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SUMMER PERFORMANCE RESULTS OBTAINED FROM SIMULTANEOUSLY TESTING TEN SOLAR COLLECTORS OUTDOORS

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16. Abstract

Ten solar collectors were simultaneously tested outdoors. The measured efficiencies reported here were obtained during the summer of 1976. These data are compared to "baseline" efficiency data obtained in a solar simulator before the outdoor tests were conducted. Outdoor exposure times varied from 8 months to 2 years and 4 months for the collectors tested. Efficiency data were correlated using a method that separates solar variables (flux, incident angle) from the desired performance parameters (heat loss, absorbtance, transmittance) which are unique to a given collector design. Tests were conducted on both clear and moderately cloudy days. Correlating data in the above manner, a 2-glass, black paint collector exhibited a decrease in efficiency of 5 percentage points relative to the "baseline" data for an exposure time of 2 years, 4 months. Condensation on the collector glazing was thought to be a contributing factor in this efficiency change. A 2-glass, black nickel collector exhibited an increase in the heat loss coefficient (U_L) after 1 year and four months of outdoor exposure. A "whitish" film was observed on the inner surface of the outer cover glazing of four collectors (1) a 2-glass, black chrome; (2) a 2-glass, black nickel; (3) a 2-glass, black paint with mylar honeycomb; and (4) a 2-glass, selective surface collector. Tests on an evacuated tubular collector indicated that this collector's efficiency should be evaluated on the basis of an all-day efficiency (sunrise to sunset) due to its relatively large thermal time constant.

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E-9066

INTRODUCTION

Tests have been carried out to evaluate flat-plate solar collectors for use in the heating and cooling of buildings. This evaluation consisted of first obtaining baseline collector efficiency in a solar simulator, and then determining collector efficiency outdoors under real-sun conditions.

Most of the present methods of evaluating collector efficiency outdoors have been limited to testing on clear days. Therefore, it is difficult to accurately predict how a collector would perform on a cloudy day. This "cloudy-day" information can be important in areas where cloudy days are relatively common.

A correlative method has been developed (ref. 1) which takes into account the effects of solar variables (i.e., incident angle, flux, etc.). This method allows collector efficiency to be determined in terms of collector performance parameters (i.e., heat loss, absorbtance, transmittance, etc.) which are unique to a given collector design.

This report presents measured thermal efficiency obtained by simultaneously testing ten solar collectors outdoors on clear and cloudy days. The efficiency for each of the ten collectors was determined using the abovementioned correlation, and any changes in efficiency with time were noted. Visual observations were made to monitor any physical degradation of the basic collector components (i.e., cover glazings, absorber plate, collector outside frame, etc.) as a result of outdoor exposure.

The efficiency of each collector was determined for clear and for moderately cloudy days alike. Collector rankings were established on the basis of thermal efficiency, for both clear and cloudy days. These efficiency results were also compared with baseline efficiency test data acquired in a solar simulator.

EXPERIMENTAL APPARATUS

The outdoor solar collector test facility is shown in figure 1. This facility consists of two collector test stands, each with the capability of simultaneously testing five flat-plate solar collectors. The mechanical components of the flow loop (pump, water tank, etc.) are

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enclosed in the instrument shed which is located in the center of each stand.

Coolant Flow Rate

The coolant used is a 50-50 mixture, by weight, of ethylene glycol and water. Corrosion inhibitors are present in the ethylene glycol (ref. 2).

Figure 2 shows a schematic of the flow loop of one of the collector test stands. Each collector has an independent flow loop in parallel with the other four collector flow loops. An expansion tank is provided to allow for changes in fluid volume.

The coolant is circulated by a 1/4 horsepower pump, with a surge tank connected at its outlet. Coolant is stored in a commercially available 80-gallon water tank which has two 5500-watt immersion heaters. In general, the tank heaters are used to maintain a constant storage temperature.

The air-liquid heat exchanger is used to regulate the inlet temperature to the collectors. In the event that the inlet manifold temperature increases above the "set" temperature, an automatic controller operates a series of valves which route the hot fluid to the heat exchanger, where the excess heat is dumped.

Flow control for each individual collector is achieved by the adjustment of a remotely operated valve. Also, since a constant pressure is required in the collector inlet manifold, a collector bypass line is provided.

For collectors with aluminum absorber plates, an aluminum screen is placed in the flow path just upstream of the inlet to the collector.

Filtration of the water-glycol mixture is provided by a 25-micron filter, located just downstream of the pump.

Instrumentation

The following measurements were recorded for each collector:

(1) Coolant flow rate

(2) Coolant temperature at the inlet to the collector

(3) Coolant temperature at the outlet to the collector

(4) Absorber plate temperature

(5) Coolant pressure at inlet to the collector

(6) Pressure differential across the collector

The coolant flow rate through each collector is measured with a turbine-type flowmeter. The flowmeters were calibrated for a 50-50 mixture of ethylene glycol and water by the vendor.

Collector temperatures are measured with chromel-constantan thermocouples (ISA - type E). The inlet and outlet thermocouples were made from the same spool of wire, and were calibrated in an oil bath. Then the inlet and outlet thermocouples were matched so that their combined error is within $\pm 0.5^{\circ}$ F.

Solar radiation is measured in the plane of the collectors and in the horizontal plane. There is a pyranometer on each test stand which is oriented at the collector tilt angle. Solar instruments located on a nearby roof also measure the total insolation (horizontal surface), the diffuse insolation (horizontal surface), and the normally incident direct radiation.

Solar instruments in the horizontal plane are used as a check on the solar instruments in the plane of the collectors. The output of the pyranometers on each test stand are also compared to each other. Agreement within ±3 percent is typical.

In addition to the collector and insolation data, the following weather data are recorded: air temperature, wind speed and direction, and relative humidity.

Data Acquisition

The outputs of the instrumentation pass through signal conditioners and then into a matrix-type patchboard. The signals are then routed to a high speed integrating voltmeter which scans each channel and digitizes the millivolt signals for storage on magnetic tape. Sufficient capacity exists for the on-line retrieval of the millivolt outputs of each channel. Also, an on-line access to a computer allows for output in engineering units.

EXPERIMENTAL APPROACH

Prior to outdoor tests, a controlled performance test was conducted on each solar collector in a solar simulator. Upon completion of this "baseline" test, the collector was then considered for outdoor testing. The primary criteria for selection of collectors for outdoor testing were:

(a) High performance as indicated from the simulator test

(b) A collector design that exhibits some special potential for advancing collector technology.

Once a collector was selected for outdoor testing, it was installed on one of the outdoor test stands. Data were then recorded over a period of time. The data were used to:

(1) Evaluate and compare the efficiency of several collectors of various types which operate outdoors simultaneously

(2) Evaluate collector efficiency degradation as a function of time

(3) Evaluate collector durability under "real" environmental conditions (rain, wind, snow, etc.)

The recorded data were correlated (ref. 1) by modifying the calculation of two parameters commonly used to generate an efficiency curve (thermal efficiency η, and $\Delta T/Q$).

These two quantities were first modified by averaging them over an interval of time, where "n" instantaneous data values were recorded.

$$\bar{\eta} = \frac{\sum_{i=1}^{n} q_{useful}}{\sum_{i=1}^{n} q_{total}}$$

where

q_{useful} = useful thermal energy collected

q_{total} = total amount of solar flux incident on the collector

and

$$\bar{\theta} = \frac{\overline{T_{in} - T_{amb}}}{\overline{q_{total}}} = \frac{\sum_{i=1}^{n} T_{in} - T_{amb}}{\sum_{i=1}^{n} q_{total}}$$

where

T_{in} = inlet fluid temperature

T_{amb} = ambient temperature

The values of $\overline{\eta}$ and $\overline{\theta}$ were then divided by a factor "X" which accounts for the collector response to (1) changes in the incident angle of the sun, and (2) changes in the amount of direct solar radiation. This process yields η^* and θ^*, which are the efficiency correlation parameters that were used:

$$\eta^* = \overline{\eta}/X$$

and

$$\theta^* = \overline{\theta}/X$$

and

$$X = (\overline{K_{\alpha\tau}} \cdot R) + (1 + b_0)(1 - R)$$

where

$\overline{K_{\alpha\tau}}$ = averaged incident angle modifier

R = ratio of direct to total insolation

b_0 = angular response constant

Thus, the "modified" efficiency curve is generated by plotting η^* on the ordinate and θ^* on the abscissa. It is in this manner that collector efficiency was determined from both clear and cloudy day data. This efficiency curve can then be used to evaluate degradation of collector efficiency with time. An increase in the slope indicates a corresponding increase in heat loss. A change in the intercept indicates that the product of the heat removal efficiency factor times the absorbtance times the transmittance ($F_R \cdot \alpha \cdot T$) has changed.

RESULTS AND DISCUSSION

Ten solar collectors were simultaneously tested outdoors during the summer months of 1976. At the time these tests were conducted, the collectors had accumulated outdoor exposure periods ranging from 8 months to 2 years, 4 months.

Figures 3(a) to (j) are plots of six-hour-averaged collector efficiencies (η^*). Both parameters (η^* and θ^*) were determined by methods discussed in reference 1. The data acquisition time of six hours corresponded to 3 hours before or after "solar noon." In some cases, data was taken for more than 6 hours.

Figures 3(b), (c), (f), and (i) do not exhibit a noticeable change in efficiency when compared with the baseline efficiency determined in a solar simulator. In the case of figures 3(c) and (i), a whitish film was observed on the inside surface of the outer glazing of each collector. Figure 4 shows the film observed on the NASA/Honeywell two-glass, black paint collector with mylar honeycomb (see fig. 3(i)). A similar film was seen on the NASA/Honeywell two-glass, black chrome collector, whose efficiency curve is presented in figure 3(c). In both instances, there was no apparent decrease in the intercept value of the efficiency curve. Since the intercept value of a collector efficiency curve is a function of glazing transmittance, a reduction in glazing transmittance should cause a corresponding decrease in the value of the intercept. It appears, then, that this whitish film had a negligible effect on collector performance. The exact composition of the film was not determined, but it could be due to outgassing from the fiber glass insulation. The whitish film was also observed on the NASA/Honeywell two-glass, black nickel collector. All three NASA/Honeywell collectors were outdoors for a period of about 1 year, 4 months.

The efficiency for a General Electric 2-lexan collector is shown in figure 3(f). No decrease in efficiency was observed after 1 year, 2 months exposure outdoors. However, some "yellowing" of the lexan plastic was noted on the inner surface of the inner glazing, where wooden dowels were supporting the glazing. Figure 5 shows a photo of the discoloration of the plastic at these points.

Figure 3(a) corresponds to a collector which was tested outdoors for a period of 2 years, 4 months. Note that the slope of the curve fit for the outdoor data is the same as the slope of the simulator line. This indicates that the coefficient of heat loss (U_L) did not change. There was, however, a decrease in the efficiency intercept valve, of about 5 efficiency points. No physical degradation of the collector frame, panel, or glazing was observed; however, condensation was frequently observed on this collector. The condensation persisted for the duration of most of the data runs, and covered approximately 20 percent of the absorber area. This film of condensation may account for the drop in the intercept value of the efficiency curve.

The efficiency curve for the NASA/Honeywell two-glass, black nickel collector is shown in figure 3(d). This collector was exposed to outdoor conditions for 1 year, 4 months. By comparing the solid fairing (baseline efficiency) with the curve fit of the outdoor efficiency data, it can be seen that the slope of the outdoor data has become more negative. This indicates that the coefficient of heat loss (U_L) increased during the time of exposure outdoors. As previously mentioned, a whitish film was noted on the inside surface of the outer glazing. However, the intercept value of the efficiency curve (for the outdoor data) did not change. This indicates that the film did not decrease the transmittance enough to affect the collector's thermal performance.

Figure 3(e) shows the efficiency for an Owens-Illinois evacuated tubular collector. In this case, the data could not be curve-fitted well, because of scatter. The scatter of the data is partially due to the fact that this collector has a time constant (1/2 hr) which is somewhat longer than that of conventional flat plate solar collectors (10 min).

Thus, the length of time during which data is acquired becomes important. More specifically, those data which fall below the curve fit (broken fairing) were recorded on days where the data collection time after solar noon was out 3 hours. Those data lying above the curve-fitted line were recorded on days where data was collected for 4 hours after solar noon. These results indicate that perhaps a more accurate way to evaluate the performance of this collector would be to use an all-day efficiency.

Figure 3(g) shows the efficiency of a Pittsburgh Plate Glass (PPG) 2-glass, black-paint collector. It was placed in an open-faced wooden box to reduce the heat loss, and then installed on the test stand. It was operated at a different flow rate from the other nine collectors. The flow rate for this collector was 14.7 lb/hr-ft^2 as compared to 10 lb/hr-ft^2 for the other nine collectors. Because this particular collector was not tested in a solar simulator before its outdoor exposure, no efficiency curve for the simulator is shown in figure 3(g).

This efficiency curve for a Revere Corp. two-glass, black paint collector is presented in figure 3(h). There was a significant difference between the outdoor efficiency and the simulator efficiency. Outdoor efficiency data obtained during the winter of 1975 also indicated a similar relation to the baseline efficiency curve obtained in a solar simulator (i.e., the outdoor efficiency was higher by the same order of magnitude). This discrepancy was not resolved.

Figure 3(j) shows the efficiency of an Intertechnology Corp. two-glass collector with selective coating. In general, its outdoor efficiency appears to lie above the baseline efficiency measured in the simulator. However, the differences between the two sets of data are not significant because they fall within the range of acceptable data scatter. Thus, an accurate evaluation of the observed outdoor results is not possible. Also, a "whitish" film was observed on the inside surface of the outer glazing. This film appeared to be similar in nature, to that observed on the NASA/Honeywell collectors. Figure 6 shows a photograph of this film. In all cases the film seemed to be more pronounced near the top of the absorber panel (the coolant flow is from the bottom to the top of the panel).

An efficiency ranking for all ten collectors is shown in table 1, for a clear summer day and a cloudy summer day. The NASA/Honeywell 2-glass, black chrome collector and the Revere 2-glass collector exhibited the highest efficiencies. Also, the collectors maintained their respec-

tive order for both days (except for the NASA/Honeywell black chrome and the Revere collectors). This is understandable because the ratio of direct to total insolation "R" was 0.886 on the clear day and 0.790 on the cloudy day. If the value of "R" had been closer to "0.6," the cloudy day efficiencies would have been considerably less than what they were (ref. 2). This ranking indicates that on days where some intermittent clouds are present, the efficiency of the collectors will "drop off" depending on the inlet temperature, the ambient temperature, the exact value of "R," and the windspeed. Reference 2 includes a collector efficiency ranking for a clear and cloudy winter day. In that reference, the effect of cloud cover was more pronounced due to lower ambient temperatures, a higher inlet temperature, and a lower value of "R."

CONCLUSIONS

Ten solar collectors were simultaneously tested outdoors. The collectors tested had exposure times ranging from 8 months to 2 years, 4 months.

Of the ten collectors tested, four showed no change in efficiency. These four collectors were operated outdoors for a period of about 1 year, 4 months.

(1) Miromit collector, 1-glass, black nickel, 1 year, 4 month exposure

(2) NASA/Honeywell, 2-glass, black chrome, 1 year, 4 month exposure

(3) General Electric, 2-lexan, Alcoa etch, 1 year, 2 month exposure

(4) NASA/Honeywell, 2-glass, black paint with mylar honeycomb, 1 year, 7 month exposure

A two-glass, black paint collector exhibited a drop of 5 percentage points in efficiency relative to baseline simulator efficiency tests. The slope of the efficiency curve remained constant; however, the intercept value decreased indicating a loss of glazing transmittance or absorptance of the absorber coating or both. An explanation of this observation may lie in the fact that condensation was frequently observed on this collector during most of the test runs. This would tend to indicate that condensation on the glazing does have a significant effect on collector performance. This collector was operated outdoors for 2 years, 4 months.

The NASA/Honeywell black nickel collector exhibited an increase in the slope of the efficiency curve following an outdoor exposure time of 1 year, 4 months. This increase in slope is indicative of an increase in the coefficient of heat loss (U_L) for the collector.

The outdoor data for the Owens-Illinois evacuated tubular collector exhibited a large amount of scatter. This was attributed to this collector's large time constant (2.4 hr), and also to the length of time used to acquire data. On those days where the afternoon collection times exceeded 4 hours (as opposed to 3), the outdoor efficiencies were characteristically higher. This confirms that a proper test of this collector's thermal efficiency should be based on an all-day averaged efficiency.

A "whitish" film was observed on the inside surface of the outer glazing of the following collectors:

(1) NASA/Honeywell, 2-glass, black chrome

(2) NASA/Honeywell, 2-glass, black nickel

(3) NASA/Honeywell, 2-glass, black paint with mylar honeycomb

(4) Intertechnology, 2-glass, selective surface

This "film" did not cause a change in the intercept value of the efficiency curve for any of the four collectors.

Besides evaluating efficiency degradation with exposure time outdoors, a collector ranking was established for all ten collectors. These results were based on data acquired on both a clear and a cloudy summer day. The ranking for the cloudy day exhibited the same relative order as for the clear day. Also, the cloudy day efficiencies exhibited an average decrease of only about 4 efficiency percentage points. This was due to the small difference between the ratio of direct to total insolation for the cloudy day (0.79) and for the clear day (0.88), as well as the moderate inlet temperature (160° F), and the high ambient temperature (85° F).

REFERENCES

1. Simon, Frederick F; Miller, Dean R.: A Generalized Correlation of Experimental Flat-Plate Collector Performance. NASA TM X-71832, 1975.

2. Miller, Dean R.: Performance Correlations of Five Solar Collectors Tested Simultaneously Outdoors. TM X-73546, 1977.

3. Miller, Dean R.: Outdoor Performance Results for NBS Round-Robin Collector No. 1. NASA TM X-73547, 1976.

TABLE I. - COLLECTOR EFFICIENCY RANKING FOR A CLEAR AND CLOUDY DAY

Collector identification	Clear day 8/20/76	Cloudy day 7/26/76
(1) Lewis Research Center: 2-glass, black paint, copper absorber	#8 n = 0.537	#3 n = 0.508
(2) Miromit: 1-glass, black nickel, steel absorber	#3 n = 0.530	#8 n = 0.478
(3) NASA/Honeywell: 2-glass, black chrome, steel absorber	#9 n = 0.516	#9 n = 0.471
(4) NASA/Honeywell: 2-glass, black nickel, aluminum absorber	#10 n = 0.492	#4 n = 0.464
(5) Owens-Illinois: Evacuated tubular (24 tube), selective coating	#4 n = 0.487	#10 n = 0.461
(6) General-Electric: 2-lexan, Alcoa etch, aluminum absorber	#6 n = 0.457	#6 n = 0.418
(7) Pittsburgh Plate Glass: 2-glass, black paint, aluminum absorber	#1 n = 0.441	#1 n = 0.393
(8) Revere Copper: 2-glass, black paint, copper absorber	#2 n = 0.42[illegible]	#2 n = 0.354
(9) NASA/Honeywell: 2-glass, black paint, alum. absorber with honeycomb	#7 n = 0.380	#7 n = 0.320
(10) Intertechnology Corp.: 2-glass, selective coating, aluminum absorber	#5 n = 0.373	#5 n = 0.297
$\overline{T}_{inlet}$	160° F	170° F
$\overline{T}_{amb}$	85° F	82° F
$\overline{Q}_{total}$	268 Btu/hr-ft^2	255 Btu/hr-ft^2
R	0.886	0.790
Flow rate[a]	10 lb/hr-ft^2	10 lb/hr-ft^2
Wind	6 mph	6 mph

[a]Collector #7 was operated at 14.7 lb/hr-ft^2.

FIG. 1 OUTDOOR COLLECTOR
TEST FACILITY

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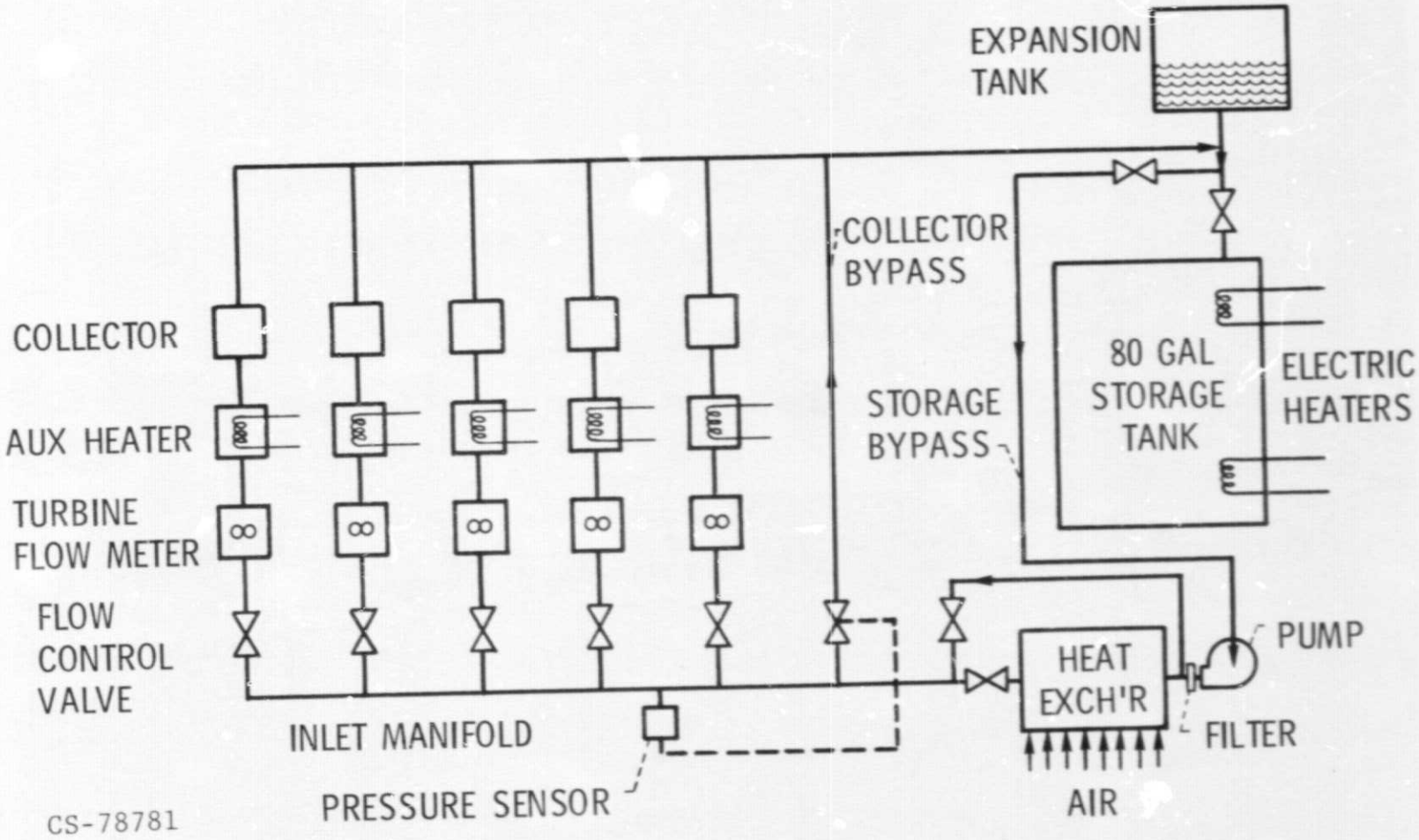


Figure 2 - Schematic of outdoor collector facility

FIG 3-A

6-HOUR AVERAGED EFFICIENCY FOR LEWIS RESEARCH CENTER COLLECTOR (GLAZING = 2-GLASS, ABSORBER = COPPER, COATING = BLACK PAINT)

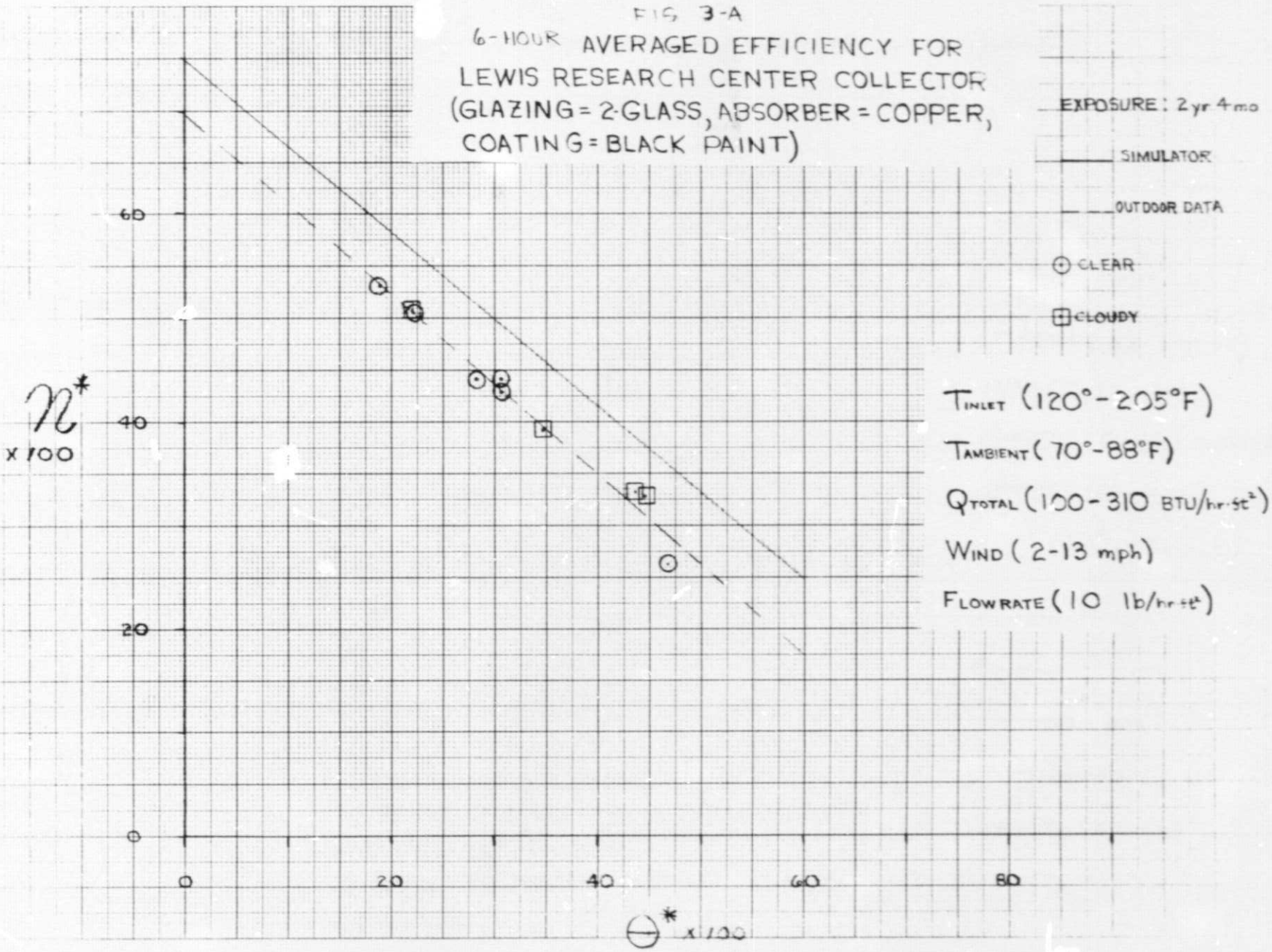


FIG 3-B

6-HOUR AVERAGED EFFICIENCY FOR MIROMIT COLLECTOR (GLAZING = 1-GLASS, ABSORBER = STEEL, COATING = BLACK NICKEL)

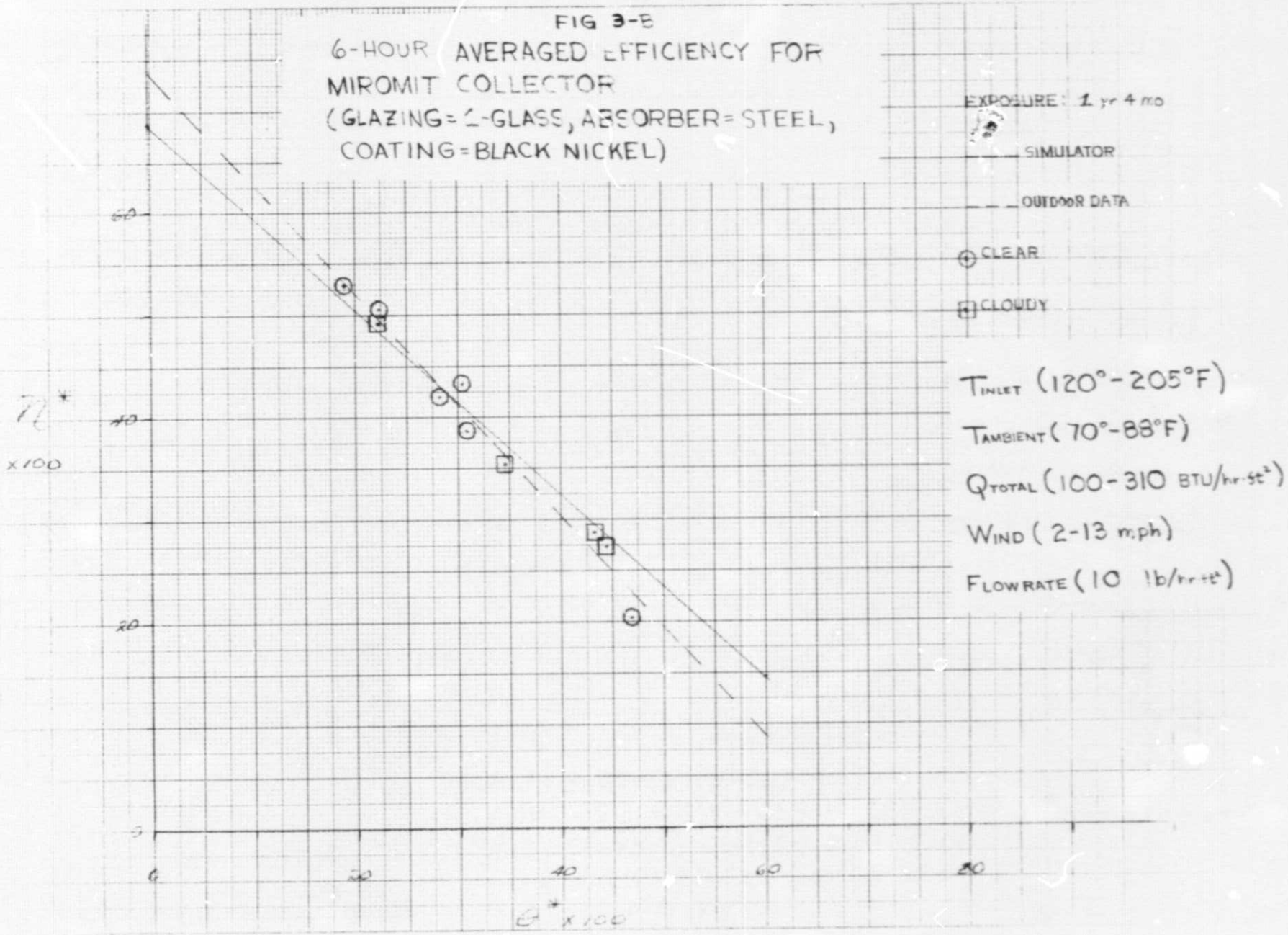


FIG. 3-C

6-HOUR AVERAGED EFFICIENCY FOR NASA/HONEYWELL COLLECTOR (GLAZING = 2-GLASS, ABSORBER = STEEL, COATING = BLACK CHROME)

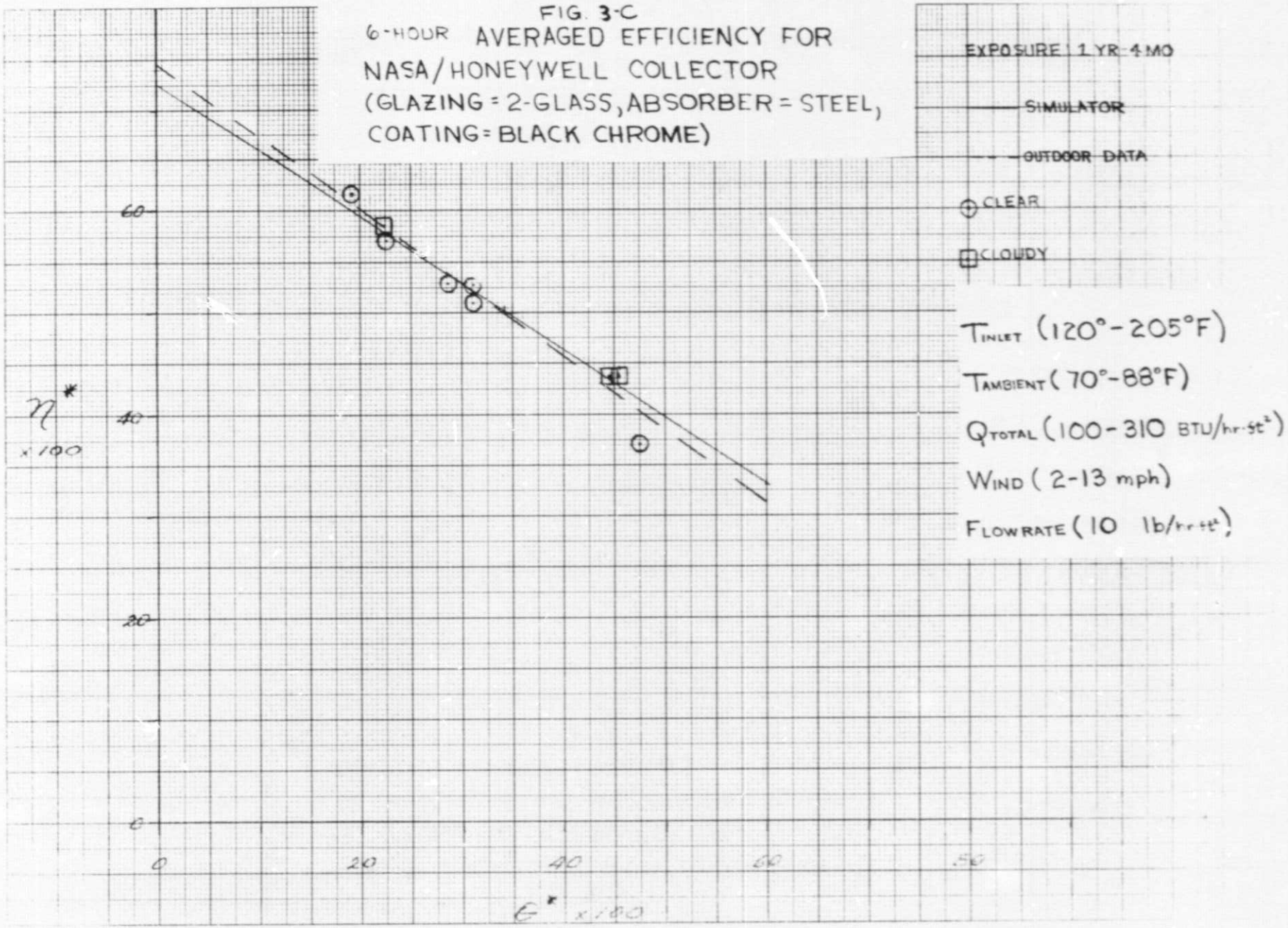


FIG. 3-D

6-HOUR AVERAGED EFFICIENCY FOR NASA/HONEYWELL COLLECTOR (GLAZING = 2-GLASS, ABSORBER = ALUMINUM, COATING = BLACK NICKEL)

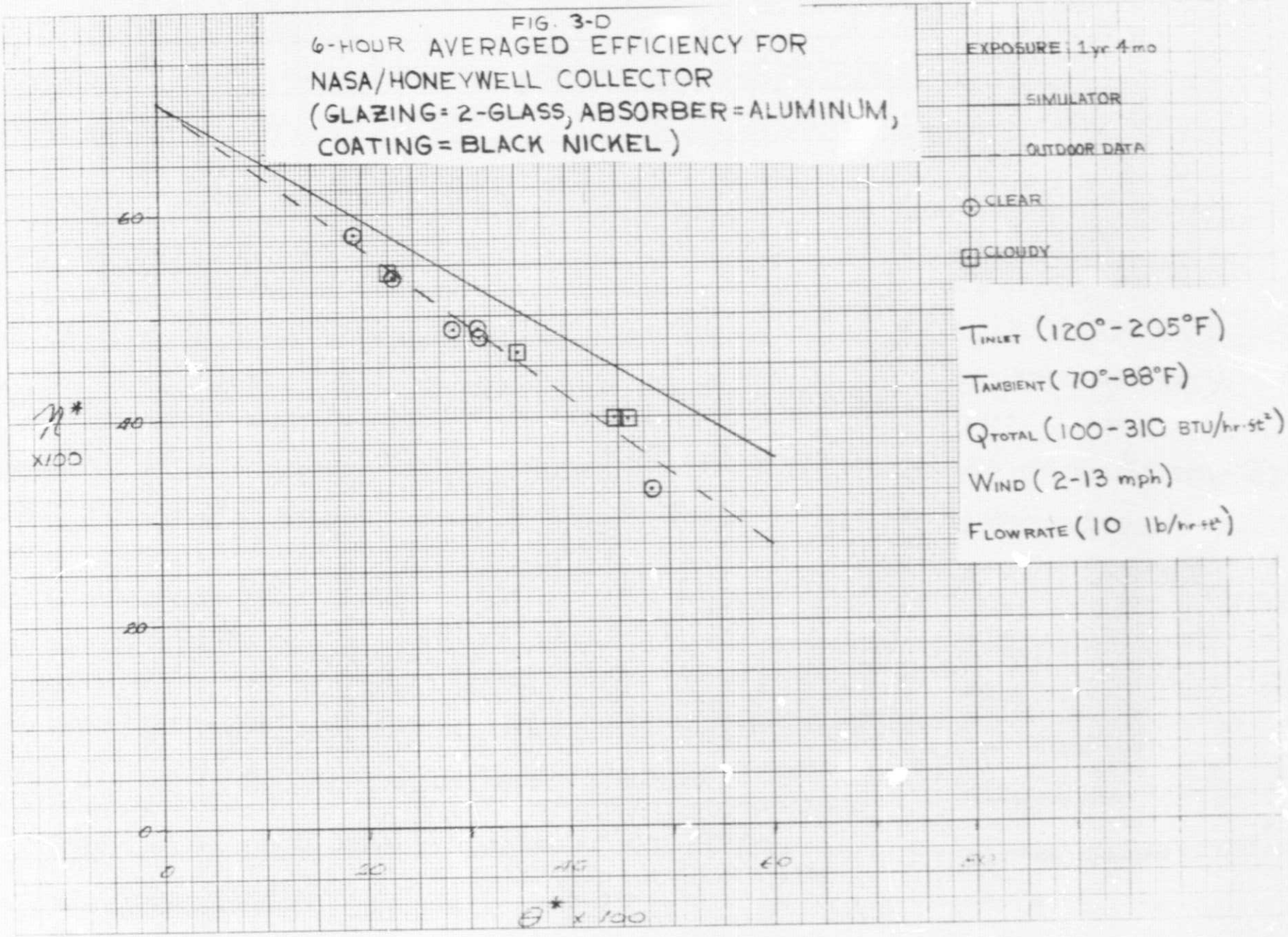


FIG 3-E

6-HOUR AVERAGED EFFICIENCY FOR OWENS-ILLINOIS COLLECTOR (EVACUATED TUBULAR, COATING: SELECTIVE)

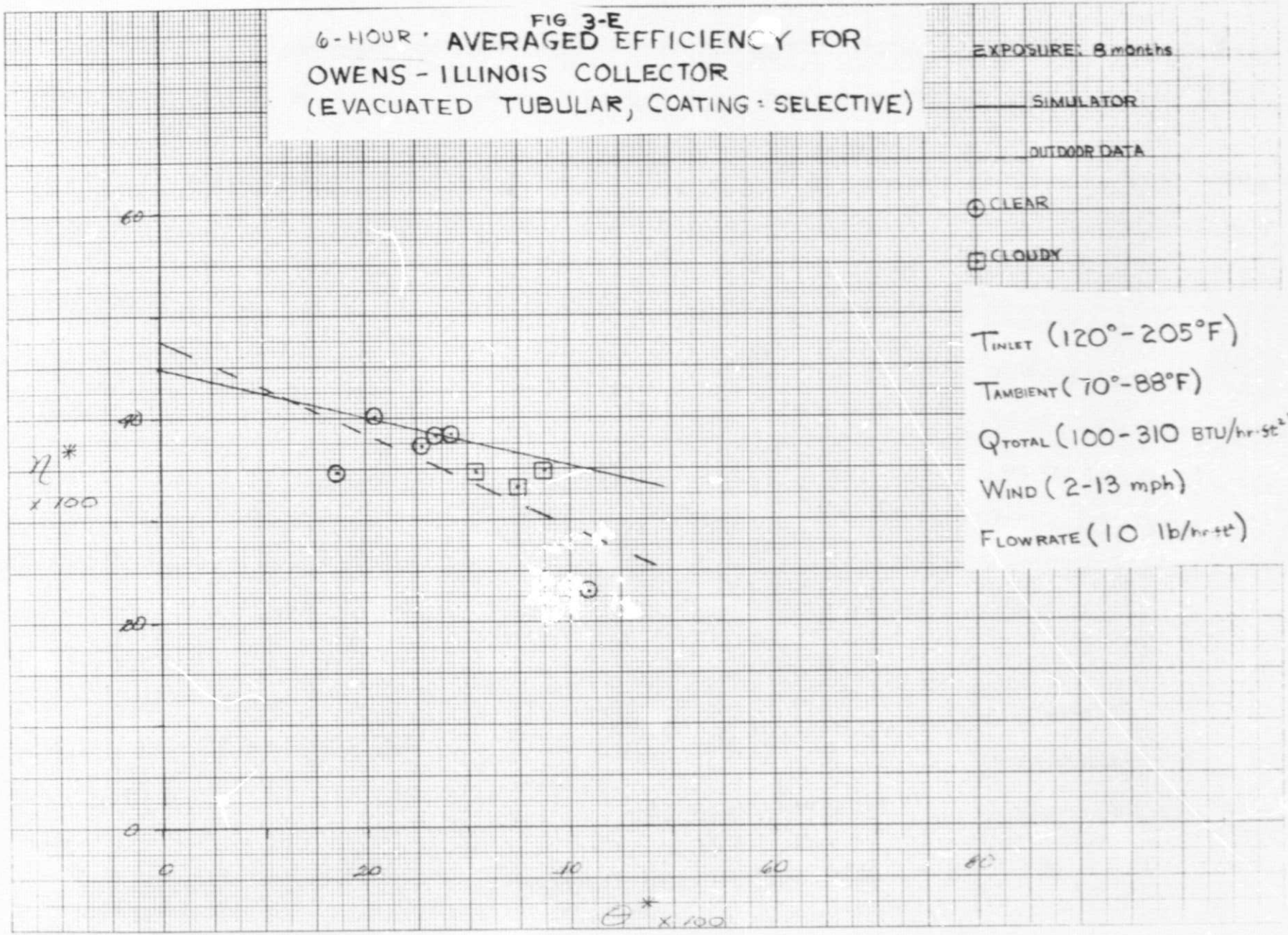


FIG 3-F

6-HOUR AVERAGED EFFICIENCY FOR GENERAL ELECTRIC COLLECTOR (GLAZING = 2-LEXAN, ABSORBER = ALUMINUM, COATING = ALCOA ETCH)

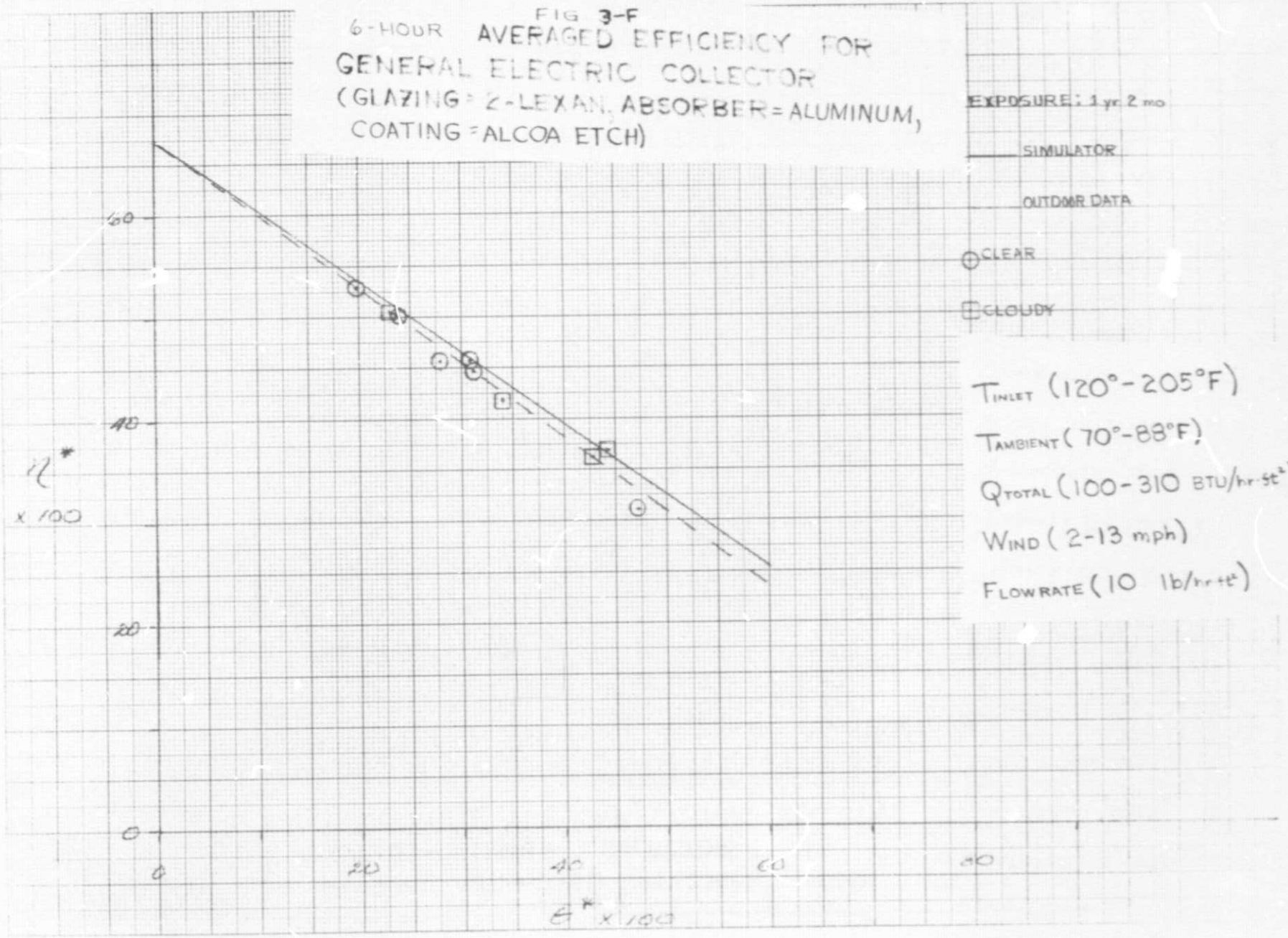
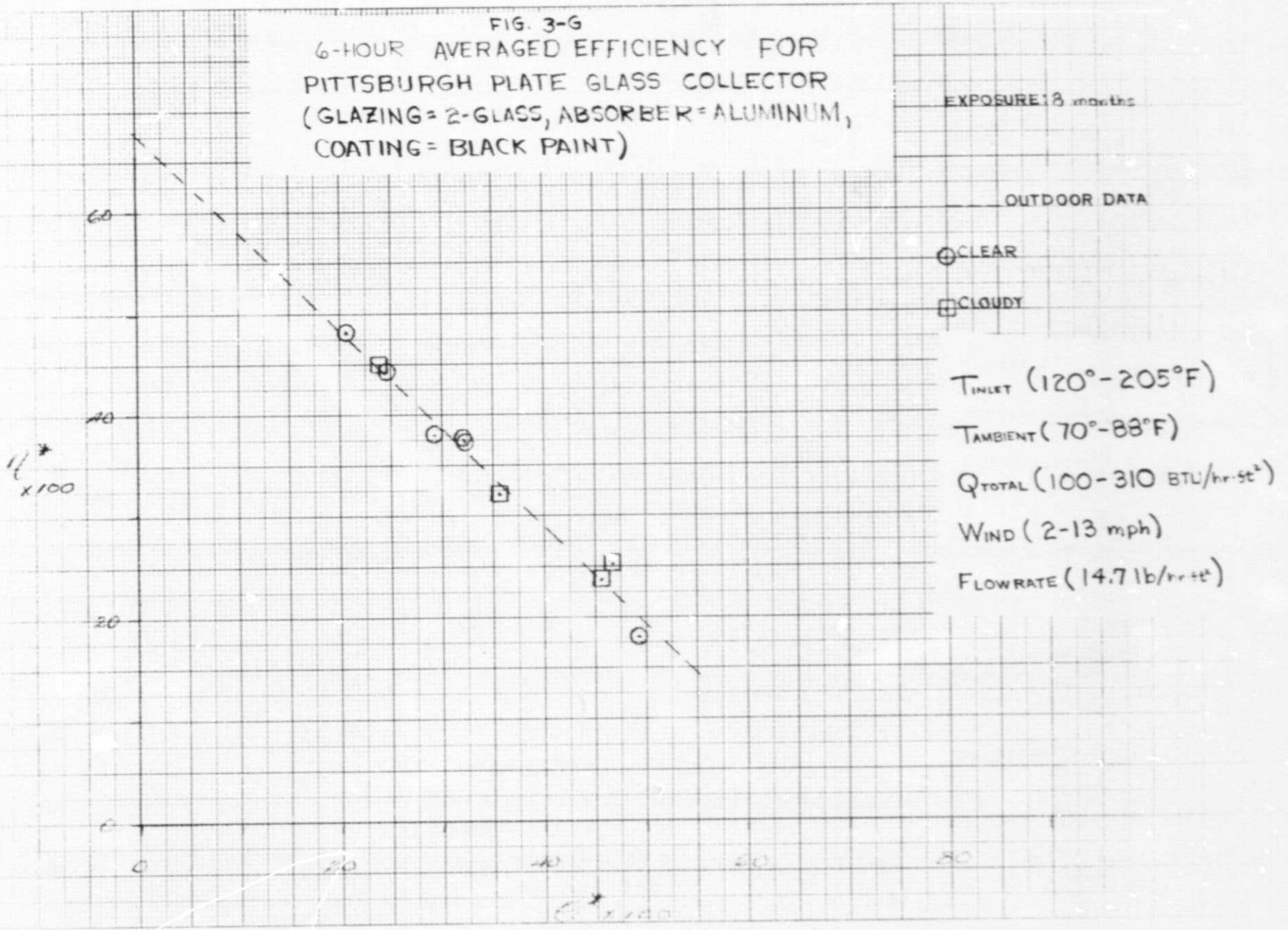


FIG. 3-G

6-HOUR AVERAGED EFFICIENCY FOR PITTSBURGH PLATE GLASS COLLECTOR (GLAZING = 2-GLASS, ABSORBER = ALUMINUM, COATING = BLACK PAINT)



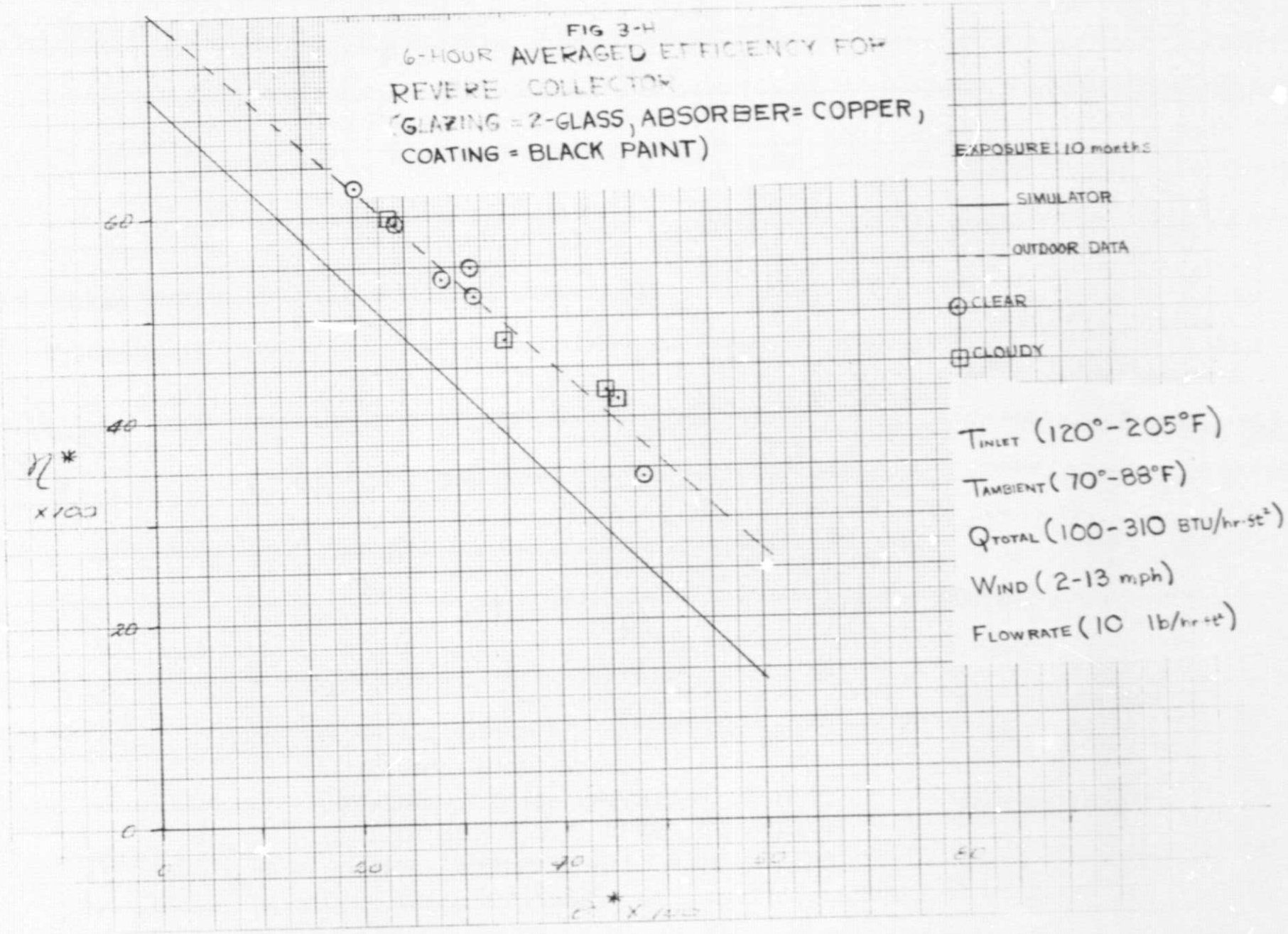


FIG 3-H
6-HOUR AVERAGED EFFICIENCY FOR
REVERE COLLECTOR
(GLAZING = 2-GLASS, ABSORBER= COPPER,
COATING = BLACK PAINT)
EXPOSURE: 10 months
SIMULATOR
OUTDOOR DATA
CLEAR
CLOUDY
T_{INLET} (120°-205°F)
$T_{AMBIENT}$ (70°-88°F)
Q_{TOTAL} (100-310 BTU/hr·ft²)
WIND (2-13 mph)
FLOWRATE (10 lb/hr·ft²)
η^* x100
60
40
20
0
0
20
40
60
80

FIG. 3-1

6-HOUR AVERAGED EFFICIENCY FOR NASA / HONEYWELL COLLECTOR (GLAZING = 2-GLASS, ABSORBER = ALUMINUM, COATING = BLACK PAINT, WITH MYLAR HONEYCOMB)

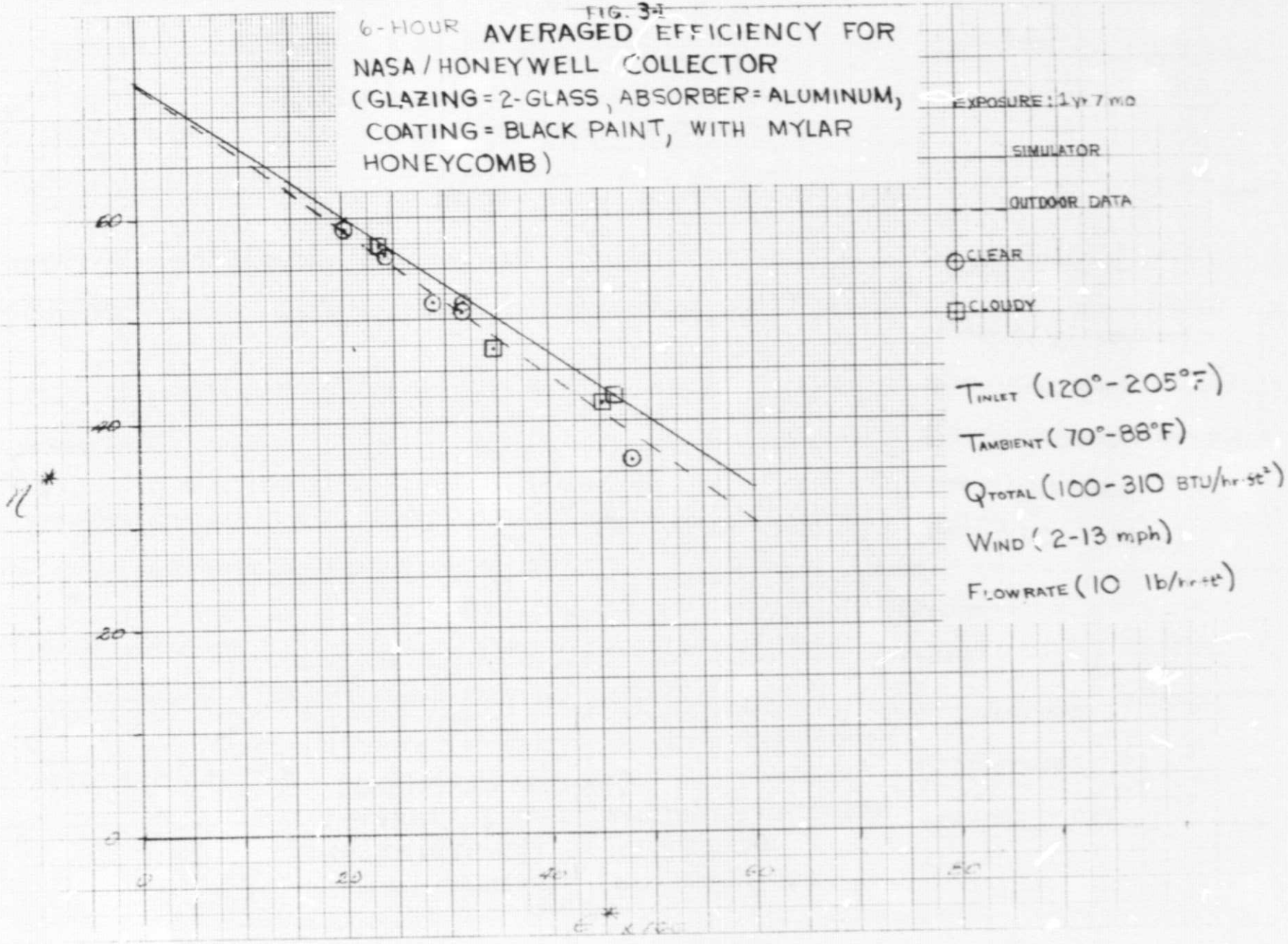
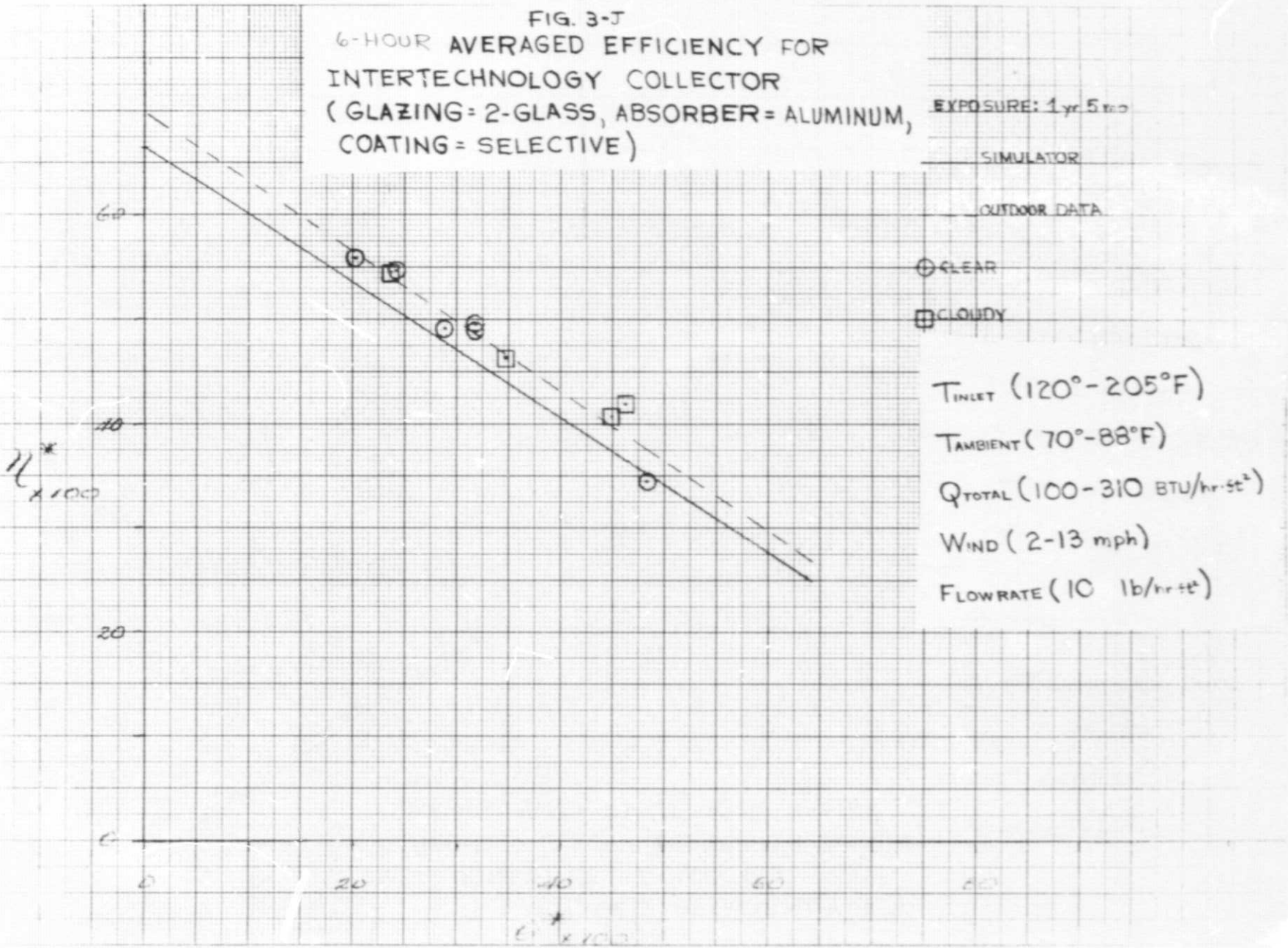


FIG. 3-J

6-HOUR AVERAGED EFFICIENCY FOR INTERTECHNOLOGY COLLECTOR (GLAZING = 2-GLASS, ABSORBER = ALUMINUM, COATING = SELECTIVE)



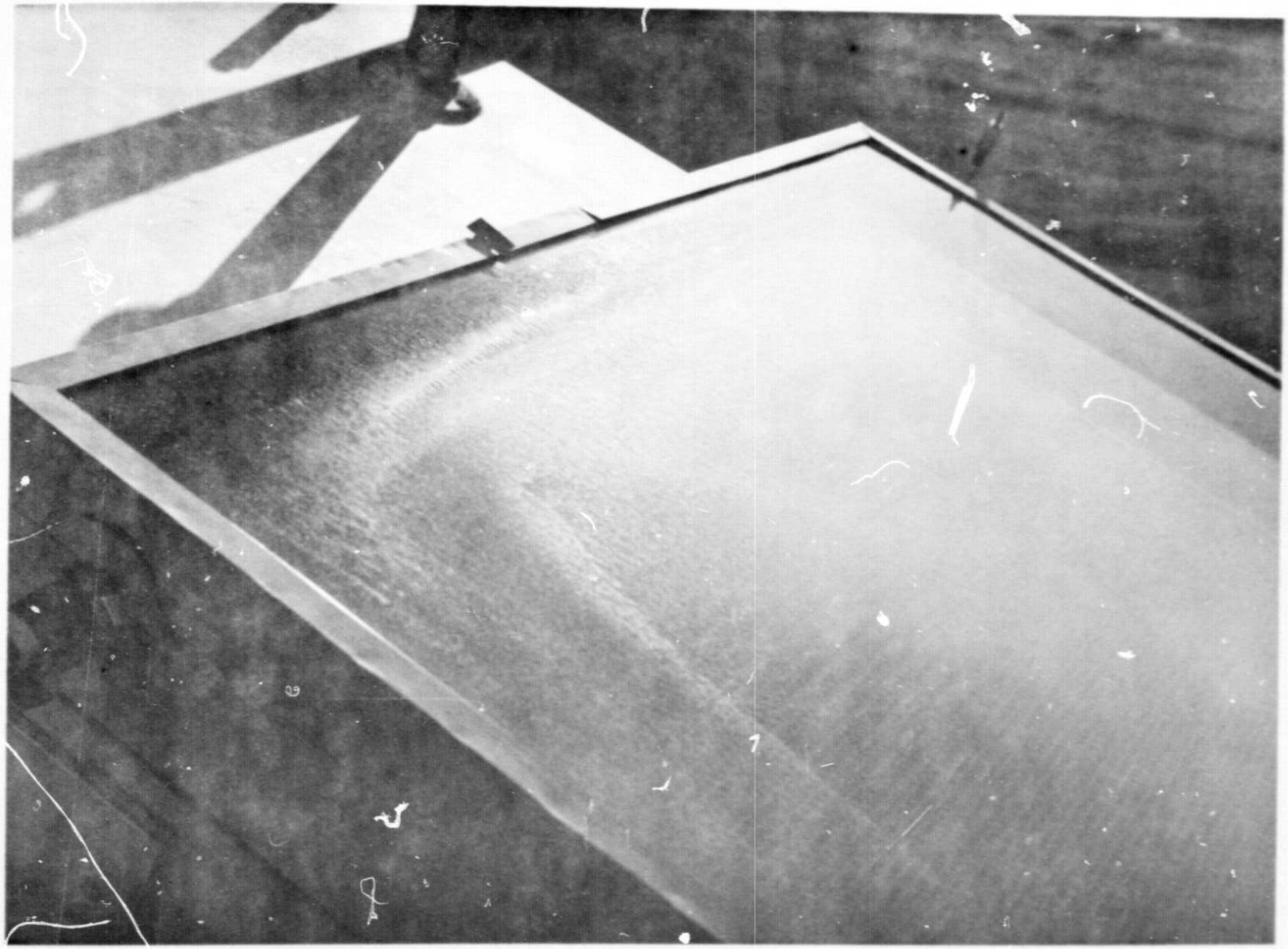


FIG. 4
FILM ON INNER SURFACE OF OUTER GLAZING OF NASA/HONEYWELL Z-GLASS, BLACK PAINT COLLECTOR WITH HONEYCOMB.

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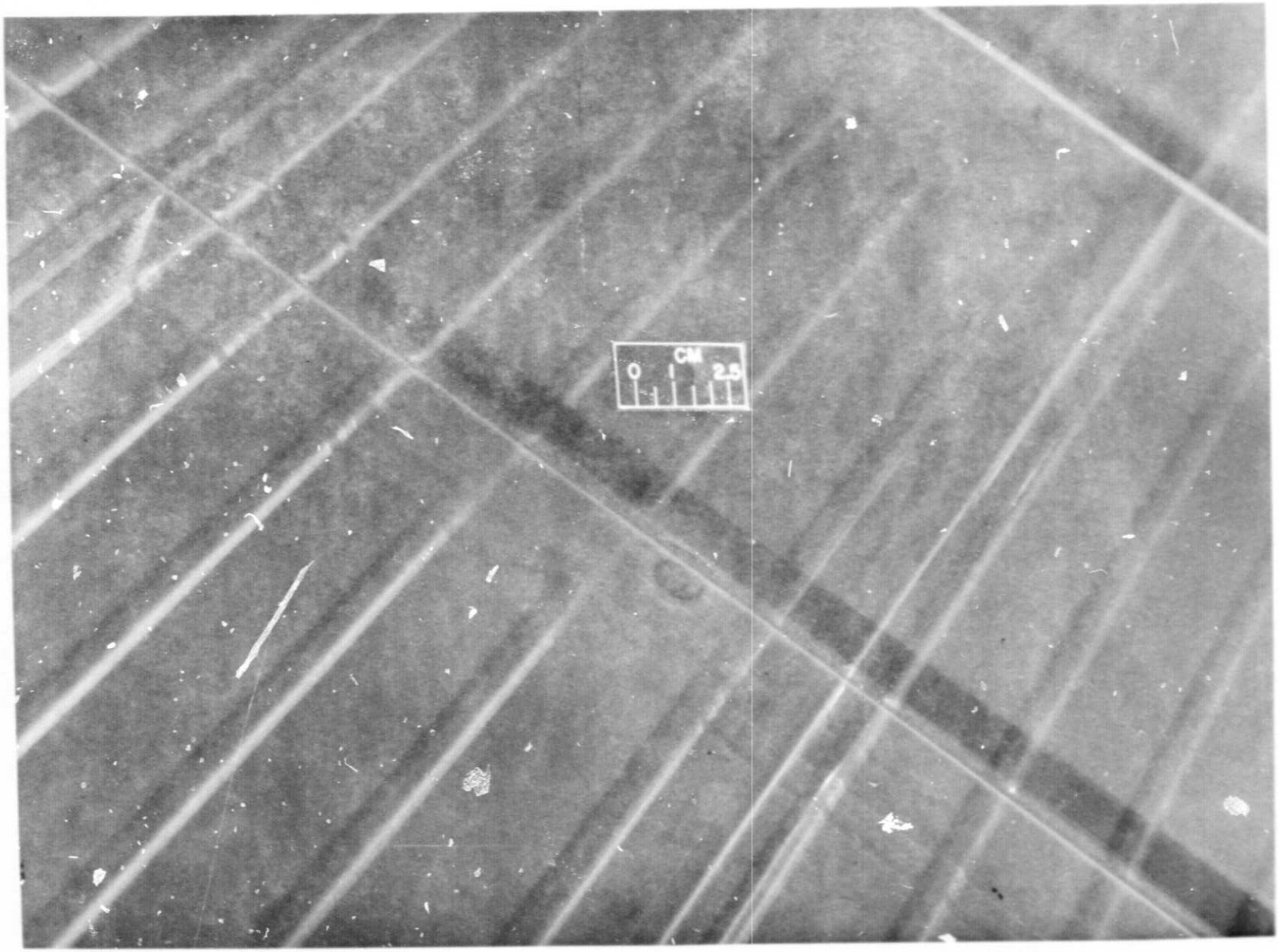

FIG. 5
DISCOLORATION OF PLASTIC GLAZING ON GENERAL ELECTRIC Z-LEXAN, SELECTIVE COATING COLLECTOR

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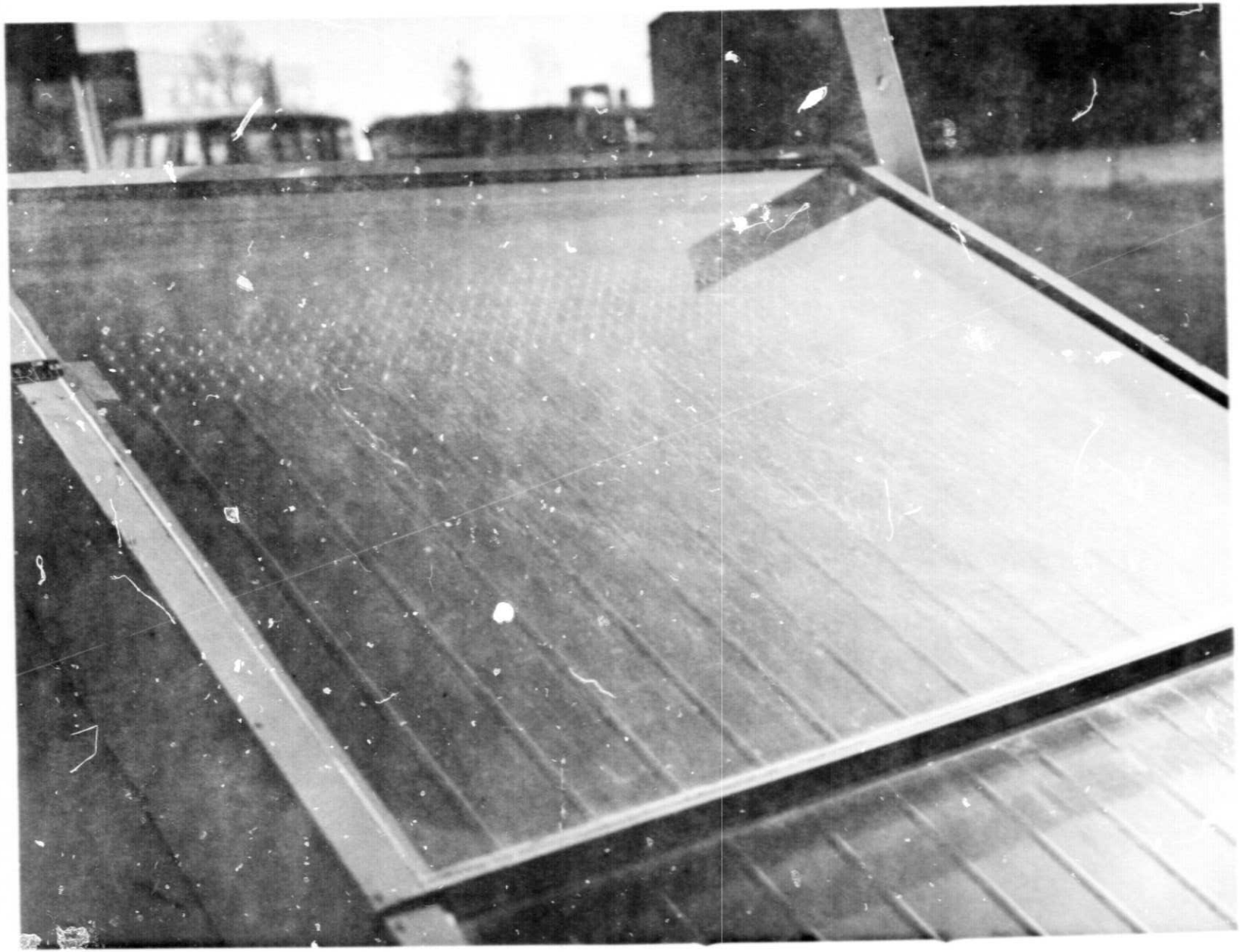

FIG. 6
FILM ON INNER SURFACE OF OUTER GLAZING OF INTERTECHNOLOGY 2-GLASS, SELECTIVE COATING COLLECTOR.