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DOE/NASA CONTRACTOR
REPORT

DOE/NASA CR-161305

INDOOR TEST FOR THERMAL PERFORMANCE OF THE G. E. TC-100 LIQUID SOLAR COLLECTOR EIGHT- AND TEN-TUBE CONFIGURATION

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Solar Energy

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1.0 PURPOSE

The purpose of this document is to present the test proce-
dures used during the performance of an evaluation test
program. The test program was established to obtain therm-
al performance data on the General Electric TC-100 eight
tube and ten tube liquid solar collectors under simulation
conditions. Each of the collectors was tested with and
without the manufacturer's accessory manifold. The test
program was accomplished by utilizing the MSFC Solar Simu-
lator in accordance with the test requirements specified
in Reference 2.1 and the procedures contained in Reference
2.2, except where noted in the test procedure to accommodate
the unique requirements of vacuum tube collectors.

2.0 REFERENCES

2.1 ASHRAE 93-77   Method of Testing to Determine the
                          Thermal Performance of Solar Collectors

2.2 MTCP-FA-SHAC-400   Procedure for Operation of the MSFC
                          Solar Simulator Facility

3.0 COLLECTOR DESCRIPTION

Manufacturer:	General Electric
Manufacturer's Address:	P. O. Box 13601 Philadelphia, PA 19101
Model Number:	TC-100 (8 tube, 10 tube)
Serial Number:	8 Tube (19965S), 10 tube (Dwg. 298E44261, Ser. 2)
Reflector Mat'l:	Coilzac (10 tube); Alglas (8 tube)
Type:	Evacuated tube, with and without manufacturer's accessory manifold
Working Fluid:	35% (volume) Prestone and water
Gross Collector Area, Ft^2:	17.41 (without manifold) 19.10 (with manifold)
Overall external dimensions:	Width, inches: 48.0 Length, inches: 57.25 (with manifold), 52.50 (without manifold) Thickness, inches: 3.25 Aperture area, Ft^2: 15.80
Collector Glazing:	Evacuated tube
Weight, lbs:	Empty - 60; Full - 62; Manifold - 15

4.0 SUMMARY

This test program was performed to evaluate the thermal performance of the G.E. TC-100 eight and ten evacuated tube collectors, under simulated conditions. The ten tube collector, the predecessor of the eight tube collector, has a vee-trough reflector, and the eight tube collector has a parabolic trough reflector. Schematics of the ten and eight tube collectors are shown in Figures 1 and 2, respectively. The test conditions and the data obtained during the test program are listed in Tables I and II for the stagnation test results, with graphic presentations in Figures 3 and 4, respectively. Tables III and IV contain the data obtained for the thermal efficiency test results of the ten and eight tube configurations, respectively. The standard installation usage of the G.E. TC-100 collectors is without a cover, but due to special requirements in high vandalism areas the ten tube collector was tested with an acrylic cover plate and with a lexan cover plate to determine their effects on thermal efficiency. These results are presented in Table V for the acrylic and lexan covers. Figure 5 is a graphic comparison of the ten tube thermal efficiency with and without the coverplates. Figures 6 and 7 are graphical presentations of the ten and eight tube collectors with and without the accessory manifold. Figures 8 and 9 provide the thermal efficiency as a function of inlet temperature for the ten and eight tube collectors, respectively. Time constant and incident angle modifier tests were performed to determine the transient effects of time varying solar insolation on collector performance. The results of these tests are shown in Figures 10 and 11 for the time constant and incident angle modifier tests, respectively.

Normally, a nine point flux map is determined for a collector tested by a lamp array, but in the case of evacuated tubes, each tube works as an independent flat plate; therefore, three flux levels were taken for each tube. Typical flux maps are shown in Figures 12 and 13 for the ten and eight tube collectors, respectively. A comparison of the ten and eight tube thermal efficiencies with the manifold are shown in Figure 14.

In comparison, the eight tube configuration, which supercedes the ten tube, has a parabolic reflector which performs well at normal incidence angles (Figure 14) but is less efficient at angles larger than 20° (Figure 11); in fact, it is less effective at these angles than the original ten tube Vee-trough reflector, as shown in Figure 11. This effect on projected all day performance is evident from comparison of data in Tables VIII and IX.

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5.0 TEST CONDITIONS AND TEST EQUIPMENT

5.1 Ambient Conditions

All tests will be performed at ambient conditions existing in MSFC Building 4619 at the time of the tests.

5.2 Instrumentation and Equipment

All test equipment and instrumentation to be used in the performance of this test program will comply with the requirements of MSFC MMI 5300.4C, Metrology and Calibration. A standard test setup is depicted in Reference 2.2.

Apparatus	Manufacturer/Model	Range/Accuracy
Liquid Loop	MSFC Supplied	0.1 - 1.12 GPM
Flowmeter	Foxboro/$^1/_2$ - 2 81T361	0.1 - 1.2 GPM $\pm$ 1%
Platinum Resistance Thermometer	Hycal	0 - 500°F $\pm$ 0.1°F
Pressure Sensor	MSFC Supplied	0 - 5.0 PSI $\pm$ 2%
Pyranometer	Eppley - PSP	0 - 800 BTU/Ft^2·Hr (Class 1)
Fans	MSFC Supplied	N/A
Digital Printer	Doric - Digitrend 220	5 - 500 MV $\pm$ 2%
Solar Simulator	MSFC Supplied	See Reference 2.2
Pressure Gauge	U. S. Gauge Co./Ashcroft	0 - 60 PSIG $\pm$ 1 PSI

6.0	TEST REQUIREMENTS AND PROCEDURES

6.1   Collector Preconditioning and Stagnation Test

6.1.1   Requirement

The collector shall be mounted on an outdoor passive
test stand at an angle of 45° from the horizontal and
facing south. The inlet and outlet ports to the col-
lector shall be capped to prevent flow. The upper cap
shall contain a small vent hole. The preconditioning
shall consist of at least three days exposure during
which the mean incident solar radiation measured in
the plane of the collector shall be 1500 $BTU/Ft^2 \cdot day$.
During this preconditioning, the following data shall be
recorded within two hours of solar noon when the insola-
tion is constant and above a minimum of 200 $BTU/Hr \cdot Ft^2$
in the plane of the collector. Data recorded shall be
the average for at least a 20-minute period at quasi-
steady state conditions.

1. Insolation rate.

2. Ambient temperature.

3. Wind velocity and direction.

4. Absorber surface temperature at either 4 or 5 loca-
   tions.

6.1.2   Procedure

1. Mount test specimen as described above.

2. Connect instrumentation.

3. Record data as described above.

6.1.3   Results

Preconditioning of the G.E. TC-100 collectors was not re-
quired, as each had been previously exposed for more than
three days. The stagnation tests were not performed in
the usual outdoor manner but were accomplished utilizing
the solar simulator. This provided a transient tempera-
ture history profile for the tubes at a constant flux of
300 $BTU/Hr-Ft^2$. The steady state results obtained during
these tests are contained in Tables I and II for the ten
and eight tube configurations, respectively. The respective
transient temperature history profiles are presented in
Figures 3 and 4.

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6.0   TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2   Collector Time Constant Test

6.2.1   Requirements

The collector time constant shall be determined by
abruptly reducing the solar flux to zero. This will
be done with the inlet temperature adjusted to within
+ 2°F of ambient while the liquid is flowing at 0.22
GPM, which is the manufacturer's recommended flowrate.

The differential temperature across the collector shall
be monitored to determine the time required to reach
the condition of:

$$\frac{\Delta T(t)}{\Delta T_i} = .368$$

where $\Delta T(t)$ is the differential temperature at time t
after the solar flux is reduced to zero and ΔT_i is the
differential temperature prior to the power down of the
solar simulator. The liquid to be used as the collector
heat transfer medium shall be as specified by the manu-
facturer. If this liquid is not specified, use water as
the fluid.

The following data will be recorded for the test:

(1)   Solar flux.
(2)   Ambient temperature.
(3)   Inlet liquid temperature.
(4)   Collector differential temperature.
(5)   Liquid flow rate.
(6)   Specified heat transfer medium.

6.2.2   Procedure

1.   Adjust the liquid flow rate to .22 GPM.*

2.   Adjust the inlet temperature to ambient $\pm$ 2°F.

3.   Power up the solar simulator and establish a solar
      flux level of 300 BTU/Ft^2·Hr.

4.   Establish wind speed of 7.5 mph.

5.   Record data for five minutes at above stabilized
      conditions.

6.   Power down solar simulator.

7.   Record the change of ΔT across the collector.

* This is the manufacturer's recommended flowrate
  for the collector.

6.0   <u>TEST REQUIREMENTS AND PROCEDURES</u> (Continued)

6.2.3   <u>Results</u>

The results obtained during the time constant tests are
shown in Figure 10. The average insolation was approxi-
mately 265 BTU/Hr-Ft^2 for the ten tube test and approxi-
mately 295 BTU/Hr-Ft^2 for the eight cube test. The eight
tube collector was tested with the manifold and the ten
tube collector was tested without the manifold.

6.0   TEST REQUIREMENTS AND PROCEDURES (Continued)

6.3   Collector Thermal Efficiency Test

6.3.1 Requirements

Utilizing the MSFC Solar Simulator and the portable closed
liquid loop, parametric performance evaluation data shall
be recorded of the following test variables and conditions.
The liquid to be used is the manufacturer's recommended
heat transfer fluid. The test shall be performed using a
mixture of 35% glycol by volume as the working fluid.

Variable/Condition	Requirement Guideline
1. Collector inlet liquid temperature differential above existing ambient temperature level	0°F, 50°F, 100°F, 150°F, 200°F
2. Collector outlet liquid temperature	Measured data
3. Incident solar flux level liquid	250, 300 BTU/Hr·Ft^2 °F
4. Liquid flow rate through collector	0.22 GPM
5. Wind speed	7.5 MPH
6. Ambient air temperature	Existing room condition
7. Pressure	Sufficient to prevent boiling

6.3.2 Procedure

1. Mount test specimen on test table at a 45° angle with
   reference to the floor.

2. Assure that simulator lamp array is adjusted to an
   angle of 45° with reference to the floor.

3. Using the procedure contained in Reference 2.2, align
   the test table so the test specimen's vertical center-
   line coincides with the vertical centerline of the
   lamp array and the distance from the top of the test
   specimen to the lens plane of the lamp array is 9 feet.

4. Insulate all liquid lines.

5. Connect instrumentation leads to data acquisition system.

6. Assure that data acquisition system is operational.

7. Perform sensor accuracy verification tests.

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6.0   TEST REQUIREMENTS AND PROCEDURES (Continued)

6.3   Collector Thermal Efficiency Test (Continued)

6.3.2   Procedure (Continued)

8.   Establish required wind speed.

9.   Start liquid flow loop and establish the required flow rate.

10. Establish the required inlet temperature.

11. Power up solar simulator in accordance with Reference 2.2 and establish the required solar flux level. Take a flux reading at top, middle and bottom of each tube.

12. Record data for a minimum of five minutes at these stabilized conditions.

13. Repeat Steps 9 through 12 as necessary to complete all the required test conditions.

14. Upon completion of testing, power down simulator and liquid loop in accordance with Reference 2.2.

6.3.3   Results

The results of the thermal efficiency tests are shown in Tables III through V and are presented graphically in Figures 5 through 9.

6.0   TEST REQUIREMENTS AND PROCEDURES (Continued)

6.4   Incident Angle Modifier Test

6.4.1   Requirements

The collector incident angle modifier shall be determined by tilting the collector at 0°, 10°, 20°, 30°, 40°, and 50° with respect to the solar simulator surface. The liquid flow rate shall be 0.22 + 0.002 GPM with the inlet temperature controlled to within + 2°F of ambient. The insolation rate shall be 300 BTU/Ft$^2 \cdot$Hr. The liquid to be used is the manufacturer's recommended fluid. If not specified, the tests shall be performed using water as the heat transfer medium. The following data shall be recorded during the tests.

(1)   Collector tilt angles.

(2)   Ambient air temperature.

(3)   Collector inlet liquid temperature.

(4)   Collector outlet liquid temperature.

(5)   Collector differential temperature.

(6)   Collector differential pressure.

(7)   Incident solar flux level.

(8)   Liquid flow rate through the collector.

6.4.2   Procedure

1.   Set up collector at required tilt angle.

2.   Establish required flowrate.

3.   Establish required inlet temperature.

4.   Establish solar simulator flux level at 300 BTU/Ft$^2 \cdot$Hr and measure the flux levels at 3 locations on each tube and record on data sheet.

5.   Record data for five minutes at above stabilized conditions.

6.   Repeat above steps as necessary to obtain required data for each tilt angle.   .

6.4.3   Results

The results of the incident angle modifier tests are presented in Tables VI and VII and are shown graphically in Figure 11.

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7.0   <u>ANALYSIS</u>

7.1   <u>Thermal Performance Test</u>

The analysis of data contained in this report is in accordance with the National Bureau of Standards recommended approach. This approach is outlined below.

The efficiency of a collector is stated as:

$$\eta = \frac{q_u/A}{I} = \frac{\dot{m}\, C_{tf}\, (t_{f,e} - t_{f,i})}{I} \qquad (1)$$

where:

q_u = rate of useful energy extracted from the Solar Collector (BTU/Hr)

A = Gross collector area (Ft^2)

I = Total solar energy incident upon the plane of the solar collector per unit time per unit area ($BTU/Hr \cdot Ft^2$)

$\dot{m}$ = Mass flow rate of the transfer liquid through the collector per unit area of the collector ($Lbm/Ft^2 \cdot Hr$)

C_{tf} = Specific heat of the transfer liquid ($BTU/Lb \cdot °F$)

$t_{f,e}$ = Temperature of the transfer liquid leaving the collector (°F)

$t_{f,i}$ = Temperature of the transfer liquid entering the collector (°F)

Rewriting Equation (1) in terms of the total collector area yield:

$$\eta = \frac{(\dot{m}A)\, C_{tf}\, (t_{f,e} - t_{f,i})}{(IA)} = \frac{\dot{M}\, C_{tf}\, (t_{f,e} - t_{f,i})}{P_i} \qquad (2)$$

Notice that:

$P_i = IA$ = Total Power Incident on the Collector.

$\dot{m}A = \dot{M}$ = Total Mass Flow Rate through the Collector.

Therefore, $\dot{M}\, C_{tf}(t_{f,e} - t_{f,i})$ = Total Power Collected by the Collector.

7.0　　　ANALYSIS (Continued)

7.1　　　Thermal Performance Test (Continued)

Substitution in Equation (2) results in:

$$\eta = \frac{Pabs}{Pinc} \tag{3}$$

where:

Pabs = Total collected power

Pinc = Total incident power

This value of efficiency is expressed as a percentage by multiplying by 100. This expression for percent efficiency is:

$$\text{Collector Efficiency} = \frac{Pabs}{Pinc} \times 100 \tag{4}$$

or, from Equation (2), collector efficiency is defined by the equation:

$$\% \text{ Eff.} = \frac{\dot{M}\, C_{tf}\, (t_{f,e} - t_{f,i})}{Pi} \times 100 \tag{5}$$

Each term in Equation (5) was measured and recorded independently during the test. The calculated values of efficiency were determined at sixty-second intervals. The mean value of efficiency was determined over a five-minute period during which the test conditions remained in a quasi-steady state. Each five-minute period constitutes one "data point" as is graphically depicted on a plot of percent efficiency versus

$$\left((t_i - t_a)/I \right)$$

where:

t_i = Liquid inlet temperature (°F)

t_a = Ambient temperature (°F)

I = Incident flux per unit area (BTU/Hr·Ft^2)

The abscissa term $\left((t_i - t_a)/I \right)$ was used to normalize the effect of operating at different values of I, t_i and t_a.

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7.0   ANALYSIS (Continued)

7.1   Thermal Performance Test (Continued)

Thermal performance tests were conducted for both the
ten and eight tube configurations with and without the
manufacturer's accessory manifold. Results for these
tests are presented in Figures 6 through 9. The secon~
order polynomial to best describe the test results is
given by:

$$\text{Efficiency} = a_0 + a_1 \tau + a_2 \tau^2$$

where:

$$\tau = (T_i - T_a)/I$$

The coefficients are listed below for the respective
configuration:

Flow Rate = 0.22 GPM

Ten Tube	Without Manifold	With Manifold
a_0	0.479	0.398
a_1	-0.191	-0.145
a_2	-0.061	0.000

Eight Tube	Without Manifold	With Manifold
a_0	0.432	0.406
a_1	-0.078	-0.105
a_2	0.000	-0.030

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7.0   ANALYSIS (Continued)

7.2   Time Constant Test

Two methods are proposed by ASHRAE 93-77 for conducting a time constant test; however, due to facility limitations, only the first method could be used. This method consisted of shutting down the simulator and maintaining a constant flow rate and inlet temperature while obtaining data.

According to the definition of time constant given in 93-77, it is the time required for the ratio of the differential temperature at time τ to the initial differential temperature to reach .368. It can be expressed as:

$$\frac{T_{f,e,\tau} - T_{f,i}}{T_{f,e,ini} - T_{f,i}} = .368 \qquad (1)$$

If the inlet liquid temperature cannot be controlled to equal the ambient air temperature, then the following equation must be used

$$\frac{F_R U_L \ (T_{f,i} - T_a) + \dfrac{\dot{m} C_p}{A_g} \ (T_{f,e,\tau} - T_{f,i})}{F_R U_L \ (T_{f,i} - T_a) + \dfrac{\dot{m} C_p}{A_g} \ (T_{f,e,ini} - T_{f,i})} = .368 \qquad (2)$$

where:

$T_{f,e,\tau}$	Exit liquid temperature at time τ
$T_{f,i}$	Inlet liquid temperature
$T_{f,e,ini}$	Initial exit liquid temperature
$\dot{m}$	Liquid mass flow rate, Lb/Hr
C_p	Specific heat of liquid, BTU/Lb·°F
A_g	Gross collector area, Ft^2
$F_R U_L$	Negative of the slope determined from the thermal efficiency curve

The inlet temperature was maintained within ± 2°F of the ambient, hence equation (1) was used for evaluation. From Figure 10 the time constant was determined to be . 4 minutes and 16 seconds for the ten tube and 4 minutes and 35 seconds for the eight tube collector.

7.0   ANALYSIS (Continued)

7.3   Incident Angle Modifier Test

Two methods are proposed by ASHRAE 93-77 for incident
angle modifier tests. For the MSFC Solar Simulator
Facility, only method 1 (tilting the collector) is
applicable. The collector was adjusted so that the
incident radiation angles were 0°, 10°, 20°, 30°, 40°,
and 50° to the normal of the collector surface. The
collector was too large to tilt 60°.

According to 93-77, the incident angle modifier is de-
fined as

$$K_{\alpha T} = \frac{\eta}{F_R(\alpha\tau)n} \tag{1}$$

where η = efficiency at tilted angle.

$F_R(\alpha\tau)n$ = Intercept of efficiency curve
at normal incident angle

For equation (1) to be applicable, the inlet liquid temp-
erature must be controlled to within $\pm$ 2°F of the ambient
air temperature. In cases where the inlet liquid tempera-
ture cannot be controlled to within $\pm$ 2°F, the following
equation must be used to evaluate the incident angle
modifier.

$$K_{\alpha T} \frac{\eta + F_R U_L \dfrac{T_{f,i} - T_a}{I}}{F_R(\alpha\tau)n} \tag{2}$$

where

$F_R U_L$ is the negative of the slope determined
from the thermal efficiency curve.

Tables VI and VII show that the inlet liquid temperatures were
not all within $\pm$ 2°F of ambient air temperature. Hence,
equation (2) was used for evaluation.

Appropriate values of $F_R \alpha T$ and $F_R U_L$ were used for the ten
and eight tube configurations. The results of these compu-
tations are shown plotted against incident angle in Figure
11.

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7.0   ANALYSIS (Continued)

7.3   Incident Angle Modifier Test (Continued)

The purpose of the incident angle modifier is to allow
a designer or analyst to predict the total daily energy
output from the collector, as the sun tracks from east
to west. Most collectors are more efficient at normal
incidence than at other angles, but some are even more
efficient at angles other than normal. The only common
ground for comparing collectors should be the "all day
efficiency" rather than $F_R \alpha \tau$. However, the prospective
application of the collector also influences the value
of "all day efficiency." That is, for low temperature
applications such as space heating or domestic hot water,
a typical flat plate collector may have an all day effi-
ciency of 40%, but for solar cooling applications the
all day efficiency might be 20%. Therefore, criteria
should be established to rate each collector for space
heating, domestic hot water, and solar cooling at a
nominal location, because efficiencies are also dependent
on outdoor ambient temperatures.

Evacuated tubes are effective for solar cooling applica-
tions; therefore, according to the procedure in NBSIR
78-1305A the all day efficiency of the ten tube collector
is 28 per cent and 26 per cent for the eight tube col-
lector for a typical solar cooling application. The
selected site dependent data in conjunction with test
data used in these determinations is shown in Tables
VIII and IX. No standard criteria has been established
for "all day efficiency"; and these calculations are de-
pendent on system operating parameters, site data, time
of year and daily weather; therefore, the above informa-
tion should be viewed as interesting but not conclusive.

TABLE I

G.E. TC-100 TEN TUBE STAGNATION TEMPERATURES

(See Figure 3)

TUBE NO.	2	2	2	7	7	7	9	9	9
SENSOR LOCATION	A	B	C	A	B	C	A	B	C
INSOLATION BTU/HR·FT^2	329.8	287.0	310.4	309.2	291.4	313.1	314.7	315.5	298.8
TEMP. °F NO COVER	640	651	556	525	534	456	614	614	614

NOTE: Tube #7 was interchanged with tube #2 and was found to produce noticeably lower temperatures in that position also. Performance data reported for the ten tube collector may be somewhat lower than normal if tube #7 is determined to be low on collection capacity.

TABLE II

G.E. TC-100 EIGHT TUBE COLLECTOR
STAGNATION TEMPERATURES

(See Figure 4)

Tube No.	1	1	1	8	8	8
Sensor Location	A	B	C	A	B	C
Insolation BTU/Hr-Ft^2	314.7	275.6	292.0	277.9	285.3	277.9
Temperature °F	499.9	599.6	601.6	529.5	645.1	663.4

TABLE III

THERMAL PERFORMANCE TEST DATA FOR THE G.E. TC-100 TEN TUBE COLLECTOR WITHOUT ACCESSORY MANIFOLD

Ambient Air Temperature (T_a), °F	73.2	76.9	74.4	77.4	78.5	75.6	75.1	83.3	79.2	76.6	77.0	79.8	72.0	78.0	85.6	80.1
Fluid Inlet Temperature (T_i), °F	87.4	86.7	88.5	83.0	91.3	100.8	100.8	123.5	128.3	125.7	125.7	154.0	147.1	150.9	151.5	179.9
Fluid Outlet Temperature (T_e), °F	106.9	108.5	111.8	109.2	111.5	119.8	123.4	142.9	146.3	143.8	148.1	171.2	164.7	172.5	169.3	195.8
Differential Fluid Temperature (ΔT), °F	19.5	21.8	23.3	26.2	20.2	19.0	22.6	19.4	18.0	18.1	22.4	17.2	17.6	21.8	17.8	15.9
Total Solar Flux (I), BTU/Hr·Ft2	248.4	246.3	298.2	299.1	249.5	246.2	299.3	249.5	248.2	246.2	299.3	246.2	247.5	299.3	249.5	246.2
Flow Rate, GPM	0.228	0.221	0.227	0.220	0.221	0.228	0.228	0.231	0.223	0.228	0.226	0.234	0.224	0.218	0.221	0.233
$(T_i-T_a)/I$, °F·Hr·Ft2/BTU	.06	.04	.05	.02	.05	.10	.09	.160	.198	.16	.20	.301	.30	.24	.26	.406
Efficiency (η), %	45.7	49.9	45.3	49.2	46.2	45.5	45.1	45.3	44.1	44.2	43.8	42.9	41.8	41.7	41.2	39.7

TABLE III (Continued)

THERMAL PERFORMANCE TEST DATA FOR THE G.E. TC-100 TEN TUBE
COLLECTOR WITH ACCESSORY MANIFOLD

Ambient Air Temperature (T_a), °F	88.8	89.0	82.2	82.3	78.3
Fluid Inlet Temperature (T_i), °F	116.6	144.2	174.7	82.3	81.6
Fluid Outlet Temperature (T_e), °F	139.0	165.1	194.6	105.4	104.2
Differential Fluid Temperature (ΔT), °F	22.4	20.9	19.9	22.6	22.6
Total Solar Flux (I), BTU/Hr·Ft2	296.4	296.4	296.4	299.2	301.2
Flow Rate, GPM	0.22	0.22	0.22	0.23	0.23
$(T_i-T_a)/I$, °F·Hr·Ft2/BTU	0.094	0.186	0.312	0.002	0.011
Efficiency (η), %	38.7	36.9	35.5	40.0	39.8

TABLE IV

THERMAL PERFORMANCE TEST DATA FOR THE G.E. TC-100 EIGHT TUBE
COLLECTOR WITH ACCESSORY MANIFOLD

Ambient Air Temperature (Ta), °F	85.8	82.9	80.1	79.4	78.4	77.2	76.0	81.8
Fluid Inlet Temperature (Ti), °F	246.7	194.2	155.6	129.9	113.3	80.0	80.1	82.3
Fluid Outlet Temperature (T_e), °F	264.1	211.9	173.4	148.3	132.4	100.2	103.3	105.4
Differential Fluid Temperature (ΔT), °F	17.4	17.7	17.8	18.4	19.1	20.2	23.2	23.1
Total Solar Flux (I), BTU/Hr·Ft²	267.1	267.1	252.6	252.6	252.6	252.6	291.2	295.2
Flow Rate, lb/min.	1.80	1.85	1.85	1.87	1.90	1.94	1.85	1.85
($T_i - T_a$)/I °F·Hr·Ft²/BTU	.602	.417	.299	.200	.138	.011	.014	.002
Efficiency (η), %	34.1	35.3	36.9	38.1	39.8	42.2	48.5	39.5

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TABLE IV (Continued)

THERMAL PERFORMANCE TEST DATA FOR THE G.E. TC-100 EIGHT TUBE
COLLECTOR WITH ACCESSORY MANIFOLD

Ambient Air Temperature (T_a), °F	76.7	77.1	77.5	77.9	77.6	78.7	78.4	81.5	84.7
Fluid Inlet Temperature (T_i), °F	106.1	109.2	131.1	128.2	144.5	151.9	197.8	250.3	281.3
Fluid Outlet Temperature (T_e), °F	128.2	131.8	152.8	150.6	165.7	173.2	217.7	268.7	296.3
Differential Fluid Temperature (ΔT), °F	22.1	22.6	21.7	22.4	21.2	19.2	19.9	18.4	15.0
Total Solar Flux (I), BTU/Hr·Ft²	291.2	298.1	291.2	298.1	291.2	298.1	291.2	297.9	267.1
Flow Rate, lb/min.	1.90	1.85	1.87	1.80	1.87	1.84	1.87	1.80	1.80
$(T_i - T_a)/I$ °F·Hr·Ft²/BTU	.101	.108	.184	.169	.230	.245	.410	.567	.736
Efficiency (η), %	39.8	38.8	38.2	37.9	38.4	37.2	36.7	32.3	30.4

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TABLE IV (Continued)

THERMAL PERFORMANCE TEST DATA FOR THE G.E. TC-100 EIGHT TUBE
COLLECTOR WITHOUT ACCESSORY MANIFOLD

Ambient Air Temperature (T_a), °F	74.0	77.8	82.8	84.3	87.2	81.9	83.2	80.3
Fluid Inlet Temperature (T_i), °F	82.2	149.2	204.2	252.5	250.6	203.9	150.1	85.2
Fluid Outlet Temperature (T_e), °F	102.5	168.2	221.6	269.8	272.1	227.0	173.1	111.0
Differential Fluid Temperature (ΔT), °F	20.3	19.0	17.4	17.3	20.5	23.1	23.0	25.8
Total Solar Flux (I), BTU/Hr.Ft^2	260.7	260.7	261.6	261.1	315.0	313.1	317.9	317.9
Flow Rate, lb/min.	1.83	1.83	1.90	1.80	1.80	1.70	1.83	1.75
$(T_i - T_a)/I$ °F·Hr·Ft^2/BTU	0.031	0.274	0.464	0.656	0.519	0.390	0.210	0.015
Efficiency (η), %	43.0	41.9	40.0	38.6	37.9	39.7	41.6	42.8

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TABLE V

THERMAL PERFORMANCE TEST DATA FOR THE G.E. TC-100 TEN TUBE COLLECTOR
WITHOUT ACCESSORY MANIFOLD FOR A LEXAN COVER AND AN ACRYLIC COVER

	With Lexan Cover					With Acrylic Cover				
Ambient Air Temperature (T_a), °F	79.6	83.1	85.7	79.0	84.2	80.2	82.2	85.7	78.5	84.7
Fluid Inlet Temperature (T_i), °F	91.1	123.5	151.7	175.8	242.0	91.1	123.7	151.7	175.8	242.8
Fluid Outlet Temperature (T_e), °F	110.1	140.4	167.2	190.9	252.4	109.5	141.0	167.8	190.7	253.5
Differential Fluid Temperature (ΔT), °F	19.0	16.9	15.5	15.1	10.4	18.4	17.3	16.1	14.9	10.7
Total Solar Flux (I), BTU/Hr·Ft2	249.5	249.5	249.5	249.5	249.5	249.5	249.5	249.5	249.5	249.5
Flow Rate, GPM	0.216	0.221	0.224	0.221	0.224	0.222	0.222	0.223	0.224	0.220
$(T_i-T_a)/I$ °F·Hr·Ft2/BTU	.05	.16	.26	.38	.65	.05	.16	.26	.38	.65
Efficiency (%), %	42.5	39.1	36.7	35.3	24.7	42.3	40.2	38.0	35.3	24.1

TABLE VI

INCIDENT ANGLE MODIFIER TEST DATA
FOR THE G.E. TC-100 TEN TUBE COLLECTOR

Angle	0°	10°	20°	30°	40°	50°
Ambient Air Temperature (T_a), °F	82.2	78.5	80.4	84.4	83.0	84.7
Fluid Inlet Temperature (T_i), °F	93.6	93.5	93.6	94.4	94.0	94.4
Fluid Outlet Temperature (T_e), °F	111.9	111.7	110.0	108.6	105.3	104.3
Differential Fluid Temperature (ΔT), °F	18.3	18.2	16.4	14.2	11.3	9.9
Total Solar Flux (I), BTU/Hr·Ft2	243.0	231.3	214.6	208.0	172.8	149.7
Flow Rate, GPM	0.230	0.227	0.226	0.226	0.223	0.225
Efficiency (η), %	44.7	46.4	44.6	39.9	37.7	38.4
Adjusted Efficiency Ratio $K_{\alpha\tau}$	.96	1.004	.965	.860	.821	.836

WITHOUT A COVER PLATE

TABLE VII

INCIDENT ANGLE MODIFIER TEST DATA
FOR THE G.E. TC-100 EIGHT TUBE COLLECTOR

Angle	0°	10°	20°	30°	40°	50°	0°	0°	0°
Ambient Air Temperature (Ta), °F	83.6	80.4	84.1	79.3	84.5	79.0	77.2	76.0	81.8
Fluid Inlet Temperature (Ti), °F	93.3	89.6	93.5	88.9	93.0	88.9	80.0	80.1	82.3
Fluid Outlet Temperature (Te), °F	117.3	111.4	114.3	104.3	105.3	98.4	100.2	103.3	105.4
Differential Fluid Temperature (ΔT), °F	24.0	21.8	20.8	15.4	12.3	9.5	20.2	23.2	23.1
Total Solar Flux (I), BTU/Hr·Ft²	290.2	289.8	274.1	249.3	220.7	181.2	252.6	291.2	295.2
Flow Rate, lb/min.	1.80	1.95	1.80	1.90	1.80	1.86	1.94	1.85	1.85
Efficiency (η), %	41.2	39.5	37.8	32.4	27.7	27.7	42.2	40.1	39.5
Adjusted Efficiency Ratio Kατ	1.025	0.983	0.942	0.810	0.695	0.683	1.040	0.990	0.970

TABLE VIII

G.E. TC-100 TEN TUBE CALCULATED ALL DAY EFFICIENCY

CALCULATION STEPS	HOUR OF THE DAY, SOLAR TIME												DAILY TOTAL
	6-7	7-8	8-9	9-10	10-11	11-12	12-1	1-2	2-3	3-4	4-5	5-6	
1. Inlet fluid temp. to collector, tf,i	185	185	185	185	188	190	193	197	200	200	200	200	
2. Ambient air temp., ta	73	74	79	82	86	90	92	93	94	94	92	90	
3. Incident radiation on collector plane, I_T (Table A2, ASHRAE 93-77)	6	60	132	197	249	281	292	281	249	197	132	60	2,144
3a. $T_{fi}-T_a/I_T$ (°F-Hr-Ft2/BTU)	18.0	1.85	.80	.52	.41	.36	.35	.37	.43	.54	.82	1.8	
4. Collector thermal efficiency at normal incidence, determined in accordance with Sections 8.3.2 and 8.5 of ASHRAE 93-77 and using data from Lines 1, 2 and 3	0	.16*	.20*	.33	.34	.35	.35	.35	.34	.32	.28*	.16*	
5. Incident angle between direct solar beam and outward drawn normal to collector plane, θ_d	90	75	60	45	30	15	15	30	45	60	75	90	
6. Incident angle modifier, determined in accordance with Sections 8.3.3 & 8.6 of ASHRAE 93-77 and using the value of θ from Line 5	-	.55*	.85*	.83	.86	1.0	1.0	.86	.83	.85	.55	0	
7. Energy output from collector [Line 3 x Line 4 x Line 6]		5.3	31.4	53.9	72.8	98.3	102.2	84.6	70.3	53.6	20.3	0	592.7
8. Collector thermal efficiency, Line 7/Line 3													.28

* Estimated or extrapolated values.

Example: 32°N Lat. Avg. - Clear Skies
42° Tilt

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TABLE IX

G.E. TC-100 EIGHT TUBE CALCULATED ALL DAY EFFICIENCY

CALCULATION STEPS	HOUR OF THE DAY, SOLAR TIME												DAILY TOTAL
	6-7	7-8	8-9	9-10	10-11	11-12	12-1	1-2	2-3	3-4	4-5	5-6	
1. Inlet fluid temp. to collector, $t_{f,i}$	185	185	185	185	188	190	193	197	200	200	200	200	
2. Ambient air temp., t_a	73	74	79	82	86	90	92	93	94	94	92	90	
3. Incident radiation on collector plane, I_T (Table A2, ASHRAE 93-77)	6	60	132	197	249	281	292	281	249	197	132	60	2,144
3a. $T_{fi}-T_a/I_T$ ($°F-Ft^2/BTU$)	18.0	1.85	.80	.52	.41	.36	.35	.37	.43	.54	.82	1.8	
4. Collector thermal efficiency at normal incidence, determined in accordance with Sections 8.3.2 and 8.5 of ASHRAE 93-77 and using data from Lines 1, 2 and 3	0	.21*	.31	.34	.36	.365	.365	.36	.355	.34	.31	0	
5. Incident angle between direct solar beam and outward drawn normal to collector plane, $θd$	90	75	60	45	30	15	15	30	45	60	75	90	
6. Incident angle modifier, determined in accordance with Sections 8.3.3 & 8.6 of ASHRAE 93-77 and using the value of $θ$ from Line 5	0	.40*	.68*	.68	.81	.97	.97	.81	.68	.68*	.40*	0	
7. Energy output from collector [Line 3 x Line 4 x Line 6]	0	5.0	27.8	45.5	72.6	99.5	103.4	81.9	60.1	45.5	16.4	0	557.8
8. Collector thermal efficiency, Line 7/Line 3													26.0

Example: 32°N Lat. Avg. - Clear Skies
42° Tilt

* Estimated or extrapolated values.

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OPTIONAL COVER

47-3/4

1 2 3 ·4 5 6 7 8 9 10

C — REFLECTOR

FRAME

52-1/2

B — GLASS SHROUD (10)
(OUTER WINDOW)

A

Sensors were mounted
in tubes 2, 7, and 9
at the positions of
A, B, and C.

40

4   4

2

FRONT

Figure 1.   G.E. TC-100 Ten Tube Solar Collector Configuration

Figure 2. Instrumentation Locations for the G.E. TC-100 Eight Tube Solar Collector Test

Gross Area = 19.1 Ft2
With Manifold
Gross Area = 17.41 Ft2
Without Manifold
Aperture Area = 15.80 Ft2

Manifold Inlet #84
Tube Inlet #80
Tube Outlet #81
Manifold Outlet #83
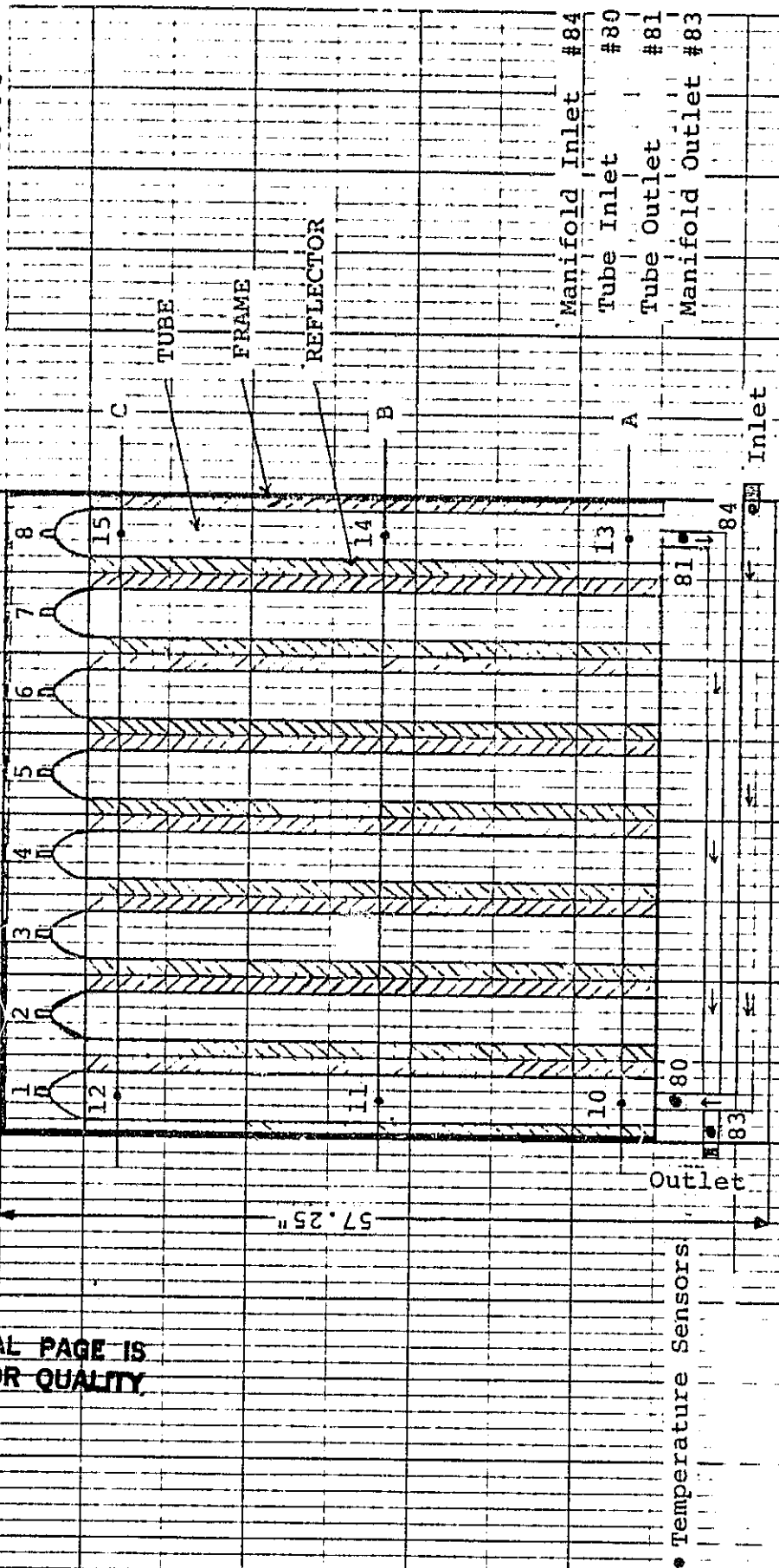
Temperature Sensors 80 and 81 were used for efficiency calculations for the no-manifold case.

• Temperature Sensors

46 0782

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OF POOR QUALITY

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Figure 3. Stagnation Temperature History for the G.E. TC-100 Ten Tube Solar Collector

46 0703

46 0782

Figure 4. Stagnation Temperature History for the G.E. TC-100 Eight Tube Tube Solar Collector

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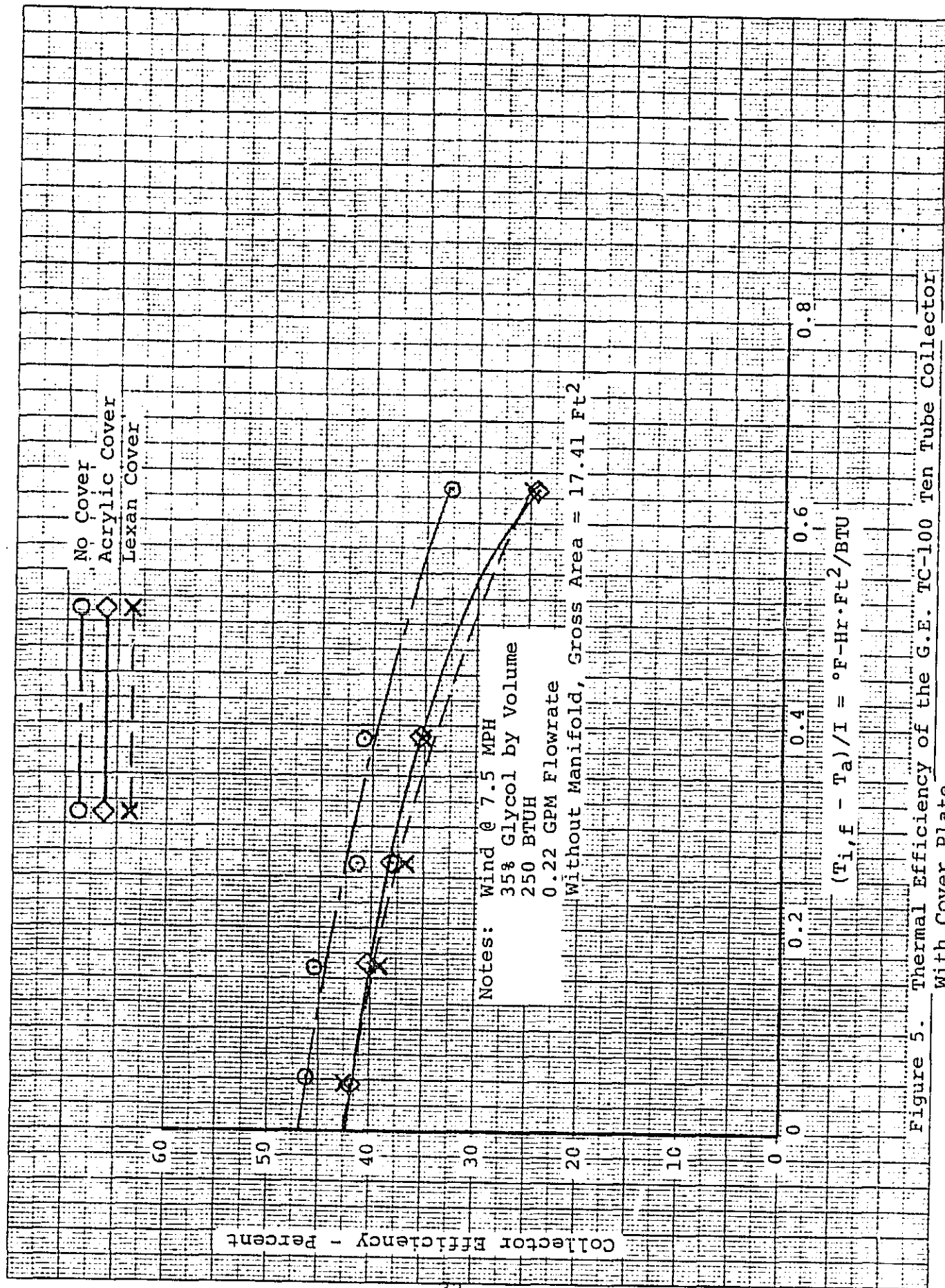
Figure 5. Thermal Efficiency of the G.E. TC-100 Ten Tube Collector
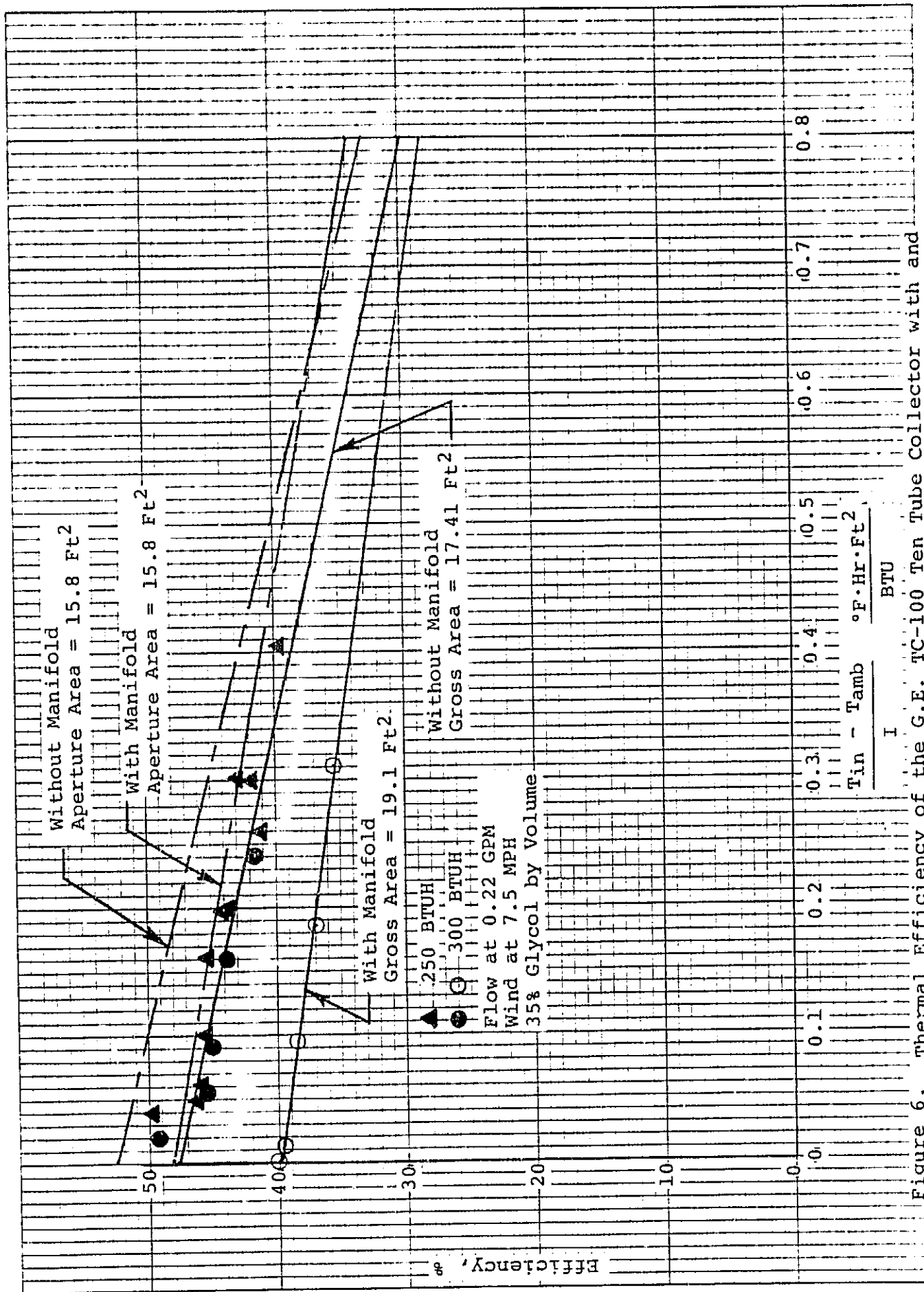
Figure 6. Thermal Efficiency of the G.E. TC-100 Ten Tube Collector with and Without the Accessory Manifold

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46 0703
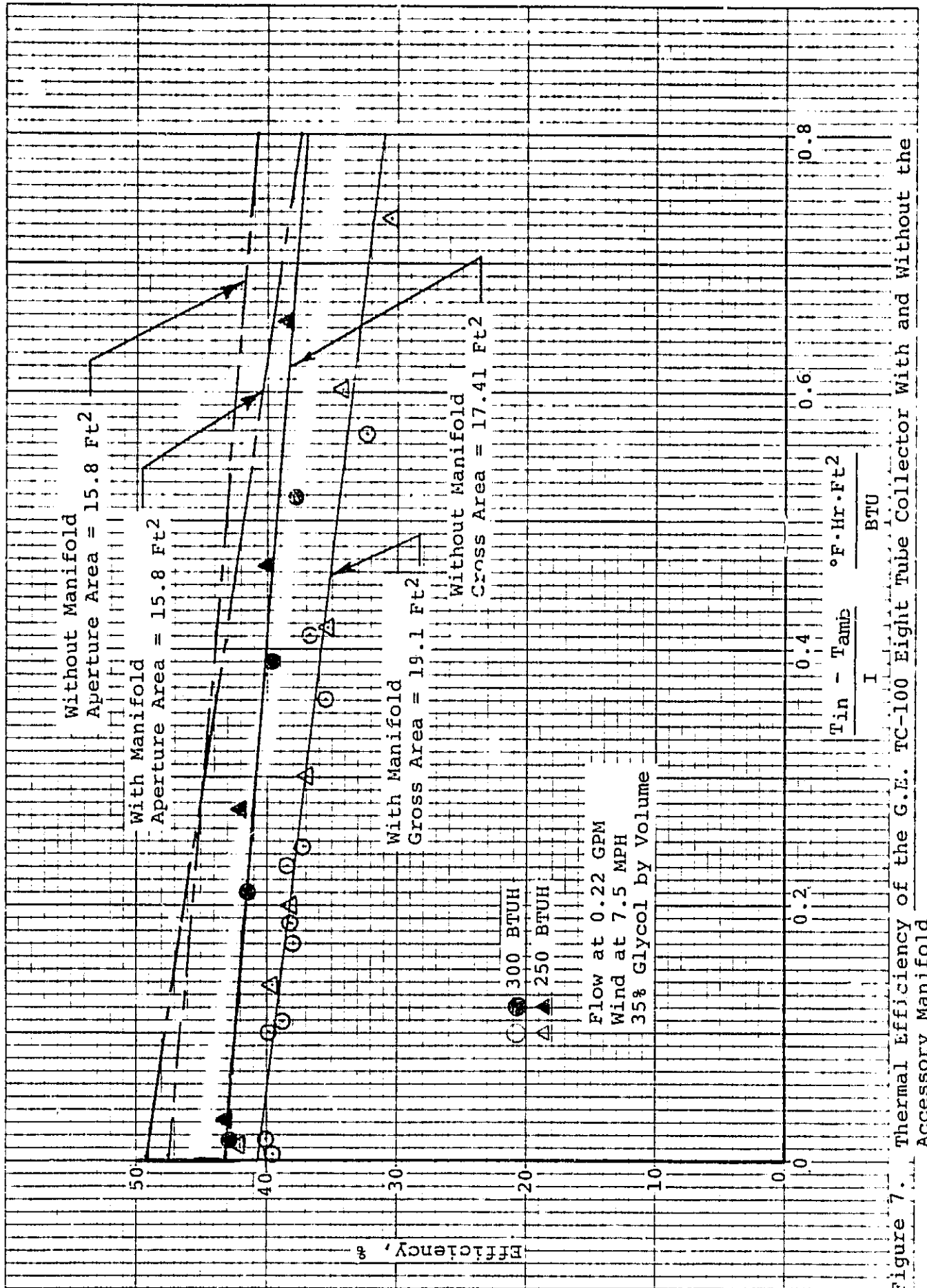
Figure 7. Thermal Efficiency of the G.E. TC-100 Eight Tube Collector With and Without the Accessory Manifold

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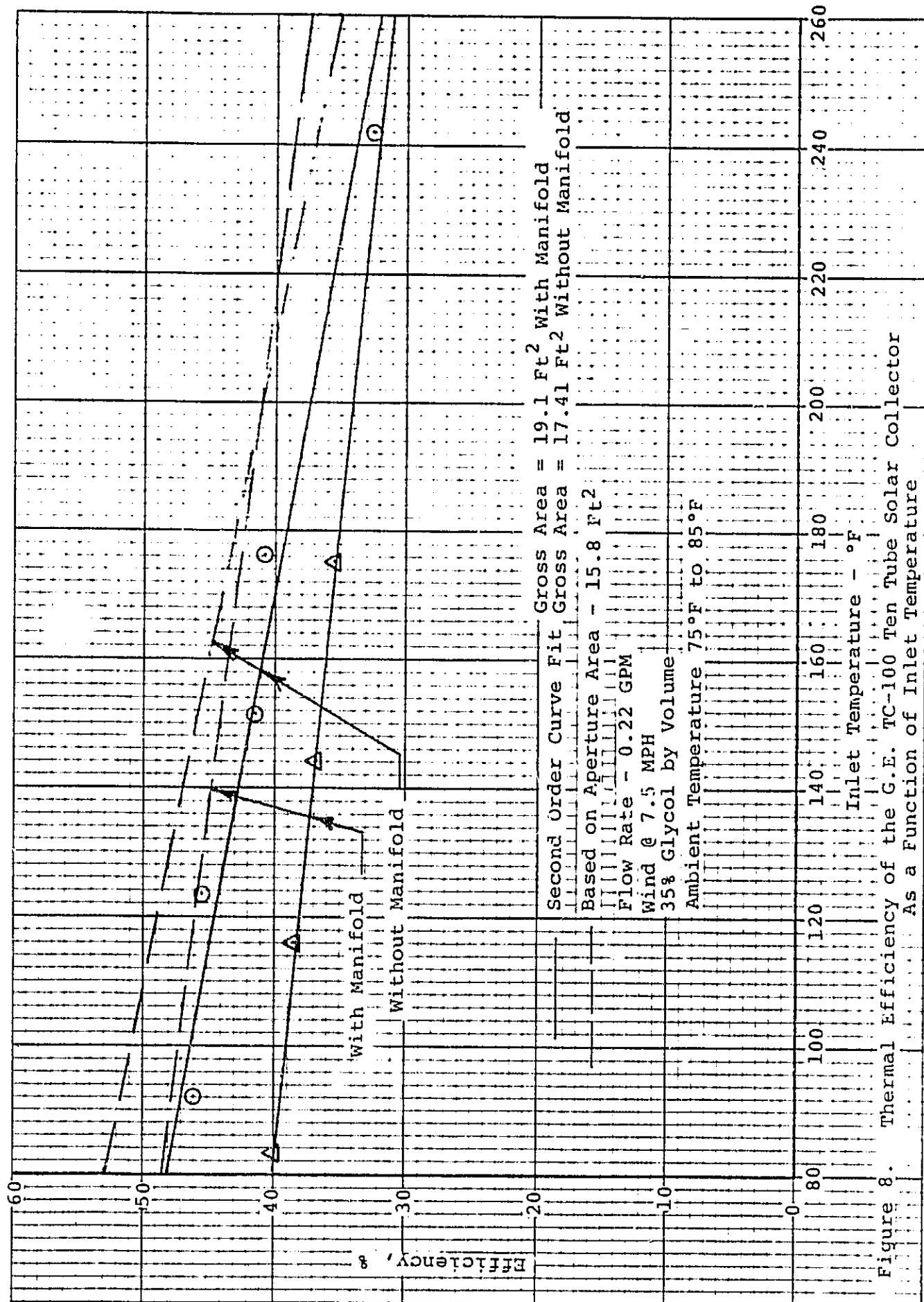
Figure 8. Thermal Efficiency of the G.E. TC-100 Ten Tube Solar Collector As a Function of Inlet Temperature
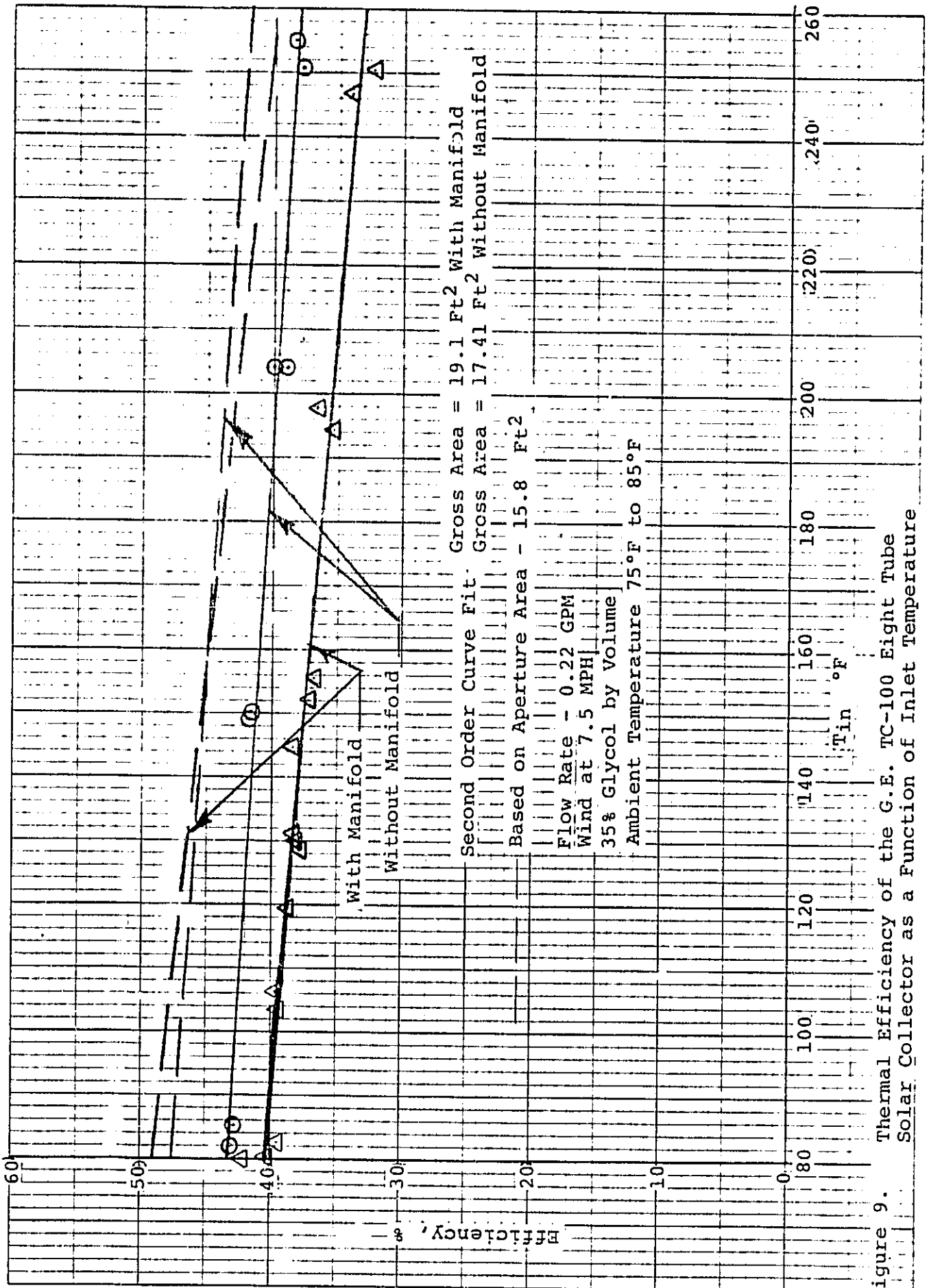
Figure 9. Thermal Efficiency of the G.E. TC-100 Eight Tube Solar Collector as a Function of Inlet Temperature
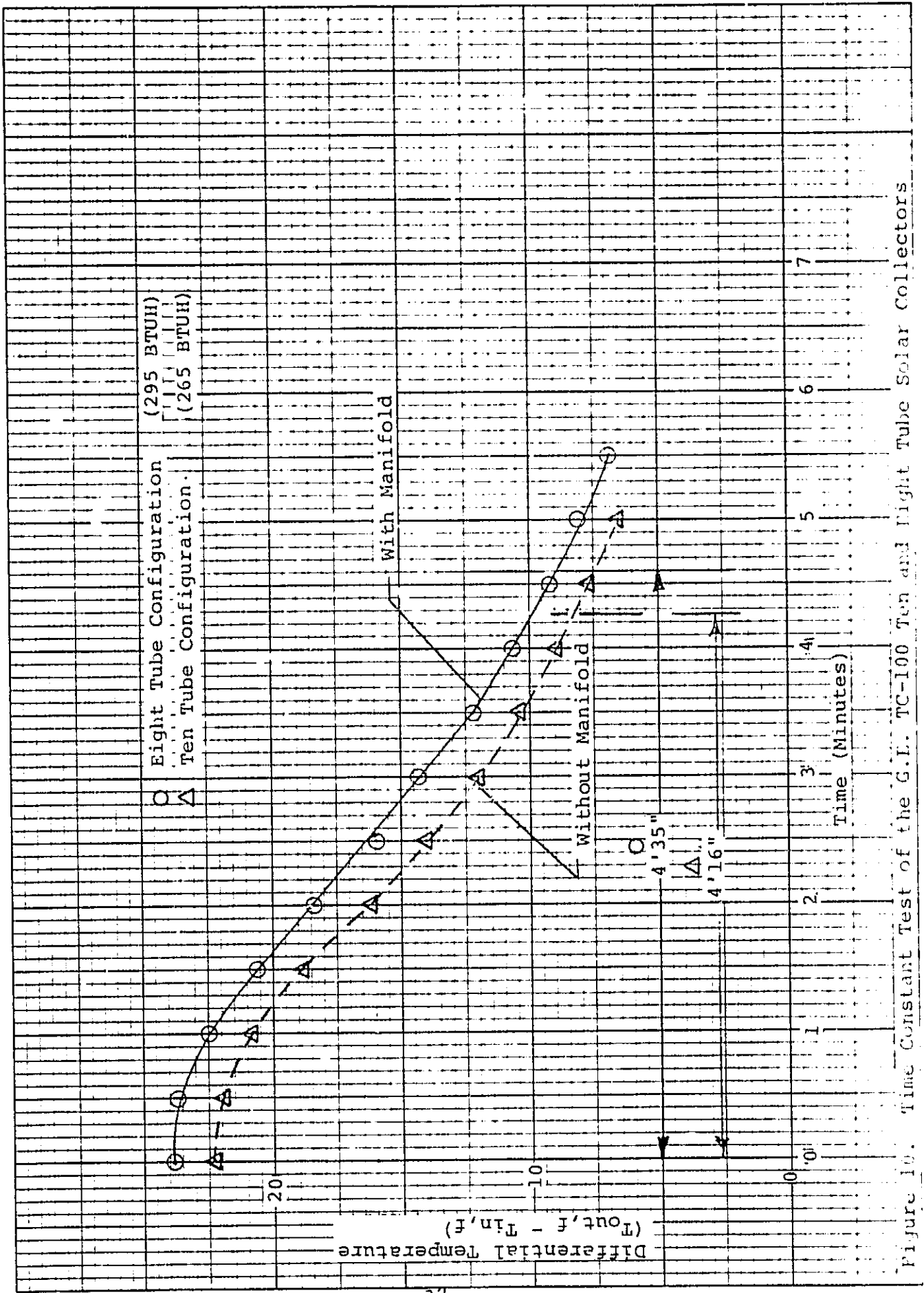
K•E 10 X 10 TO THE INCH • 7 X 10 INCHES
KEUFFEL & ESSER CO. MADE IN U.S.A.

Figure 10. Time Constant Test of the G.E. TC-100 Ten and Eight Tube Solar Collectors
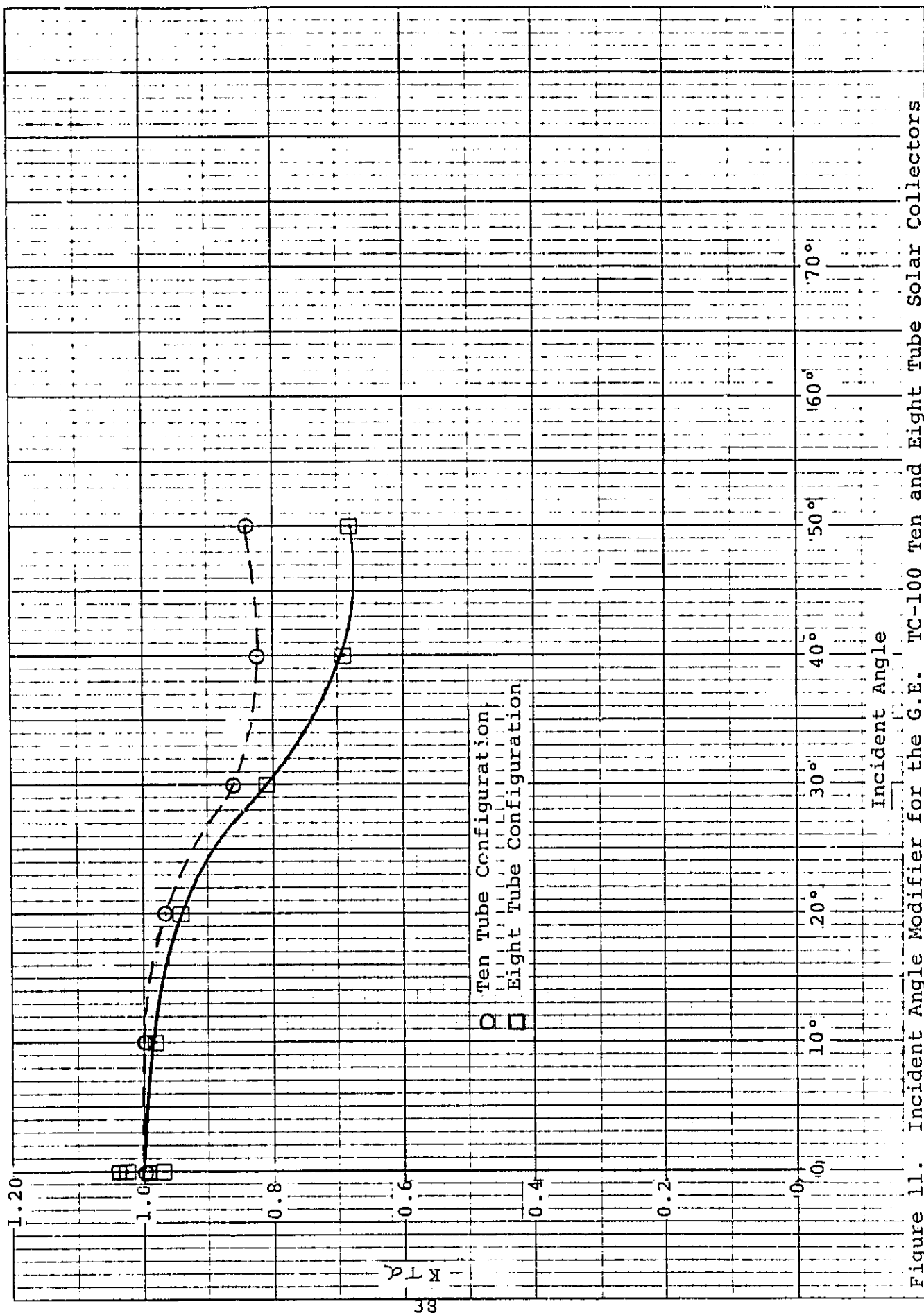
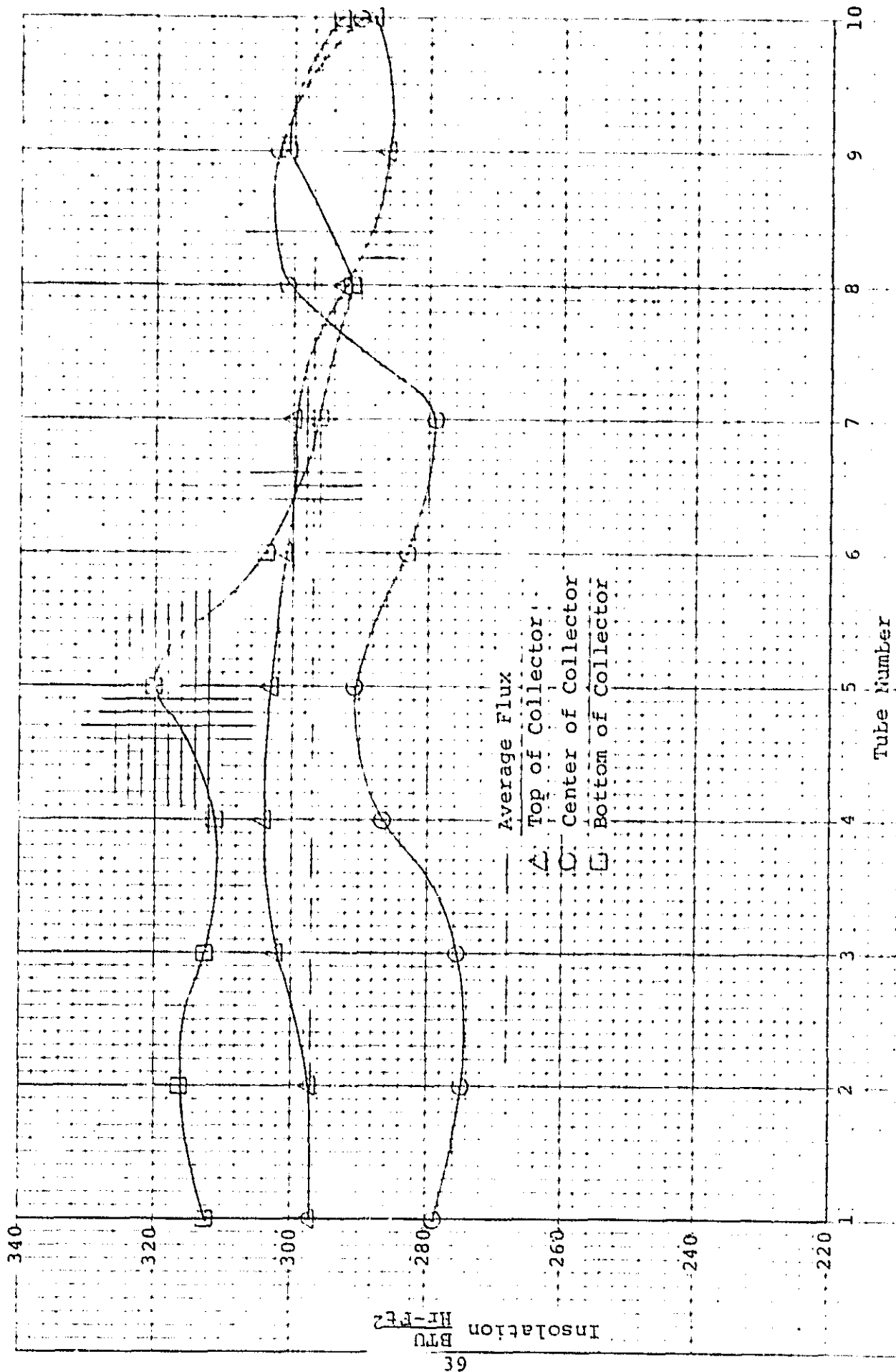Figure 11. Incident Angle Modifier for the G.E. TC-100 Ten and Eight Tube Solar Collectors

K·E HE IN TO THE INCH· KEUFFEL & ESSER CO. MADE IN U.S.A.

Insolation $\frac{BTU}{HR\cdot FT^2}$

340
320
300
280
260
240
220

Tube Number

1 2 3 4 5 6 7 8 9 10

Average Flux
Top of Collector
Center of Collector
Bottom of Collector

Figure 12. Typical Flux Map for the G.E. TC-100 Ten Tube Collector Tests
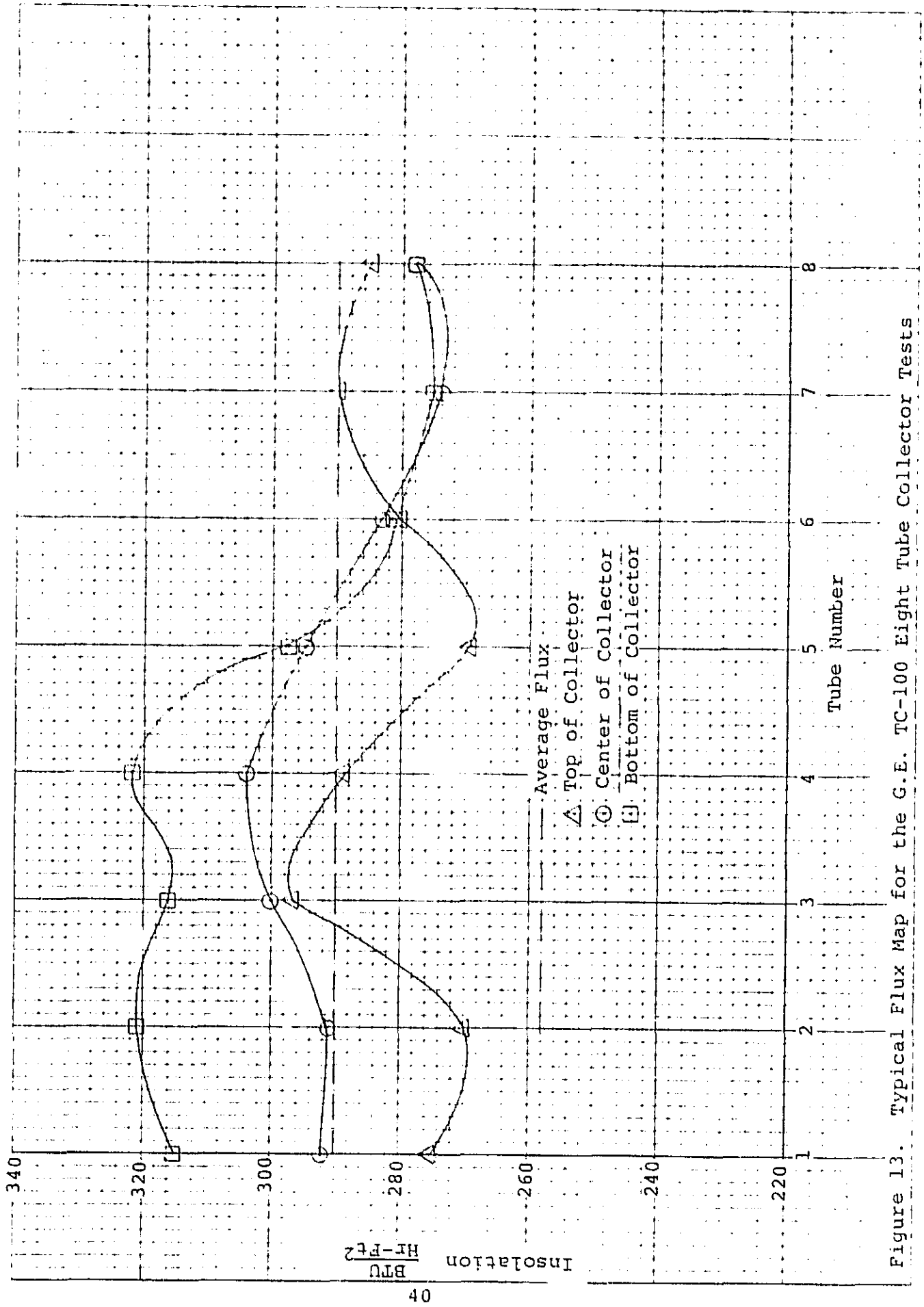
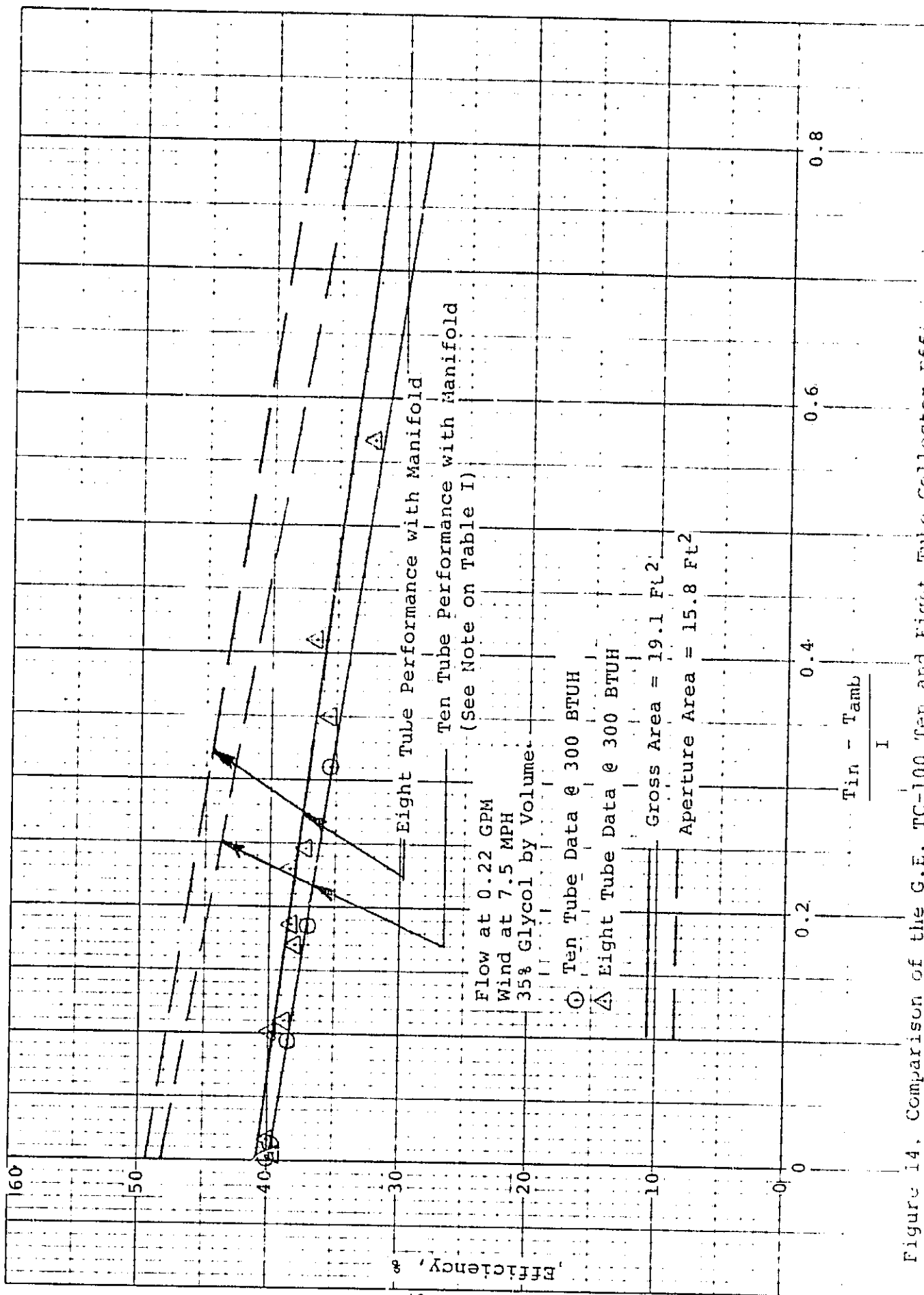Figure 13. Typical Flux Map for the G.E. TC-100 Eight Tube Collector Tests

46 0782

Figure 14. Comparison of the G.E. TC-100 Ten and Eight Tube Collector Efficiencies

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