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**Performance Testing of the
Acurex Solar-Collector
Model 3001-03**

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PERFORMANCE TESTING OF THE
ACUREX SOLAR COLLECTOR
MODEL 3001-03

SAND-80-0872

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ABSTRACT

This report summarizes results of tests conducted at the Collector Module Test Facility on an Acurex Model 3001-03 Parabolic Trough Concentrating Solar Collector. Test temperature range was 100°C to 300°C. Tests were conducted with the collector axis oriented east-west and again with the collector axis oriented north-south. Three collectors were tested: one using polished aluminum mirrors, one using glass mirrors, and another using an aluminized acrylic film mirror.

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PERFORMANCE TESTING OF THE
ACUREX SOLAR COLLECTOR MODEL 3001-03

INTRODUCTION

A series of concentrating solar collector designs are being tested at the Collector Module Test Facility (CMTF) located at the Sandia National Laboratories, Albuquerque, New Mexico. The CMTF is a part of the Midtemperature Solar Systems Test Facility (MSSTF). These facilities are operating as part of a Department of Energy program to characterize selected solar collector modules for possible use in commercial energy systems.

The subject of this report is the performance characteristics of the Model 3001-03 solar collector manufactured by Acurex Corporation, Mountain View, California. Earlier versions of this collector were used at the Shallow Well Irrigation Project, Willard, New Mexico. The COILZAK mirror version of the collector was installed at Coolidge, Arizona, to provide thermal energy for the Deep Well Irrigation Project. The collector field at Coolidge was later retrofitted with acrylic film mirrors. The glass mirror version of the collector was installed at Almeria, Spain, in a solar thermal project sponsored by the International Energy Agency.

TEST OBJECTIVE

Test objective for this test series was definition of performance characteristics for the Acurex Model 3001-03 solar collector, in both east-west and north-south orientations, over a temperature range from 100°C to 300°C.

COLLECTOR DESCRIPTION

Figure 1 shows the Acurex collector field installation at Coolidge, Arizona. The installation aperture area is 2140 m² (23,040 ft²); it provides 150 kW of electrical power for irrigation pumping. The collector axis orientation at Coolidge is north-south. Figure 2 shows the COILZAK mirror version of the Acurex collector installed on the CMTF test pad. The initial installation at the CMTF was with the axis oriented east-west. After completion of a series of tests, the collector was moved to a north-south orientation for a second test series. A third version of the collector, using an aluminized, second-surface acrylic film mirror, was also evaluated. All three collectors were operated with both east-west and north-south axis orientations.

The Acurex 3001-03 collector is a line-focus, single-axis tracking parabolic trough. A cross section of the trough is shown in Figure 3. With

Figure 1. Accurex Collector Field at Coolidge Arizona.

Figure 2. Accurex Collector Installed at the CMTF.

Figure 3. Cross-Section of Accurex Collector

the exception of the mirror, steel sheet metal and tubing was used for all collector construction. Support for the rotating trough was provided by bearings mounted on 10 cm-square (4 inch), vertical steel posts; four one-inch bolts anchored in poured concrete footings provided the foundation.

The collector trough was built in modules measuring 182.88 cm (72 inches) across the aperture and 304.8 cm (20 inches) long. Each COILZAK collector module weighed 128 Kg (272 lbs). A fully enclosed stepping motor drive and gear box actuator assembly rotated the collector; rotation limits were 70° below the horizon in one direction to 20° below the horizon in the other direction. Four mirror modules were used in each of the three collectors tested. The motor drive unit was installed in the center of the collector for the first east-west test series, with two mirror modules on each side of the drive unit. This configuration was also used for all the north-south tests. Figure 4 is a sketch showing the approximate dimensions of this installation.

For the east-west tests using the glass and FEK acrylic mirror modules, a new foundation was laid out. This installation, shown in Figure 5, used four mirror modules with the motor drive unit at the west end. Normal field installation practice is four modules on each side of the drive unit.

The mirror used on the first collector tested was COILZAK, a chemically polished, anodized aluminum sheet manufactured by Alcoa. Three COILZAK mirror sheets, each 101.5 cm wide, were used on each collector module and were held in place by sheet metal clamps along the edges of the module (see Figure 3). Total aperture for four COILZAK mirror modules was 22.141 m^2 .

The second collector tested was nearly identical to the first, except that glass mirrors were used. The second-surface, tempered glass sheets were manufactured by Glaverbel in Belgium. The flat glass sheets were bonded to 105 x 75.5 cm, 0.75 mm steel sheets.

Eight of these glass mirror sheets were used on each collector module, four on each side of the module centerline. For mirror installation, each glass/sheet-metal sandwich was simply hand pressed into shape in the collector module. The mirror sheets were held in place by a retaining strip along the center of the collector and a clamp along the outer edge. Installation does not permanently deform the reflector sheet; if the clamps are removed, the glass/sheet-metal sandwich returns to the original flat sheet. The sandwich construction assures that the glass remains in compression as the sheet is bent into place in the collector module. Total aperture for four glass mirror modules was 22.003 m^2 .

The third version of the collector was very similar to the COILZAK mirror module; the mirror was made up from aluminum sheet covered by an aluminized, second-surface acrylic film. The reflective film used was FEK-244,

THIS LAYOUT WAS USED WITH COILZAK MIRROR E-W AXIS AND ALL MIRRORS N-S AXIS

FIGURE 4 ACUREX COLLECTOR INSTALLATION LAYOUT WITH DRIVE UNIT AT CENTER OF COLLECTOR ROW

THIS LAYOUT WAS USED WITH GLASS AND FEK ACRYLIC MIRRORS E-W AXIS

FIGURE 5 ACUREX COLLECTOR INSTALLATION LAYOUT WITH DRIVE UNIT AT END OF COLLECTOR ROW

manufactured by the 3M Company. This third version of the collector also had slightly changed mirror clamps to improve the focus of light reflected from the outer edges of the mirror. Installation of the mirror sheets was identical to the COILZAK version. Total aperture for four acrylic film mirror modules was 22.065 m^2 .

In case of mirror damage in a field installation, individual mirror sheets of any of the three types can be easily replaced.

The Acurex receiver assembly was a 3.18 cm O.D. steel absorber tube, covered by a 5.08 cm O.D. PYREX glass tube. The absorber surface was solar-spectrum-selective black chrome plating over dull nickel. Concentration ratio, defined as the ratio of collector aperture area to illuminated absorber area, was about 36.7:1.

The absorber tube used on the COILZAK mirror collector contained an internal, thin steel strip, twisted to spiral about once each 30 cm. The purpose of this spiral tape was to increase turbulence in the heat-transfer fluid, and thereby assist in heat transfer from the tube walls into the fluid. The absorber tube used on the glass and acrylic mirror collectors was identical to the first, except that the spiral tape was not installed.

Tracking of the Acurex COILZAK collector was accomplished with a Sandia-provided shadowband sun-sensor. The glass and acrylic mirror collectors used a new, Acurex-designed shadowband sun-sensor and associated electronics.

Other collector data is summarized in Appendix 1.

TEST FACILITY DESCRIPTION

The CMTF's Fluid Loop 1 is designed to supply Therminol 66 as a heat-transfer fluid at temperatures from about $100\text{--}300^\circ\text{C}$. Therminol 66 is a synthetic oil manufactured by the Monsanto Industrial Chemicals Corp. Properties of Therminol 66 are given in Reference 2. Design flow-rates available from Loop 1 range from 4 L/min to 40 L/min.

Low-temperature water from the Albuquerque city water mains has been used in recent test series to determine a low-temperature efficiency point near the optical efficiency of the collector. The temperature of the water has been found to be quite stable, varying only a degree or so throughout a day's test run. Water pressure variations are common, requiring that a pressure regulator be used on the water supply line to achieve a stable flow-rate.

A typical test day began by heating the fluid loop with electric heaters; the collector was placed in focus as soon as an appropriate fluid

flow was established. An additional parabolic trough collector system was often used in parallel with Acurex to speed heating of the fluid system to the desired operating temperature. Data collection was usually attempted at only one operating temperature in one day, due to the requirement for peak efficiency data at solar noon and the time required for temperature stabilization. During an individual test, both the input temperature and fluid flow-rate were maintained constant, while the output temperature was allowed to vary according to the test conditions.

Temperature control of the fluid system was maintained by an automatic control system controlling electric heaters. All other fluid loop control was manually operated. Automatic fluid-flow control systems have been found to generate fluctuations in fluid flow, which in turn cause unacceptable variations in collector input temperature. A high-pressure centrifugal fluid pump, throttled by a manually operated flow-control valve, produces a highly stable fluid flow-rate.

Fluid flow-rate was measured with a turbine flowmeter. At intervals during the test series, the flowmeter calibration was checked by flowing fluid into a container. The fluid container weight vs. time was measured to determine the true flow-rate.

Input and output fluid temperatures were measured with type T thermocouples. Direct solar radiation measurement was provided by an Eppley pyrheliometer. Total horizontal solar radiation, ambient air temperature, wind speed and wind direction were also recorded.

Analog test data was converted to digital format by several analog-to-digital data systems. An HP 1000 minicomputer system processed the input data and provided output of critical test data. Real-time plots of insolation and efficiency were made during all test runs, and all data was recorded on magnetic tape for future analysis.

Figures 6 and 7 contain reproductions of the printed data output for an efficiency test and for a thermal loss test, respectively. Unless otherwise indicated, the temperatures are in degrees Celsius. The delta temperature column shown in the printouts is not the arithmetic difference of the input and output temperatures, but was calculated from the differential voltage output of the in-out thermocouples.

Thermocouples used at the CMTF are calibrated, and carefully selected matched pairs are used for input-output temperature measurements. The output of these matched pairs of thermocouples has been found to be quite stable and repeatable. Because matched pairs are used, the collector temperature differential, as determined by differential voltage measurement, is more accurate than the absolute temperature values measured. Collector performance values quoted in this report are based on the differential delta-T;

```

***** ACUREX PARABOLIC TROUGH EFFICIENCY TEST *****
TEST DATE: 25 OCTOBER 1979          TIME: 12:49:52 (MDT)
                                      11:59:34 (SOLAR)

21.2      (DEG C)  AMBIENT TEMPERATURE  (DEG F)  70.16
236      (DEGREES) WIND DIRECTION
.64      (M/SEC)  WIND SPEED            (MPH)    1.4

TEMP      TEMP      (SOLAR)  DELTA      FLOW      EFFICIENCY
IN        OUT        WATTS/M^2  TEMP      LITERS/MIN  PERCENT
143.39    162.64     1009.2   19.33     22.81      62.0
143.35    162.74     1009.7   19.37     22.83      63
143.39    162.64     1010.1   19.35     22.8      62.8
143.31    162.76     1011.3   19.35     22.79     62.7
143.25    162.78     1012.8   19.33     22.77     62.5
143.25    162.68     1010.7   19.33     22.79     62.7
143.31    162.7      1011.1   19.41     22.81     63
143.33    162.7      1011.2   19.41     22.81     62.9
143.33    162.66     1012.4   19.47     22.79     63
143.35    162.68     1013.5   19.31     22.82     62.5

10 POINT AVERAGES
143.326    162.698    1011.25   19.366     22.802     62.79

62.81      AVG EFFICIENCY USING SUB. DELTA T
62.79      AVG EFFICIENCY CORRECTED FOR OFF-NOON LOSSES
50288.3    AVG HEAT GAIN (KJ/HR)
634.917    AVG HEAT GAIN (W/M^2)
131.452    AVG RECVR TEMP MINUS AMB TEMP
.12999     (AVG TEMP-AMB T)/I
10931.9    REYNOLDS NUMBER

```

END OF DATA BLOCK 56

Figure 6. Sample of Efficiency Data Printout

```

***** ACUREX PARABOLIC TROUGH THERMAL LOSS TEST *****
TEST DATE: 13 MARCH 1979  HOUR 13  MINUTE 17  (SOLAR TIME)

18.83      (DEG C)  AMBIENT TEMPERATURE  (DEG F)  65.89
208      (DEGREES) WIND DIRECTION
.6      (M/SEC)  WIND SPEED            (MPH)    1.3

TEMP      TEMP      DELTA      FLOW      WATTS
IN        OUT        TEMP      LITERS/MIN  GAIN/LOSS
226.33    221.17     -5.39     9.55      -1702.8
226.39    221.17     -5.39     9.55      -1702.9
226.39    221.17     -5.33     9.56      -1685.7
226.39    221.17     -5.41     9.55      -1709.5
226.33    221.17     -5.33     9.54      -1682.1
226.39    221.17     -5.39     9.57      -1706.4
226.33    221.17     -5.39     9.57      -1706.3
226.33    221.17     -5.41     9.56      -1710.9
226.39    221.17     -5.46     9.55      -1725
226.39    221.17     -5.46     9.58      -1730.4

10 POINT AVERAGES
226.366    221.17     -5.396     9.558     -1706.3

AVERAGE INSOLATION = 1011.87 WATTS/M^2
AVG LOSS USING SUB. DELTA T (WATTS) = -1639.88
AVG LOSSES: (KJ/HR)=-6142.17 (W/M^2)=-77.065 (W/M)=-1193.21
AVG RECVR TEMP MINUS AMB TEMP 205.191
AVG REYNOLDS NUMBER 5138.54

```

END OF DATA PASS 87

Figure 7. Sample of Thermal Loss Data Printout

however, the collector delta-T is also calculated from the subtracted difference in collector input and output temperatures. Both delta-T measurements produce efficiency values that are less than one percentage point different (see test sample printout in Figure 6). The two different methods of measuring collector delta-T use different channels in the analog-to-digital data systems and different calculations in the computer software, thus ensuring some degree of redundancy and a cross check on possible errors in all parts of the system, except the thermocouples.

The speed of the data system was such that all the data channels could be read, calculations performed, and a line in the data table printed in about 15-20 seconds. Fifty measured and calculated data values were generated during each of these data cycles. All were recorded on magnetic tape, but only those shown in Figures 6 and 7 were printed out. Data collection was continuous whenever the system was operating; however, only those data blocks occurring under the best stable conditions are included in this report. The all-day efficiency plots shown later in this report result from 2000-3000 separate measurements of all the collector data.

HEAT GAIN/LOSS PERFORMANCE TEST DEFINITION

During a test run, both the specific heat and density of the heat transfer fluid were calculated for each data set, using the average temperature of the fluid in the absorber tube and fluid properties from Reference 2. Heat gain (or loss) was then calculated from:

$$Q = \dot{m} C_p \Delta T$$

in which

$$\begin{aligned} Q &= \text{heat gain, kJ/hr} \\ \dot{m} &= \text{mass flow-rate of fluid, kg/hr} \\ C_p &= \text{specific heat of fluid, kJ/kg}^\circ\text{C} \\ \Delta T &= \text{in-out temperature differential, }^\circ\text{C} \end{aligned}$$

Heat gain (efficiency) tests were conducted with the collector focal point adjusted for maximum efficiency at solar noon. If required, mirror surfaces and absorber glass were cleaned daily with detergent and de-ionized water.

Receiver thermal loss tests were conducted in two different ways. "Shaded" thermal loss was determined with the collector defocused and rotated towards the stow position far enough that the reflector assembly shaded the receiver assembly from direct sunlight.

The second set of thermal loss measurements was made with the collector defocused as far as possible, so that no light from the mirror would fall on the receiver assembly, but positioned so that the receiver remained exposed to direct sunlight.

A successful heat gain/loss measurement is defined as at least one ten-point block (preferably preceded by a number of others of equal stability) during which the values for input and output temperatures remained constant to within 0.1°C or less, the flow-rate varied by 0.1 L/min or less, and the receiver delta temperature changed by 0.1°C or less. These values do not imply that the absolute accuracy of the measurement are that good; the objective is to achieve the best stability possible.

EFFICIENCY TEST DEFINITION

The stability requirements for an efficiency test point are the same as for a thermal loss test, except that the direct solar radiation input must remain constant to about 1% during the measurement period and have an absolute value greater than about 900 W/m². Measured efficiency of concentrating solar collectors has been found to change significantly with changes in insolation; therefore, the CMTF attempts to make all the peak efficiency characterization test runs within a narrow range of insolation between 900 and 1050 W/m². Other tests are scheduled, as required, to define the performance of the collector under less than ideal solar radiation input.

Given the required stability, efficiency was then calculated from:

$$\eta = \frac{Q/A}{I}$$

in which

η = solar collector efficiency
 Q = heat gain, W
 A = collector aperture area, m²
 I = direct solar radiation, W/m²

The measured efficiency data is shown in this report in four different ways: in tabular form, and in three different graphical formats. Each of the three graphical formats has advantages and also some disadvantages. When the efficiency data is shown vs. the collector output temperature, the curve is actually correct only when the ambient air temperature matches that existing when the data was measured, and also only at the same solar irradiance existing during the test measurements.

Two other data curve formats eliminate the problem with changes in ambient air temperature, but do nothing to show how the efficiency varies with changes in solar irradiance level. These data plots show measured efficiency as a function of average receiver fluid temperature above ambient air temperature, or as average temperature above ambient, quantity divided by the solar irradiance (Delta T/I). The Delta T/I presentation is the most deceiving, because even though the solar irradiance I appears in the efficiency equation, I is not a variable but is actually a constant. The best presentation would be as a three-variable equation, containing efficiency,

average temperature above ambient, and solar irradiance. Such an equation in graphical form would appear as a three-dimensional surface, with a parabolic curvature along the temperature axis and with a hyperbolic curvature along the solar irradiance axis. There are no less-complex curves that will correctly show the collector performance under all operating conditions. The problem of solar irradiance level and its effect on collector efficiency will be discussed further later in this report.

THERMAL STABILITY REQUIREMENT

The temperature, flow-rate and solar radiation stability criteria outlined above are necessary because the heat gain formula used assumes steady-state conditions. If near steady-state conditions can be achieved during a collector test, the computed values for heat gain (or loss) and efficiency will be nearly constant also, with some scatter in the data due to noise. Because of the thermal mass of the collector and fluid loop system, any change in temperature, flow-rate or insolation will result in transient measurements that do not correctly represent the performance of the collector.

Even on a clear, sunny day that appears ideal for testing a solar collector, there are still variations in solar radiation. However, these variations can be relatively small, as can be seen in several of the test data plots later in this report. Small, rapid variations of this kind produce scatter in the efficiency data, but no long-term systematic errors.

As operated at the CMTF, the heat-transfer fluid supply loop tends to produce fluid flow-rate variations similar to those seen in the solar radiation input--small, rapid fluctuations with no long-term trend towards a higher or lower flow-rate. These flow variations also produce scatter in the measured data.

Small, rapid temperature fluctuations also appear in the measured data, again producing data scatter. However, the temperature measurements are subject to fairly long-term, slow changes which can result in fairly large, systematic errors in heat gain/loss and efficiency calculations. One typical source of this kind of temperature drift is the constantly increasing temperature that occurs each test day as the fluid system is heated towards the intended operating temperature. Even after the fluid coming out of the heater is at a constant temperature, the fluid at the collector inlet may not be--the fluid must still transfer enough energy to the large mass of fluid pipe and pipe insulation to reach an equilibrium with heat losses. The same problem in reverse occurs with the temperature decay that continues for very long times after the collector system is defocused to begin a thermal loss test.

At the CMTF, collector input and output temperatures are usually measured less than one second apart in time. However, the fluid whose temperature is being measured at the collector input may not arrive at the collector output for a relatively long time--from several seconds to several minutes. Thus, an efficiency or heat gain/loss measurement will not be valid unless the input and output temperatures are unchanging for at least as long as the transit time of the heat-transfer fluid through the system.

Because of the thermal mass of both the fluid supply system and the collector, stable temperatures must be held for relatively long periods of time before the complete system is in thermal equilibrium and valid measurements can be made. A small, constant drift in temperature can produce test data that looks quite acceptable; however, it contains a systematic error because of the thermal mass shift of in/out delta temperature.

In tests with another collector system of greater thermal mass, a slow drift in temperature of about 0.3°C per minute produced an efficiency measurement 15 percentage points lower than the true value.

If the input temperature drift is towards lower temperatures, errors of similar magnitude result, but the measured efficiency will be greater than the value obtained under stable conditions.

The same problem, as outlined above for an efficiency measurement, also occurs during thermal loss measurements. The error in thermal loss from unstable temperatures is larger than the efficiency error because the receiver delta temperature during a loss test is usually much less than during an efficiency measurement.

The requirement for 0.1°C stability in measured temperatures for a usable data point is empirically based. It appears to produce valid data and is also about as good as the fluid loop and collector system can attain in the outdoor test environment.

CALCULATION OF INCIDENT ANGLE MODIFIER

The efficiency of a concentrating solar collector is at its maximum value only when the incoming solar radiation is perpendicular to the reflector aperture. For a single-axis tracking collector, with an east-west axis, zero incident angle occurs only at solar noon. At other times of the day, efficiency is less than the noon value and is approximately proportional to the cosine of the incident angle. Incident angle is defined as the angle between direct solar radiation from the sun and a perpendicular to the plane of the collector's aperture. Thus, the incident angle on an east-west axis, solar-elevation-tracking collector such as Acurex is zero at solar noon. Incident angle for a two-axis tracking collector is always zero.

ASHRAE Standard 93.77 defines a test method for determining the quantity K_{θ} , called the incident angle modifier. (ASHRAE 93-77 defines testing standards for flat-plate solar collectors, but many of the procedures also apply to concentrating collectors). The incident angle modifier, K_{θ} , defines the change in collector efficiency as the incident angle increases. The incident angle modifier experimentally combines the cosine effect with several other factors, such as mirror slope errors, reflections from the receiver cover glass at large angles, etc.

Incident angle modifier can be experimentally defined as the ratio of optical efficiency at a given incident angle to the optical efficiency at a zero incident angle, both quantities measured on an infinitely long collector row.

Measured efficiency from a short collector module cannot be used directly to calculate the incident angle modifier; corrections for end loss must first be applied. For parabolic troughs with a receiver length equal to the aperture length and with negligible thermal losses from the unilluminated portion of the receiver, measured efficiency can be converted to an equivalent efficiency for a long collector row by use of the relationship:

$$\eta = \eta_s \left(1 + \frac{\tan \theta (fw + w^3/48f)}{wL - \tan \theta (fw + w^3/48f)} \right)$$

where:

η_s = Efficiency measured on a short row
 η = Efficiency corrected for end loss
 θ = Solar Radiation Incident Angle
 f = Collector focal length
 w = Width of collector aperture
 L = Length of collector aperture

The efficiency test to be used for determining incident angle modifier must be done with the collector receiver operating at ambient air temperature. If this cannot be done, corrections for thermal loss must also be made.

TEST RESULTS FOR THE COILZAK MIRROR WITH EAST-WEST AXIS

The next seven figures are data plots made in real time during the east-west efficiency testing of the Acurex COILZAK mirror collector. Plots such as these are made during each test day; they have proven invaluable in detecting data trends and oscillations that are not obvious in tabular printed data output. Each 15-20 second data measurement cycle produces a solar radiation measurement and an efficiency point (plus many other data values which are recorded on magnetic tape); these two values are plotted on the data curves as single dots. With stable measurements, the dots blend into continuous curves; with less stable conditions, the data rate is high enough to trace transients. Nearly 3000 data sets are found on some of the all-day curves.

Figure 8 shows the results of a test at the lowest temperature that could be maintained with Fluid Loop 1's available cooling capacity. The gap in the data trace at 11:10am was caused by shutdown of the computer system. Other disturbances in the radiation trace were caused by small, thin, high clouds. The other transients visible on the efficiency curve are the result of disturbances in solar radiation input or by a change of flow-rate. Peak efficiency was 54% at solar noon. The collector was defocused at 12:30pm to begin loss testing.

Figure 9 is the result of a test at a slightly higher temperature. The oscillation in the efficiency curve at 11:20am was the result of the heating and cooling systems fighting each other for temperature control of the system. This oscillatory behavior is also visible in several of the later data plots. The explanation for the other features visible on the curve is the same as for Figure 8. Peak noon efficiency was 48.1%. Figure 9 also shows an abrupt break in slope at three hours off-noon, due to a mistracking sun sensor. This Sandia-provided sun sensor had a very wide light-acceptable angle and tended to be distracted by reflections from bright objects around the test area.

The overall shape of the efficiency curve in Figure 9 is typical of an east-west oriented parabolic trough. Most approach zero heat gain at about four hours off-noon (approximately 60° incident angle).

Figure 10 shows another all-day run similar to the previous two curves. The irregularities in the solar radiation curve were caused by slight variations in a high, thin haze layer that was nearly invisible to the eye. Peak efficiency was 50.9% at solar noon.

Figure 11 was made on a less ideal testing day than the previous three figures. Small, thin clouds drifted past throughout the day, causing a very rough solar radiation curve. However, efficiency is a weak function of radiation level, at least above about 800 W/m^2 , so the efficiency curve is much smoother than the input solar radiation. Actual heat output from the collector directly follows the solar input; efficiency at these radiation levels is actually even smoother than indicated by the curve. Most of the efficiency variations shown on the data plots are not real efficiency changes, but are the result of the thermal mass of the collector and fluid system being unable to respond quickly to changes in input radiation levels.

Figure 12 is the result of an all-day run at 250°C . At this temperature, the available heating capability of the collector plus electric heaters was not large enough to heat the fluid system to the intended operating temperature until 11:20am. Since the curve should be symmetrical about solar noon, the afternoon portion of the curve can be reflected to obtain a representative all-day performance. Again, there was a slight change in slope of the efficiency curve beginning at about 14:40, due to the mistracking sun sensor.

FIGURE 8 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 92.2 °C INPUT

FIGURE 9 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 108.6 °C INPUT

FIGURE 10

ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 143.6 °C INPUT

FIGURE 11 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 187.2 °C INPUT

FIGURE 12 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 239 DEG C INPUT

Figure 13 was obtained at the highest output temperature reached by the Acurex collector during this test series: 289°C. Again, the morning was spent heating the system; temperatures were not stabilized until 11:35am. The curve looks quite good, yet the true all-day capability of the collector at this temperature is not correctly represented by the plot because of constantly changing temperatures before 11:35am. At 08:30, the input temperature was only 170°C. This curve should therefore not be used to represent all-day performance. Peak noon efficiency at 289°C was 42.1%.

Fluid flow-rates used during the test series ranged from 32 L/min (about 9.5 gal/min) to 4.7 L/min (about 1.25 gal/min). Any efficiency dependence on flow-rate within this flow range is believed to be less than two percentage points.

Table 1 contains the efficiency data obtained during the east-west COILZAK mirror test series. Figure 14 is a plot of these data as a function of output temperature. Figure 15 is the same data, plotted as a function of average receiver temperature above ambient. A polynomial, least-squares curve fit to the test data produced the efficiency equations in Figures 14 and 15.

TABLE 1. ACUREX EFFICIENCY TEST DATA FOR COILZAK MIRROR

Test Date	Direct Insolation (W/m ²)	Temp Out (°C)	Receiver Delta T (°C)	Avg Temp Above Amb (°C)	Flow Rate (L/min)	Efficiency (%)
2/ 9/79	1055	254.8	16.1	238.4	18.7	44.9
2/10/79	1066	113.6	21.3	93.2	19.7	54.1
2/12/79	1045	204.1	16.9	183.8	20.1	48.1
2/13/79	1044	162.0	18.5	135.5	20.1	50.9
2/14/79	1067	288.6	14.4	263.9	20.0	42.2
2/19/79	985	232.9	59.4	191.3	5.4	48.6
3/ 7/79	1043	126.1	20.1	100.7	14.6	54.4 *
3/ 7/79	1045	130.8	25.9	102.0	14.6	49.6 **
3/ 8/79	1037	287.1	13.1	264.5	20.1	39.7
3/12/79	1065	135.1	26.5	106.5	15.0	51.7

* 30 cm mask along edges of mirror
 ** mask removed

Because the outer portions of the Acurex COILZAK mirror surface appeared less accurately formed than the inner portion of the curve, another test was run as a check on this factor. For this test, the outer 30 cm along each edge of the mirror was masked with a black plastic film. A corresponding reduction in aperture was used in the efficiency equation. The test was run at a low temperature so that thermal losses would have the least possible effect.

Figure 16 shows the results of the masked mirror test. Stable operation was achieved just after 11:20am. The mirror was masked until 12:45pm, when the mask was quickly removed. No change in other operating conditions was made, except to again change the efficiency equation to

FIGURE 13 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 274 DEG C INPUT

FIGURE 14

ACUREX EFFICIENCY VS OUTPUT TEMPERATURE

FIGURE 15 ACUREX EFFICIENCY VS TEMPERATURE ABOVE AMBIENT

FIGURE 16 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 105 DEG C INPUT

reflect the true mirror aperture being used. The result was an abrupt change of four percentage points in measured efficiency. This efficiency change shows that the outer portion of the mirror was not as efficient as the inner portions, i.e. much of the light reflected from this portion of the mirror was being scattered and was not reaching the absorber surface. Calculations indicate that the optical efficiency of the outer 30 cm on each side of the mirror was about 12 percentage points lower than the remainder of the mirror.

TEST RESULTS FOR THE COILZAK MIRROR WITH NORTH-SOUTH AXIS

Testing of the Acurex 3001-03 COILZAK mirror collector resumed on April 6, 1979, after the collector had been disassembled and moved to position the collector axis north-south. A north-south orientation is often used in field installations such as the Coolidge, Arizona, irrigation project to maximize the energy output during the summer months.

Figure 17 is the result of an all-day run at approximately 160°C fluid output temperature. The oscillations in the morning portion of the efficiency curve were caused by the heating/cooling systems attempting to stabilize the collector input temperature at 140°C. The dip in the efficiency curve, beginning just about 16:00, was caused by the Sandia-provided, wide-angle shadowband sun-sensor being influenced by sunlight reflecting off the metal roof of a nearby building. This effect was discovered and corrected at about 17:00. Reflected light biasing the sun-sensor caused problems throughout the COILZAK mirror test series.

A zero incident angle for solar radiation on a north-south axis collector should occur at noon $\pm$ 4:08 hours on May 12. The collector efficiency should peak at this point and should correspond to the noon efficiency peak measured at the same temperature and insolation level in an east-west axis installation. Except for the difficulty with the sun tracking, the afternoon efficiency peak in Figure 17 appears to be at the right time and matches the 51% efficiency measured at noon on February 13 (see Figure 10).

If the data from the May 12 test is replotted to show power output rather than efficiency, Figure 18 is obtained. Total energy under the curve of Figure 18 for five hours after noon is 2.12 kW-HR/m², or 4.24 kW-HR/m², for a ten-hour day. This energy output can be compared to energy available at the same fluid temperatures with the collector axis oriented east-west (see Figure 19). Figure 19 was obtained from the all-day test previously shown in Figure 10; the energy output from the February 13 test day was 2.87 kW-HR/m² for an eight-hour day. The energy recovery, more than four hours off-noon in the east-west configuration, is essentially zero.

For the ten-hour day shown in Figure 18, the N-S orientation of the collector recovered about 48% of the energy available. The E-W orientation shown in Figure 19 recovered only about 31% of the energy available in ten

FIGURE 17 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION

FIGURE 18

ACUREX PARABOLIC TROUGH POWER OUTPUT VS TIME FOR NORTH-SOUTH ROW

FIGURE 19 ACUREX PARABOLIC TROUGH POWER OUTPUT VS TIME FOR EAST-WEST ROW

hours. An E-W axis parabolic trough collector would have approximately the same energy recovery on any day of the year, given the same level of solar radiation input. The energy recovery per day with the N-S orientation changes significantly throughout the year, as will be seen in the later tests.

Figure 20 shows another north-south test, with an output fluid temperature near 200°C. Figure 21 is the same data showing the power output.

Figure 22 was obtained from a test at 250°C fluid output temperature; Figure 23 contains the power output curve. Continuing difficulty was experienced with sun tracking when the sun was relatively low in the sky; the wide-angle view of the Sandia shadowband sun-sensor tried to follow every beam of light reflected from buildings and equipment around the test area. For the May 14 test shown in Figures 22 and 23, the shadowband sun-sensor was switched off after 16:30. The manual sun-tracking made the curve somewhat rough, but did succeed in preventing the fast, false drop in efficiency after 17:00 seen in the previous two test days.

The 160°C test previously made on February 13 (east-west) and May 12 (north-south) was repeated on June 19, only two days from summer solstice. Figures 24 and 25 contain the data from the summer solstice test. The spikes and irregularities in the efficiency and power curves were caused by malfunctions of the fluid loop cooling/temperature control system. For this test, the Sandia shadowband sun-sensor was greatly reduced in sensitivity and the view angle severely restricted by baffles. These changes enabled fairly accurate sun tracking until 18:02, when a building shadow began to cover the collector mirror.

Normal incidence of solar radiation occurs at noon $\pm$ 3:28 hours on June 19; the efficiency peak of 49.9% was again close to the 51% obtained earlier on February 13 and May 12. The incident angle at noon on June 19 was about 11.6°; the 47.5% measured efficiency is somewhat lower than the 49% measured at the same incident angle on February 13 (noon + 0:48).

The June 19 test terminated the testing of the Acurex 3001-03 collector using COILZAK mirrors.

TEST RESULTS FOR EAST-WEST AXIS WITH GLASS MIRRORS

Testing of the glass mirror version of the Acurex collector began on October 11, 1979, with the collector axis oriented east-west. This was a completely new collector but, except for the glass mirrors, was nearly identical to the COILZAK mirror collector tested earlier. Figure 26 is a photograph of the collector installed at the CMTF.

FIGURE 20 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 181.3 °C INPUT

FIGURE 21 ACUREX PARABOLIC TROUGH POWER OUTPUT VS TIME FOR NORTH-SOUTH ROW

FIGURE 22 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 239.2 DEG C INPUT

FIGURE 23 ACUREX PARABOLIC TROUGH POWER OUTPUT VS TIME FOR NORTH-SOUTH ROW

FIGURE 24 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 141 °C INPUT

FIGURE 25 ACUREX PARABOLIC TROUGH POWER OUTPUT VS TIME FOR NORTH-SOUTH ROW

Figure 26. Accurex Collector with Glass Mirrors Installed at the CMTF.

After completing the earlier east-west axis tests on the COILZAK mirrors, the collector foundations were pulled from the ground, and the extraction forces were measured. In general, the foundations were more resistant to overturning forces than predicted. See References 4 and 5 for a more complete report on these test results.

A new set of concrete foundations was poured prior to installation of the glass mirror collector. The collector layout used for the east-west glass mirror tests (see Figure 5) differed from that used earlier with the COILZAK mirrors (see Figure 4). Because of this layout difference, the collector end losses are different at solar beam incident angles other than zero. Therefore, the east-west axis, all-day test plots for the glass mirror collector should not be directly compared to those obtained with the COILZAK mirrors without corrections for the different end losses. End losses would be less of a problem with a long collector row, but end losses have a significant effect on a short test module.

Figure 27 is a plot obtained during the October 11 test. Beginning at about 10:30, the sun-tracking shadowband position was adjusted several times to locate the optimum position for maximum efficiency. The best efficiency point was located at about 10:48, and the sun-sensor assembly remained in approximately the same position for the remainder of the test series. As noted earlier, the sun-tracking system used for the glass mirror tests was a new Acurex design, replacing the Sandia system installed for the COILZAK tests. A maximum collector efficiency of 66.3% was measured at solar noon on October 11. A comparable test using the COILZAK mirror was shown earlier in Figure 8, where the peak noon efficiency was 54.1%. It is believed that the measured efficiencies are representative of the collector's best performance, and that any difference in measured efficiencies because of the different tracking systems is small.

Since the remaining test data plots for the first five test days are very similar to Figure 27, only one more will be shown here. Figure 28 was obtained during a test at about 250°C on October 15. Stable fluid temperatures at the desired operating point were established at 09:45; peak efficiency at solar noon was 59.3%. A comparable test using the COILZAK mirror was made on February 9 (Figure 12); peak efficiency at solar noon on February 9 was 44.9%.

At this point in the glass mirror test series, five efficiency measurements had been made, covering the temperature range from 114°C to 318°C. As with most collectors tested, some light from the mirrors could be seen missing the receiver assembly. Some of the missing light was coming from the outer edges of the mirrors, where almost all collectors have difficulty in forcing the mirror sheet to conform to the correct parabolic contour. The glass mirror Acurex collector also had the same problem near the center of the mirror, where the two mirror halves were joined.

FIGURE 27 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 98.0 °C INPUT

FIGURE 28

ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 240.5 °C INPUT

It was decided that some improvement in performance might be achieved by moving the receiver assembly slightly to attempt to capture some of the stray, reflected light. Receiver assembly mounting holes were enlarged to allow repositioning the receiver, and the receiver was moved slightly farther away from the mirror.

Figure 29 shows a repeat of the test conditions shown earlier in Figure 27. The new receiver location was not an improvement; peak efficiency was now 63.8%, about 2.5 percentage points lower than before. Several attempts were made to position the receiver so as to improve, or at least duplicate, the performance observed in the original receiver position. In the limited time available, the original focal position for the receiver could not be exactly duplicated, so all the subsequent efficiency measurements were 1-2.5% lower than the first five.

Figure 30 is a plot of a test at about 270°C, near the intended operating point for the installation at Almeria, Spain. Peak efficiency at solar noon was 55.8%. A shadow from a nearby building began encroaching on the collector mirror at 16:40, so the exact time of zero net heat gain is not known.

Figure 31 was obtained from the October 24 test data by replotting to show the power output curve. The energy collected was about 1.44 kW-HR/m² for the five hours from noon to 17:00, or about 2.88 kW-HR/m²/day.

The next two figures show the results of an all-day test run on October 25 at 162°C output temperature. The same test was made with the COILZAK mirror collector oriented east-west on February 13 (Figures 10 and 19). A similar test was made for the north-south orientation on May 12 (Figures 17 and 18). Figure 32 is the efficiency plot for October 25. The efficiency curve does not begin until 07:30 because the shadow from a water supply tank lay across the entire collector. The curve effectively terminates at 16:40, when the shadow of a nearby warehouse building began to cover the west end of the collector.

Figure 33 shows the October 25 data replotted as a power output curve. Energy collected was 1.79 kW-HR/m² for the five hours from 12:00-17:00, or 3.58 kW-HR/m²/day, 40% of that available.

Table 2 lists the efficiency test data accumulated during the test series on the east-west axis, glass mirror Acurex collectors. The data from Table 2 is plotted in Figure 34 as a function of collector output temperature. Figure 35 is the same test data shown as a function of average temperature above ambient air temperature.

FIGURE 29 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 99.9 °C INPUT

FIGURE 90 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 264.7 °C INPUT

FIGURE 91

ACUREX PARABOLIC TROUGH POWER OUTPUT VS TIME

FIGURE 32 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 143.4 °C INPUT

FIGURE 33

ACUREX PARABOLIC TROUGH POWER OUTPUT VS TIME

FIGURE 34 ACUREX EFFICIENCY VS OUTPUT TEMPERATURE

FIGURE 95 ACUREX EFFICIENCY VS TEMPERATURE ABOVE AMBIENT

TABLE 2: ACUREX EFFICIENCY TEST DATA FOR GLASS MIRROR

Test Date	Direct Insolation (W/m ²)	Temp Out (°C)	Receiver Delta T (°C)	Avg Temp Above Amb (°C)	Flow Rate (L/min)	Efficiency (%)
10/11/79	1039.5	114.3	16.3	80.2	30.9	66.3
10/12/79	1026.4	207.1	10.4	175.8	40.4	61.2
10/13/79	955.7	318.2	15.1	289.4	20.3	51.8
10/14/79	979.2	160.8	14.3	130.3	30.9	64.5
10/15/79	1000.3	253.1	12.6	225.9	30.5	59.3
10/20/79	996.6	115.5	15.3	85.5	30.3	63.8
10/22/79	1043.5	115.7	15.9	95.6	30.5	64.0
10/24/79	1003.7	276.3	11.4	250.6	31.2	55.8
10/25/79	1011.3	162.7	19.4	131.5	22.8	62.8
10/26/79	1055.7	234.5	9.5	206.2	39.9	59.3 *
10/26/79	1054.4	235.3	10.1	206.8	39.9	58.5 **

* 30 cm mask along edges of mirror

** mask removed

Receiver thermal loss data for the glass mirror test series was combined with the COILZAK mirror data, since the receivers were essentially the same from a thermal loss standpoint. Thermal loss data is shown later in this report.

TEST RESULTS FOR NORTH-SOUTH AXIS WITH GLASS MIRRORS

The Acurex glass mirror collector was disassembled on December 12, 1979, and moved to the north-south axis foundations occupied earlier by the COILZAK mirror collector. Operation was resumed on December 15. Objective of this series of tests was accumulation of some north-south test data under winter solstice conditions for comparison with earlier data obtained at the summer solstice and near the spring equinox. Note that the north-south axis installation layout was as shown in Figure 4 and, therefore, had different end losses than the Figure 5 layout used for the east-west testing. The end losses were high during all the December tests of the collector, since the incident angles at noon were all near 58° , an angle that would occur at about four hours from noon with an east-west axis.

Figure 36 was obtained on December 15, with the collector operating near 199°C . Efficiency at noon was about 16.5%, rising to about 31% at three hours off-noon as the solar angle of incidence became smaller. Approaching four hours off-noon, the solar radiation was falling rapidly, reducing the collector's efficiency. At 3:55 after noon, shadows from a nearby building began covering the bottom of the mirror, terminating the test. Not much more energy would be available even if the building shadow was not present, as sunset was less than an hour away and the solar radiation intensity was falling rapidly.

The solar tracking system stopped working at about 15:15 on December 16, causing the large drop in the efficiency curve in Figure 36. This difficulty was finally traced to mercury switches in the sun sensor head that were supposed to have been disconnected for this installation. When these

FIGURE 36 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 196.1 °C INPUT

switches were removed from the circuit, no further problems were encountered with sun tracking.

Figure 37 was obtained on December 17 at an output temperature near 300°C . The fluid system was stabilized at 297°C input temperature at 11:15. Efficiency at noon was 8.3%, increasing to about 23% just before shutdown at 15:45.

Figure 38 was obtained on December 18 at an operating temperature near 250°C . Noon efficiency was 12.4%, increasing to about 29.5% at 15:25. The sun tracking problem had not yet been fixed, so this test terminated about 15:45. A test was not obtained exactly at the winter solstice (December 21), but the incident angles change very little for a week or two either side of solstice, so the December tests of the north-south glass mirror collector are very close to the solstice performance.

An unusually long series of cloudy days prevented further data acquisition until January 23, 1980. Figure 39 was made on January 23 with a fluid input temperature of 104°C . By this time, the problem with sun tracking had been corrected, so except for a few steps in the efficiency curve caused by tracking adjustments, a good efficiency curve was obtained until interrupted by a building shadow at 15:59. Noon efficiency was 23.5%, increasing to 44.6% at 15:58.

Figure 40 shows the collector performance on January 25 at about 150°C . Noon efficiency was 24.3%, increasing to 44% at 15:55. The test was terminated by the ever-present building shadow at 15:58.

Figure 41 is the January 25 test replotted to show the power output curve. Not very much energy is available per day at the large solar radiation incident angles seen by a north-south axis collector during the winter season.

After January 25, another lengthy stretch of bad weather prevented any data acquisition until February 24. All-day runs were then resumed, producing the curves shown in Figures 42 through 45. The morning half of these curves is not shown because of changing temperatures caused by loop heating to operating temperature during the morning hours. Stable operating conditions existed for all the afternoon hours during each test, until interrupted by building shadows at about 16:30-16:45.

All-day tests at approximately 162°C output temperatures were obtained on December 15 and 31, January 23, and March 7. The test repetition was necessary to observe the collector performance over a wide range of incident angles. Several efficiency points from these tests were corrected for the different end-loss of the north-south installation (see Figure 4) and overplotted on the October 25 all-day efficiency curve at the appropriate

FIGURE 37 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 297.5 °C INPUT

FIGURE 38 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 248.4 °C INPUT

FIGURE 39 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 103.9 °C INPUT

FIGURE 40. ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 149.1 °C INPUT

FIGURE 41 ACUREX PARABOLIC TROUGH POWER OUTPUT VS TIME

FIGURE 42 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 96.7 °C INPUT

FIGURE 43 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 245.1 °C INPUT

FIGURE 44 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 144.6 °C INPUT

FIGURE 45 ACUREX (GLASS) NORTH-SOUTH EFFICIENCY EVALUATION AT 193.5 °C INPUT

incident angle. The result is shown in Figure 46. Figure 46 shows that, as expected, the collector performs in the same way under the same temperature and solar radiation conditions. Once the collector's performance is defined for a given operating temperature, solar radiation input, and solar beam incident angle, that same performance can be expected to apply for that set of operating conditions regardless of the orientation of the collector axis.

Efficiency testing of the glass mirror Acurex collector was terminated with the March 9 test shown in Figure 45.

TEST RESULTS FOR NORTH-SOUTH AXIS WITH FEK-244 ACRYLIC MIRRORS

The glass mirror Acurex collector modules were removed on March 13, 1980, and modules using 3M's FEK-244 acrylic film mirror surface were installed. A new receiver assembly was also installed. The original drive system and mounting pylons were used again. An extensive series of all-day tests were made to define the collector performance over a range of temperatures, solar radiation levels, and solar beam incident angles.

Figure 47 shows an all-day run at an input fluid temperature near 100°C. Figure 48 shows a similar test made about two months later. All-day performance of the collector was slightly different during the two tests because of different incident angles and solar radiation levels.

Figures 49 through 52 were all made with output temperatures near 160°C. Figures 53 through 55 were made during tests near 200°C. Figures 56-58 were obtained from tests near 250°C, and Figures 59-61 are the result of tests near 300°C.

Note the change in shape of the all-day efficiency curves as the incident angles change with time.

In all cases, the collector performance was nearly the same for a given operating temperature, solar radiation level, and incident angle. Over the operating temperature range, the collector efficiency using the FEK-244 acrylic mirror was about four percentage points lower than the test results obtained with glass mirrors.

Not all the observed performance difference was due to the difference in specular reflectance between glass and FEK-244 film. Visual observation of the focused light patterns showed light from both types of mirror was being spilled past the receiver because of an imperfect focus. However, the focus of the FEK acrylic mirror was better than that of the glass mirror.

On June 27, 1980, the Acurex collector was disconnected from the CMTF's Fluid Loop 1 (Therminol 66) and plumbed to the near-ambient-temperature

FIGURE 46 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 143.4 °C INPUT

FIGURE 47 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 100.8 °C INPUT

FIGURE 48 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 101.8 °C INPUT

FIGURE 49 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 137.8 °C INPUT

FIGURE 50 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 148.3 °C INPUT

FIGURE 51 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 146.8 °C INPUT

FIGURE 52

ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 149.0 °C INPUT

FIGURE 53 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 197.6 °C INPUT

FIGURE 54 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 186.5 °C INPUT

FIGURE 55 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 197.2 °C INPUT

FIGURE 56 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 242.4 °C INPUT

FIGURE 57 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 245.9 °C INPUT

FIGURE 58

ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 247.2 °C INPUT

FIGURE 59 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 298.3 °C INPUT

FIGURE 60 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 300.9 °C INPUT

FIGURE 61 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 295.6 °C INPUT

city water supply. Fluid flow rate was adjusted to achieve an operating temperature as close as possible to ambient air temperatures.

Zero incident angle occurred at 8:35 with an insolation of 867 W/m^2 . Measured efficiency was 66.3%; average receiver temperature was 0.3°C below ambient air temperature. This efficiency value should be very close to the optical efficiency of the Acurex FEK-244 acrylic mirror collector. The June 27 cool water test concluded the north-south axis test series.

TEST RESULTS FOR EAST-WEST AXIS WITH FEK-244 ACRYLIC MIRRORS

The Acurex collector was removed from the N-S axis installation on July 24, 1980. It was reassembled on the E-W axis foundation occupied by the glass mirror version nearly a year earlier. The collector layout was the same as that used by the glass mirror collector (see Figure 5).

Initial testing was accomplished with low-temperature water from the Albuquerque city water supply, with an input temperature of about 24°C . Flow rate was adjusted so that the average receiver temperature was less than 1°C from the ambient air temperature.

Figure 62 was obtained on August 21, using low-temperature water. Peak efficiency at solar noon was 67.3%, about one percentage point higher than that observed on June 27 in the north-south configuration. No specific reason is known for the difference in efficiency measurements. The measured efficiency points plotted are more scattered than in most of the tests using Therminol. The scatter was caused by fluctuations in the water flow-rate, which was caused by fluctuations in city water pressure. A water pressure regulator (not available during this test) was used to reduce the data scatter during later tests.

Plumbing was changed on August 25 to supply Therminol 66 to the collector from the CMTF's Fluid Loop 1. Testing resumed on August 27. Three of the all-day test runs from this test series are shown in Figures 63-65. Peak noon efficiency test data obtained during the test series is summarized in Table 3. During these tests, the efficiency data accumulated from the east-west series did not exactly match the results from the north-south test series. Figure 66 compares these two sets of efficiency data. No specific reason is known for the difference in the two curves. A similar comparison of data from the glass reflector tests was much better (Figure 46).

Figures 67 and 68 show the efficiency data from Table 3 (east-west tests) in graphical form.

FIGURE 62 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 23.8 °C INPUT

FIGURE 63 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 298.5 °C INPUT

FIGURE 64 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 145.4 °C INPUT

FIGURE 65 ACUREX PARABOLIC TROUGH EFFICIENCY EVALUATION AT 100.4 °C INPUT

FIGURE 66

ACUREX DATA COMPARISON - FEK-244 N-S VS FEK-244 E-W

FIGURE 67 ACUREX EFFICIENCY VS OUTPUT TEMPERATURE

FIGURE 68 ACUREX EFFICIENCY VS TEMPERATURE ABOVE AMBIENT

TABLE 3. ACUREX EFFICIENCY TEST DATA FOR
FEK-244 ACRYLIC MIRROR

Test Date	Direct Insolation (W/m ²)	Temp Out (°C)	Receiver Delta T (°C)	Avg Temp Above Amb (°C)	Flow Rate (L/min)	Efficiency (%)
8/20/80	1002.2	31.8	8.2	0.4	26.3	67.3 *
8/21/80	985.8	32.5	8.8	- 0.3	23.9	67.3 *
8/22/80	957.2	35.0	11.2	- 0.6	18.3	67.4 *
8/27/80	970.1	113.4	10.7	78.8	42.1	63.4
8/28/80	965.6	215.2	13.0	178.4	28.4	57.5
9/ 2/80	974.1	309.3	10.8	271.0	28.3	50.2
9/ 3/80	992.6	162.7	17.5	122.5	24.6	62.0
9/17/80	988.4	114.8	14.5	77.5	31.8	63.6

* Data taken with ambient temperature water
All other data taken with Therminol 66

ACUREX RECEIVER THERMAL LOSS TEST RESULTS

Since the receiver assemblies on two of the Acurex collectors tested were identical, and the third differed only by having a spiral steel tape inserted inside the absorber tube, thermal loss test data from all the tests have been combined into a single set.

Thermal losses from the Acurex receiver were measured under two conditions: (1) with the collector rotated so that the mirror shaded the receiver, and (2) with direct insolation on the receiver assembly, but with the collector defocused so that no reflected light from the mirror assembly would strike the receiver.

With the collector defocused and with direct sunlight on the absorber surface, the receiver acts as a non-concentrating collector, absorbing energy both from the direct radiation and from the available diffuse light. This absorbed energy is measurable, but quite small because of the small area of the absorber tube surface. In fact, the difference between the "sun-on-receiver" and "receiver-shaded" data is just the non-concentrated energy absorbed by the receiver. When the two measurements were made at the same temperature, flow rate, incident angle, and insolation, the correlation was quite good. This absorption of non-concentrated light also occurs during in-focus operating conditions, in addition to the absorption of concentrated energy from the mirror assembly.

Flow rate has been found to have an influence on measured thermal loss. This dependence of thermal loss on flow rate does not appear to be caused by changes in heat transfer to the tube walls because of changes in fluid turbulence. Instead, the change in measured thermal loss correlates with the heat-transfer fluid differential pressure drop across the receiver. The pressure drop appears as energy added to the fluid, thus reducing apparent thermal loss. Other than the differential pressure effect, no dependence of thermal loss on fluid flow rate has been found. Heat flow rates during thermal loss tests are relatively small compared to the heat transfer rates

found under high-concentration ratio, in-focus operating conditions. High Reynolds numbers are therefore somewhat less important for loss tests than during efficiency measurements. No correlation was expected between measured thermal loss and wind speed, and none was found.

Table 4 contains the data measured during the loss test series. The data are also plotted in Figure 69.

TABLE 4: ACUREX RECEIVER THERMAL LOSS MEASUREMENTS

Test Date	Receiver Tavg-Tamb (°C)	Direct Insolation (W/m ²)	Receiver Delta T (°C)	Flow Rate (L/min)	Wind Speed (m/sec)	Thermal Loss (W)
9/6/80	116.4	960		20.6	3.0	25.3 *
1/17/79	190.8	0.6	3.9	7.7	3.2	2153 *
2/18/79	127.6	863	1.8	12.3	0.9	690
2/10/79	83.6	999	2.5	5.8	0.2	445
2/12/79	164.0	989	3.2	21.0	0.4	1039
2/12/79	163.7	927	3.4	10.1	2.4	1082
2/15/79	136.2	258	1.6	18.6	1.1	905 *
2/15/79	135.8	626	1.3	18.6	1.5	723
2/15/79	130.4	990	2.4	8.0	1.6	606
2/15/79	90.0	1016	0.9	8.0	1.5	202
2/15/79	87.9	936	1.4	8.0	0.2	318 *
2/19/79	156.3	975	6.4	5.3	2.3	1077
2/28/79	166.3	871	9.4	4.4	0	1301
2/28/79	165.2	834	11.1	4.3	0.2	1518 *
3/ 8/79	251.4	993	5.0	14.9	0.9	2547
3/13/79	205.2	1012	5.4	9.6	0.6	1706
3/13/79	204.9	973	6.3	9.5	0.3	1987 *
10/11/79	68.8	740	1.2	11.1	0.6	394 *
10/12/79	164.9	810	2.5	14.3	2.1	1150
10/12/79	164.2	832	3.0	14.3	1.8	1374 *
10/14/79	122.8	943	0.5	30.7	0.6	485
10/14/79	123.5	964	0.8	30.7	0.9	736 *
10/15/79	207.3	1010	4.0	11.7	0.6	1562
10/15/79	205.3	962	4.8	11.7	0.9	1865 *
10/15/79	205.8	950	4.2	11.7	1.0	1629
10/20/79	77.2	488	1.6	9.7	1.1	466 *
10/26/79	192.3	738	4.2	9.9	0.6	1384
10/26/79	190.5	720	4.9	9.8	0.6	1591 *
11/17/79	284.9	822	3.4	27.1	0.9	3168
11/17/79	284.9	831	3.7	27.0	0.8	3504 *

* Receiver Shaded

Three ordinates have been shown for the measured thermal loss in Figure 69. The right ordinate is the total thermal loss from the receiver, as measured. The left ordinate shows both loss per unit collector aperture area and loss per unit receiver length. Loss per unit receiver length is useful for assessing and comparing similar receiver designs, without regard to the rest of the collector. Thermal loss per unit collector aperture area is useful for comparisons of different, complete collector designs and also can serve as an indicator of good match between collector area and receiver area.

Equations are shown in Figure 69 for each of the two loss curves plotted. These equations were obtained from a least-squares fit to the test data. The loss equations give thermal loss in watts per square meter of mirror aperture area as function of average receiver fluid temperature above ambient air temperature.

FIGURE 69

ACUREX 3001-03 RECEIVER THERMAL LOSS

Figure 70 treats thermal loss in a different way: as a fraction of the total energy gained from the sun. The total energy absorbed by the receiver can be separated into two parts: E_a , the energy absorbed into the heat transfer fluid, and E_L , the energy that is lost again through radiation, conduction and convection. Energy leaving the collector in the fluid is measured during the efficiency test series. As noted previously, the energy loss measured during thermal loss testing is not exactly the true thermal loss under operating conditions, but this is as close as we can get to E_L . Comparing the total energy to the loss:

$$\frac{E_a + E_L}{E_L} \times 100 = \% \text{ thermal loss}$$

To obtain the curves shown in Figure 70, the heat loss E was calculated from the shaded receiver thermal loss curve in Figure 69. The heat gain E_a was calculated from curves of efficiency vs. $\Delta T/I$ (Figures 15 and 35). A solar radiation input of 1000 W/m^2 and an ambient temperature of 25°C was assumed for the calculations. Only the curves for glass mirrors and the COILZAK mirror are shown; the curve for FEK-244 would be between the two curves shown in Figure 70.

As an end result, we find that more than 25% of the energy absorbed by the receiver at operating temperatures near 300°C is lost again through various thermal losses; this amount of thermal loss is not unusual or peculiar to the Acurex collector. The relatively high thermal loss at high temperatures emphasizes the necessity for excellent thermal design of the receiver assembly in order to achieve high operating efficiency. The thermal loss percentage for the glass mirror is somewhat less than for the COILZAK mirror or FEK-244 acrylic film versions because the total energy output is greater for the glass mirrors, while the thermal loss is approximately constant for the same receiver design at a given temperature, regardless of mirror type.

All of the above discussion of thermal loss is based on the thermal loss measurements made during the test series. But neither of the two measured thermal losses truly reflects the actual thermal loss that occurs when the collector is focused and operating at temperature.

Under in-focus operating conditions, the absorber glass temperature is higher than during the out-of-focus thermal loss tests, and the absorber surface temperatures are much higher than the bulk fluid temperature. No surface temperature measurements are made on the Acurex collector, but these measurements have been made on two other similar solar collector modules. During these tests, the absorber surface temperature during an out-of-focus thermal loss test was found to be approximately the same as the temperature of the bulk heat-transfer fluid in the receiver. The surface temperature, when in-focus, was 25 to 60°C higher than the fluid temperature, with the exact

FIGURE 70

ACUREX PERCENT THERMAL LOSS VS TEMPERATURE

temperature difference depending on fluid flow rate and level of direct solar radiation input. Measured surface temperatures were always more than 20°C higher than the fluid at all flow-rates and operating temperatures, even with a Reynolds number of 50,000 at 300°C. Since thermal loss depends mostly on surface temperatures rather than on the fluid temperature, thermal loss must be higher when in-focus than when out-of-focus.

If a solar collector could be operated at a low enough temperature, the thermal losses would be reduced to zero, and the measured efficiency of the collector would then be the optical efficiency. In a practical test setup, the optical efficiency cannot be directly measured in this way, since there is no single operating temperature at which conduction loss, convective loss, and radiation loss are all simultaneously zero. However, a reasonably close approach to optical efficiency is achieved during tests with cold water at high flow rates at near-ambient-air temperatures. Optical efficiency is a constant for a given collector; it depends on the optical properties of the mirrors, receiver cover glass, absorber surface, etc., but not on the operating temperature of the receiver (assuming that the optical properties do not change with temperature).

If there were no thermal loss, the collector would always operate at optical efficiency. The reduced heat gain (and efficiency) that occurs as the operating temperature is increased from that of the cold water efficiency tests is directly caused by thermal loss; we can derive an in-focus thermal loss curve from the decrease in efficiency as the temperature is increased. Figure 71 shows two thermal loss curves: the lower curve is the shaded loss curve shown earlier in Figure 69; the upper curve is the in-focus thermal loss as derived from the delta T/I efficiency curve shown in Figure 68. A solar radiation input of 1000 W/m² and 25°C ambient air temperature were assumed for the calculation.

Note that the in-focus thermal loss curve is nearly parallel to the measured thermal loss curve but displaced towards a higher loss rate, as would be expected from the higher surface temperatures. The actual surface temperatures would be a function of direct solar radiation intensity, so the in-focus thermal loss should change with the input solar radiation, producing a family of loss curves. Measurements on another solar collector have produced just such a set of loss curves in which thermal loss appears to scale linearly between the 1000 W/m² in-focus loss curve and the zero insolation curve (represented by the measured out-of-focus loss curve).

COLLECTOR PERFORMANCE ESTIMATES FOR OTHER OPERATING CONDITIONS

Most of the efficiency measurements at the CMTF are made with a direct solar irradiance near 1000 W/m². Collector performance will not be the same at lower levels of solar radiation. The variation of thermal loss with insolation was discussed in the previous section of this report; that loss

FIGURE 71 ACUREX THERMAL LOSS IN-FOCUS AND OUT-OF-FOCUS

variation will also show up as a change in the collector efficiency as the insolation drops from 1000 W/m^2 . Heat gain from an in-focus collector also varies directly with changes in insolation, so both effects must be considered together to determine the collector performance with a variable solar radiation input.

Because the solar irradiance I appears in a $\Delta T/I$ equation, such as is often used for plots of solar collector test data, there is a great temptation to insert any value of I that is of interest and calculate the resulting efficiency. This procedure is incorrect; in fact, the I in the $\Delta T/I$ equations is not a variable at all but is a constant equal to the solar irradiance existing when the data was measured.

Most people recognize that extrapolating an equation based on limited test data outside the range covered by actual data may produce erroneous results. Therefore, few would feel justified in substituting some high temperature that is outside the range tested, such as 500°C , into the efficiency equations in this report. Changing the solar irradiance I in the $\Delta T/I$ efficiency equations has the same effect as extrapolating the operating temperature outside the test limits and is equally invalid. In the cases where a test has been possible, the error in efficiency becomes increasingly large as I is reduced, reaching a value more than 50% lower than the measured value at a solar irradiance near 600 W/m^2 .

Figure 72 illustrates the problem. The data shown in Figure 72 was not obtained from the Acurex collector, but was measured using a similar solar collector module. A dotted line is shown extending the efficiency curve measured at 1000 W/m^2 ; this is exactly what happens when an arbitrary value of I is substituted into a $\Delta T/I$ equation. Suppose we were interested in the collector's efficiency at a ΔT of 293°C with a solar irradiance of 600 W/m^2 . The resulting $\Delta T/I$ is 0.477; there is a point on all the curves where 0.477 $\Delta T/I$ can be found. In Figure 72, the 0.477 point is marked on the 1000 W/m^2 curve extension with a star; the actual measured data point is marked with a "+" on the 600 W/m^2 curve. The error between the two values is about 25 points in efficiency, with the extrapolated point lower than the true value.

The same magnitude of error would result from the same calculation if either of the other two types of efficiency data curves were used. However, when using a curve of efficiency vs. temperature, there is no illusion that the solar irradiance has been normalized and can be ignored.

But solar collectors spend only a limited time operating at the high levels of solar radiation by the efficiency equations in this report. The problem is to extend these actual test conditions to cover a more useful set of operating limits. Some data was obtained during this test series on the operation of the Acurex collector with a variable solar irradiance. These data

FIGURE 72

ERROR RESULTING FROM EXTRAPOLATION OF $\Delta T/I$

are present in all of the all-day test runs, but it is difficult from these data plots to provide an easy answer to the collector efficiency at any given values of operating temperature and incident solar radiation.

Tests on another similar collector have provided a procedure that appears to provide a useful answer to the problem (see Reference 3). The thermal loss occurring at any given level of solar irradiance can be extracted from Figure 71 by linear scaling between the two curves. Determination of the in-focus thermal loss could be done by graphical scaling directly from the curves, but it is more convenient to calculate the thermal loss from the two thermal loss equations, which are also shown in Figure 71. The in-focus thermal loss at any insolation I can be expressed:

$$L_I = L_o + (L_{1000} - L_o) I/1000$$

where:

$$\begin{aligned} L_I &= \text{thermal loss, in-focus at insolation } I \\ L_{1000} &= \text{thermal loss, in-focus at } 1000 \text{ W/m}^2 \\ L_o &= \text{thermal loss, at zero insolation} \\ I &= \text{insolation at which performance is to be calculated} \end{aligned}$$

For purposes of this calculation, the efficiency measured at ambient air temperature with cool water is assumed to be equal to the optical efficiency. This is not true, because the receiver surface temperatures are higher than the fluid temperatures, and the thermal losses are not zero. The resulting error is estimated to be small (5% or less). The heat gain available at the desired level of solar irradiance, when operating at the approximate optical efficiency, is:

$$Q_I = \eta_o I$$

If the thermal loss L_I is subtracted from the heat gain Q_I , the result will be a net heat gain for that set of operating conditions. The net heat gain, divided by the input solar irradiance, is the desired efficiency value.

$$\eta_I = \frac{Q_I - L_I}{I}$$

where:

$$\begin{aligned} \eta_I &= \text{collector efficiency at insolation } I \\ Q_I &= \text{heat gain at optical efficiency, insolation } I \\ L_I &= \text{thermal loss, in-focus at insolation } I \\ I &= \text{insolation at which performance is desired} \end{aligned}$$

The procedure outlined above assumes that the in-focus thermal loss curve was obtained from efficiency tests made with a solar irradiance near 1000 W/m^2 , as were the tests covered by this report. The procedure should also work for data obtained when less insolation is available, such as 700 or

800 W/m². The measured efficiency could then be scaled up to find the efficiency at 1000 W/m², as well as scaling down to lower values. Scaling efficiency up to 1000 W/m² from data taken at a low solar irradiance has not been checked out with actual test data.

Figures 73-75 were obtained by using the calculational procedure outlined above. No actual test data was obtained on the Acurex collectors to support these curves, except that shown in the all-day test plots. However, test data was obtained on another similar collector (see Reference 3); the procedure used for Figures 73-75 was worked out from that test data. In the case of the other collector, the calculational procedure used here reproduced the actual test data to within about one percentage point for solar radiation levels from 500-1000 W/m².

Actual efficiency points from Tables 1, 2 and 3, measured during the Acurex collector test series, appear to fall at the right places on Figures 73-75, but most of the measurements were taken with a solar irradiance near 1000 W/m², so a crosscheck on the accuracy of the curves is not available.

ESTIMATES OF ANNUAL THERMAL PERFORMANCE

Estimates of the annual thermal performance of the Acurex collectors have been made (see Reference 7-9). The annual performance estimates utilized delta T/I efficiency curves derived from the test series discussed in this report. However, the efficiency equations used were based on early, preliminary data analysis, and thus are not exactly identical to those shown in the present report. The differences in the equations used and those in this report are not large enough to significantly change the results of the annual performance estimates.

The annual performance estimates use Typical Meteorological Year (TMY) data for five cities: Fresno, Albuquerque, Fort Worth, Charleston, and Boston. The solar irradiance available in those five cities varies significantly between cities and throughout the year. The Acurex Delta T/I efficiency equations are actually correct only for an insolation very close to 1000 W/m², where the test data was actually obtained. No efficiency corrections for low levels of solar irradiance (see Figures 73-75) were applied to the annual performance estimates because this data was not available when the estimates were being prepared. If corrections for low insolation levels were applied to the annual performance estimates found in References 7-9, annual thermal output would be somewhat larger than shown in the reports. In Reference 3, a new set of annual thermal performance calculations was made using the new data on collector performance at low levels of solar irradiance. For cities with high levels of irradiance throughout the year, such as Albuquerque and Phoenix, the original estimate (using only a Delta-T/I equation) was 7-10% low. For cities with low levels of solar irradiance, such as Boston or Charleston, the original estimate (using only a Delta-T/I equation) was 25-30% low. These relative values should also apply to the estimates for the Acurex collectors.

FIGURE 73

ACUREX (COILZAK) EFFICIENCY VS TEMPERATURE AND INSOLATION

FIGURE 74

ACUREX (GLASS) EFFICIENCY VS TEMPERATURE AND INSOLATION

FIGURE 75

ACUREX (FEK-244) EFFICIENCY VS TEMPERATURE AND INSOLATION

DETERMINATION OF INCIDENT ANGLE MODIFIER

For a fixed collector axis, the peak efficiency curves shown in this report apply only when the solar radiation angle of incidence on the collector is zero. For an East-West axis, zero incident angle occurs at solar noon; for a North-South collector axis, zero incident angle occurs twice each day--morning and afternoon. During part of the year, zero incident angle for a North-South collector may only occur before sunrise and after sunset (see Figures 36-38). Collector efficiency decreased with increasing incident angle, as is shown in most of the all-day efficiency test plots in this report. To determine the total energy that can be obtained from the collector over a period of time, the collector's performance must be defined for incident angles other than zero. The all-day efficiency data plots, such as Figure 66, provide some of this information, but such plots are not available for every possible operating temperature. One way of estimating the collector's performance at any given time of day is to modify the peak noon efficiency at the desired operating temperature by an incident angle modifier, K_0 .

When possible, the incident angle modifier should be obtained from a test run at near-ambient-air temperatures, so that thermal losses will not confuse the results. Unfortunately, no ambient temperature tests were made with either the Coilzak or the glass reflector versions of the Acurex collector. Incident angle data for the glass reflectors was taken from two test runs at elevated temperature: 20 October 1979, at 100°C (Figure 29), and 25 October 1979, at 160°C (Figure 31). Actual incident angles occurring during the tests are shown along the top abscissa of each data plot.

Corrections for thermal loss were required for the data from both test days. The shaded thermal loss equation shown in Figure 69 was used. In addition, because of the short length of the test module, corrections were made for end loss, as outlined in the Performance Definition section of this report. A ten-point average heat-gain value was obtained from the measured data at each 5 degree change in incident angle. For the 20 October test at 100°C, only the morning data was available. For the 25 October test at 160°C, morning and afternoon heat-gain values were averaged at each 5 degree increment of incident angle. Finally, all the incident angle curves shown were obtained from second-order polynomial, least-squares curve fits to the test data.

Figure 76 shows the relative performance of the glass reflectors as a function of incident angle. If the optical characteristics of the reflectors, absorber glass, absorber surfaces, etc. were the same for all angles of incidence, the performance curves would follow the cosine curve, which is also shown in Figure 76. The 100°C and 160°C performance curves are not exactly the same, probably because of small errors in the thermal loss corrections, and also from collector performance changes with level of solar irradiance (see previous section).

FIGURE 76

ACUREX (GLASS) COLLECTOR PERFORMANCE VS INCIDENT ANGLE

Figure 77 shows the incident angle test data with the cosine factor removed; the ordinate in the figure is the incident angle modifier. The difference between the two curves appears to be larger in Figure 77 because of the expanded scale of the ordinate.

Data from the August 21, 1980, cold water test shown in Figure 62 were used to determine the incident angle modifier for the FEK-244 acrylic film version of the Acurex collector. Actual incident angles occurring during the test are shown on the top abscissa of Figure 62. Measured data values were again corrected for end loss, but thermal loss corrections were not required. Ten-point average heat/gain values were again used at each five degree increment of incident angle. Morning and afternoon values were then averaged for the final, plotted value. Thus, each point plotted in the figures actually is the average of twenty measured data points, centered in time on the incident angle. The curve shown in Figure 78 was obtained from a second-order polynomial, least-squares fit to the test data. Figure 79 shows the incident angle modifier, which is the same test data with the cosine factor removed.

MISCELLANEOUS TEST RESULTS

Figure 80 was obtained from measurements of fluid pressure drop across the Acurex receiver for a wide range of flow rates and at several fluid temperatures. The left ordinate in Figure 80 is the total pressure drop for the receiver; the right ordinate shows pressure drop per meter of receiver length. As expected, pressure drop was less for the receiver with no turbulence generating tape inside the absorber tube. Inside diameter was 2.75 cm for both receivers. The data shown in Figure 80 is nearly the same as data obtained from other receivers of the same diameter. Note that the flex hoses were not included in the pressure measurements.

Several other tests were made during the evaluation of the Acurex collectors. See References 4 and 5 for a report on the forces required to overturn or extract a poured concrete foundation pillar. As mentioned earlier, these forces were higher than predicted, which may make possible smaller and more economical foundations.

Samples of the glass/sheetmetal sandwich were also given a simulated hail damage test. The tests simulated hailstones of 12.7 mm, 19.1 mm, and 25.4 mm diameters in both still air and a 50 km/hr wind. The only damage occurred at the edge of an unsupported reflector assembly, using 25.4 mm (1 inch) simulated hailstones (polyethylene) impacting at about 25 m/sec (82 ft/sec).

FIGURE 77

ACUREX (GLASS) COLLECTOR INCIDENT ANGLE MODIFIER

FIGURE 78

ACUREX (FEK-244) COLLECTOR PERFORMANCE VS INCIDENT ANGLE

FIGURE 79

ACUREX (GLASS) COLLECTOR INCIDENT ANGLE MODIFIER

FIGURE 80

ACUREX RECEIVER DIFFERENTIAL PRESSURE

On March 13, a 45.7 cm-long lever arm was bolted to a drive coupling at the north end of the Acurex collector string, and a torque was applied to simulate an asymmetric wind loading. Initial load applied was 3660 Nm (2700 ft-lb). The collector drive motor was then energized and the load increased to 5227 Nm (3855 ft-lb) before the clutch in the drive unit released. After the initial clutch slip, subsequent loads of 3518 Nm (2595 ft-lb) released the clutch.

Neither the glass mirrors nor the drive unit were damaged by the torque test, which simulated an asymmetric loading of a 12-module collector string in a wind of about 50 km/hr (31 mph). The collector string should be capable of normal tracking at 50 km/hr, and should survive winds up to 145 km/hr (90 mph).

An evaluation of the collector drive system was also conducted to determine the power required to operate the collector. These tests found that the sun-tracking electronics consumed about 5.5 watts constant throughout the day. The drive motor alone consumed about 230 watts when running steadily. The power consumption figures given are the maximums measured; the power measurements varied with the available power-line voltage each day, down to about 7% less than that quoted above. Drive speed was about 25.7 degrees change in collector elevation per minute of motor operation. Run time from the stow position (focal line 70° below horizontal) to horizontal was about 2.72 minutes. Drive power required was about 0.149 W-hr per degree of rotation. These figures result in a collector drive power requirement of about 130 W-hr for a ten-hour day with a north-south axis (stow to stow). For a N-S installation, drivepower consumption should be approximately the same on each day of the year.

The drive power consumption in an E-W installation would vary on each day of the year as the solar elevation changed. About 95 W-hr power consumption was measured on October 25, 1979, in 9 hours 40 minutes with an east-west axis collector.

SUMMARY OF RESULTS AND CONCLUSIONS

Peak efficiencies measured with glass mirrors were higher than those measured with the FEK-244 acrylic film reflectors, which were in turn higher than found with the Coilzak polished aluminum reflectors. Differences in measured efficiencies with the three reflector materials were not exactly the same as the differences in reflectivity, because the focus accuracy of the three reflectors also varied slightly.

Thermal loss was the same for all three collectors, since all used identical receiver assemblies. Thermal loss was shown earlier in Figure 69.

Figure 81 is a summary of the peak efficiency test data for the three reflector materials, plotted as a function of output temperature. Figure 82 is the same test data, plotted as a function of $\Delta T/I$. Figure 83 shows the test data as a function of average receiver fluid temperature above ambient air temperature.

Note that Figures 81 through 83 are all subject to misinterpretation; all are valid only at the solar irradiance existing when the data was obtained. Figure 82 ($\Delta T/I$) is the easiest to misuse because it is not obvious that I in the equation is only another constant. A more correct presentation of the data would be an equation giving efficiency as a function of two independent variables: temperature and solar irradiance. The statistical analysis of the test data to derive such an equation had not yet been done when Figures 73, 74, and 75 were made. A multiple regression analysis of the calculated data used to generate Figures 73 through 75 was completed after this report was ready for printing. The multiple regression analysis (see Reference 3) provided an equation of collector performance that correctly accounts for collector operation at temperatures from 50°C to 300°C, and with solar irradiance from zero to 1050 W/m.

Figures 84, 85, and 86 are plots of the performance equations for the three reflector types used during the Acurex test series. The equation used to draw the plot is given in each figure. When used with the appropriate values of temperature and irradiance, the equations shown in Figures 84 through 86 can reproduce any of the other performance curves in this report. The three equations shown in Figures 84 through 86 should be used to determine peak collector efficiency under all operational conditions.

An unusually large number of tests were made on the Acurex collectors to define the performance in different orientations, and with different reflector surfaces. All the collectors performed much as expected, and the data obtained from the different collector variations correlated well. As a result of the extensive test series, it is now possible to confidently predict the thermal performance of a concentrating solar collector with many fewer tests.

FIGURE 81

ACUREX PERFORMANCE WITH GLASS, FEK ACRYLIC AND COILZAK MIRRORS

FIGURE 82

ACUREX PERFORMANCE WITH GLASS, FEK ACRYLIC AND COILZAK MIRRORS

FIGURE 83

ACUREX PERFORMANCE WITH GLASS, FEK ACRYLIC AND COILZAK MIRRORS

FIGURE 84

ACUREX (GLASS) EFFICIENCY VS TEMPERATURE AND IRRADIANCE

FIGURE 85 ACUREX (FEK-244) EFFICIENCY VS TEMPERATURE AND IRRADIANCE

FIGURE 86

ACUREX (COILZAK) EFFICIENCY VS TEMPERATURE AND IRRADIANCE

APPENDIX 1

COLLECTOR MODULE INFORMATION SHEET

Manufacturer: Acurex Solar Corporation
485 Clyde Avenue
Mountain View, California 94042

Operating Temperature: 100°-320°C

Module Size: 3.04 m x 1.83 m (120" x 72")

Module Construction: Steel Tube Backbone 7.8 m Dia. (8")
Sheet Steel Ribs
Sheet Steel Face Sheets

Rim Angle: 90 degrees

Reflectors: Glaverbel Glass Mirrors
Second-Surface Silvered
Measured Reflectance: 0.94
Aperture: 5.50 m² (59.21 ft²)

3M FEK-244 Acrylic Film Mirrors
Second-Surface Aluminized
Measured Reflectance: 0.86
Aperture: 5.52 m² (59.38 ft²)

COILZAK Chemically Polished Aluminum
Front Surface Reflector
Measured Reflectance: 0.70
Aperture: 5.53 m² (59.58 ft²)

Focal Length: 45.72 cm (18")

Concentration Ratio: 37.5:1 (Aperture area/Illum. Absorber Area)

Receiver: Absorber Diameter: 3.18 cm (1.25 in)
Black Chrome Plated Steel Tubing
Measured Absorptance: 0.94
Measured Emittance: 0.20 (300°C)
5.08 cm Dia Pyrex Glass Cover

Sun Tracking: Single-Axis Elevation Tracking
Shadowband Sun Sensor
Separate Field-Light-Level Control

Tracking Drive System: 115vac Powered
Stepping Motor Drive
Integral Motor/Gear Box/Clutch

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