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Midtemperature Solar Systems Test Facility Program for Predicting Thermal Performance of Line-Focusing, Concentrating Solar Collectors

Thomas D. Harrison

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MIDTEMPERATURE SOLAR SYSTEMS TEST FACILITY PROGRAM FOR
PREDICTING THERMAL PERFORMANCE OF LINE-FOCUSING,
CONCENTRATING SOLAR COLLECTORS

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ABSTRACT

The program at Sandia National Laboratories, Albuquerque, for predicting the performance of line-focusing solar collectors in industrial process heat applications is described. The qualifications of the laboratories selected to do the testing and the procedure for selecting commercial collectors for testing are given. The testing program is outlined. The computer program for performance predictions is described. An error estimate for the predictions and a sample of outputs from the program are included.

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SYMBOLS USED

Symbol	Definition
A_a	Collector aperture area
A_g	Gross collector area
A_r	Receiver surface area
C_p	Specific heat of coolant fluid
F_R	Solar collector efficiency factor
f	Focal length of collector reflecting surface
I	Direct solar irradiation
K	Incident angle modifier
$\dot{m}$	Mass flow rate
Q	Useful energy collected by transfer fluid
t_a	Ambient temperature
$t_{f,e}$	Transfer fluid temperature at exit
$t_{f,i}$	Transfer fluid temperature at inlet
w	Width of collector aperture
θ	Angle of incidence of direct sun's rays with aperture plane
ρ	Reflectance of receiver cover
γ	Fraction of solar radiation incident on aperture which is intercepted on the receiver absorbing surface
η	Efficiency
η_p	Solar noon peak efficiency
Δt	$t_{f,e} - t_a$
$(\tau\alpha)_e$	Effective transmission - absorption product
n	Subscript indicating normal incidence

MIDTEMPERATURE SOLAR SYSTEMS TEST FACILITY PROGRAM FOR
PREDICTING THERMAL PERFORMANCE OF LINE-FOCUSING,
CONCENTRATING SOLAR COLLECTORS

Introduction

This document describes a program for making thermal performance predictions for line-focusing solar collectors that have potential for use in producing industrial process heat (IPH). The program was authorized by the Department of Energy (DOE), Division of Solar Thermal Energy Systems, and is partially funded through the Solar Energy Research Institute (SERI). The thermal performance predictions, one for each collector evaluated, will be published in separate documents.

The program involves seven steps:

1. Establish qualification requirements for the commercial laboratories performing the collector testing,
2. Survey commercial laboratories and determine which meet the qualifications,
3. Define specifications for collectors to be tested under the program,
4. Select collectors which meet the specifications,
5. Define and execute a test program to acquire the necessary data,
6. Prepare a computer program which uses weather data and test data to predict performance, and
7. Calculate predictions of thermal performance.

Each of these seven steps is discussed in a separate section of this report.

The predictions consider only the thermal performance. The following factors should also be considered.

1. Losses at the ends, at gaps, and from shadowing due to packing. The predictions of thermal performance assume 1 square meter of collector aperture in the middle of a row of infinite length, with no end or gap losses and no shadowing due to packing. End losses are included if the configuration of the collector requires that it be of finite length.
2. Collector warm-up penalties. A further assumption is made that piping in the collector is at operating temperature at start-up. Therefore, there is no collector warm-up penalty.
3. Degradation of performance. Collectors tested were new and were not on test long enough to permit an accurate estimate of performance degradation due to such factors as changes in reflectivity, shape, and receiver losses.
4. Cost of the collector. Cost is a highly variable factor dependent on, among other things, efficiency of design, efficiency of management, quantity produced, interest rates, and method of payment.
5. Losses in the energy transport system and system warm-up penalties. Losses in the energy transport system degrade overall system performance. Testing experience at Sandia National Laboratories, Albuquerque (SNLA) reveals these losses to be much greater than predictions indicated. Development activities and testing are under way at SNLA to identify major causes of losses and to take corrective action. System warm-up penalties are a function of the thermal masses associated with the energy transport systems and the thermal load. System warm-up penalties are usually independent of the collector.
6. Reliability. No collector was on test long enough to obtain reliability data. Also, most of the control equipment was part of the test setup rather than a part of the collector

system itself. Therefore, no data at all are available on control system reliability.

7. Cost of installation. Cost of installation is highly variable, depending on, for example, whether the collector is mounted on a rooftop or on the ground. If mounted on the ground, the cost of the occupied real estate, in addition to the cost of foundations, must be considered.
8. Cost of operation and maintenance. Operation and maintenance costs are also highly variable. A collector with a slightly more inferior performance than another may be far more cost-effective simply because cleaning is easier.
9. Wind effects. Wind degrades collector performance by distorting the reflective surface and by increasing thermal energy losses, particularly from the receiver. Wind effects are not included in these predictions because no standard test method, nor equipment, has been developed to evaluate the effects.

Qualifications for Commercial Laboratories

The validity of any computer-generated performance predictions can be no higher than the validity of the input data. To ensure acquisition of valid performance data for solar collectors, a set of qualifications was developed for selecting the laboratories to do the collector testing. The basis for these qualifications was that the laboratories

1. Have a demonstrated expertise in solar collector testing,
2. Have the necessary instrumentation,
3. Be capable of testing at temperatures up to 300°C (572°F),
4. Be able to handle the collectors under consideration,
5. Operate under rules and procedures necessary for good testing practice, and
6. Be independent.

Specific qualifications were generated from References 1, 2, and 3 and from previous experience acquired by SNLA in similar situations.

Experience at SNLA's Midtemperature Solar Systems Test Facility (MSSTF) has shown that high-temperature environments at sensor locations, long instrumentation leads, and signal conversion equipment can introduce significant measurement errors which will not be corrected by separate calibration of the individual components of the data acquisition system. Additional requirements were imposed by SNLA to limit the magnitude of these errors.

Survey of Commercial Laboratories and Testing Agencies

Twelve laboratories or testing agencies were initially considered by SNLA. Only one of these laboratories possessed the equipment to test at 300°C (572°F), and one other was willing to make the necessary investment to upgrade his equipment. Two modules of an Acurex collector owned by SNLA and previously tested at SNLA's Collector Module Test Facility (CMTF) were retested by these two laboratories. A Sandia representative was present during a portion of the testing to determine that each candidate adhered to his own procedures which had previously been judged by SNLA to be adequate. During early testing, the candidate's test results did not conform to those of SNLA in a few minor respects. The test methods were re-evaluated, and the cause for nonconformance was determined and corrected so that each candidate could repeat the results of the tests made at SNLA.

The two laboratories meeting the qualifications and selected by SNLA to do the collector testing for this project were

1. DSET Laboratories, Inc., Box 1850, Black Canyon Stage, Phoenix, AZ 85029.
2. Wyle Laboratories, 7800 Governor's Drive West, Huntsville, AL 35807.

Other commercial laboratories which believe themselves to be qualified and which wish to be considered for inclusion in the above list should

contact the supervisor, Experimental Systems Operations Division, Sandia National Laboratories.

Requirements for Collectors To Be Tested

By its charter, the testing program is limited to line-focusing collectors with potential for use in producing IPH. IPH is defined as "thermal energy used in the preparation and treatment of goods produced by manufacturing processes."⁴ IPH consumes about 19 quads of energy annually, or about 25% of the total national energy consumption. The use of IPH energy is spread over a wide range of end-use temperatures. For example, of the 19 quads, 12 are below 370°C (700°F), which is within the temperature range achievable by line-focusing collectors. Figure 1 shows the percentage breakout for four contiguous temperature bands.

Based on these figures, the minimum operating temperature was specified as 100°C (212°F). No maximum operating temperature was specified since the maximum testing capability would be 300°C (572°F) in any case. Size and weight limitations were set in order to ensure compatibility with the testing laboratory's collector mounting equipment.

These collector specifications were combined with administrative and contractual requirements of the project and were published as an advertisement in the Commerce Business Daily on 26 September 1979.

Selection of Collectors

The advertisement in the Commerce Business Daily brought responses from only two firms, one of which subsequently decided not to participate in the program. In order to assure that all eligible firms were given an opportunity to participate, a search was made to gather the names of firms which manufacture line-focusing, concentrating solar collectors. Thanks to the assistance of various magazines

Figure 1. Percent of IPH Energy Consumption versus End-Use Temperature

devoted to solar energy, a list of 19 firms was prepared. All were contacted by telephone. Expressions of interest were followed by a visit from a Sandia representative to explain the program and to make judgment as to whether or not the collector actually met criteria. If the collector met criteria, a formal agreement was established through SNLA's purchasing organization.

Test Program

The collector test program was designed around the Hottel-Whillier-Bliss equation,⁵ modified for use with concentrating collectors:

$$Q = F_R [I A_a (\tau \alpha)_e \rho \gamma \cos \theta - U_L A_r \Delta t] \quad (1)$$

The symbols are defined on page 7.

For clarity, the following functions are defined.

$$\text{Efficiency} = \eta = Q/A_g I$$

$$\text{Incident angle modifier} = K = \frac{(\tau\alpha)_e \rho \gamma \cos\theta}{\left[(\tau\alpha)_e \rho \gamma\right]_n}$$

$$\text{"y" intercept} = a_1 = F_R \frac{A_a}{A_g} \left[(\tau\alpha)_e \rho \gamma\right]_n$$

$$\text{Loss term} = -F_R \frac{A_r}{A_g} U_L \frac{\Delta t}{I} = a_2 \frac{\Delta t}{I} + a_3 \left(\frac{\Delta t}{I}\right)^2. \quad (\text{See Appendix A.})$$

In the "loss term," the factor U_L is assumed to be a function of $\frac{\Delta t}{I}$, which justifies the expansion.

Substitution into Equation 1 yields

$$\eta = a_1 K + a_2 \frac{\Delta t}{I} + a_3 \left(\frac{\Delta t}{I}\right)^2 \quad (2)$$

When the sun's rays are at normal incidence upon the collector aperture, then

$$\theta = 0, \eta = \eta_p \text{ and } K = 1$$

which gives

$$\eta_p = a_1 + a_2 \frac{\Delta t}{I} + a_3 \left(\frac{\Delta t}{I}\right)^2 \quad (3)$$

Subtracting Eq. (3) from Eq. (2) and rearranging gives

$$K = \frac{\eta - \eta_p + a_1}{a_1}$$

Further manipulation gives

$$K = \frac{\eta + \text{LOSS TERM}}{a_1} \quad (4)$$

The objective of the test program is to determine the values of a_1 , a_2 , and a_3 and to evaluate K as a function of the incident angle θ .

The heat collected, Q , can be measured experimentally from

$$Q = \dot{m}C_p(t_{f,i} - t_{f,e}), \quad (5)$$

and η can then be calculated. The first step in the test program is to make this measurement with $\theta = 0$ (normal incidence) for several values of coolant inlet temperature, $t_{f,i}$. This results in several data pairs, $(\eta_p, \frac{\Delta t}{I})$. By standard statistical techniques, the values of a_1 , a_2 and a_3 are determined.

The second step is to set the coolant inlet temperature at 125°C (257°F) and measure Q for several values of the angle of incidence, θ . The value of K corresponding to each θ can then be calculated from Eq. (4), provided the "loss term" is known.

The third step in the test program is the measurement of the loss term. The collector is defocused, or shaded from the sun, and Q is determined from Eq. (5). Under these conditions, the measured value of Q is the loss term, and K can be calculated.

End losses of the collector contribute to the value of K . As the length of continuous collector increases, the ratio of end loss to collected energy decreases. The collectors under test are relatively short compared to what would be the case in a collector field for IPH applications. To generalize the test results and allow for application to collectors of any length, the incident angle modifier is considered in the following form:

$$K = K_O \cos\theta \left[\frac{A_a - (wf - w^3/48f) \tan\theta}{A_a} \right] \quad (6)$$

where the term in brackets is the end loss coefficient. K_O , the optical loss coefficient, is calculated for each value of θ used during the test measurements and is presented in tabular or algebraic form.

The data developed by this test procedure allow the efficiency of a collector of any length to be calculated from Eq. (2), where the value of K for that collector is calculated from Eq. (6).

Immediately subsequent to testing, the owner of the collector was given a copy of the test results in order to examine them for anomalies. If he felt that the test results did not fairly represent the capabilities, he was allowed to withdraw from the program. The data, however, remained in the possession of DOE.

Computer Program To Predict Performance

The performance prediction program developed by SNLA has two major inputs: the collector efficiency data described above and meteorological data. Several sources for meteorological data are available.⁶ The model chosen was the Typical Meteorological Year (TMY). The TMY tapes are available from the National Climatic Center, Asheville, North Carolina, for 26 sites in the U.S. Long-term (15 to 23 years) weather data records were used to develop the TMY tapes. Each TMY is constructed by joining Typical Meteorological Months (TMMs). The TMMs were selected by examination of statistics and persistence structure associated with mean daily dry bulb temperature and daily total global solar radiation. A detailed description of the TMY selection method is given in Reference 7. Each TMY tape lists, on an hour-by-hour basis, an extensive array of meteorological parameters. The application in this project required the use of only the

ambient temperature and the direct normal solar radiation for input into the computer calculation.

An existing computer program was modified for making the solar collector thermal performance calculations for this project. The computer program does not account for the effect of collector row length (i.e., end losses) or wind speeds exceeding 3.5 m/s (7.6 mph). No attempt was made within the computer program to simulate an actual IPH system application and, therefore, the collector fluid inlet temperature, $t_{f,i}$, can be arbitrarily selected. Low values of receiver temperatures bias the performance predictions toward high efficiencies for the solar collector system. To reduce such bias, the receiver temperature was set equal to the output temperature. This choice yields a conservative estimate for the amount of useful energy, Q , collected by the solar system. The general sequence of calculations performed by the computer program is shown in Figure 2. The calculation is repeated for each hour of the day through the entire year. The collector heat output for each hour is summed to provide daily, monthly, and annual totals. The entire calculation is repeated three times, once for each of three different collector output temperatures. The output temperatures selected were 100°C, 200°C, and 300°C (212°F, 392°F, and 572°F). Performance predictions were calculated for both N-S and E-W orientations of each collector. The five geographical locations selected were Fresno, California; Albuquerque, New Mexico; Ft. Worth, Texas; Charleston, South Carolina; and Boston, Massachusetts. The first location was chosen because of its potential for enhanced oil recovery applications. The next three locations were chosen because they are at approximately the same latitude (32.5°N to 35°N) but in different zones of solar irradiation intensity. Boston (42.5°N) was selected because it is a highly industrialized area and a potential location for solar IPH installations.

At the present time, the collectors for which predictions are being made are listed in Table 1.

**COMMERCIAL COLLECTOR TEST PROGRAM
METHOD FOR CALCULATING THERMAL PERFORMANCE**

Figure 2. Method of Calculating Performance Predictions

Table 1
Collectors for Which Performance
Predictions Were Made

<u>SNLA</u>	<u>DSET</u>	<u>WYLE</u>
Suntec (glass)	Alpha Solarco	Toltec
Acurex (FEK 244)	Sun Heet	SKI (T-600)
Acurex (glass)	Polisolar	AAI
SKI T-700 (FEK 244)	Viking	
SKI T-700 (glass)		
Custom Engineering (glass and 2 types of receivers)		

Error Estimate

Errors in the performance prediction estimate accumulate from both the collector testing program and the TMY data tapes. The maximum measurement errors in the testing program are listed in Table 2.

Table 2
Errors in Measurement

<u>Measurement</u>	<u>One Standard Deviation (%)</u>
Differential temperature (Δt)	± 0.7
Coolant mass flow rate ($\dot{m}$)	± 1.7
Test setup	± 1.7
Tracking error (θ)	± 0.3
Pyrheliometer (I_{DN})	± 0.7

Assuming that the errors are normally distributed, statistical addition yields the one standard deviation value of $\pm 2.56\%$ for testing errors.

No extensive validation has been performed for the TMY data. However, P. J. Hughes, formerly at the University of Wisconsin Solar Energy Laboratory, has assessed the TMY data for Madison, Wisconsin, by using the Transient System Simulation (TRNSYS) routine to compute the heat output for a solar collector system for the years 1953 through 1974.⁷ The standard deviation of the annual output compared to the mean of the 22-year data base was 4.44%. For the purpose of this report, the error contributed by the TMY data is assumed to be $\pm 4\%$.

Combining testing errors and meteorological errors yields a standard deviation for variations in energy output of $\pm 4.75\%$. A more accurate estimate of error will require a detailed comparison of the weather data for each locality against the TMY data for that locality.

Individual Collector Test Reports

For each collector tested, a separate report will be published. Each report will

- a. Describe the collector,
- b. Provide the collector efficiency and receiver thermal loss equations,
- c. List the optical loss coefficient, K_o , in 5-degree increments,
- d. Tabulate the predicted annual thermal output for Fresno, Albuquerque, Ft. Worth, Charleston, and Boston (Table 3 is a typical example of this tabulation), and
- e. Present graphs of the predicted monthly thermal output for the same five cities. (Figures 3 and 4 are typical examples of these graphs.)

Table 3

Predicted Annual Thermal Output (kWh/m²·yr)

	Solar Energy Available (kWh/m ² ·yr)	Output Temperature					
		100°C		200°C		300°C	
		Orientation		Orientation		Orientation	
		E-W	N-S	E-W	N-S	E-W	N-S
Fresno	2260	999	1195	844	977	639	712
Albuquerque	2582	1160	1334	1001	1121	792	857
Fort Worth	1764	805	894	662	702	479	482
Charleston	1358	633	652	485	480	315	298
Boston	1173	505	533	378	382	236	228

Figure 3. Thermal Output of a Typical High-Performance Collector with E-W Orientation and Albuquerque, NM, TMY Solar Data

Figure 4. Thermal Output of a Typical High-Performance Collector with N-S Orientation and Albuquerque, NM, TMY Solar Data

Summary

Within the limitations previously noted, thermal performance predictions will be published for 14 or more commercially available line-focusing collectors at 5 locations for 3 different collector output temperatures. These documents will be identified by the same number as this document (SAND80-1964) with a numerical suffix added. The one standard deviation error in these predictions is estimated to be less than 5%. The TMY tapes provide typical long-term weather data, but short-term deviations are to be expected.

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¹ASHRAE 93-77.

²Laboratories Technically Qualified to Test Collectors in Accordance with ASHRAE 93-77: A Summary Report, U.S. Department of Commerce PB 289 729 (Washington: National Engineering Laboratory [NBS], November 1978).

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⁵J. A. Duffie and W. A. Beckman, Solar Energy Thermal Processes (New York: John Wiley and Sons, 1974).

⁶E. C. Boes, "Insolation Modeling Overview," Solar Energy, vol 4, 1979.

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APPENDIX A Possible Sources for Error

The efficiency equation is

$$\eta = a_1 K + a_2 \frac{\Delta t}{I} + a_3 \left(\frac{\Delta t}{I} \right)^2 \quad (1)$$

The power output of a solar collector, $\dot{Q}$, is

$$\dot{Q} = A_g I \times \eta = A_g I \left[a_1 K + a_2 \frac{\Delta t}{I} + a_3 \left(\frac{\Delta t}{I} \right)^2 \right] \quad (2)$$

which reduces to

$$\dot{Q} = A_g I a_1 K + A_g a_2 \Delta t + A_g a_3 \frac{\Delta t^2}{I} \quad (3)$$

These equations represent the current consensus of the solar industry. However, recent testing at SNLA has revealed two potential sources for error.

The first potential error involves implied receiver losses. The last two terms in Eq. (3) can be considered to express receiver losses with the implication that receiver losses are inversely related to I.

In practice, the value of a_3 is usually very small. Application of I and Δt data taken during tests at SNLA's MSSTF shows that for the data selected, large variations in I have an insignificant effect on the value of the last two terms of Eq. (3). The use of $\frac{\Delta t}{I}$ as an independent variable in the efficiency equations introduces an error

in Eq. (2). Even though the error appears to be so small as to approach insignificance, SNLA is attempting to find better methods than Eq. (1) for expressing efficiency.

The second potential error is that the equation for efficiency is normalized for a value of $I = 1000 \text{ W/m}^2$. A two-axis tracker recently installed by SNLA enables measurement of efficiency at 0° incident angle (solar noon conditions) early in the morning and late in the evening when the value of I is much lower than 1000 W/m^2 . In these cases, measured efficiency is significantly lower than that obtained by substituting the observed values of I and Δt into the efficiency equation for the collector being tested.

SNLA is conducting tests to quantify the variation in efficiency with I and also conducting studies to determine whether or not this variation significantly affects predicted thermal output in locales where I is generally low, such as Boston and Charleston.

Until the aforementioned tests and studies are complete, SNLA will continue to use methods generally accepted by the solar community to express efficiency and to predict thermal output.

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