 + \left(\frac{WV_2}{V_2} \right)^2 + \dots + \left(\frac{WV_n}{V_n} \right)^2 \right]^{\frac{1}{2}}$$

In the experiments described in section 7 of this report, the experimental thermal efficiency of the Chamberlain solar collector is determined by the relationship,

$$\eta = \frac{Q_u}{IA_c} = \frac{Q_{RHS}}{IA_c} \cdot \frac{\Delta T_c}{\Delta T_{RHS}}$$

Thus values of η are obtained by individual measurements of temperature rise across the solar collector and reference heater, measurements of reference heater power input and total solar radiation incident on the collector surface.

Power measurements to the reference heater were made with a Scientific Columbus, Inc. "Halltiplier" Watt Transducer, Model WT 5C5A1. The accuracy of this device is $\pm 1\%$ of a full scale reading. The accuracy of the measurement of power input to the heat transfer fluid is estimated to be $\pm 2\%$ overall. The measurement of solar radiation introduces the largest uncertainty and is estimated at $\pm 5\%$ of reading. Errors in the measurement of temperature rise across the collector were $\pm 0.1^\circ\text{C}$.

Therefore the uncertainty values are;

$$\ln Q_{\text{RHS}} = \frac{WQ_{\text{RHS}}}{Q_{\text{RHS}}} = \pm 2\%$$

$$\ln I = \frac{WI}{I} = \pm 5\%$$

$$\Delta T = W\Delta T = \pm 0.1^\circ\text{C}$$

The values are based on best estimates of the values taking into account the manufacturer's calibration of the measurement equipment. The values represent the odds of 20 to 1 that measured values will fall within these limits. This may be representative of a confidence interval corresponds to 99.7% of the values following within 3σ , (three standard deviations as defined in the classical statistical sense).

Applying the analysis (76), the uncertainty in determining η is;

$$W\eta = \pm \left[\left(\frac{Q_{RHS}}{Q_{RHS}} \right)^2 + \left(\frac{WI}{I} \right)^2 + \left(\frac{W\Delta T}{\Delta T_{RHS}} \right)^2 + \left(\frac{W\Delta T}{\Delta T_c} \right)^2 \right]^{\frac{1}{2}} \cdot \eta$$

The uncertainty calculation is dominated by the uncertainty estimate in the radiation measurement I . The value of $W\eta$ varies along the performance curve as a function of the value of the temperature rise across the collector. At high values of η the value of ΔT_c is large and decreases linearly with decreasing η . The error function is linear and smooth across the ranges of $(T_{fi} - T_a)/I$. The range of values observed is demonstrated below for the two limiting cases corresponding to $(T_{fi} - T_a)/I = 0$ and 0.1 . For the case of $\eta = 40\%$, $\Delta T_c \approx 3.5^\circ\text{C}$

$$\Delta T_{RHS} \approx 6^\circ\text{C}$$

Thus

$$\begin{aligned} W\eta &= \pm \left[(0.02)^2 + (0.05)^2 + \left(\frac{0.1}{6} \right)^2 + \left(\frac{0.1}{3.5} \right)^2 \right]^{\frac{1}{2}} \cdot 40 \\ &= 0.06 (40) = \pm 2.4 \text{ Percentage Points} \end{aligned}$$

for the case $\eta = 75$, $\Delta T_c \approx 9^\circ\text{C}$

$$\Delta T_{RHS} = 6^\circ\text{C}$$

$$\begin{aligned} W\eta &= \pm \left[(0.02)^2 + (0.05)^2 + \left(\frac{0.1}{6} \right)^2 + \left(\frac{0.1}{9} \right)^2 \right]^{\frac{1}{2}} \cdot 75 \\ &= 0.057 (75) = \pm 4.3 \text{ Percentage Points} \end{aligned}$$

With an uncertainty estimate of 20 to 1, (3σ) that the measured values will fall within this range.

END

0	6	1	0	9	1	8	4
---	---	---	---	---	---	---	---

FIN