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Performance Testing of the TOLTEC TI-410 Concentrating Solar Collector

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PERFORMANCE TESTING OF THE TOLTEC TI-410 CONCENTRATING SOLAR COLLECTOR

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ABSTRACT

This report summarizes results of tests conducted by the Collector Module Test Facility on a Toltec TI-410 Solar Collector. Collector efficiency, thermal loss, and receiver differential pressure were measured at fluid temperatures from 20°C to 200°C. The collector was evaluated with a glass mirror and with an acrylic/polyester film reflector surface. Four different receiver designs were tested.

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PERFORMANCE TESTING OF THE TOLTEC TI-410 SOLAR COLLECTOR

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.

This report contains test results obtained during performance testing of a Toltec TI-410 concentrating solar collector built by Toltec Industries, Inc., Clear Lake, Iowa 50428.

TEST OBJECTIVE

Objective for this test series was definition of performance characteristics for the Toltec TI-410 solar collector, using two types of parabolic trough mirrors and four different receiver designs, over a temperature range from 20^{o}C to 200^{o}C.

COLLECTOR DESCRIPTION

Figure 1 shows the Toltec collector during the CMTF tests. The collector tested was an assembly of four line-focusing, parabolic trough concentrators with the concentrator axis oriented north-south. The collector was delivered on a trailer, already assembled, and was tested in-place on the trailer.

The individual parabolic troughs were 101.6cm wide and 294.6cm long. Initial testing was accomplished with a reflector made up from 1.02mm thick, second-surface silvered, segmented glass mirrors impregnated into the basic glass fiber structure. The glass mirrors were made by General Glass International Corp., New Rochelle, New York 10801. See Figure 2 for a cross-section of the reflector construction. The glass fiber reflector assembly was supported on a steel tube structure. Each of the glass mirror reflectors weighed 45kg (100 lbs).

Tests were also made with a second reflector design using a new film reflector material manufactured by the 3M Company's Energy Control Products Division, St. Paul, Minnesota 55101. The YS-91A film is a first-surface, aluminized reflective coating on a 3M polyester film base. A front-surface, acrylic overcoat protects the aluminized layer. The 0.064mm thick, reflective film was applied directly to the inner surface of the basic glass fiber reflector structure. Each film reflector weighed 20.4kg (45 lbs).

A third reflector assembly using thermally sagged glass mirrors was also scheduled for test, but quality glass mirrors could not be obtained in time to be used in this test series.

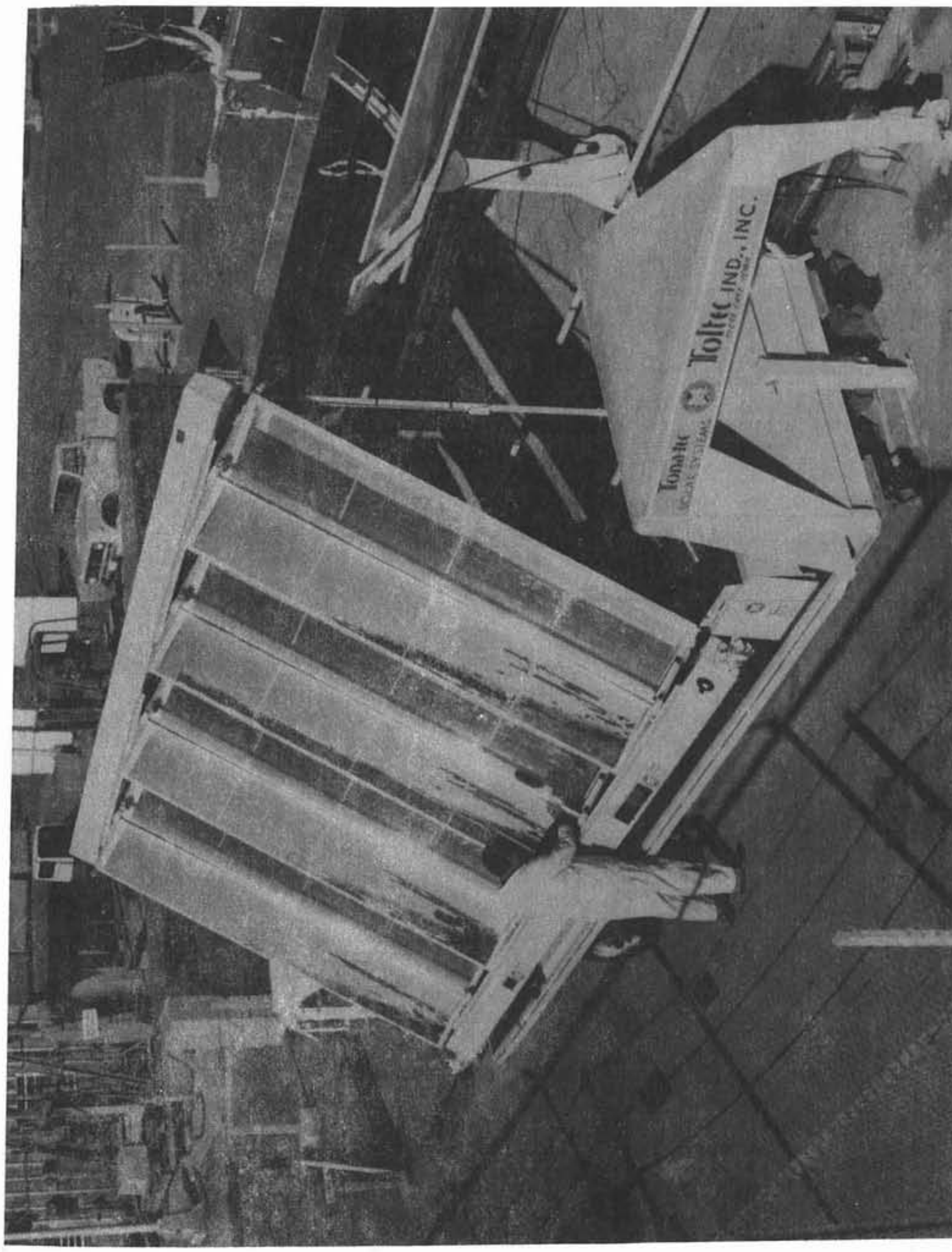

FIGURE 1. TOLTEC COLLECTOR AT THE CMTF

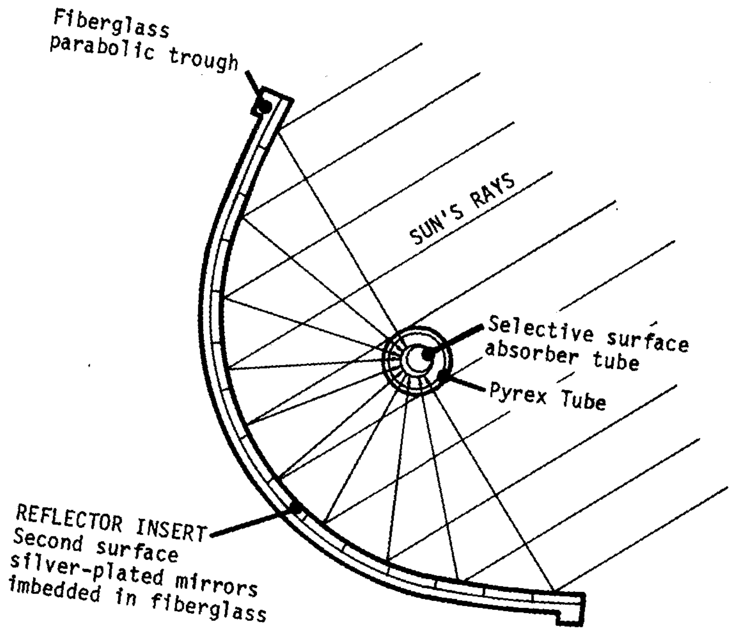

FIGURE 2. TOLTEC SEGMENTED GLASS REFLECTOR

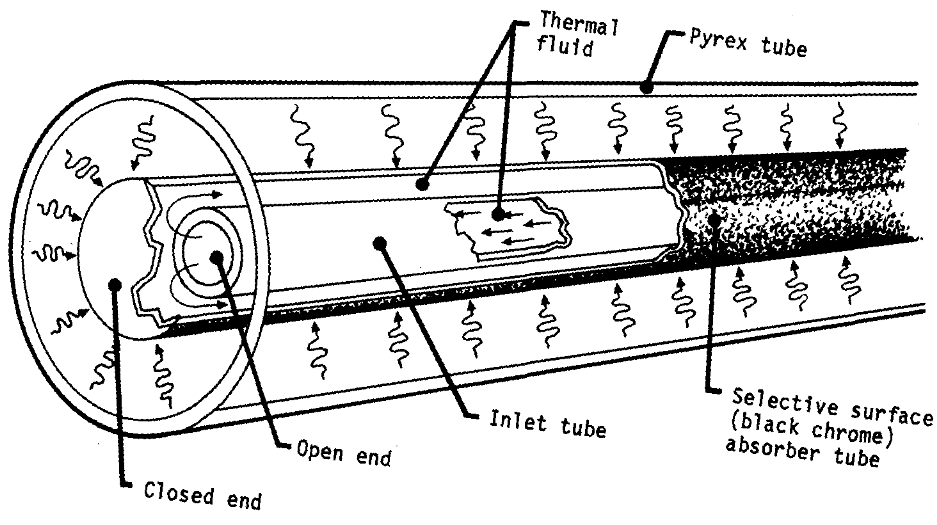

FIGURE 3. TOLTEC COUNTERFLOW RECEIVER

A Toltec alta-azimuth collector mounting rack was used for solar tracking. Solar elevation tracking used a shadow-band sun sensor with a 12vdc gearmotor driving a jack screw assembly to change the elevation of the north end of the collector array. Solar azimuth tracking used a separate shadow-band sun sensor, controlling a second 12vdc gearmotor driving a worm and spur gear assembly at the lower end of the collector array. The solar tracking drive motors and associated electronics package were powered by a single 12v battery, recharged as necessary from 115vac commercial power.

The solar tracking electronics were designed and built by Toltec Industries. In addition to the two shadow-band sun sensors used for tracking, a third light sensor was incorporated into the electronics package to sense overall ambient light levels. This ambient light sensor and associated logic controlled the morning startup from stow, returned the collector troughs to the stow position at night, and could be adjusted to stop collector tracking when the light levels fell below a preset level. The ambient light level control also helps prevent the shadow-band sensors from "chasing" cloud edges.

The first receiver tested was a counterflow design; a sketch of the receiver is shown in Figure 3. Heat transfer fluid flow was down the inner tube from the top of the collector assembly, returning to the top of the collector through the annulus between the inner and outer tubes. Outside diameter of the Corning borosilica Pyrex glass receiver envelope was 4.7cm. Outside diameter of the absorber surface was 2.86cm; the inner tube was 1.59cm outside diameter. Both tubes were made of copper; the absorber surface was solar-spectrum-selective black chrome plate applied by Olympic Solar Corp. over a Watts nickel plating.

A second receiver assembly tested was identical in external dimensions to the counterflow receiver discussed above but had a different internal construction. The second receiver was direct flow-thru with smooth inner walls and no internal plug or other turbulence generating devices. Absorber tube material was copper with black chrome surface plating.

Two other receiver designs were also evaluated. The absorber tubes in both were copper forgings with 16 thin copper fins, 0.32cm high, formed into a spiral pattern on the inner walls of the tube. These fins were intended to generate turbulence in the fluid flow and improve transfer of heat from the absorber tube walls into the heat transfer fluid. These two receiver designs differed only in outside diameter; one had an absorber 2.54cm in diameter covered by a Pyrex glass envelope 4.7cm in diameter; the other absorber was 3.49cm outside diameter covered by a 5.94cm diameter Pyrex glass envelope. The absorber surface had the same black chrome plating used as the other receiver designs.

A list of Toltec collector parameters is contained in the Collector Module Information sheet, Appendix 1.

TEST FACILITY DESCRIPTION

The CMTF's Fluid Loop 1 was designed to supply Therminol 66 as a heat transfer fluid at temperatures from about 100-300^{o}C. The properties of Therminol 66 were taken from Reference 2. Design flow rates from Fluid Loop 2 range from 4 L/min to about 40 L/min.

A typical test day began by heating the heat transfer fluid with the fluid loop's electric heaters. When an appropriate fluid flow was established, the collector was placed in-focus as soon as permitted by collector tracking limits. Two additional parabolic trough collectors were often used in addition to Toltec to speed heating of the fluid system to the desired operating temperature. During a test, both the collector input temperature and the fluid flow rate were maintained constant, while the output temperature was allowed to vary according to the test conditions.

Fluid flow rate was measured with a matched pair of turbine flowmeters. 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 printed 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 4 and 5 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.

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. Sixty 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 4 and 5 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.

HEAT GAIN/LOSS TEST DESCRIPTION

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. Heat gain (or loss) was then calculated from:

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

in which

Q = heat gain, kJ/hr

$\dot{m}$ = mass flow rate of fluid, kg/hr

C_p = specific heat of fluid, kJ/kg ^{o}C

ΔT = in/out temperature differential, ^{o}C

**** TOLTEC SEGMENTED GLASS TROUGH EFFICIENCY TEST ****

TEST DATE: 26 JANUARY 1981 TIME: 14:34:26 (MST)
14:15:36 (SOLAR)

11	(DEG C)	AMBIENT TEMPERATURE	(DEG F)	51.8
320	(DEGREES)	WIND DIRECTION		
2.66	(M/SEC)	WIND SPEED	(MPH)	6

TEMP IN	TEMP OUT	SOLAR WATTS/M^2	DELTA TEMP	FLOW LITERS/MIN	EFFICIENCY PERCENT
197.53	213.48	973.6	15.99	11.22	51
197.52	213.52	974.2	16.03	11.2	51
197.51	213.5	972	16.01	11.2	51
197.54	213.46	972.1	16.01	11.19	51
197.53	213.48	971.5	15.96	11.17	50.7
197.54	213.5	970.8	15.98	11.13	50.7
197.55	213.46	972	15.94	11.21	50.8
197.56	213.44	972.6	15.96	11.25	51.1
197.58	213.45	971.2	15.92	11.22	50.9
197.58	213.48	970.5	15.94	11.23	51
10 POINT AVERAGES					
197.544	213.477	972.05	15.974	11.202	50.92

50.78	AVG EFFICIENCY USING SUB. DELTA T
49.68	AVG EFFICIENCY, EAST TROUGH ONLY
53.68	AVG EFFICIENCY, WEST TROUGH ONLY
49.8678	AVG EFFICIENCY, CENTER TROUGHS
21323.7	AVG HEAT GAIN (KJ/HR)
494.82	AVG HEAT GAIN (W/M^2)
194.272	AVG RECVR TEMP MINUS AMB TEMP
.199858	(AVG TEMP-AMB T)/I
2.103	AVG WIND SPEED (M/SEC)
7774.6	REYNOLDS NUMBER

END OF DATA BLOCK 77

FIGURE 4. SAMPLE DATA PRINTOUT FROM EFFICIENCY TEST

**** TOLTEC SEGMENTED GLASS TROUGH THERMAL LOSS TEST ****

TEST DATE: 25 JANUARY 1981 TIME: 15: 8: 1 (MST)
14:49:24 (SOLAR)

11.44	(DEG C)	AMBIENT TEMPERATURE	(DEG F)	52.59
278	(DEGREES)	WIND DIRECTION		
2.23	(M/SEC)	WIND SPEED	(MPH)	5

TEMP IN	TEMP OUT	SOLAR WATTS/M^2	DELTA TEMP	FLOW LITERS/MIN	GAIN/LOSS WATTS/M^2
197.73	195.98	882.3	-1.73	25.97	-122.575
197.72	195.96	861.5	-1.75	26.02	-124.23
197.74	195.94	855.6	-1.73	26.07	-123.047
197.74	195.92	863.8	-1.76	25.97	-124.697
197.73	195.9	875.1	-1.78	25.98	-126.161
197.72	195.91	880	-1.78	26.02	-126.356
197.73	195.94	887.1	-1.76	25.97	-124.699
197.72	195.96	894.8	-1.75	25.99	-124.089
197.7	195.95	896.7	-1.71	25.99	-121.25
197.69	195.93	895	-1.73	26.04	-122.903
10 POINT AVERAGES					
197.722	195.939	879.19	-1.748	26.002	-124.001

341.35	(W/M^2)	AVERAGE TOTAL HORIZ INSOLATION
1.482	(M/SEC)	AVERAGE WIND SPEED
-125.774	(W/M^2)	AVERAGE LOSS (SUB DELTA T)
-5343.01	(KJ/HR)	AVG LOSSES (WATTS)= -1484.29
-123.691	(W/M)	AVG LOSS PER M OF RECVR L.
184.181		AVG RECVR TEMP MINUS AMB TEMP
16774.3		AVG REYNOLDS NUMBER

END OF DATA BLOCK 72

FIGURE 5. SAMPLE DATA PRINTOUT FROM THERMAL LOSS TEST

Receiver thermal loss tests were conducted by defocusing the collector as far as possible toward the stow position so that no reflected light from the mirror would strike the receiver but still positioned so that the receiver remained exposed to direct sunlight. Rotational limits of the test collector prevented obtaining "shaded loss" measured on some other collectors.

A successful loss measurement is defined as at least one ten-point data 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 measurements 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 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/m^2. 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/m^2. Tests are also sometimes scheduled at lower values of solar radiation in order to define the collector's response to insolation that is less than ideal.

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, m^2

I = direct solar radiation, W/m^2

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 temperature at the collector inlet may not be stable. The fluid must 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. With one collector tested, a constant temperature increase of 0.7^{O}C per minute produced an efficiency measurement that had a very small data scatter and had a nearly constant efficiency value for more than an hour. This measured efficiency value turned out to be five percentage points lower than the efficiency measured later with more stable temperatures.

In another case with a collector system of greater thermal mass, a similar slow drift in temperature 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^{O}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.

SEGMENTED-GLASS REFLECTOR TESTS

TEST RESULTS WITH A COUNTERFLOW RECEIVER

The Toltec collector was delivered on 5 January 1981 and was positioned and adjusted to operational condition by Toltec Industries' personnel. Plumbing to the CMTF Fluid Loop 1 (Therminol 66), installation of instrumentation, and data collection program checkout were completed on 6 January. Testing began on 7 January but was interrupted by clouds before any usable efficiency data was obtained.

Figure 6 shows the efficiency and solar radiation plot from a test run on 14 January using the segmented-glass mirror assemblies and the counterflow receiver. Two-axis sun tracking was being used. Between 9:20 and 12:07, efficiency measurements were made at five flow rates, all at about 104°C input fluid temperatures. The maximum flow rate attempted was 17 L/min, which also resulted in maximum allowable input fluid pressure of 689.5kPa (100 psi). Calculated Reynolds numbers during these tests ranged from 1000 at the minimum flow rate of 4.3 L/min to 3200 at the maximum 17 L/min flow rate. These Reynolds numbers indicate that the fluid in the receiver was probably not generating the turbulent flow conditions required for efficient heat transfer from the heated absorber into the heat transfer fluid. The measured efficiencies support this view, with efficiency dropping from 58.3% at the high flow rate to 54.7% at the lowest flow rate.

With the aid of another collector to help heat the fluid system, the Therminol 66 heat transfer fluid temperatures were increased to 156°C. At 13:10, measured efficiency at 156°C output was 55.8%. Reynolds number was 5500 at 17.5 L/min flow, 144.5°C input temperature.

Temperatures were again increased to above 200°C. Three efficiency measurements were made at flow rates from 7.6 L/min to 23.5 L/min, the maximum flow obtainable within the input pressure limit. A Reynolds number of nearly 12000 was obtained at the highest flow rate; efficiency was 52.5%. Again, the efficiency dropped as the flow was reduced, to 48.2% at 7.6 L/min, with a Reynolds number of only 3900.

On the following day, 15 January, the Therminol 66 plumbing was removed, the collector flushed, and hoses were added to supply ambient temperature water from the Albuquerque city water mains. Figure 7 shows the efficiency and solar radiation plot from the 15 January test. Another water user somewhere in the local area was switching his flow on-and-off at about 30-second intervals, causing large pressure and flow fluctuations. At 12:05, a water supply pressure regulator was added, after which the flow rate became acceptably stable. Measured efficiency at 25°C output temperature was 65.5%; average receiver temperature was 11 degrees above ambient air temperature. This 65.5% efficiency should be very close to the optical efficiency of the collector with the counterflow receiver.

The viscosity of cold water is not very different from that of hot Therminol; therefore, the Reynolds numbers obtained during the cold water tests were similar. When the flow rate was reduced from 15 L/min (Re=9000) to 8 L/min (Re=5300), the measured efficiency dropped slightly -- from 65.5% to 65.0%. The counterflow receiver design seemed to be unusually sensitive to flow rate. Unfortunately, we could not get flow rates higher than about 23 L/min to find out if this sensitivity would disappear at higher flow rates.

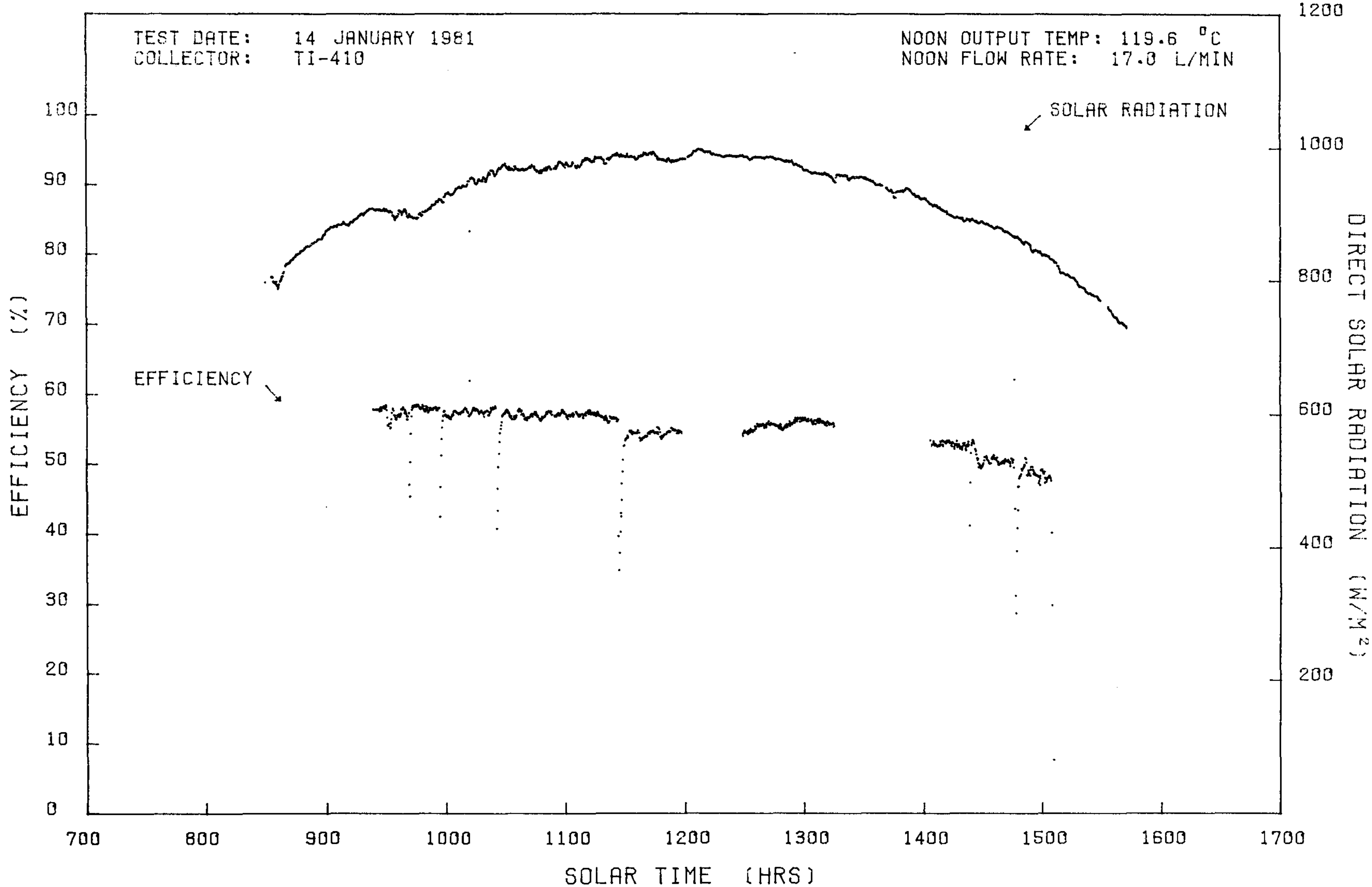

FIGURE 6 TOLTEC SEGMENTED GLASS TROUGH EFFICIENCY EVALUATION AT 105.3 °C INPUT

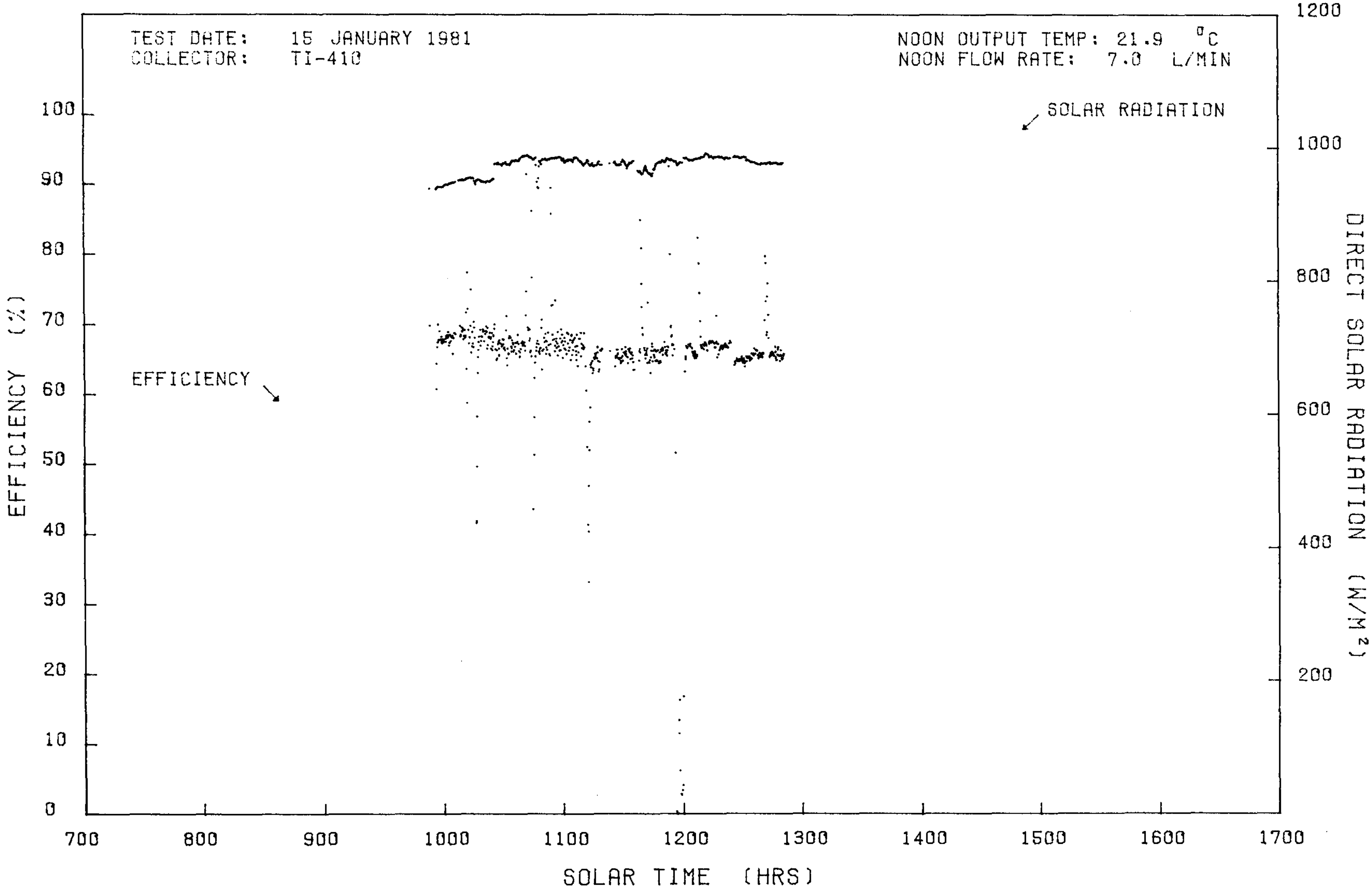

FIGURE [illegible] TOLTEC SEGMENTED GLASS TROUGH EFFICIENCY EVALUATION AT 18.4 °C INPUT

During the tests described above, some reflected light from the mirror assembly was observed to be missing the receiver. Most of the stray light seemed to be coming from the outer fringes of the segmented glass mirror. In order to identify the source of the stray light, and to find out the effect on collector efficiency, the outer three mirror segments on each side of the reflector assemblies were masked with 5cm wide strips of paper. The mask reduced the aperture width from 101.6cm to 96.5cm; the aperture was reduced from $11.97m^2$ to $11.38m^2$. Using cold water as the heat transfer fluid, the measured efficiency of the masked mirrors was 66.9%. When the mask was quickly ripped off, the measured efficiency dropped to 65%, indicating an optical efficiency of only about 29% for the area under the mask.

The masked mirror tests concluded the testing with the counterflow receiver design. Efficiency test data is shown in Table 1. The data is also shown in Figures 8 and 9.

Table 1. Toltec Efficiency Test Data
Segmented-Glass Mirror, Counterflow Receiver

Test Date	Direct Insolation (W/m^2)	Temp Out (^oC)	Receiver Delta T (^oC)	Flow Rate (L/min)	Delta T / I ($^oCm^2/W$)	Efficiency (%)
1/13/81	893.7	125.8	13.15	15.4	0.1183	57.5
1/14/81	894.3	116.1	12.52	16.6	0.1085	58.3
1/14/81	949.3	122.9	18.85	11.5	0.1055	57.6
1/14/81	989.4	131.8	27.37	8.0	0.1087	56.5
1/14/81	981.9	153.3	47.43	4.3	0.1200	54.7
1/14/81	997.1	122.9	13.47	17.0	0.1062	58.3
1/14/81	959.9	156.2	11.64	17.5	0.1433	55.8
1/14/81	893.3	203.2	7.27	23.5	0.2094	52.5
1/14/81	875.4	204.9	10.36	15.5	0.2116	50.4
1/14/81	838.0	212.2	19.20	7.6	0.2241	48.3
1/15/81	984.8	30.9	12.69	8.5	0.0116	66.9*+
1/15/81	985.3	30.9	12.76	8.6	0.0118	65.0*
1/15/81	976.3	25.3	7.17	15.3	0.0113	65.5*

* Data taken with cold water

+ Data taken with mask on mirror

TEST RESULTS WITH AN OPEN-TUBE RECEIVER

On 16 January the counterflow receiver was replaced with a 2.86cm outside diameter, straight-thru flow, open-tube receiver. The absorber tube had smooth internal walls with no plug or other turbulence generating devices. Outside diameter of the absorber and the glass envelope was identical to the counterflow receiver. Testing was again delayed by clouds, resuming on 19 January.

Figure 10 was made during a test run on 22 January. Efficiency measurements were made at three temperatures: 104^oC from 9:30 to 10:30, 150^oC from 11:10 until 12:10, and 200^oC from 14:40 until 15:30. The blank area in the efficiency curve from 12:30 until 14:00 resulted from defocusing the collector for a thermal loss test.

A really good focus was never achieved with the open-tube receiver. The collector troughs had accidentally been run past the west limit switches into mechanical stops, which caused the four troughs to move relative to each other. Several attempts were made during the 22 January test to get all the troughs back into proper alignment. From the patterns of light observed to be missing the

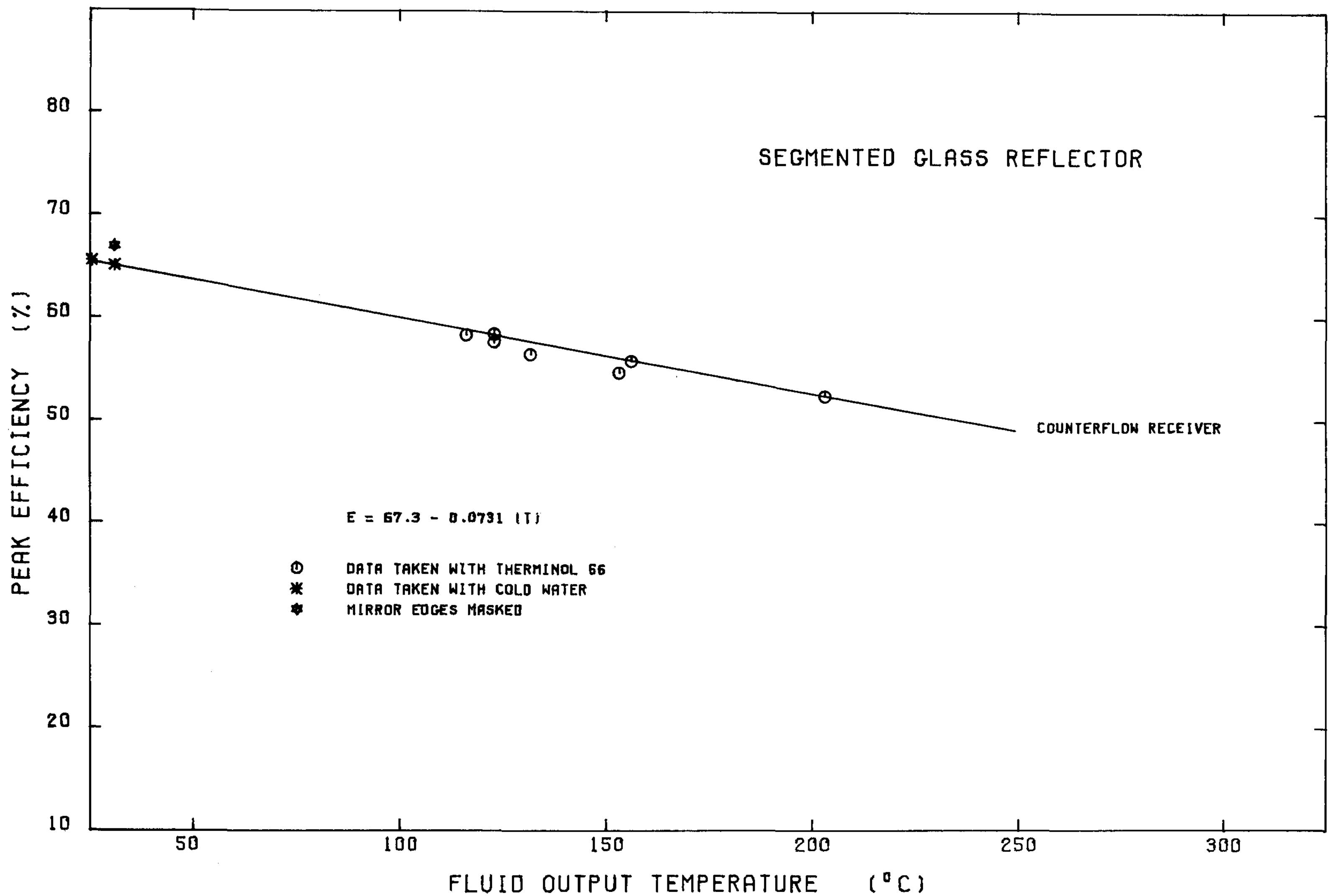

FIGURE 8. TOLTEC TI-410 EFFICIENCY VS OUTPUT TEMPERATURE

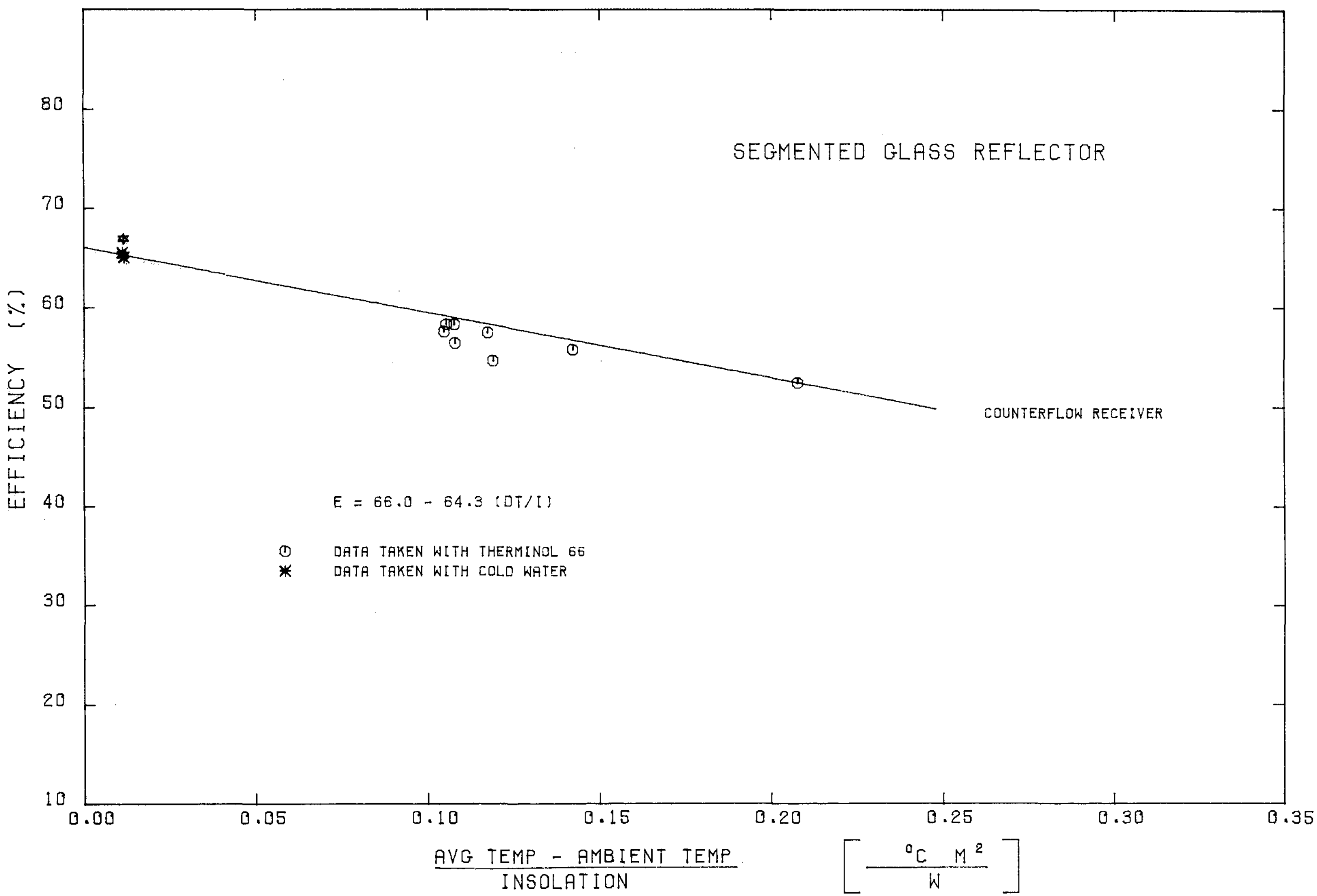

FIGURE 9 TOLTEC TI-410 EFFICIENCY VS DELTA T / I

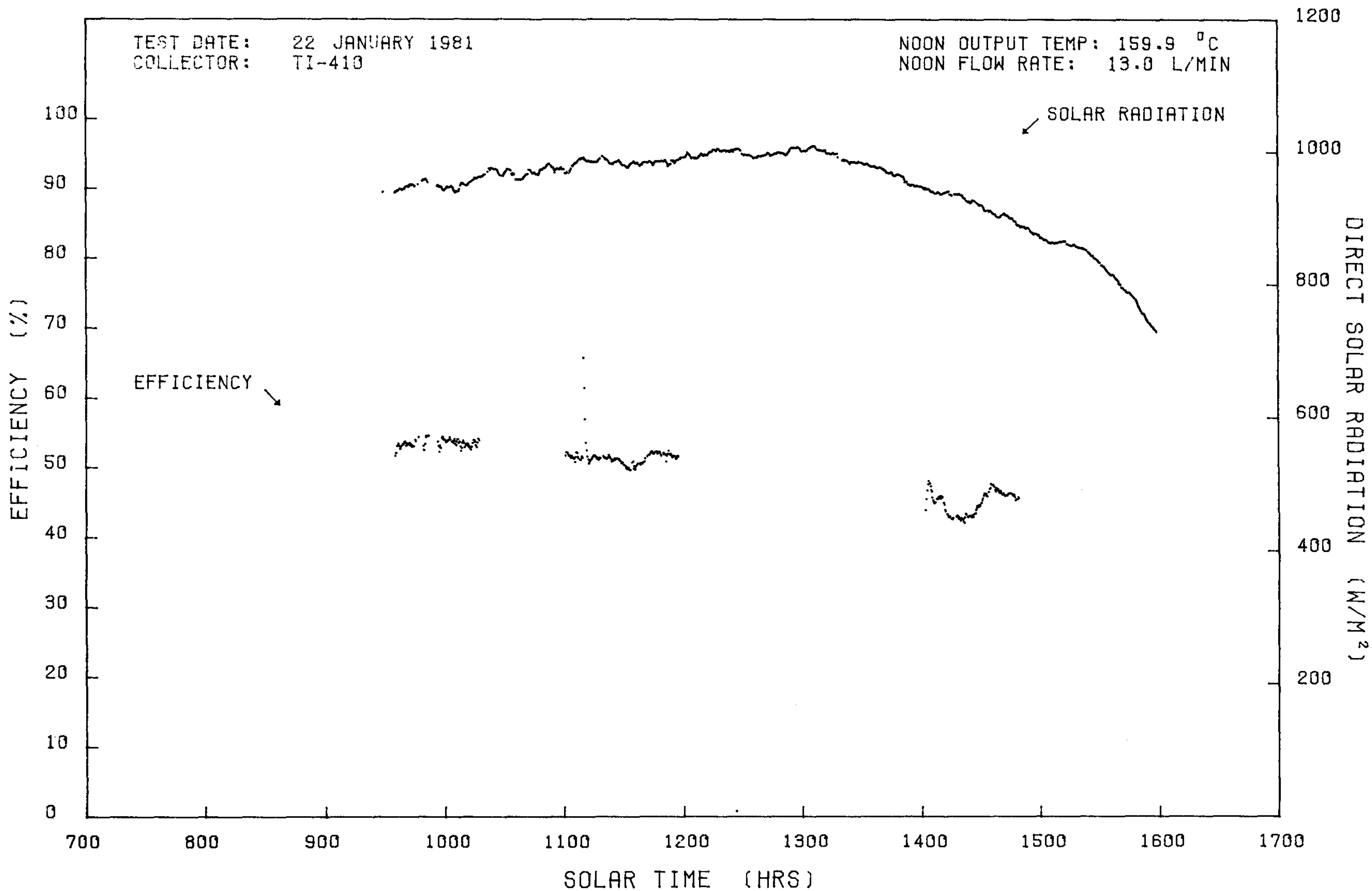

FIGURE 10 TOLTEC SEGMENTED GLASS TROUGH EFFICIENCY EVALUATION AT 146.8 °C INPUT

receiver, correct focus was never quite achieved. The measured efficiency data, shown in Table 2 and in Figures 11 and 12, also reflect the misalignment -- the efficiency curve is about 3.5 points lower than that obtained with the counterflow receiver. Several flow rates were tried; the open-tube receiver showed little of the flow sensitivity found with the counterflow receiver.

Table 2. Toltec Efficiency Test Data
Segmented-Glass Mirrors, Straight-thru Flow, Open-Tube Receiver

Test Date	Direct Insolation (W/m^2)	Temp Out (°C)	Receiver Delta T (°C)	Flow Rate (L/min)	Delta T / I (°Cm^2/W)	Efficiency (%)
1/20/81	959.9	21.1	7.06	15.1	0.00955	68.1*
1/22/81	945.0	117.0	12.23	16.6	0.1051	54.0
1/22/81	982.7	160.6	14.36	13.0	0.1429	50.3
1/22/81	904.7	208.2	15.02	10.1	0.2054	46.1

* Data taken with cold water

TEST RESULTS WITH A 3.49cm FINNED RECEIVER

Rather than spend another day with further tests of the 2.86cm OD open-tube receiver, Toltec personnel decided to continue with the next receiver. The open-tube receiver assemblies were removed on 22 January and replaced with a larger diameter, 3.49cm outside diameter receiver design. Alignment of all the reflector assemblies was checked to make sure all were tracking together. It was hoped that the larger diameter receiver would capture more of the light from the reflectors. The new receiver was also different in internal design; it was a copper forging with 16 thin fins, 3.2mm high, formed on the internal walls of the absorber. These fins were arranged in a spiral pattern down the inner walls of the absorber, similar to the rifling in a gun barrel. The fins were intended to promote heat transfer from the absorber walls into the fluid.

Figure 13 shows one of the test days with the rifle-finned receiver. Tests at about 100°C were made until about 11:45 at flow rates of 8, 16 and 31 L/min. The fluid loop was then heated to 150°C for further tests at 8 and 16 L/min.

Testing of the internally finned receiver continued on 25, 26 and 27 January. Figure 14 was made during the 26 January test. Test points near 100°C and 200°C were repeated, and a masked mirror test was performed at 200°C. As in the previous masked mirror test, the outer three mirror segments along both edges of each trough were covered with a paper mask. Aperture area was changed concurrently with the installation and removal of the mask. With the mask in place, very little light could be observed to miss the receiver. When the mask was removed, the measured efficiency dropped, indicating the optical efficiency of the outer mirror segments was less than that of the inner mirror area. On 27 January the masked mirror test was repeated again with cold water. In both masked mirror tests, most of the light from the outer two mirror segments was found to be missing the receiver. This was an improvement over the smaller diameter counterflow receiver, where most of three mirror segments were not focused on the receiver.

Efficiency was strikingly better with the finned receiver, outperforming both of the two earlier designs tested. The larger absorber diameter intercepted more focused light, and all four troughs were now in better focus on the tube. Measured

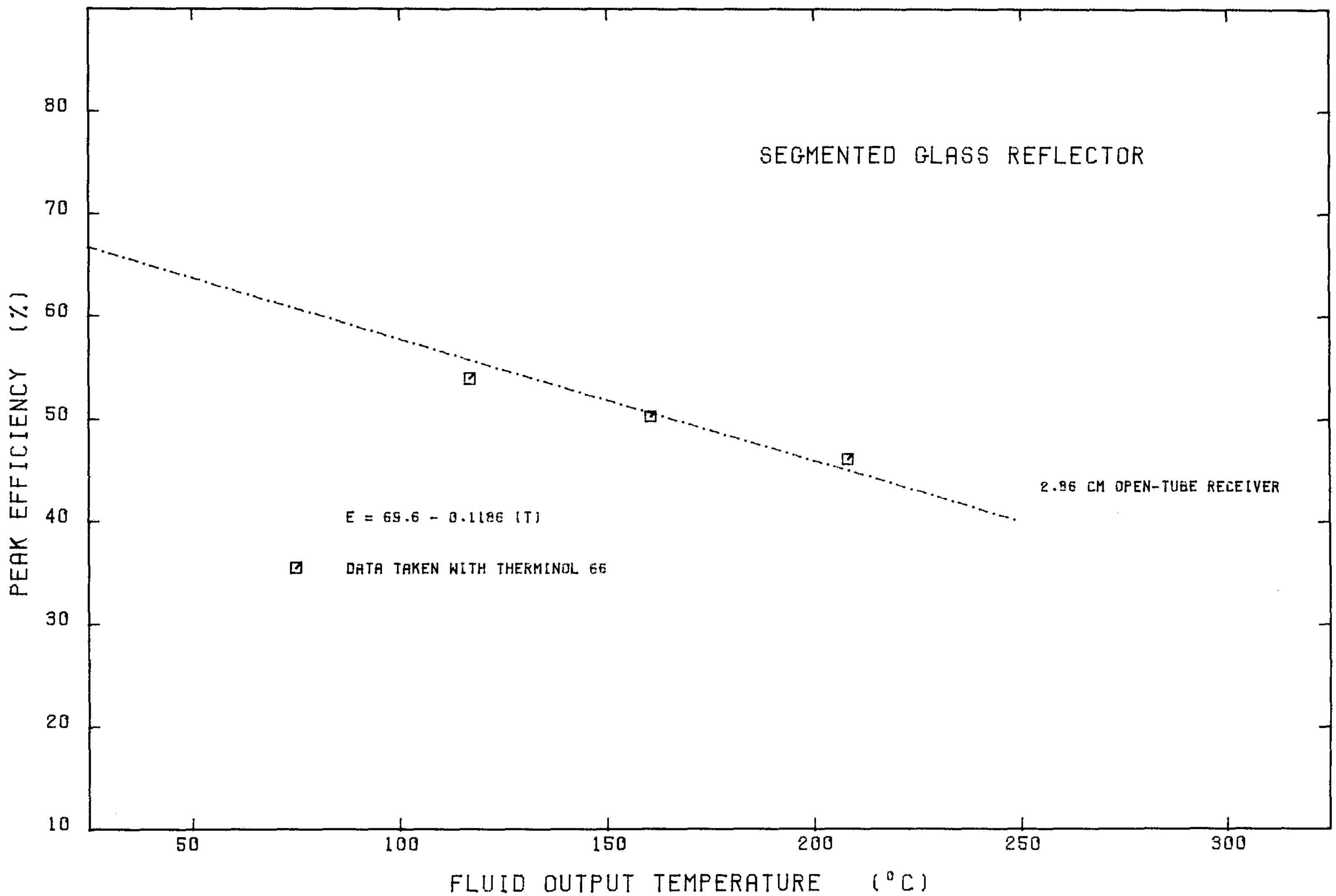

FIGURE 11 TOLTEC TI-410 EFFICIENCY VS OUTPUT TEMPERATURE

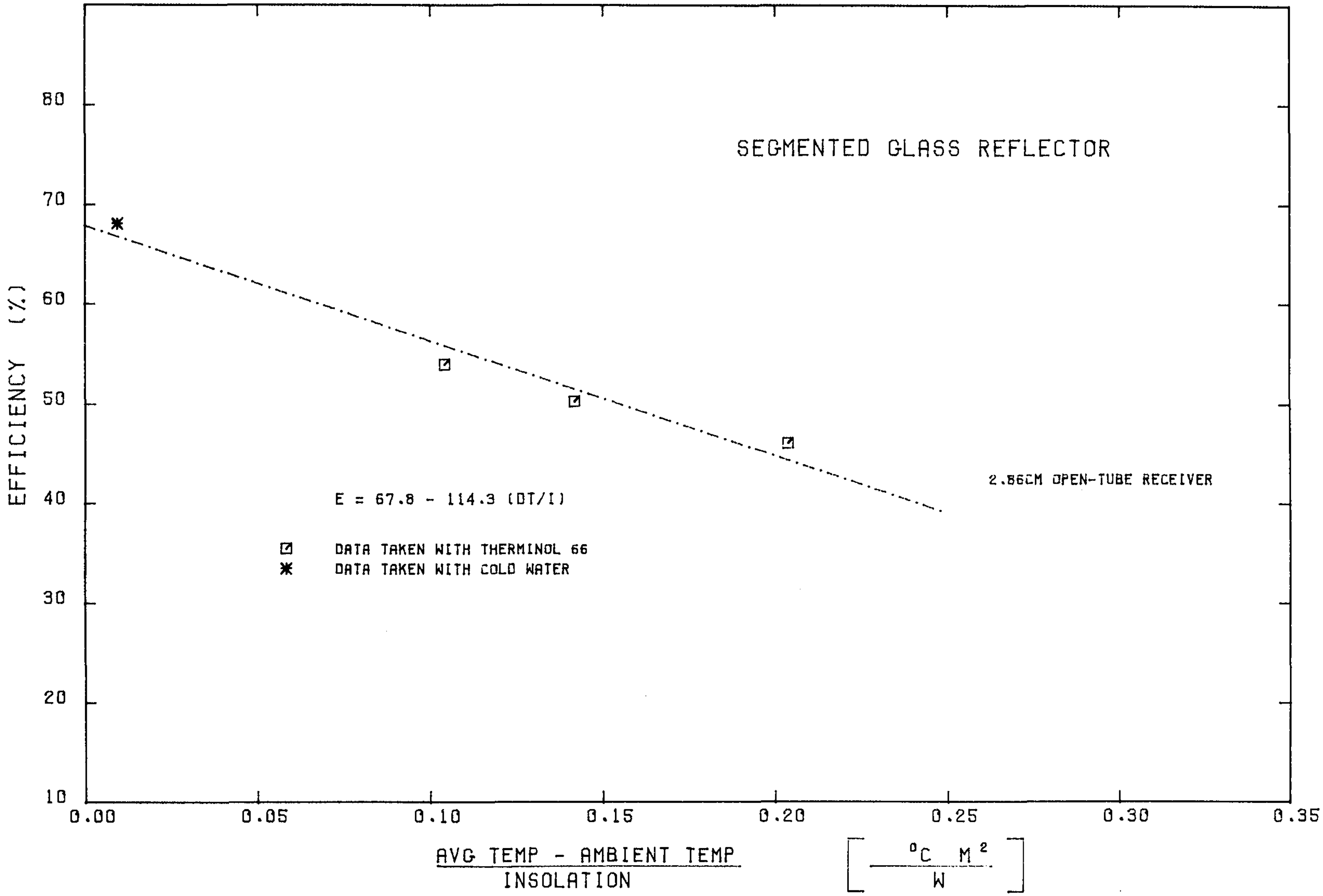

FIGURE 12 TOLTEC TI-410 EFFICIENCY VS DELTA T / I

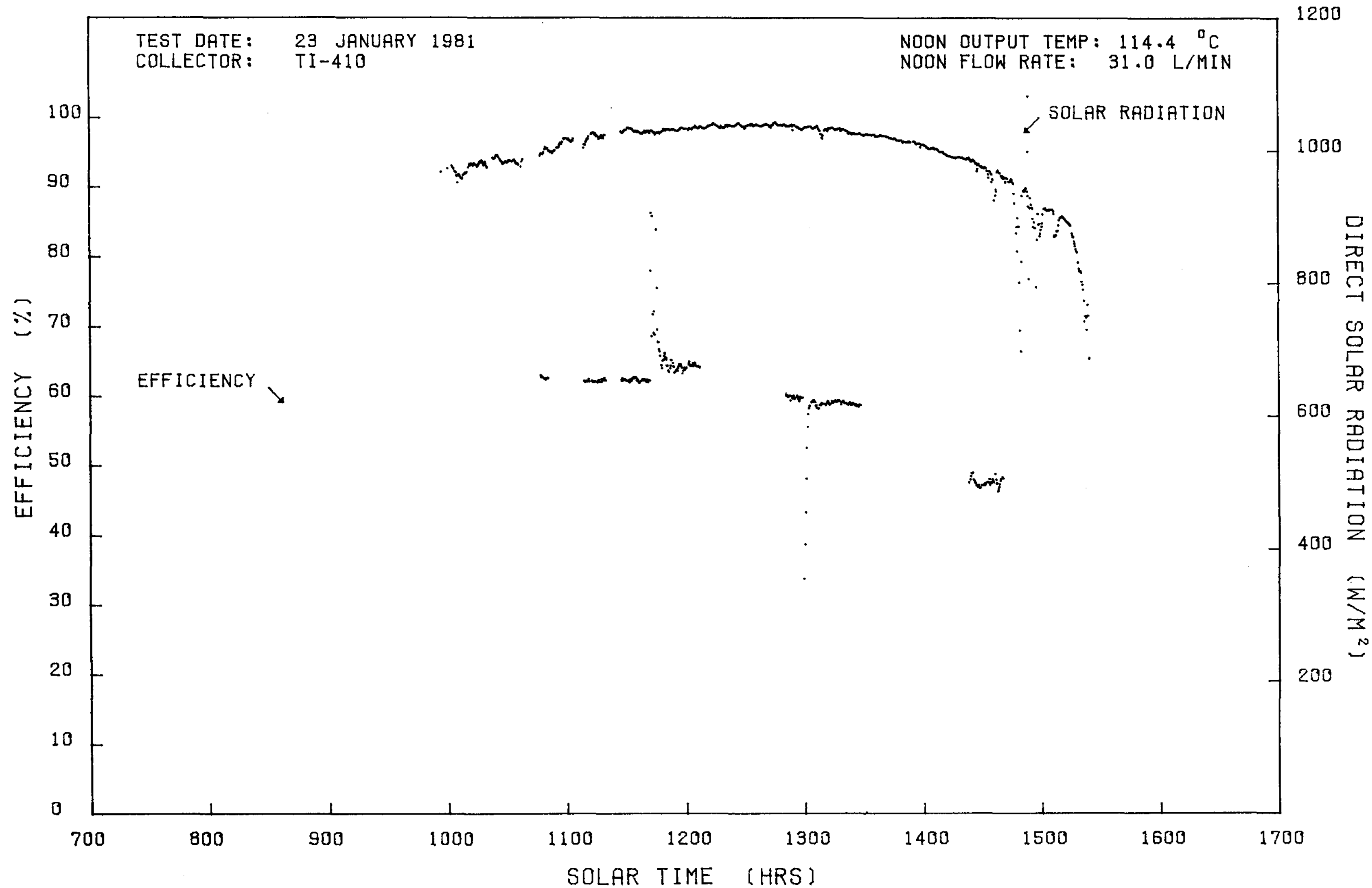

FIGURE 13 TOLTEC SEGMENTED GLASS TROUGH EFFICIENCY EVALUATION AT 106.0 °C INPUT

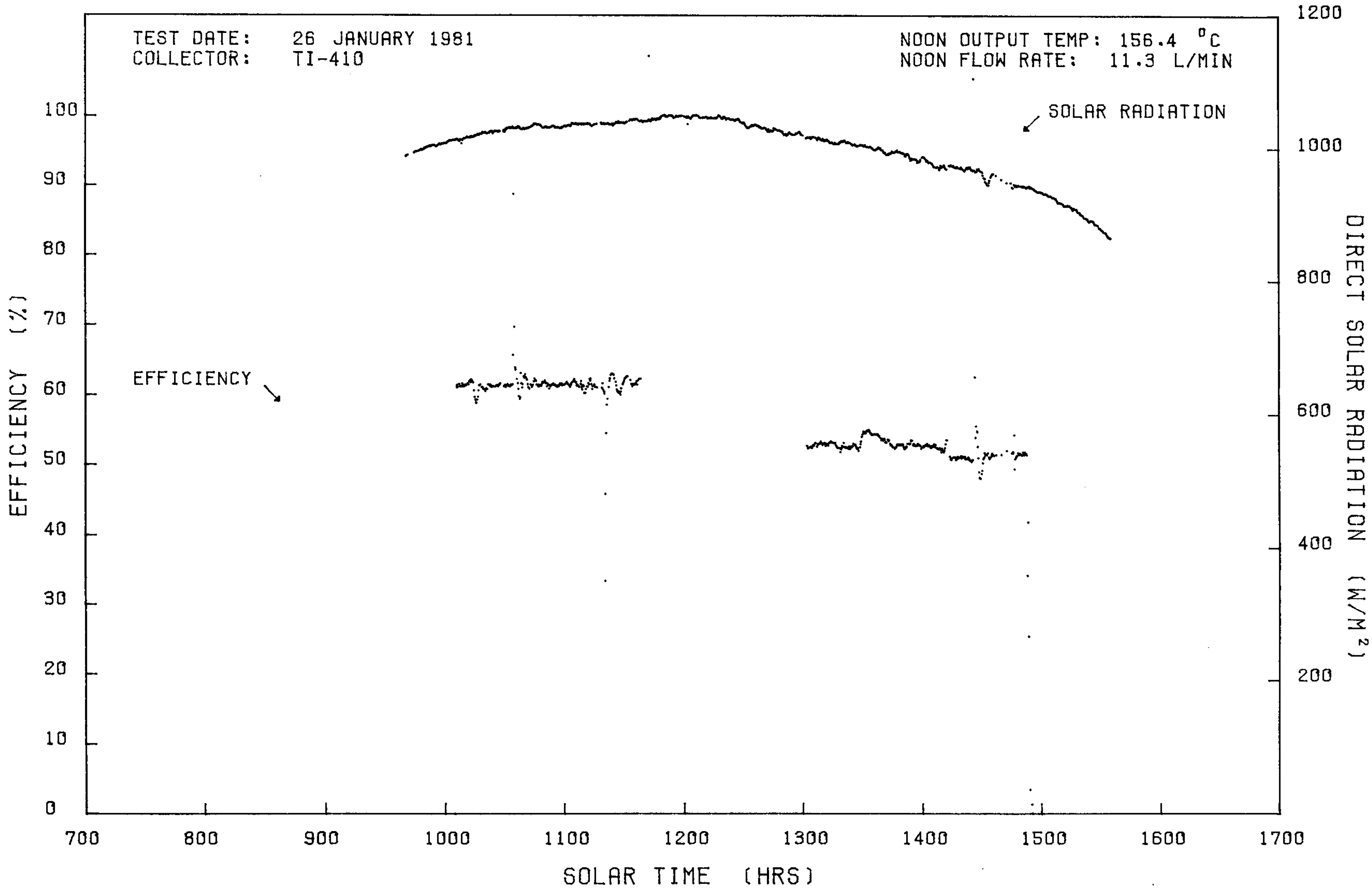

FIGURE 14 TOLTEC SEGMENTED GLASS TROUGH EFFICIENCY EVALUATION AT 138.6 °C INPUT

efficiency data, shown in Table 3 and plotted in Figures 15 and 16, was about 5 points better than achieved with the counterflow receiver and about 8.5 points better than the smaller open-tube design.

Table 3. Toltec Efficiency Test Data
Segmented-Glass Mirrors, 3.49cm Rifle-Finned Receiver

Test Date	Direct Insolation (W/m^2)	Temp Out (°C)	Receiver Delta T (°C)	Flow Rate (L/min)	Delta T / I (°Cm²/W)	Efficiency (%)
1/23/81	1000.5	120.4	15.49	16.0	0.0977	62.6
1/23/81	1028.3	137.6	32.06	7.8	0.1051	62.3
1/23/81	1034.9	114.4	8.57	31.0	0.0936	64.5
1/23/81	1037.6	162.5	14.03	16.7	0.1362	59.8
1/23/81	1034.1	174.7	26.94	8.5	0.1402	59.2
1/25/81	961.7	209.9	8.67	20.5	0.1996	51.0
1/25/81	986.9	206.5	6.94	26.2	0.1925	50.6
1/25/81	974.4	207.9	10.46	16.9	0.1957	49.9
1/26/81	1028.1	119.4	15.65	15.9	0.0971	61.3
1/26/81	1032.1	113.6	8.98	28.1	0.0965	61.4
1/26/81	984.5	213.3	15.90	11.2	0.1975	52.7+
1/26/81	972.1	213.5	15.97	11.2	0.1998	50.9
1/26/81	942.7	206.2	6.02	29.3	0.2020	51.5
1/27/81	939.3	23.3	7.44	14.7	0.0115	71.6*+
1/27/81	948.5	23.4	7.58	14.7	0.0083	68.6*

* Data taken with cold water

+ Data taken with mask on mirror

ACRYLIC-POLYESTER FILM REFLECTOR TESTS

TEST RESULTS WITH A 3.49cm FINNED RECEIVER

Testing with the segmented-glass reflectors was completed on the morning of 27 January. The glass reflectors were then replaced by the acrylic-polyester film reflectors, and testing was resumed with the same 3.49cm finned receiver.

Using cold water as the heat-transfer fluid, measured efficiency was 68.6% with the glass mirrors. Using the acrylic film reflectors under the same test conditions, measured efficiency was 71.5%. A very small amount of light from the acrylic film mirror was still missing the receiver but was now confined to an area about 1cm wide along the edges of the mirror.

Tests at 100, 150 and 200°C were performed on 29 January, again producing slightly better measured efficiencies than obtained with the glass mirrors. The cold water efficiency point was repeated on the morning of 30 January before again changing the receiver. Efficiency test data from this test series is shown in Table 4 and in Figures 17 and 18.

Table 4. Toltec Efficiency Test Data
Acrylic-Polyester Film Mirror, 3.49cm Rifle-Finned Receiver

Test Date	Direct Insolation (W/m^2)	Temp Out (°C)	Receiver Delta T (°C)	Flow Rate (L/min)	Delta T / I (°Cm²/W)	Efficiency (%)
1/27/81	1011.8	25.9	8.40	14.8	0.0082	71.5*
1/29/81	986.9	113.1	7.44	33.3	0.0991	63.1
1/29/81	960.0	162.8	15.12	14.1	0.1490	58.6
1/29/81	887.5	203.0	9.04	18.5	0.2101	51.8
1/30/81	995.3	25.5	8.74	13.9	0.0085	71.4*

* Data taken with cold water

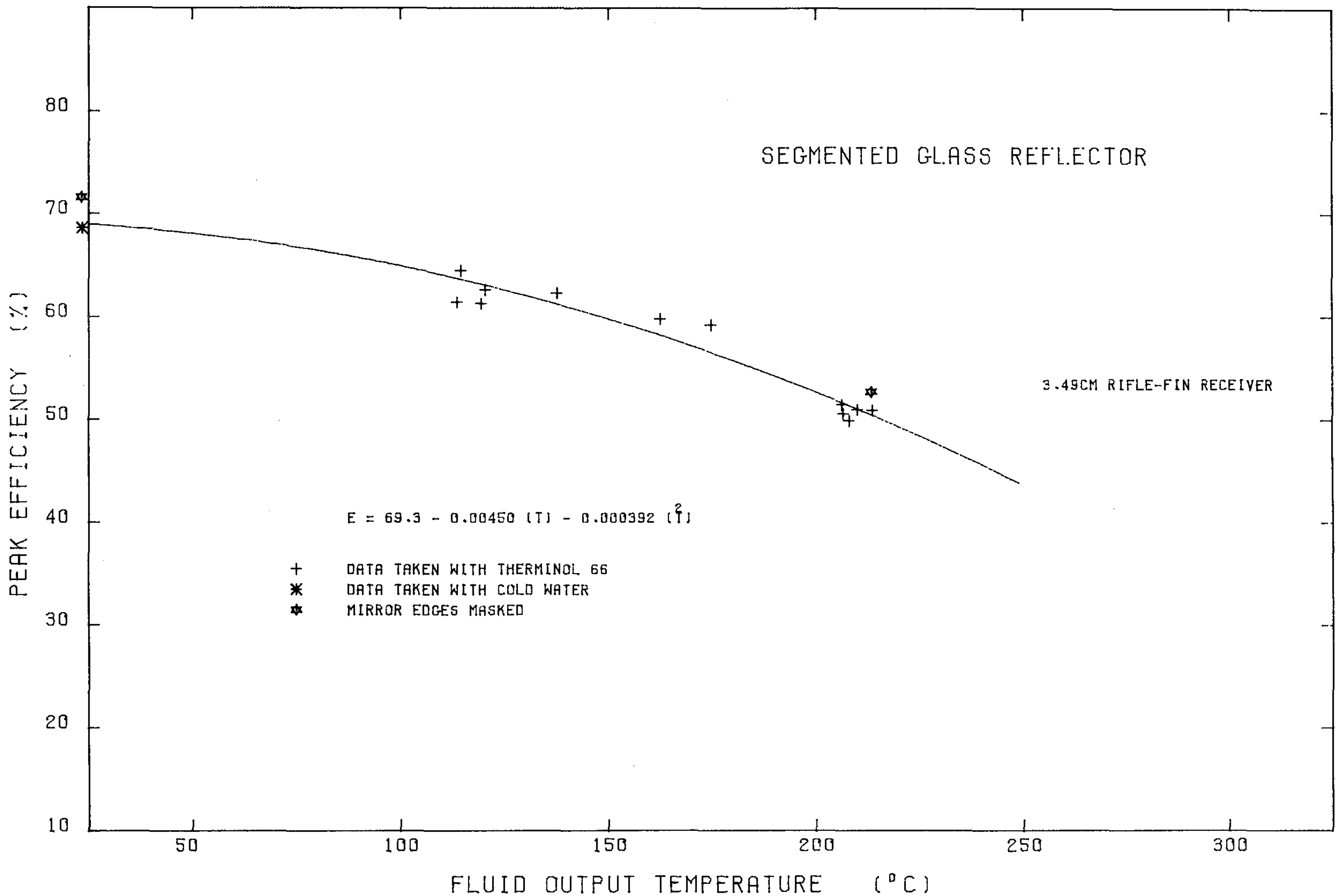

FIGURE 15 TOLTEC TI-410 EFFICIENCY VS OUTPUT TEMPERATURE

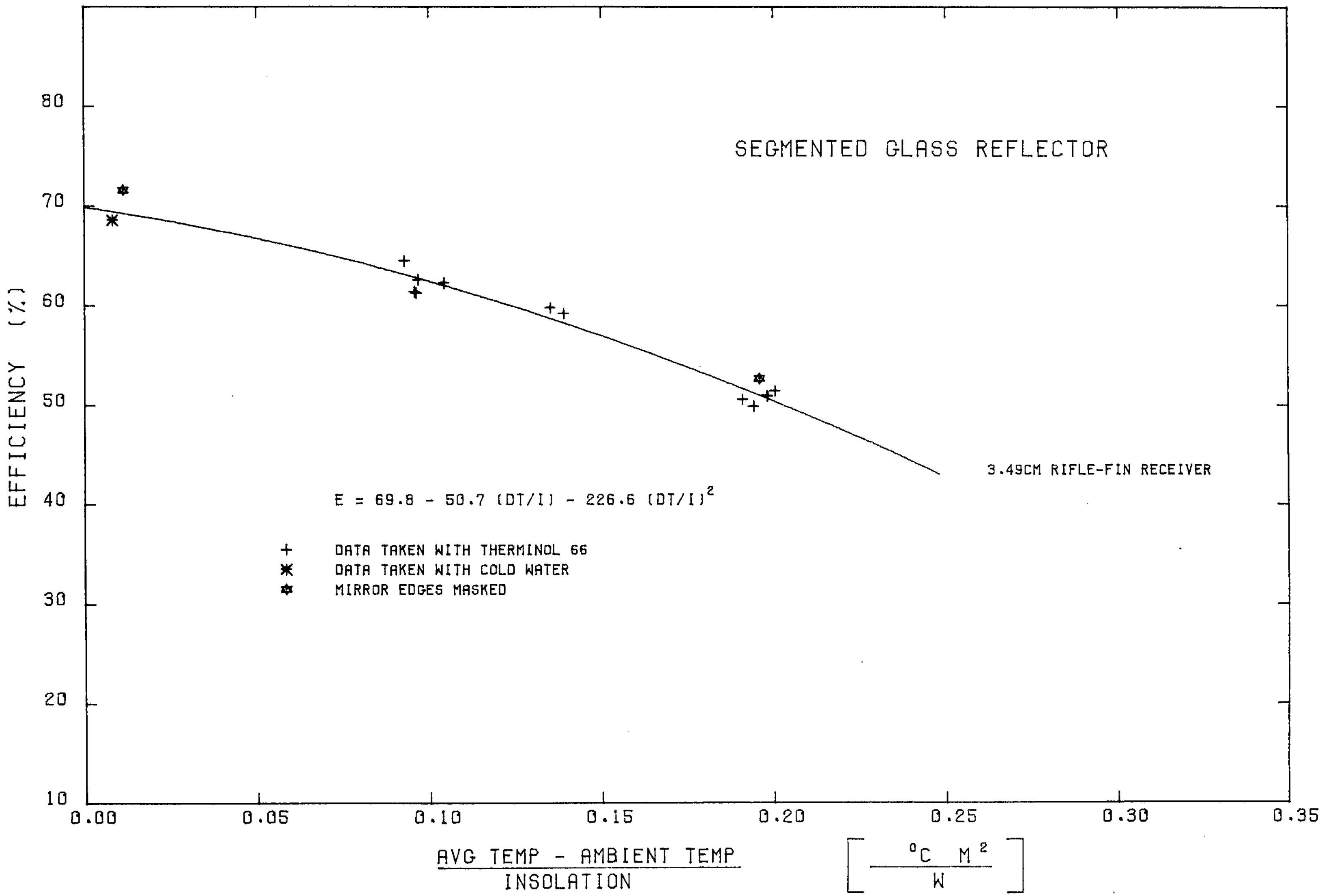

FIGURE 16 TOLTEC TI-410 EFFICIENCY VS DELTA T / I

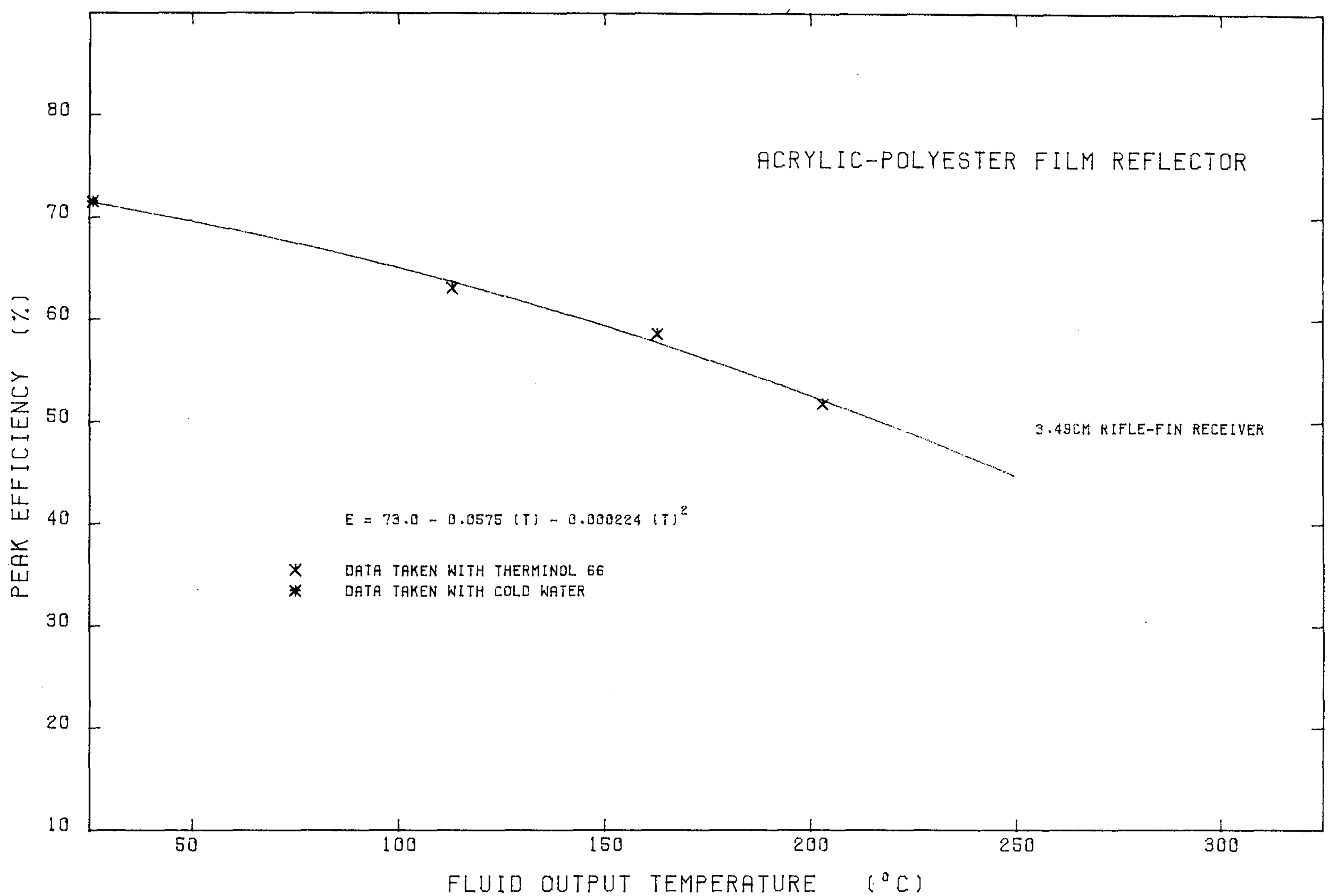

FIGURE 17 TOLTEC TI-410 EFFICIENCY VS OUTPUT TEMPERATURE

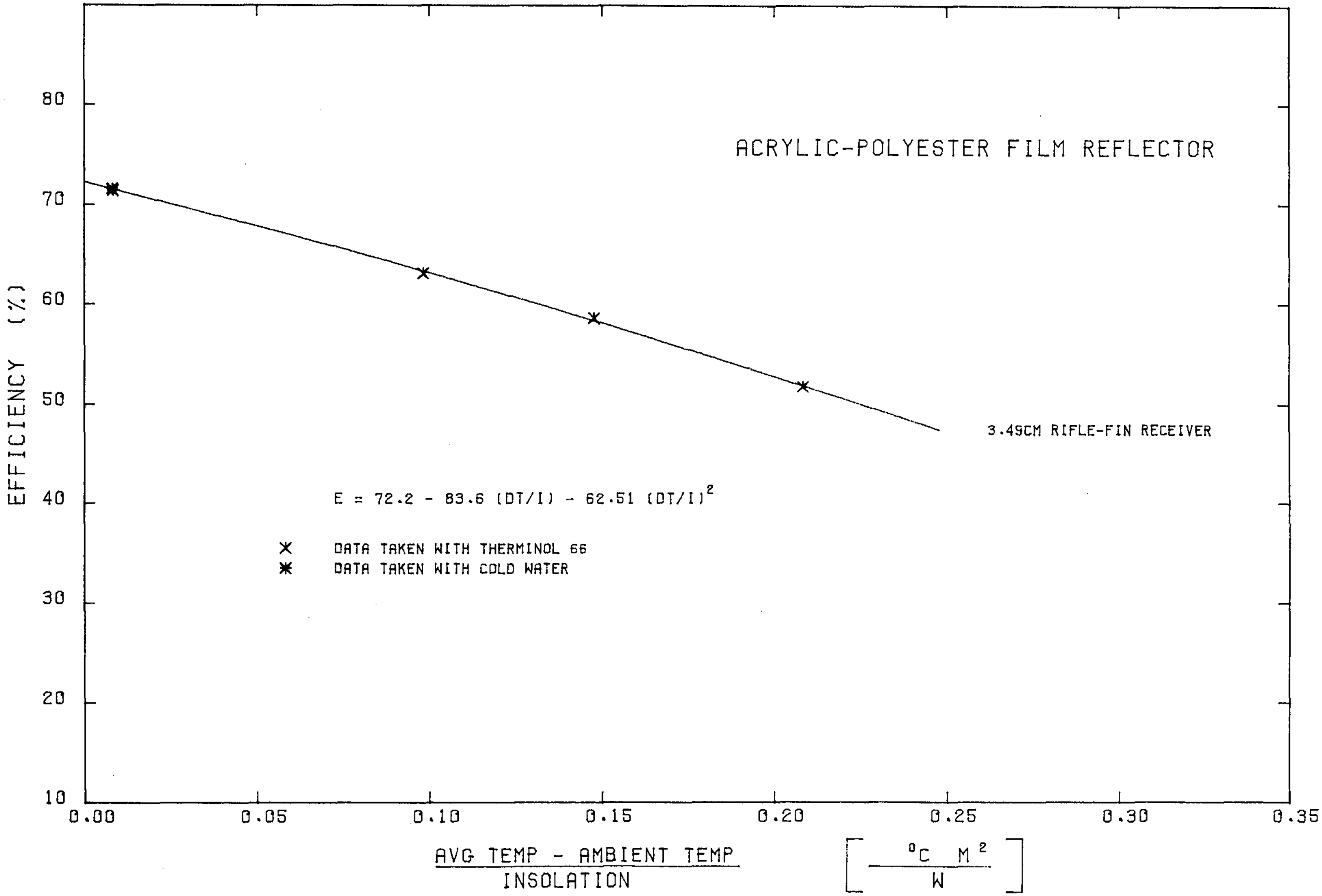

FIGURE 18 TOLTEC TI-410 EFFICIENCY VS DELTA T / I

TEST RESULTS WITH A 2.86cm OPEN-TUBE RECEIVER

Test results on the 2.86cm open-tube receiver were not entirely satisfactory when it was tested with the segmented-glass mirrors. The simplicity and low cost of the open-tube receiver design makes it an attractive alternative to the other receivers, so the open-tube receiver was tested again with the acrylic film reflectors.

A low-temperature efficiency point was obtained on 30 January using cold water. After switching to Therminol 66 heat-transfer fluid, other tests were made at 100, 150 and 200^{o}C. Results were again somewhat disappointing in that the measured efficiencies were lower than expected. Collector focus and sun tracking were checked many times without making any significant improvements in the efficiency measurements. The efficiency data obtained is shown in Table 5 and in Figures 19 and 20. The 2.86cm receiver was removed on 2 February and replaced by another finned receiver design.

Table 5. Toltec Efficiency Test Data
Acrylic-Polyester Film Mirror, 2.86cm Open-Tube Receiver

Test Date	Direct Insolation (W/m^2)	Temp Out (^{o}C)	Receiver Delta T (^{o}C)	Flow Rate (L/min)	Delta T / I $(^{o}Cm^{2}W)$	Efficiency (%)
1/30/81	1017.5	24.3	7.21	16.2	0.0075	66.9*
1/30/81	1008.1	24.3	7.22	16.2	0.0069	67.8*
1/30/81	941.4	112.5	11.81	17.8	0.0972	56.0
1/31/81	1035.1	159.3	11.31	18.5	0.1424	53.2
1/31/81	968.7	206.9	7.54	22.7	0.2031	48.6

* Data taken with cold water

TEST RESULTS WITH A 2.54cm RIFLE-FINNED RECEIVER

Except for the 2.54cm outside diameter, this receiver design was identical to the 3.49cm diameter design tested earlier. Since a small amount of light from the reflectors was missing the larger tube, somewhat more was expected to miss the smaller tube. Efficiency measurements at 100, 150 and 200^{o}C were indeed slightly less than with the larger tube, but the penalty was small -- only about one percentage point. Differential pressures were slightly greater due to the smaller internal diameter.

Figure 21 was made on 2 February during testing of the 2.54cm finned receiver. Additional tests were attempted on 3 February, but were not successful due to clouds; 3 February was the last test day for the Toltec collector. Measured efficiency data obtained is shown below in Table 6. Plots of the same data are shown in Figures 22 and 23.

Table 6. Toltec Efficiency Test Data
Acrylic-Polyester Film Mirror, 2.54cm Rifle Finned Receiver

Test Date	Direct Insolation (W/m^2)	Temp Out (^{o}C)	Receiver Delta T (^{o}C)	Flow Rate (L/min)	Delta T / I $(^{o}Cm^{2}/W)$	Efficiency (%)
2/ 2/81	1025.5	164.1	13.50	16.2	0.1466	56.6
2/ 2/81	1058.2	171.9	23.10	7.8	0.1467	56.9
2/ 2/81	1059.7	198.1	51.70	4.2	0.1573	55.3
2/ 2/81	917.2	115.5	14.64	15.2	0.1061	60.8

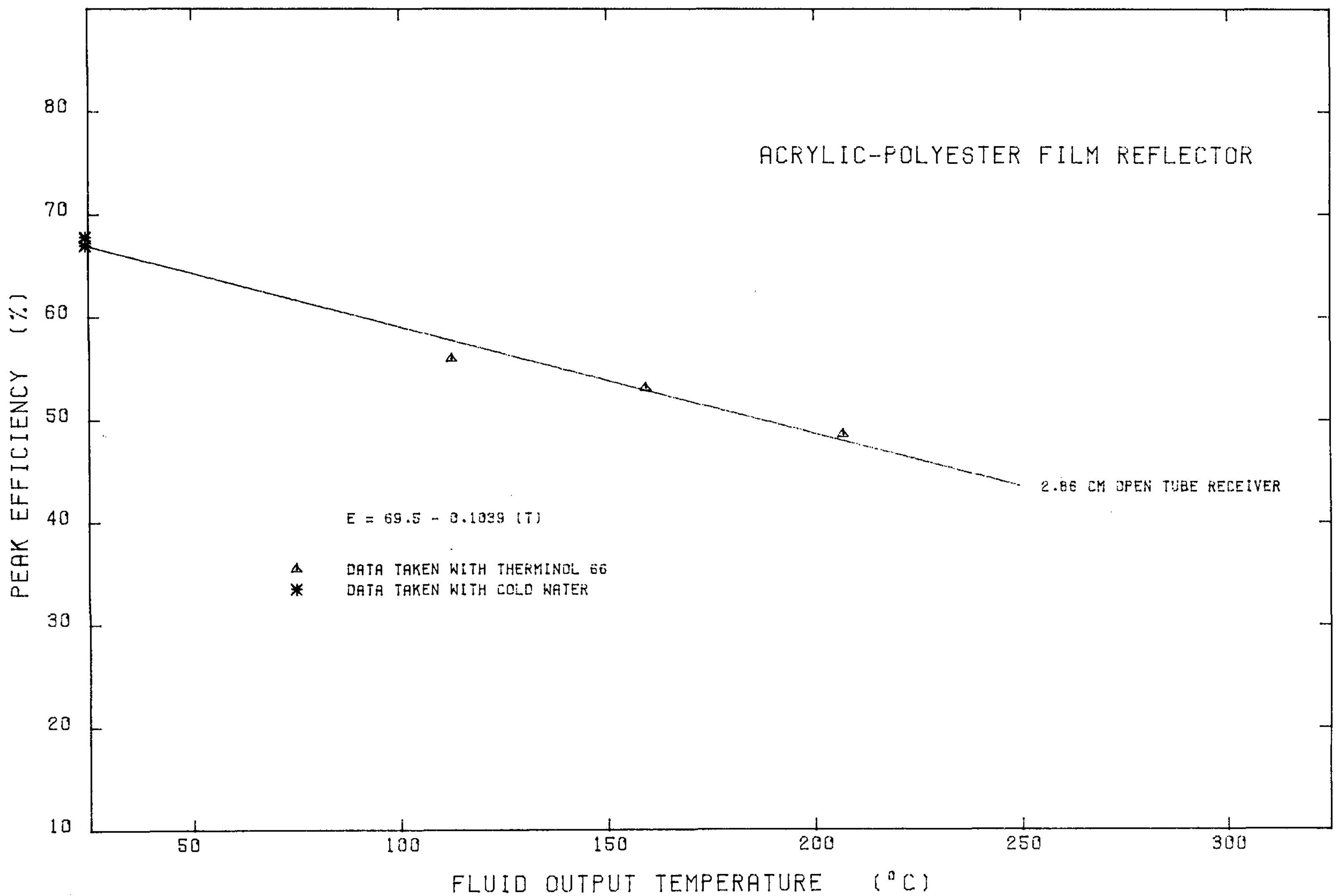

FIGURE 19 TOLTEC TI-410 EFFICIENCY VS OUTPUT TEMPERATURE

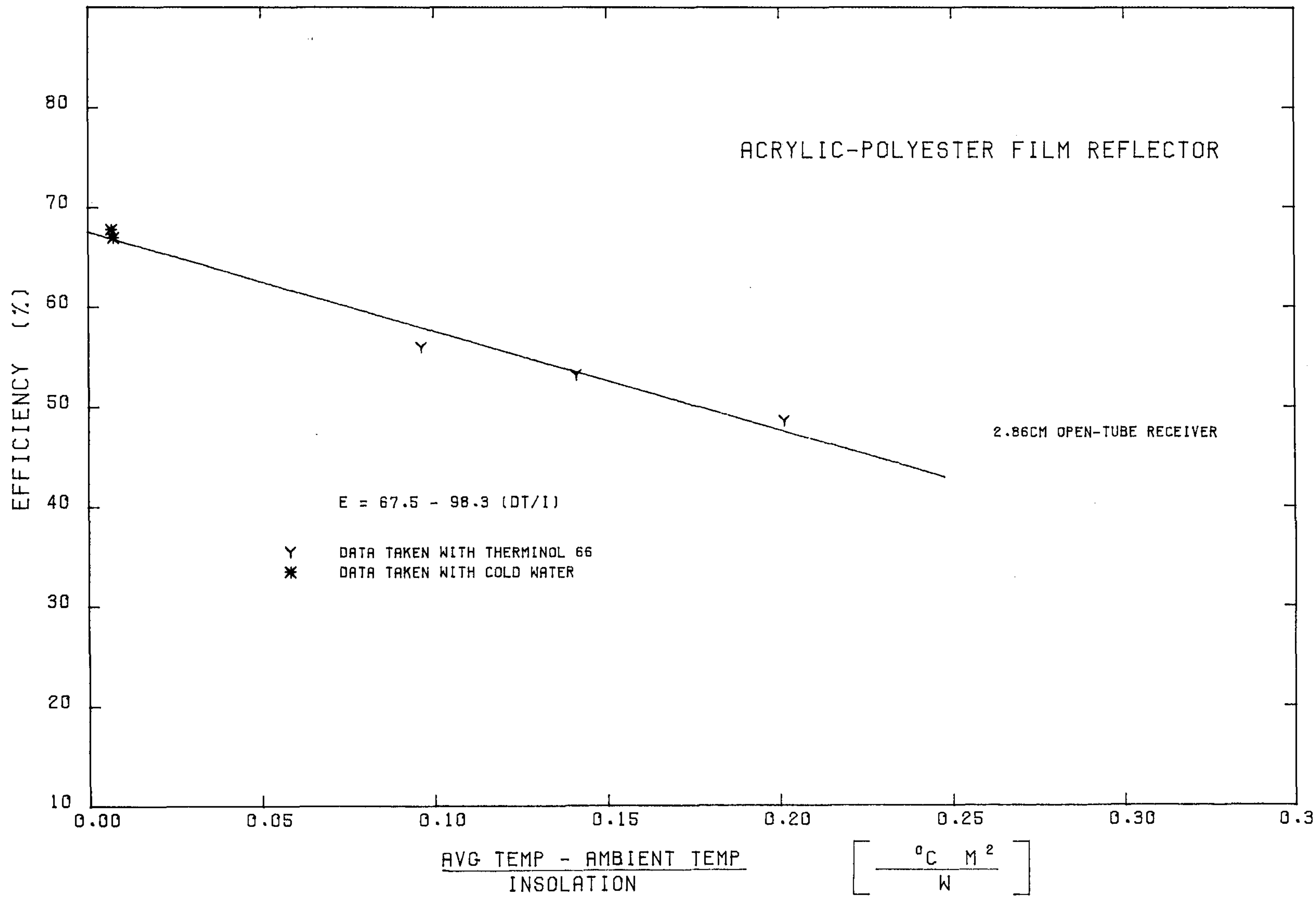

FIGURE 20 TOLTEC TI-410 EFFICIENCY VS DELTA T / I

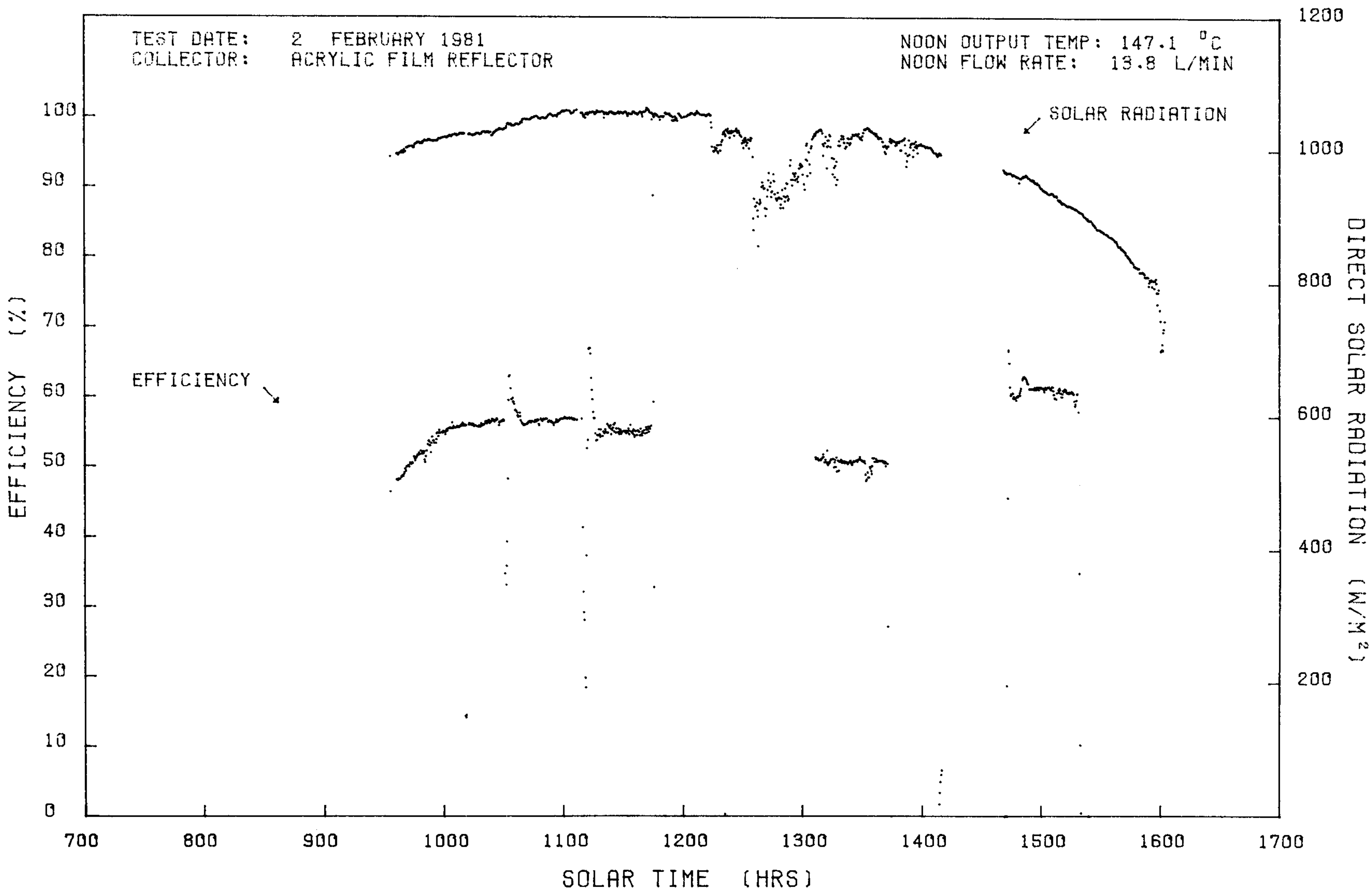

FIGURE 21 TOLTEC TI-410 PARABOLIC TROUGH EFFICIENCY EVALUATION AT 149.2 °C INPUT

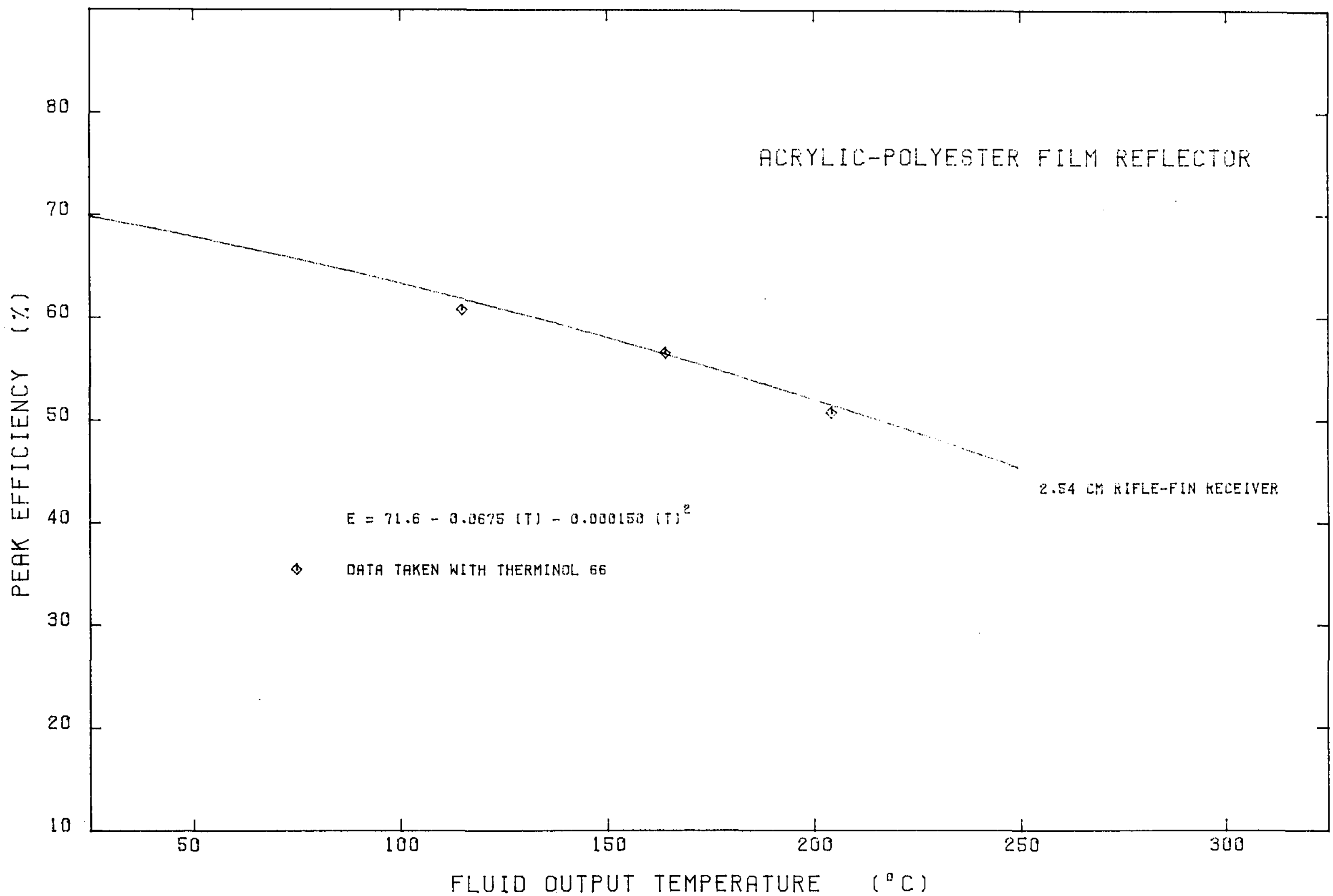

FIGURE 22 TOLTEC TI-410 EFFICIENCY VS OUTPUT TEMPERATURE

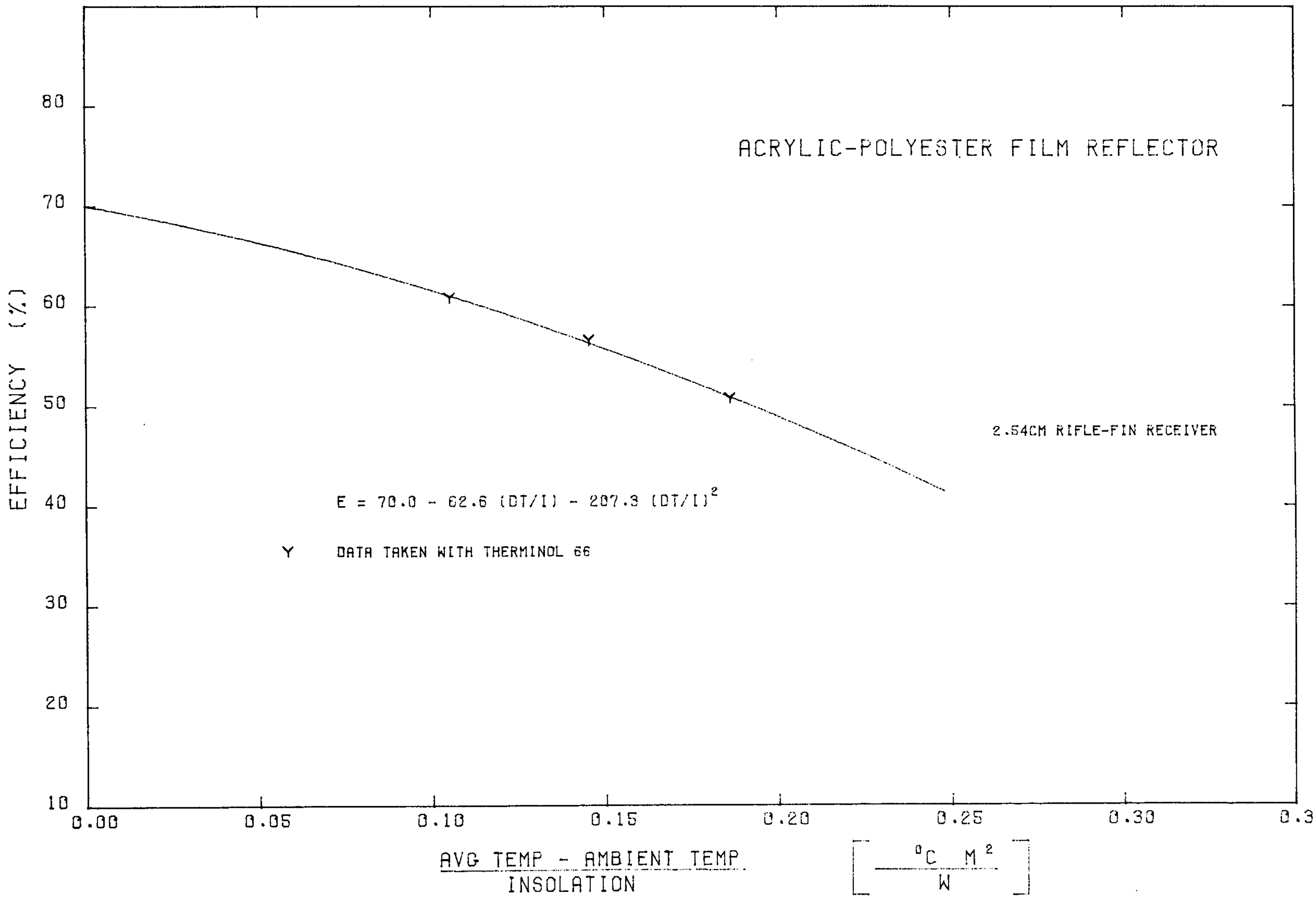

FIGURE 23 TOLTEC TI-410 EFFICIENCY VS DELTA T / I

DIFFERENTIAL PRESSURE MEASUREMENTS ON TOLTEC RECEIVERS

Differential pressure measurements were made on all four of the Toltec receiver designs. Differential pressure can give some indication of the power that will be required to circulate the heat-transfer fluid through the collector at various flow rates. Figure 24 shows the pressure curves obtained on the counterflow receiver. Measurements were made at four temperatures, three using Therminol 66 as the heat-transfer fluid and one using cold water. Compared to other receiver designs, the pressure drop through the counterflow receiver was fairly high.

Figure 24 also shows the pressure drop measured on the open-tube receiver design. Both absorber tubes had the same outside diameter (2.86cm); pressure drop through the open tube was an order of magnitude less than that through the counterflow design.

Figure 25 shows the differential pressure data from the larger 3.49cm OD rifle-finned receiver. The larger internal diameter would be expected to reduce the pressure drop, while the fins should cause an increase in pressure over that of a smooth-walled absorber. The end result seen in Figure 25 was a differential pressure nearly identical to the smaller 2.86cm OD smooth-walled absorber tube.

Figure 25 also shows the differential pressure curves for the 2.54cm rifle-finned receiver design. Because of the smaller diameter, the pressures were nearly twice as large as measured with the larger 3.49cm receiver.

ABSORPTANCE, EMITTANCE AND REFLECTANCE MEASUREMENTS

Measurements of black chrome absorptance and emittance were made on three of the four receiver designs. There were four troughs in the collector array; black chrome measurements were made on receivers taken from the input-end trough and the output-end trough. Receivers from the two center troughs of the collector array were not evaluated. No measurements were made on the smaller (2.54cm) finned receiver.

Solar spectrum absorptance was measured using Devices and Services Solar Spectrum Reflectometer, and emittance was measured using a Gier-Dunkle Model DB-100 Infrared Reflectometer. The absorptance values are accurate to ± 0.02 absorptance units, while the $\varepsilon(300^{o}C)$ values are accurate to ± 0.03 emittance units. As shown in Table 7, most of the measurements are within expected limits for black chrome absorber platings.

Table 7. Black Chrome Absorptance and Emittance

Receiver Type	Surface Absorptance	Emittance (300°C)
Finned Receivers	0.94	0.34
3.49cm (Input)	0.96	0.31
	0.96	0.33
3.49cm (Output)	0.94	0.34
	0.96	0.30
	0.91	0.30
2.86cm (Sample)	0.965*	0.095*
Counterflow Receiver	0.94	0.15
2.86cm (Input)	0.94	0.15**
2.86cm (Output)	0.95	0.16
Open-Tube Receiver	0.94	0.16
2.86cm (Input)	0.93	0.16
2.86cm (Output)	0.94	0.16
	0.95	0.16

* Measured by Olympic Solar Corp. on a coupon during manufacture

** Variable around tube; in some areas $a = 0.90$, $\varepsilon = 0.12$

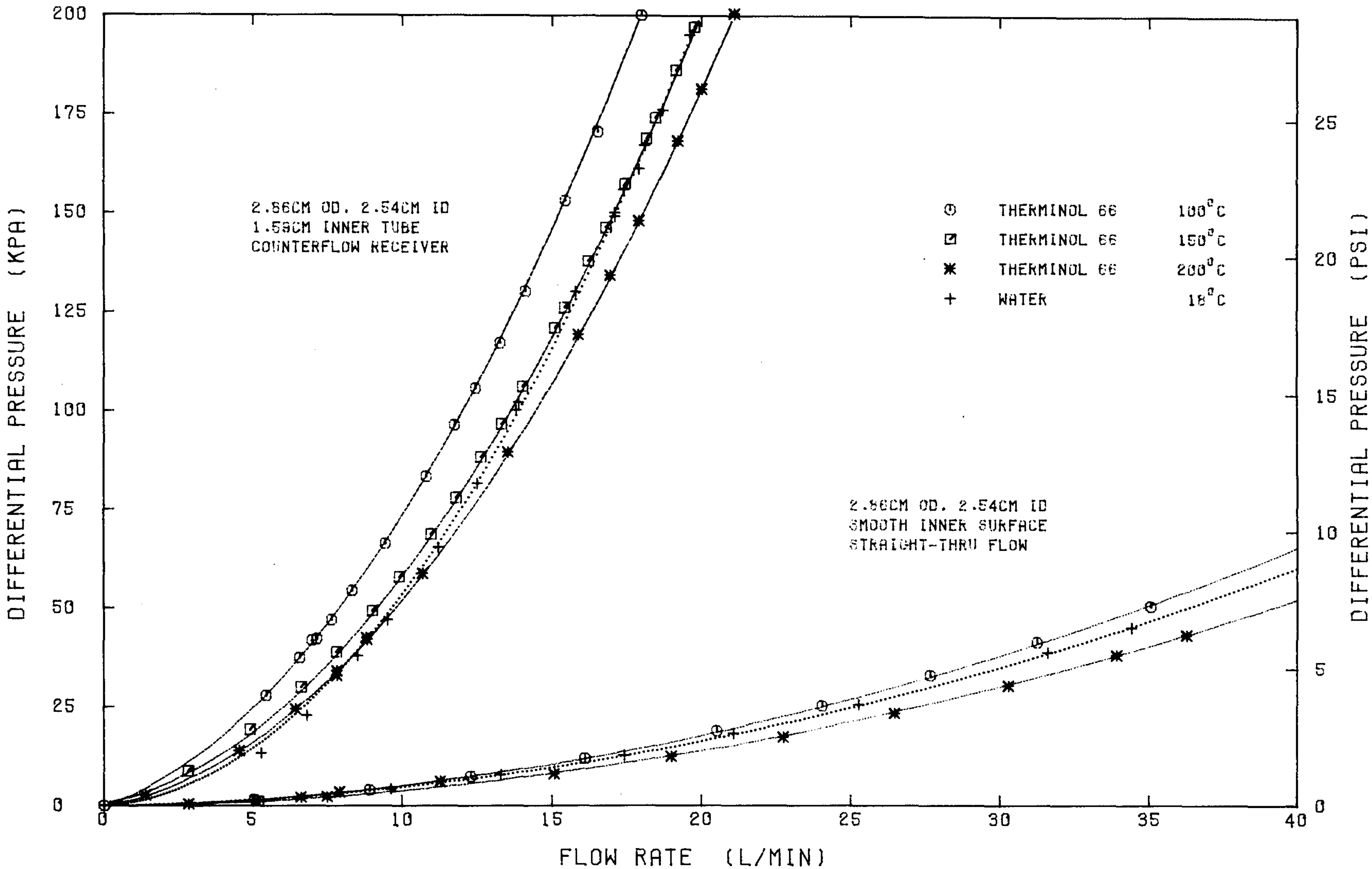

FIGURE 24 TOLTEC TI-410 RECEIVER DIFFERENTIAL PRESSURE (FOUR TROUGHS)

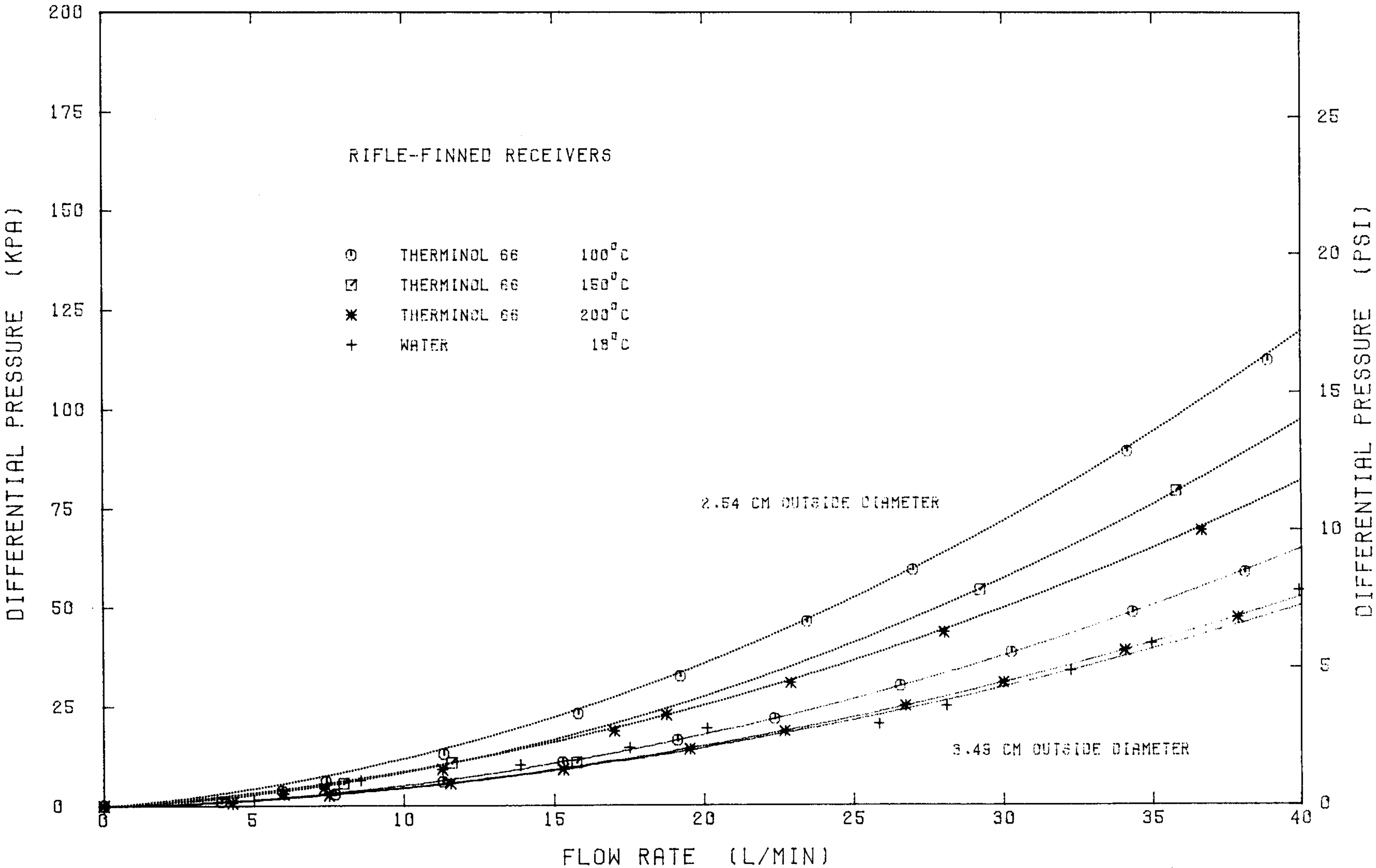

FIGURE 25 TOLTEC TI-410 RECEIVER DIFFERENTIAL PRESSURE (FOUR TROUGHS)

Reflectance measurements were made on both the glass and film mirrors. The narrow glass segments imbedded in the reflector assemblies proved too narrow to measure with the available equipment, so measurements were made on a larger glass sample from which the narrow segments had been cut. Film mirror reflectance was measured in-place on the reflector assemblies. Average reflectance for the glass was 0.94; average reflectance for the YS-91A film mirrors was 0.84. These values are within expected limits for the materials.

TOLTEC RECEIVER THERMAL LOSS TEST RESULTS

Thermal loss measurements were made on each of the Toltec receiver designs; no appreciable difference in thermal loss was found. The four troughs were mounted on the test collector in such a way that their rotational travel was restricted. Because of the rotational limits, the receiver assembly could not be shaded; therefore, only one type of thermal loss measurement was made: collector defocused as far as possible but with direct sunlight on the receiver assembly.

Thermal loss test data obtained is listed in Table 8. The same data is shown in Figure 26, plotted as loss per unit area of reflector aperture vs. average receiver temperature above ambient air temperature. The bottom curve shown in Figure 26 was obtained from a least-squares fit to the test data.

Table 8. Toltec 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/m^2)
		2.86cm Diameter, Counterflow Receiver				
1/12/81	138.2	247.2	3.80	7.2	1.0	70.6
1/14/81	194.1	832.2	0.73	16.4	0.51	29.7
1/14/81	178.5	777.1	5.42	7.8	0.28	114.4
		2.86cm Diameter, Open-Tube Receiver				
1/22/81	94.4	958.2	0.69	16.5	0.68	29.0
1/22/81	137.3	948.5	2.27	13.1	0.78	77.9
1/22/81	178.4	732.6	3.02	15.4	0.48	126.4
		3.49cm Diameter, Rifle-Finned Receiver				
1/23/81	127.5	712.9	2.69	8.5	0.55	59.6
1/25/81	185.1	920.4	1.75	26.0	0.63	124.0
1/25/81	98.9	693.3	0.59	25.5	1.18	37.8
		2.54cm Diameter, Rifle-Finned Receiver				
2/ 2/81	141.2	1046.3	2.22	13.8	2.08	79.6
2/ 2/81	180.2	1006.5	2.91	16.1	2.49	126.6
2/ 2/81	96.0	815.5	1.47	11.7	1.22	42.8

Since the surface area of the larger diameter receivers is slightly larger than the smaller diameter receivers, a difference in thermal loss would be expected. However, the thermal loss test data shows little difference between the four receiver designs.

Thermal loss that occurs when the collector is in-focus is not the same as that measured with the collector out-of-focus. When thermal loss measurements are made on a defocused collector during a test series, the heat flow rate from the receiver is small, and the absorber surface temperatures are nearly the same

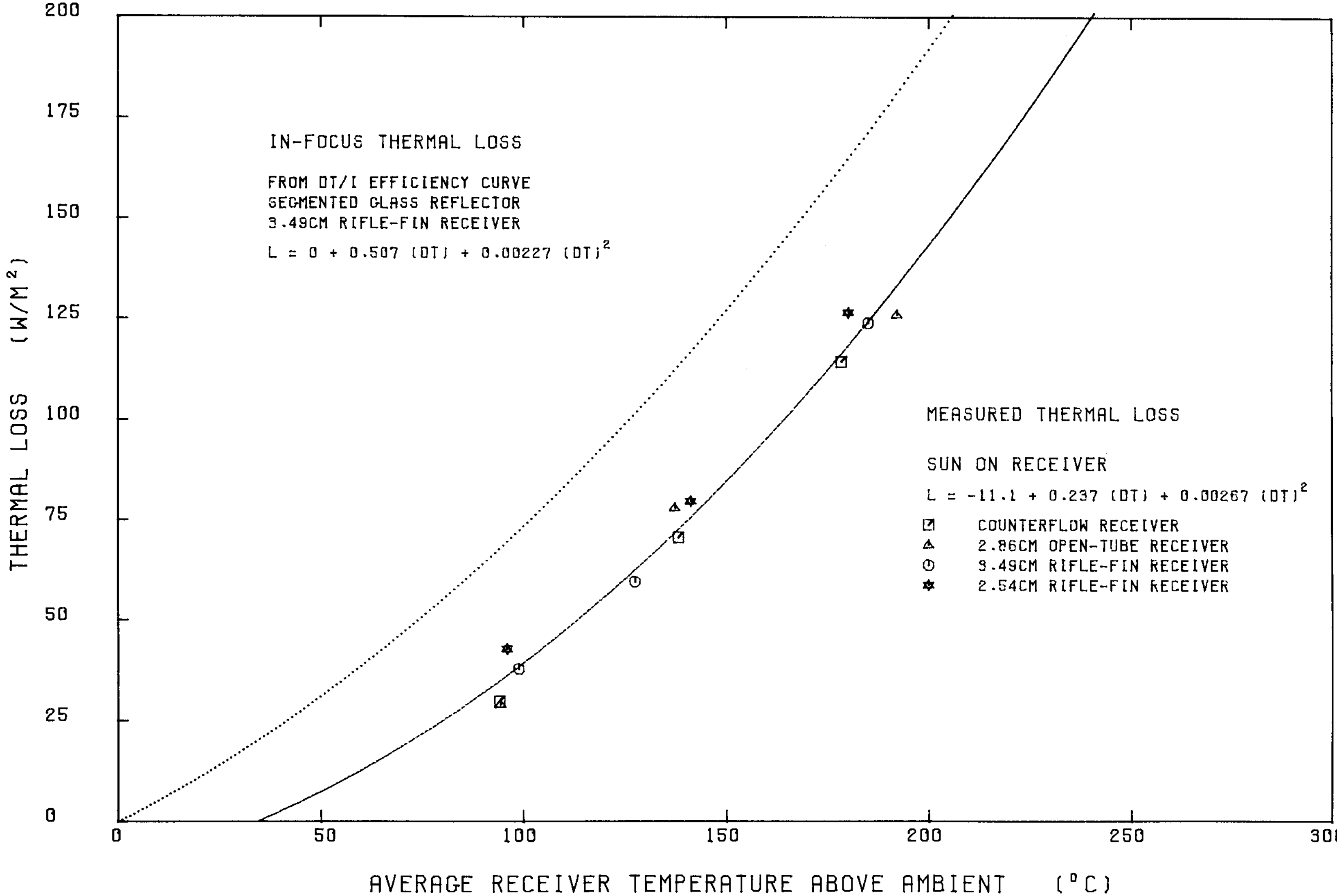

FIGURE 26 TOLTEC TI-410 RECEIVER THERMAL LOSS

as the temperature of the heat-transfer fluid inside the receiver. However, when in-focus, the heat flow rate is large, and absorber surface temperature and receiver cover glass temperature are much higher than the temperature of the bulk fluid inside the absorber. The actual surface temperatures will change with the level of solar radiation, collector concentration ratio, mirror reflectivity, etc.

The Toltec collector was not instrumented for absorber surface temperature, but measurements on a similar-sized absorber on another collector showed absorber surface temperatures up to 50°C higher than the fluid temperature. (In the referenced test, fluid temperature was measured at the center of the absorber tube, directly under the surface temperature thermocouple).

If surface temperatures are higher when in-focus, thermal losses might be reasonably expected to be higher also. Thermal loss cannot be directly measured on an in-focus, operating solar collector, but the loss can be calculated from the effect of thermal loss on the operating efficiency of the collector. If the collector were operated at a low enough temperature, there would be no thermal loss, and the measured efficiency would be the optical efficiency. As the operating temperature of the collector is increased, measured efficiency decreases; the decrease in efficiency is caused by increasing thermal losses. In-focus thermal loss can therefore be derived from the curvature of the measured efficiency curve.

Like in-focus thermal loss, optical efficiency cannot be directly measured, but the cold water efficiency test is a close approximation. During the cold water test, fluid flow rate was adjusted so that the average receiver fluid temperature was as close as possible to the ambient air temperature. This procedure does not achieve zero thermal loss. As discussed above, when the collector is in-focus, receiver cover glass temperature and absorber surface temperatures are significantly higher than the fluid temperatures. However, the efficiency measured with cold water is as close to the optical efficiency as we are going to get with a practical field test procedure.

Assuming that the cold water test point is approximately the same as the optical efficiency, any decrease in that efficiency value as the operating temperature is increased must be caused by increasing thermal loss. The Delta T/I efficiency curve shown earlier in Figure 17, with an assumed solar radiation input of 1000 W/m^2 and an assumed ambient air temperature of 20°C, was used to calculate the energy leaving the collector. The difference between the calculated energy value and the energy that would have been available at the assumed optical efficiency was plotted as thermal loss in the top curve of Figure 26. The calculated in-focus loss curve parallels the measured loss curve and is offset by approximately 35°C. The curve is shown to pass through zero loss when the average receiver temperature is equal to the ambient air temperature; this is probably not true, as discussed above. The actual receiver fluid temperature at zero thermal loss is not known, as it depends on the surface temperatures.

If thermal loss changes with surface temperature and surface temperatures change with changing solar radiation input levels, then thermal loss must also change as the insolation changes. This leads to the conclusion that there is a family of loss curves falling between the two loss curves shown in Figure 26. The top curve represents a near-maximum thermal loss for the Toltec collector, when in-focus at 1000 W/m^2 insolation, while the bottom curve represents the loss with a very low level of insolation.

PERFORMANCE ESTIMATES FOR OTHER OPERATING CONDITIONS

Most of the efficiency measurements at the CMTF are made with an insolation very close to 1000 W/m^2; collector performance will not be the same at lower levels of solar radiation. Heat gain varies directly as the incoming solar radiation and collector thermal losses also change with the solar radiation level. Thermal loss will cause measured heat gain and efficiency to decrease as the insolation decreases. Unfortunately, stable, low radiation levels seldom occur in Albuquerque, so no measurements of the effect of low radiation levels were made on the Toltec collector. The efficiency change with solar radiation is calculated below.

Optical properties of the mirror, receiver cover glass, and absorber surface do not change appreciably with operating temperature. At a given solar radiation input level, the energy delivered to the absorber from the reflector should be approximately constant at all operating temperatures possible with the Toltec collector. Not all the energy delivered to the receiver by the reflectors can be captured in the collector's heat-transfer fluid; some is going to escape as thermal loss. The amount of thermal loss under in-focus operating conditions can be estimated, as in the top curve in Figure 26; a new thermal loss curve is obtained for each different level of solar radiation. If thermal loss at a desired operating temperature and solar radiation level is subtracted from the heat gain determined with optical efficiency at the same insolation level, a net heat gain is obtained for that set of operating conditions. Because the thermal loss at a given temperature decreases slowly, while heat gain decreases rapidly as the insolation level falls, efficiency must decrease with decreasing insolation.

Figures 27 and 28 show efficiency curves estimated for two of the Toltec collector configurations under decreasing insolation levels. In both cases, optical efficiency was assumed equal to the value measured with cold water. Thermal loss under in-focus conditions was determined by linear interpolation between the two loss curves shown in Figure 26, as determined by the insolation level being used.

There were no tests of the Toltec collector at low insolation levels to confirm the performance predicted by Figures 27 and 28. All the Toltec collector tests shown in this report were made at insolation levels between 900 and 1050 W/m^2; these actual test points fit at the proper places on the curves shown in Figures 27 and 28.

Another collector (Ref. 3) has been tested at solar radiation levels from 500 W/m^2 to 1050 W/m^2. The calculation procedure used to derive Figures 27 and 28 was worked out from that actual test data. The procedure produced a set of calculated efficiency curves that matched the test data curves to within about one efficiency percentage point. Figures 27 and 28 are thus the best available estimates of the Toltec collector performance at low insolation levels.

Estimates of annual thermal performance of the Toltec collector have also been made (Ref. 5). The annual performance estimates utilize the film reflector Delta T/I efficiency curve from this report (Figure 18) and Typical Meteorological Year data for five cities: Fresno, Albuquerque, Fort Worth, Charleston and Boston. No corrections for low insolation levels were applied, as this data was not available at the time the annual performance estimates were being prepared. If corrections for low insolation levels were applied to the annual performance estimated from Reference 5, annual thermal output would be somewhat larger.

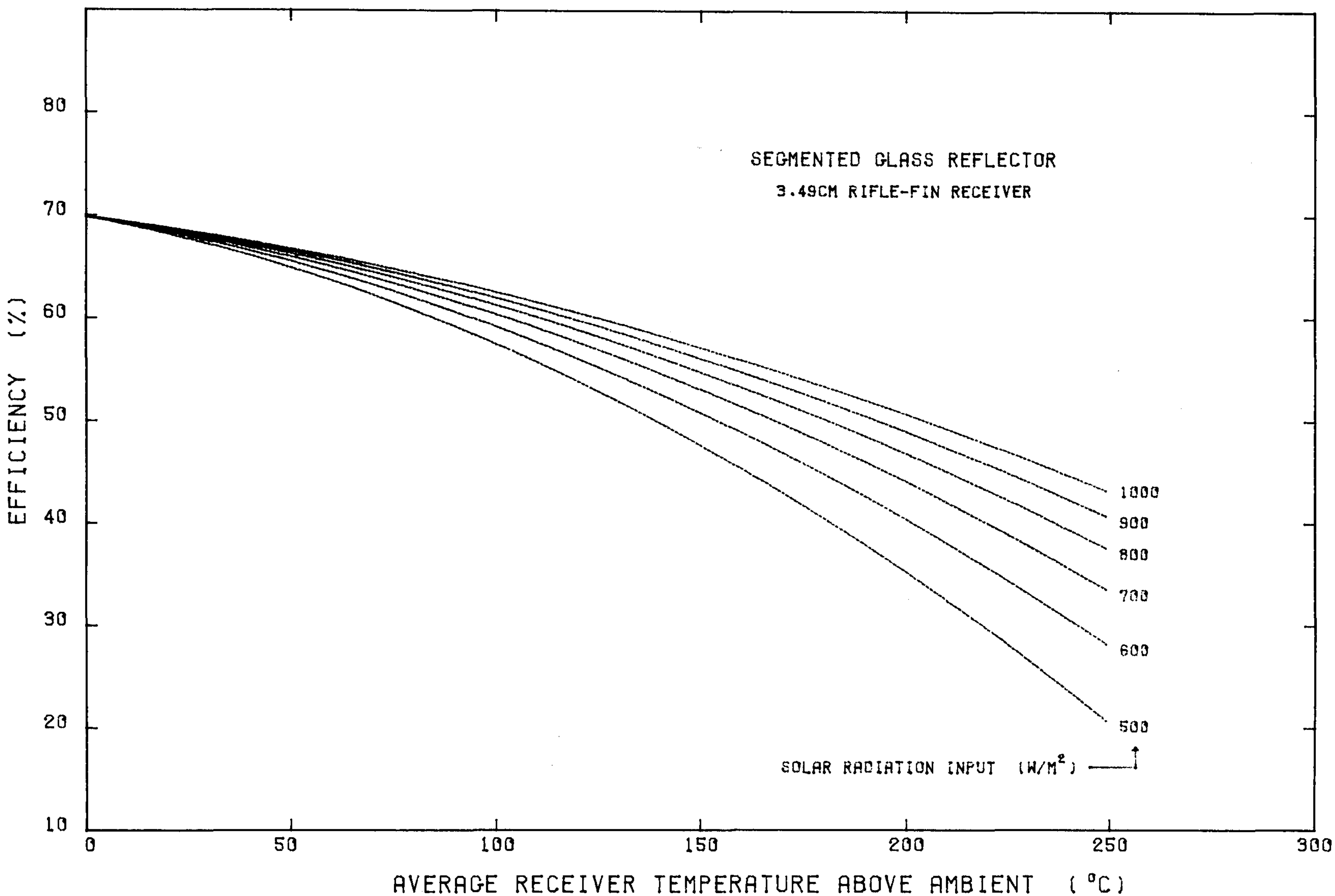

FIGURE 27 TOLTEC TI-410 EFFICIENCY VS TEMPERATURE AND INSOLATION

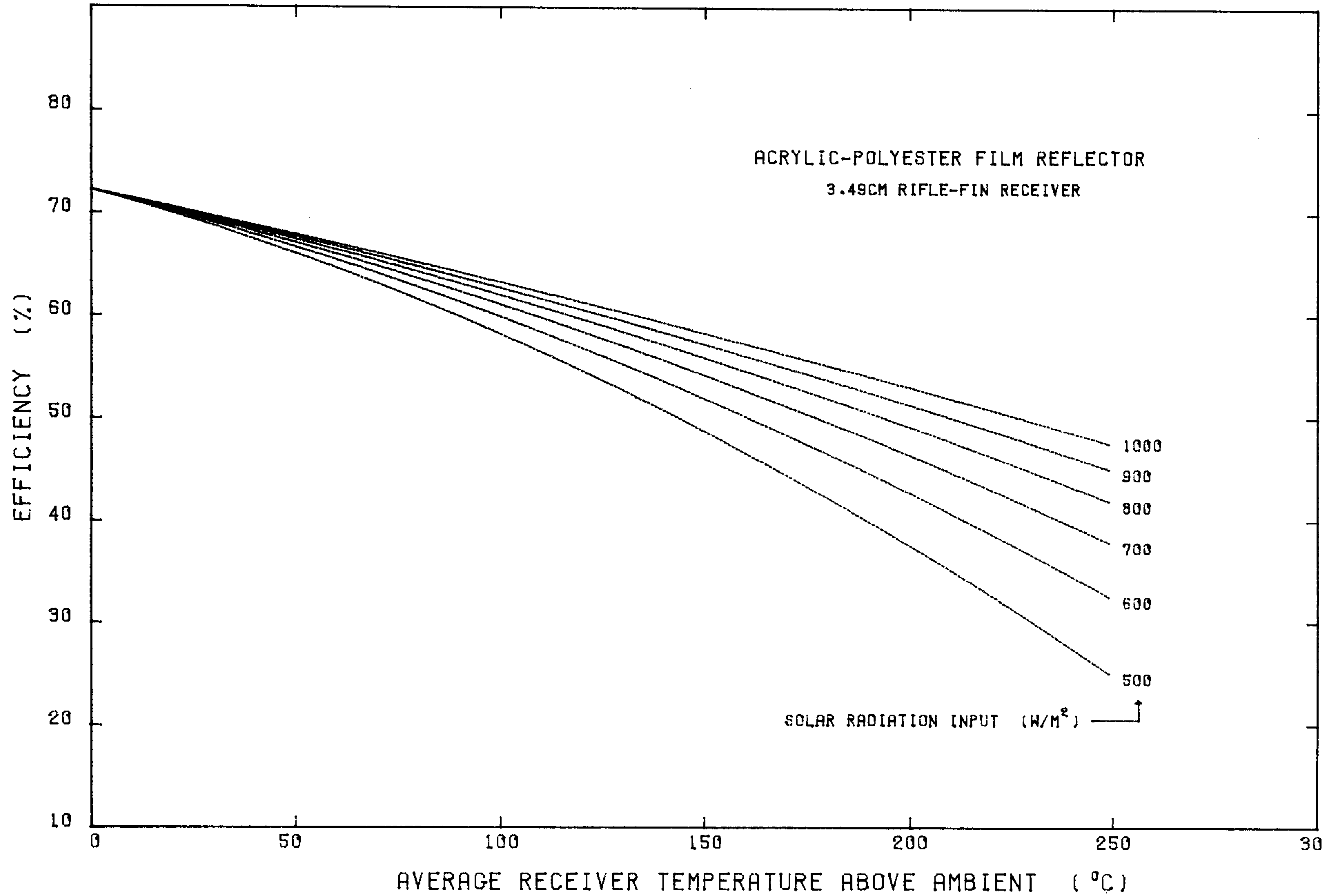

FIGURE 28 TOLTEC TI-410 EFFICIENCY VS TEMPERATURE AND INSOLATION

Self-shadowing of a collector array must also be considered in determining the total energy recovery from the array. Self-shadowing of the Toltec array was not evaluated during the CMTF test series because of mechanical rotation limits on the test array. These rotational limits would not be the same in an operational collector system, and the collector could track the sun for a longer period of time. During the CMTF test series, shadowing of one trough by an adjacent trough was just beginning at about three hours from solar noon. The amount of shadowing, and thus the reduction in total collector array output per day, would change with time-of-day and day-of-year. Self-shadowing effects were not considered in developing the annual power output curves shown in Reference 5.

SUMMARY OF RESULTS AND CONCLUSIONS

The acrylic-polyester film mirror outperformed the segmented-glass reflectors during testing of the Toltec collector. The glass had a better surface reflectivity (about 0.95 vs. about 0.86 for the YS-91 film), but the film reflector had a more accurate parabolic contour, thus placing more reflected light on the absorber tube. The collector focus was visually better when using the film reflectors, and the measured efficiency at ambient temperature was higher. The glass mirror contour error was not a problem over the whole mirror surface; most of the spilled light came from the outer three mirror segments along each edge of the reflector trough. The film reflector also showed some distortion along the edges, but the area was much narrower.

The origin of the glass reflector contour error is believed to be in the materials and procedures used in laying up the glass fiber substrate, rather than in a basic error in the mold contour. Because of a materials shortage, the glass reflectors were made up using a substitute resin. The resin used cured at a higher temperature than usual, causing more material shrinkage and edge distortion. The resin also tended to slump slightly during the cure, causing the edges to thicken, compounding the temperature problem. After identifying the problem, Toltec has since constructed more glass reflectors using the proper resin. Laser ray-trace measurements on the latest production mirrors indicates that the edge distortion problem has been substantially reduced.

The counterflow receiver and the open-tube receivers had the same outside diameter (2.86cm) and similar optical efficiencies. However, the slope of the efficiency curves with temperature was different, indicating that the counterflow receiver had slightly less thermal loss. Thermal loss tests failed to confirm any difference in thermal loss between the two receivers. The counterflow design exhibited high pressure losses at all temperatures, probably because of the small diameter of the inner tube. A fluid flow velocity high enough to ensure turbulent flow along the heated absorber walls was difficult to achieve at low temperatures with Therminol 66 without exceeding the pressure limitations of the copper tubing. This problem could be eased by enlarging the inner tube to equalize the cross-sectional area available for fluid flow.

The 3.49cm diameter rifle-finned receiver design produced the best efficiency measurements with both the glass and film reflectors; this was expected, since it also was the largest diameter, largest target for focused light. The smaller 2.54cm rifle-finned receiver worked almost as well as the larger one, showing about two percentage points less efficiency with cold water and no measurable penalty at 200^{o}C. The only disadvantage of the finned absorber tube would be the possible higher cost of forging the finned tubing.

All of the efficiency curves are summarized in Figures 29 and 30. These curves show a slightly larger slope with temperature than that seen on some other, much larger aperture collectors. This is consistent with the observed ratio of aperture area to absorber surface area.

Overall, the Toltec collector performed very well. The low temperature efficiency was excellent -- one of the highest efficiencies we have measured with a film reflector surface. Future production samples of the glass reflector design should have little of the edge distortion identified during this test series. Efficiency with the glass reflectors should then be even higher than that measured with the film reflectors.

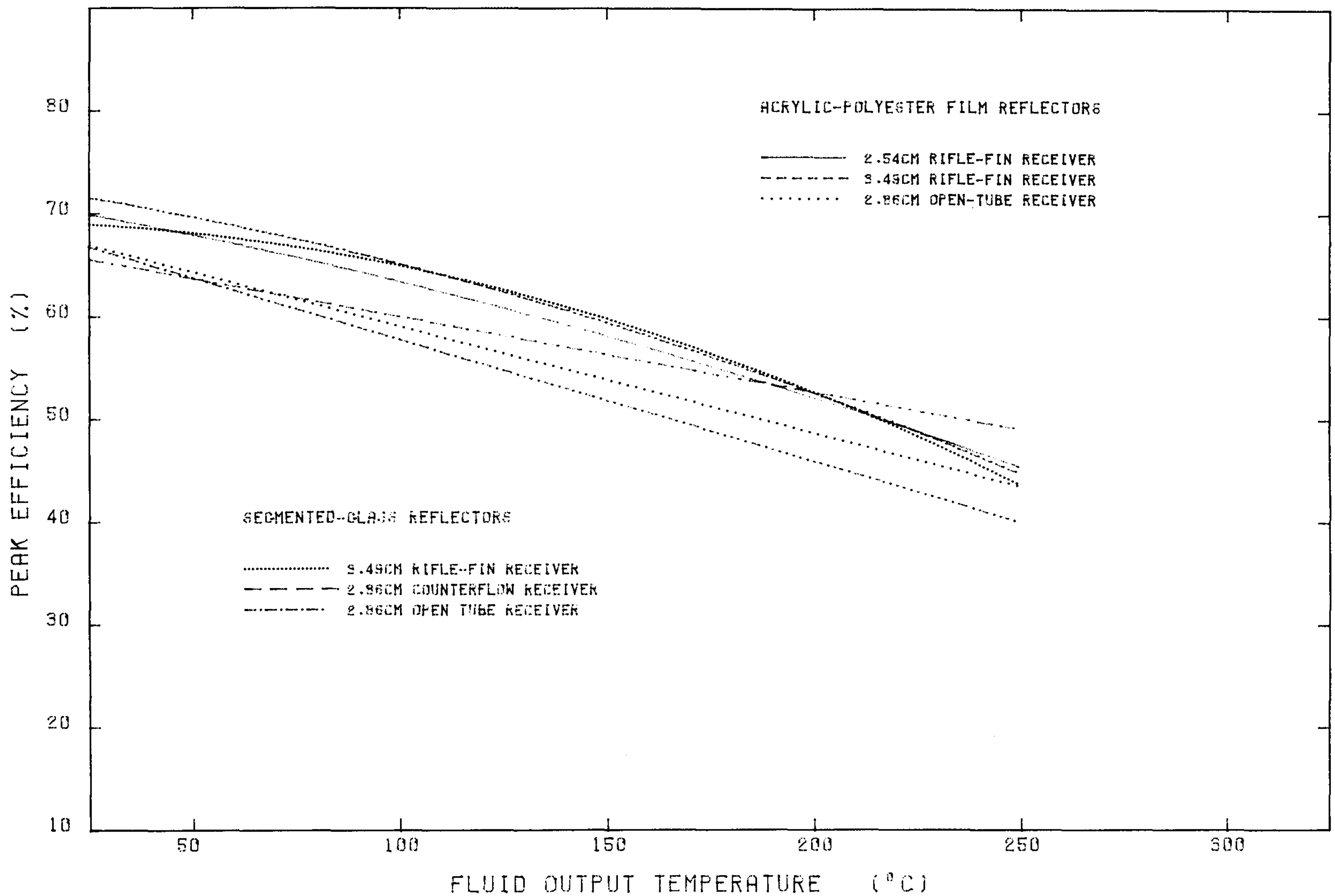

FIGURE [illegible] TOLTEC TI-410 EFFICIENCY VS OUTPUT TEMPERATURE

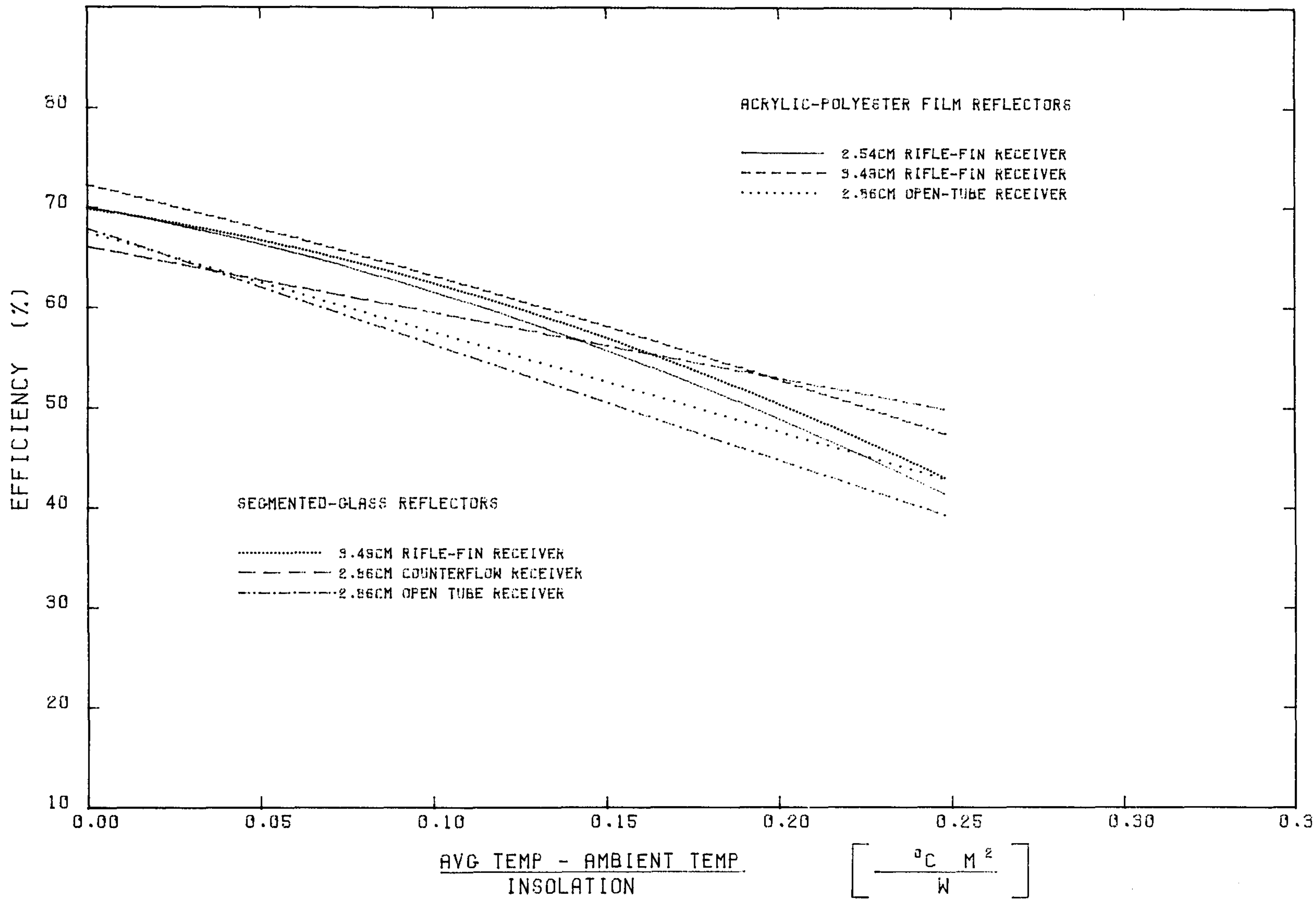

FIGURE 30 TOLTEC TI-410 EFFICIENCY VS DELTA T / I

Appendix 1

Collector Module Information Sheet

Manufacturer:	Toltec Industries, Inc. Clear Lake, Iowa 50428
Model:	TI-410
Operating Temperature:	100-200^{o}C
Configuration Tested:	Four Parabolic Trough Array
Module Size: (one trough)	116.8 x 304.8cm (46" x 120")
Aperture: (one trough)	2.99m^2 (32.2 ft^2).
Module Construction:	Steel Tube Framework Glass Fiber Reflector Inserts
Rim Angle:	85^{o}
Reflector:	(1) Silvered, Segmented Glass (2) Aluminized, Acrylic-Polyester Film (3M YS-91A)
Focal Length:	27.9cm (11")
Concentration Ratio:	40:1 (2.54cm OD absorber) 29:1 (3.49cm OC absorber)
Receiver:	Black Chrome Plated Copper Absorber Corning Borosilica Pyrex Glass Cover Counterflow Design (1) 2.86cm OD outer tube, 1.59cm inner tube Direct Flow Design (2) 2.86cm OD, Smooth inner surface (3) 2.54cm OD, Finned inner surface (4) 3.49cm OD, Finned inner surface
Sun Tracking:	Alta-azimuth collector mounting Two shadow-band sun sensors 100^{o} trough rotation travel 45^{o} trough elevation travel
Tracking Drive System:	12vdc motors Worm/Gear/Screwjack

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