

THE EFFECTS OF MATERIAL PROPERTY CHANGES ON
SOLAR COLLECTOR THERMAL PERFORMANCE

by

Mark Alan Monroe

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APPROVED:

W. C. Thomas, Chairman

D. R. Jaasma

T. E. Diller

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NOMENCLATURE

α_p	Absorber Plate Absorptance
A	Net Area, Arrhenius Model Intercept
B	Arrhenius Model Slope
C_p	Specific Heat, kJ/kg K
δ	Fractional Change in Property Value
Δt	Temperature Difference, $t_{f,i} - t_a$, C
ϵ_p	Absorber Plate Emittance
F_R	Heat Removal Factor
G	Total Hemispherical Solar Radiation, W/m^2
k	Thermal Conductivity, W/m-C
$\dot{m}$	Mass Flow Rate, kg/s
η	Efficiency, Percent
P	Property Value
t	Temperature, C or K
θ	Time, s
τ	Transmittance
U_L	Overall Heat Loss Coefficient, W/m^2-C

Subscripts

a	Ambient
f	Fluid
c	Collector
e	Exit
i	Inlet
in	Insulation
s	Stagnation
sb	Solar Beam

Chapter 1

INTRODUCTION

The cost-to-benefit ratio for solar collector systems is highly dependent on the life cycle of the collector. Economic analyses of these systems are based on collectors performing for at least 20 years, yet little data is available on the durability of solar collectors over this long time period. In addition, no industry-consensus standards exist for measurement of long term performance. This study is concerned with analyzing short term degradation tests performed in a little more than two years.

The method most often used to determine the degradation of collector performance is to compare the collector efficiency before and after exposure to environmental conditions. The only accepted means for measuring collector efficiency is the ASHRAE standard 93-77 [1]. The standard defines methods and conditions acceptable for measuring the thermal performance of different collectors. The results of these tests can be used to compare the performance of a collector before and after environmental exposure, thus providing an indication of collector durability.

Collector durability may be a function of the durability of the individual materials in the collector. The present investigation is concerned with the relationship between changes in material properties of solar collector materials and changes in the thermal performance of the overall collector. If small scale tests on material samples can provide data on overall collector

degradation and the results of the material tests extrapolated to full-scale collectors, a powerful tool would result for determining the long term performance of the collectors.

One of the problems in designing material exposure tests is that dominant degradation mechanisms are not known precisely. As a result, a broad spectrum of tests must be performed to expose samples to a number of degradation environments. Collectors and material samples must be exposed to operating conditions at the same time so that actual degradation can be compared to degradation by accelerated or laboratory exposures.

The National Bureau of Standards (NBS) has been conducting a program to develop standards for solar collector reliability and durability [2]. The program involves both laboratory and outdoor exposure of collectors and material samples representative of products now available commercially. The main purposes of the NBS study are 1) to determine transfer mechanisms leading to the development of accelerated aging tests, and, 2) to develop a large data base on the durability of commercially available solar collectors. The present investigation examines changes in material sample properties and collector performance and will attempt to develop relationships between the two.

1.1 Collector Performance

Figure 1.1 shows a schematic diagram of a typical flat-plate, liquid-heating solar collector. The thermal performance

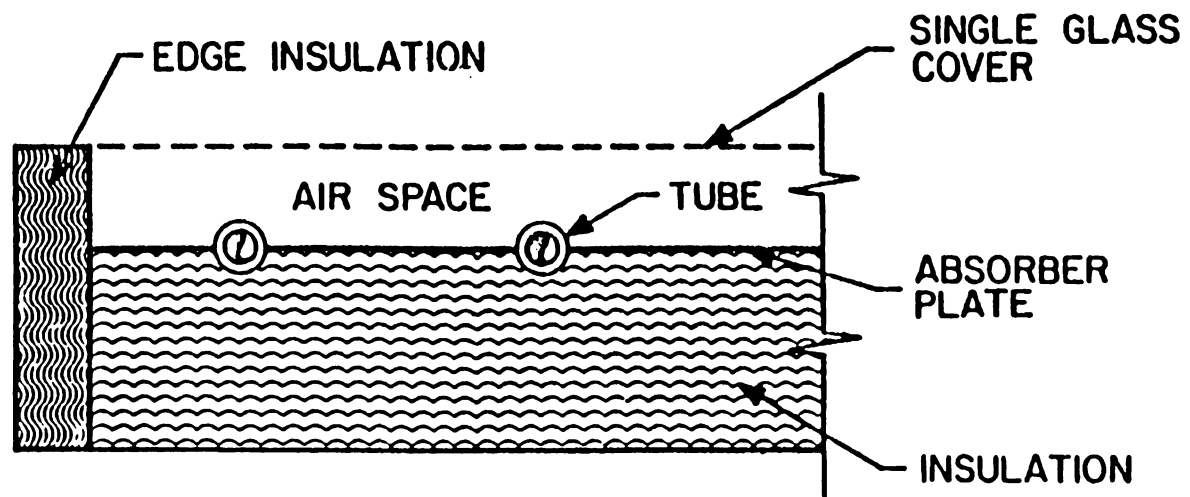


Fig. 1.1. Typical Flat-Plate Solar Collector Cross Section

of the collector is gauged by the efficiency. The efficiency is defined as the ratio of useful energy gain to the solar energy incident on the collector. This ratio can be determined experimentally by measuring the temperature increase between collector inlet and outlet, the mass flow rate of heat transfer fluid, and the incident solar radiation. The experimental efficiency can then be found as

$$\eta = \frac{mC_p [t_{f,e} - t_{f,i}]}{A_c G} \quad (1.1)$$

The same efficiency can also be calculated using the well documented Hottel-Whillier-Bliss (HWB) theory of flat-plate collector performance [3]. The HWB model determines collector efficiency using the relationship

$$\eta = F_R (\tau\alpha) - F_R U_L \left[\frac{t_{f,i} - t_a}{G} \right] \quad (1.2)$$

where F_R is the heat removal factor, $(\tau\alpha)$ the effective transmittance-absorptance product, U_L the overall collector heat loss coefficient, and t_a the ambient temperature. The heat removal factor is comparable to a convention heat exchanger effectiveness, which is defined as the ratio of the actual heat transfer to the maximum possible heat transfer. The parentheses around $\tau\alpha$ indicate that the effects of multiple reflections and absorption by the cover materials have been accounted for, not that F_R is a function of τ and α .

The standard method of presenting collector efficiency test results is to plot measured efficiency versus $[t_{f,i} - t_a]/G$. A typical plot is shown in Fig. 1.2. The points, representing the measured efficiency at a specific inlet temperature, are generally fit with a straight line representing the efficiency curve. From Eq. 1.2, the slope of the efficiency curve is $F_R U_L$ and the intercept of the curve is $F_R(\tau\alpha)$. The inference here is that $F_R(\tau\alpha)$ and $F_R U_L$ are constants, i.e. independent of any test parameter. In actuality, $F_R(\tau\alpha)$ and $F_R U_L$ may depend on plate temperature and therefore inlet temperature. However, scatter in experimental data tends to mask any higher order effects so that the linear approximation is accepted as a valid representation by most researchers.

The effects of changes in material properties on the efficiency curve would be evidenced by changes in the slope and intercept of the curve. The relationships which determine the collector performance parameters, $F_R(\tau\alpha)$ and $F_R U_L$, show which material properties are important to collector performance. In general, the mechanical properties such as strength, impact resistance, toughness, etc., do not affect the thermal performance of solar collectors directly. Optical properties, such as cover solar transmittance, absorber coating absorptance and emittance, primarily influence the value of $F_R(\tau\alpha)$. Heat transfer characteristics, such as insulation conductivity, primarily influence $F_R U_L$. However, changes in heat transfer

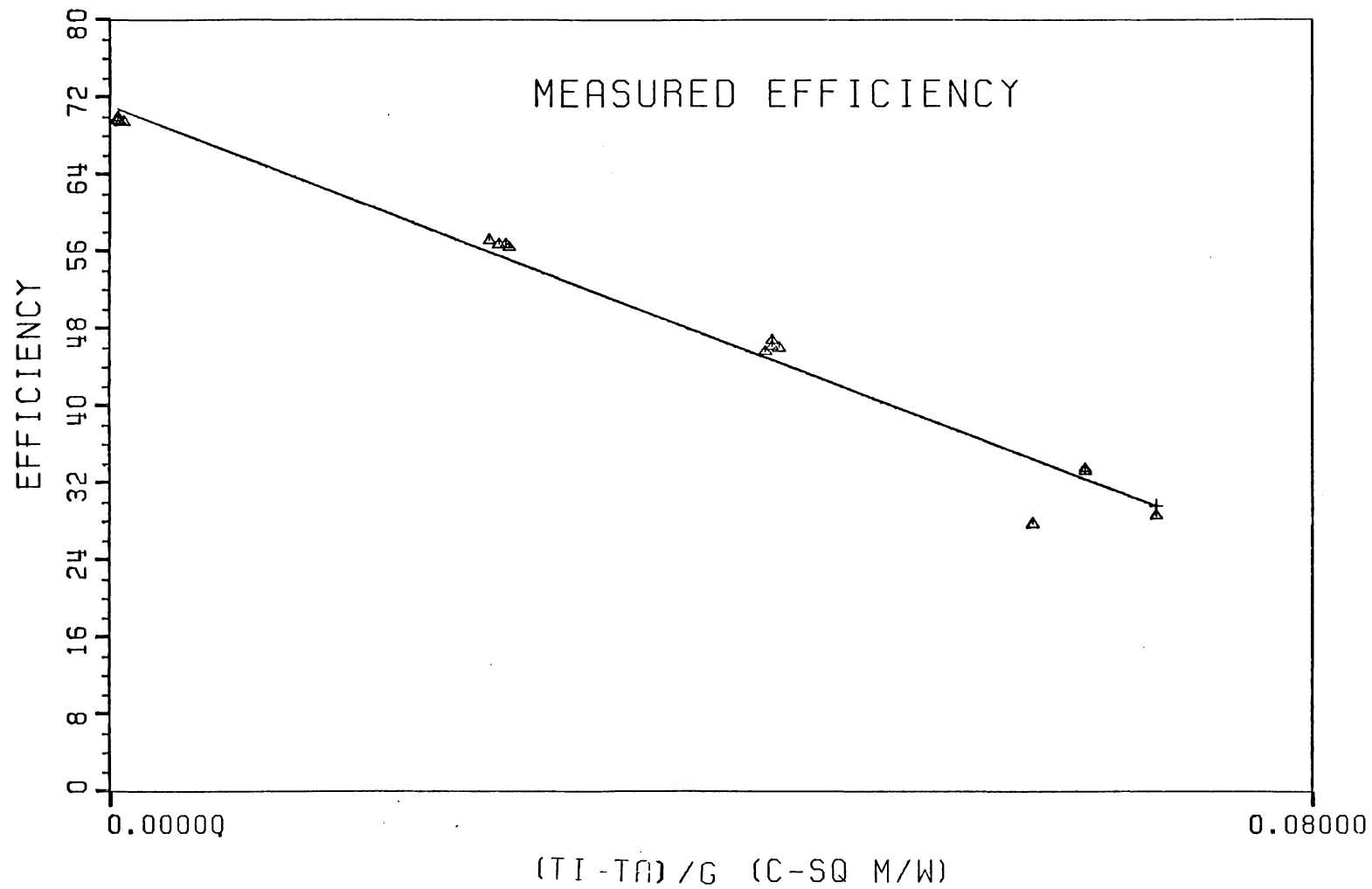


Fig. 1.2. Typical Collector Efficiency Curve

characteristics also affect $F_R(\tau\alpha)$, as will be shown in Chapter 3. The theoretical relationships will be used later in this paper to predict changes in actual collectors using the mathematical model of Eq. 1.2 and material property change data from exposure tests.

1.2 Literature Review

Background literature surveyed was divided into three major topic areas: studies which dealt with changes in material sample properties, studies which exposed full scale collectors to aging tests, and studies which attempted to relate material properties to collector performance.

Literature available on the degradation of material properties can be categorized into data on cover materials and data on absorber materials. The optical properties measured for cover materials are solar beam transmittance and infrared transmittance. The beam, or normal incidence, transmittance should be high and the infrared transmittance low for an effective cover material. A cover material with these properties allows as much solar energy as possible into the collector while trapping reradiated longwave radiation inside to reduce losses. Absorber coatings should have high solar absorptances and low infrared emittances. Mechanical properties measured for cover materials include elongation to failure, impact strength, abrasion resistance, and tensile strength. Absorber coating mechanical properties deal with the ability of the coating to stay on the

absorber plate, so adhesion, impact resistance, and abrasion resistance are measured. Nearly all reports researched used small samples in laboratory tests to gather the data presented.

One interesting article by Zerlaut, et al. [4], is worth mentioning before the separate categories are discussed. The authors make a distinction between reliability and durability which is convenient for use in the present investigation. Reliability encompasses all effects which may occur because of poor design, poor workmanship, etc., which will be manifest in a time period of 30 to 60 days after exposure begins. Durability, on the other hand, deals with the defects and changes which appear after approximately 60 days and affect the long term performance of the collector. Reliability data available in the NBS program exhibit considerable scatter, so the performance of the collectors after 480 exposure days will be considered in greater detail than the other retests in this report.

A wide variety of cover materials have been tested under laboratory exposure. Glass and polytetrafluoroethylene (TeflonTM or FEP) are generally not tested because of proven stability [2,5]. Sandia Laboratories developed a generalized solar materials handbook [6], which compiled data from many authors. The handbook provides qualitative data on the weatherability of glass, fiber-reinforced plastics (FRP), polymethyl methacrylate (acrylic sheet), and polyvinyl fluoride (PVF). Most of the data presented indicate changes in solar transmittance of 1 to 5

percent caused by exposure of 12 months to 5 years. White [7] documented changes of 10 to 50 percent loss of original transmittance in 3 types of FRP. The changes were caused by exposure to outdoor conditions and sustained high temperature tests, respectively. Whitridge [9] states that moisture or high humidity can be damaging to FRP, causing a phenomenon known as blooming. Blooming weakens the glass-resin bond and results in loss of strength and transmittance.

Several studies [5,6,9,10] attempt to relate condensation or deposition of foreign substances onto the cover material to decreases in transmittance. All note the appearance of the condensate or precipitate on the cover sheets, but no specific measurements are given about the thickness of the deposits or the measured effect on transmittance.

Gilligan [11] notes a particularly interesting observation and offers a qualitative explanation. In several cover materials tested, he notes an increase in transmittance over the first 1 to 3 months of actual outdoor exposure for certain polycarbonate materials. Gilligan states that the phenomenon is caused by the loss of one or more of the ingredients in the polymer, most likely the ingredients with high solar absorptivity. The data from the NBS study [2] agree with this observation that certain polymers increase in transmittance in the first 30 to 60 days of exposure. In addition, several collectors showed increases in

measured performance during this period which may possibly be attributed to the same mechanism.

The literature which involved absorber coating tests all used small samples for tests. Beatty and Raghunathan [12] report that black chrome retained virtually all of the original mechanical properties after 5 years of exposure, but that the optical properties exhibited significant change in a little over a year. Wolf, et al. [13] performed a series of accelerated degradation tests on 13 black paint samples. They measured a 5 percent decrease in the absorptivity of these coatings when blistering occurred.

Another report by Gilligan [5] is a comprehensive guide for both cover and absorber coating degradation. The author presents data in the form of tables and plots on changes in optical properties caused by outdoor exposure. Data on changes in mechanical properties are also provided. The samples in Gilligan's study were exposed as long as 34 months. Some samples were removed from exposure after 3 to 6 months since they exhibited no change during this period.

One reference was located that described the degradation of insulation materials in solar collector applications [6]. The discussion described various outgassing products released by insulation materials, but presented no quantitative data on changes in conductivity as a result of outgassing. Since no insulation materials were tested separately in the NBS program,

the analysis of the effects of changes in insulation properties will be purely theoretical in this report.

The literature dealing with full scale collector testing showed trends close to the ones presented later in this report. Two reports originated from Wyle Laboratories in Huntsville, Alabama [14,15]. The first report documents changes in the slope and intercept of measured efficiency curves of four out of five collectors exposed. The collectors were exposed under stagnation conditions (no heat transfer fluid flow) for one year and exhibited changes in efficiency as great as 20 percentage points. The second report presents data on a single collector exposed over an 18-month period outdoors. The collector performance parameters exhibited enough change in this case to cause a decrease in efficiency of 9 percent at $\Delta t/G$ equal to $0.11 \text{ C-m}^2/\text{W}$.

Five other collectors tested at NASA's Lewis Research Center proved to be more stable than the collectors in Huntsville [16]. Only one collector exhibited significant degradation in the NASA study. There are several possible explanations for the observed differences between the Huntsville collectors and the collectors at NASA. First, Lewis Research Center is located in Ohio, a much more temperate zone than Huntsville. Temperature and humidity effects would be much more prominent in Huntsville. Also, the initial performance tests on the NASA collector were performed outdoors, while the final performance tests were made in a solar simulator. There is evidence that tests performed using solar

simulators may produce higher efficiencies than outdoor tests. The apparent lack of degradation at NASA may be a result of these facts.

Knoll and Johnson [10] documented changes in efficiency of as much as 10 percent after outdoor exposures of 3 to 9 weeks at NASA's Langley Research Center. They attributed the changes in efficiency to degradation in cover transmittance and absorber coating absorptance, but had no measurements to back up their hypothesis.

In studies where material properties are related to collector performance, the results presented are all theoretical predictions of change. Zerlaut, et al. [4], use the HWB equation to determine which properties will affect the thermal performance of solar collectors. They analyze each term of Eq. 1.2 in detail and predict the influence of absorptance, emittance, transmittance, and weather conditions on theoretical efficiency calculations. Woodman [17] and Wolf, et al. [13], present plots of efficiencies generated using mathematical models and variable material properties. In both references, the values of absorptance and emittance are varied to observe the effect of the change on calculated efficiency, but neither study tests the agreement of the theoretical degradation with actual degradation measurements.

1.3 Scope

The literature points to the need for developing material sample and solar collector degradation test procedures. In addition, there is a need to analyze material sample results and full-scale collector performance degradation. The primary goal of the analysis should be to develop methods of predicting collector degradation using the material sample measurements. Long term collector durability could then be estimated using the results of relatively inexpensive material sample tests. This investigation will deal primarily with two aspects of the NBS Durability/Reliability Program [2]. Chapter 2 describes Material Sample exposure test procedures and presents the results of these tests. Chapter 3 describes full scale collector test procedures, presents the results of these tests, and describes and tests an analytical prediction procedure using a mathematical model of the solar collectors. Results are discussed further in Chapter 4 and Conclusions and Recommendations are presented in Chapter 5.

Chapter 2

MATERIAL SAMPLES

This chapter presents the procedures and representative results from small-scale material sample tests. Material samples, called coupons, were cut from commercially available solar collectors. Though results may be referred to as "Collector E" or "Sample N", all results are measured from sample coupons under exposure. The collectors span a wide range of designs, flow configurations, and materials of construction. The samples are divided into two general categories: cover samples and absorber samples.

Both indoor and outdoor tests were used for the samples. Outdoor exposures were performed using actual outdoor conditions and accelerated degradation conditions using solar energy concentrated by reflectors. Thermal shock in the form of water spray was also used on some of the outdoor samples. Indoor tests included exposure to high temperature, combinations of high temperature and high ultraviolet (UV) radiation, high humidity, thermal cycling, and a solar simulator. The purpose of these tests is to isolate specific degradation mechanisms and observe the importance of each.

In an attempt to minimize site-specific effects, the samples were placed at four test sites around the United States. The sites selected and criterion used are given in Table 2.1.

Table 2.1

Test Site Selection Criteria
(From Reference 2)

DSET Labs, Inc., Phoenix, Arizona (Test Site 1):

Hot, dry
High solar radiation
High Ultraviolet
Rural, desert environment

Florida Solar Energy Center, Cape Canaveral, Fla. (Test Site 2):

Hot, humid
High solar radiation
Low to moderate Ultraviolet
Coastal, salt air environment

Lockheed Research Laboratory, Palo Alto, Calif. (Test Site 3):

Moderate, dry
High solar radiation
Moderate Ultraviolet
Urban environment

National Bureau of Standards, Gaithersburg, Md. (Test Site 4):

Moderate, humid
Moderate solar radiation
Moderate to low Ultraviolet
Suburban environment

Ambient temperature, humidity, solar radiation levels, and UV levels are some of the important factors considered in site selection. All exposures and measurements were performed by the laboratories with results sent to VPI&SU for analysis.

2.1 Cover Samples Exposure Procedures

The materials tested and exposure conditions used are summarized in Tables 2.2 and 2.3, respectively.

The outdoor samples were placed in an exposure apparatus which was designed to simulate the temperatures and exposure parameters seen in actual service. A schematic diagram of an exposure mini-box is shown in Fig. 2.1. Five boxes were constructed for each sample to allow one control sample and one box to be removed from exposure at 80-day intervals up to 480 total exposure days. An exposure day was chosen to be a day when the daily solar radiation in the plane of the collector is at least 17.1 MJ/m^2 (1500 BTU/ft^2). Cover transmittances in all cases were measured using ASTM standard E424, Method A [18].

Indoor samples were exposed as outlined in Table 2.3 with samples removed and measurements taken at the prescribed intervals.

2.2 Absorber Samples Exposure Procedures

The material samples tested and exposure conditions are listed in Tables 2.4 and 2.5, respectively.

Table 2.2

Cover Material Samples Tested in NBS
Durability/Reliability Program
(From Reference 2)

Code ¹	Cover Material	Transmittance ³ (controls)
E	FRP Type Ia	0.85
G	FRP Type II	0.84
H ²	Polyester/FEP (outer) (inner)	0.85/0.96
J	Polycarbonate	0.88
K	Polyvinyl Fluoride	0.89
L	FRP Type Ib	0.84
M	FRP Type III	0.78
N	Polymethyl methacrylate (acrylic)	0.90
O ²	Glass ⁴ /Polyvinyl Fluoride (outer)(inner)	0.86/0.89

¹Code letters E, G and H indicate materials coupon specimens cut from solar collectors E, G and H. Codes J, K, L, M, N and O tested at the materials level only.

²Materials to be exposed as a combination in the cover mini-boxes (see 2.3.2.1 and 2.3.2.2) and in the accelerated weathering machine (see 2.3.2.4). Materials to be exposed individually in all other tests. Glass and FEP materials are not to be used for individual tests because of proven stability.

³These properties are dependent on the formulations and manufacturing processes used. Other products within a generic class of materials may have significantly different properties.

⁴Ordinary plate glass.

Table 2.3

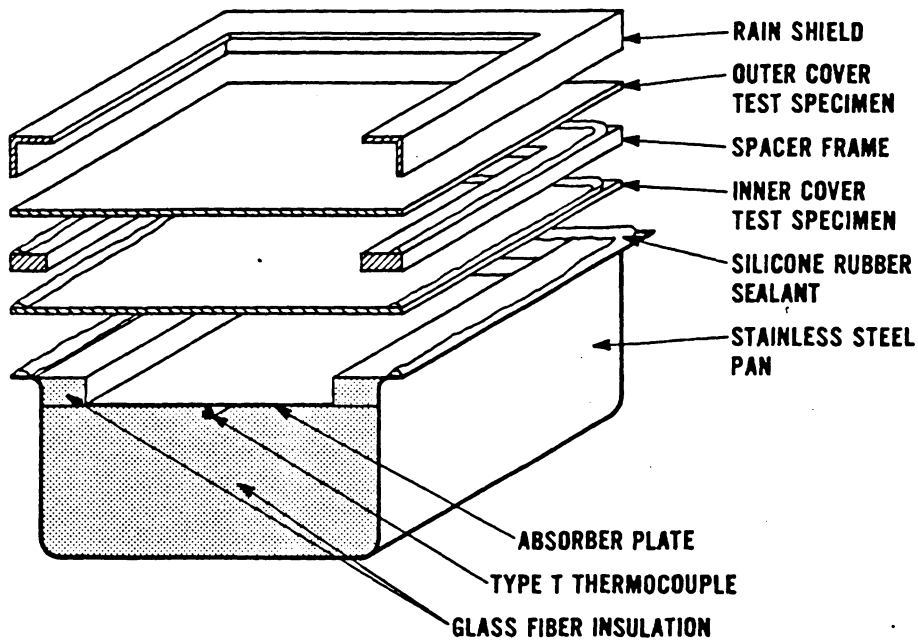
Cover Sample Exposure Conditions and Measurement Schedule
(From Reference 2)

Exposure Condition	Value or Range	Exposure Time
Temperature (indoor)	a) 70 C b) 90 C c) 125 C	500, 1,000 and 2,000
Temperature and Humidity (indoor)	a) 50 C and 98% RH b) 70 C and 95% RH c) 90 C and 95% RH	500, 1,000 and 2,000
Temperature and Radiation (indoor)	Xenon arc weather- ing machine a) 70 C b) 90 C	500, 1,000 and 2,000
Solar Simulator	a) Tungsten b) Xenon simulators with irradiance of 950 W/m^2 and 70 C	30, 60 and 120 cycles*
"Real Time" Outdoor	1 sun at 60 C	80, 160, 240 and 480 days**
Accelerated Outdoor	6 suns at 70 C	6, 12 and 24 equivalent months**

*Each cycle consists of 5 irradiation and 1 hr. cooling, as defined in Tables 2-6 and 2-7.

**Radiant exposure must exceed $17,100 \text{ kJ/m}^2$ for each day.

***One equivalent month equals $6.625 \times 10^8 \text{ J/m}^2$.



Notes:	Stainless Steel Pan	22 x 12 x 10 cm without rim
	Glass Fiber Insulation	64 kg/m ³ density
		Bottom thickness 10 cm
		Edge thickness 2.5 cm square
		Baked out at 230 C for 24 hours
	Absorber Plate	Black chrome on copper
	Silicone Rubber Sealant	Between covers and pan, and
		between covers and spacer
	Cover Test Specimens	26 x 16 cm
	Rain Shield	16 ga stainless steel, clamped
		to pan
	Spacer Frame	6 mm thick aluminum

Fig. 2.1. Cover Sample Exposure Mini-Box Schematic Diagram
(From Reference 2)

Table 2.4

Absorber Material Samples Tested in NBS D/R Program
(From Reference 2)

Code ¹	Absorber Material		Optical Properties ³	
	Coating	Substrate	Absorptance ³	Emittance ³
A	Black Nickel	Steel	0.87	0.13
C	Flat Black Paint	Copper	0.98	0.92
D	Black Chrome	Steel (nickel flashed)	0.97	0.07
E	Flat Black Paint	Copper	0.95	0.87
F	Copper Oxide	Copper	0.96	0.75
G	Black Porcelain Enamel	Steel	0.93	0.86
H	Flat Black Paint	Aluminum	0.95	0.89
I	Black Chrome	Stainless Steel	0.88	0.19
J	Black Chrome	Aluminum	0.98	0.14
L	Lead Oxide	Copper	0.99	0.29
M	Oxide Anodized	Aluminum	0.94	0.10
N	Oxide Conversion Coating	Aluminum	0.93	0.51
P	Black Chrome	Copper	0.96	0.08

¹Code letters A through H indicate materials coupon specimens cut from solar collectors A through H. Codes I through P tested at the materials level only.

²These properties are dependent on the formulations and manufacturing processes used. Other products within a generic class of materials may have significantly different properties.

³Average values based on a minimum of ten test specimens.

Table 2.5

Absorber Sample Exposure Conditions and Measurement Schedule
(From Reference 2)

Exposure Condition	Value or Range	Exposure Time
Temperature (indoor)	a) 150 C	500, 1,000 and 2,000
Temperature and Humidity (indoor)	90 C and 95%	500, 1,000 and 2,000
Thermal Cycling (indoor)	-10 C to 175 C	5, 15 and 30 cycles
Temperature and Radiation (indoor)	Xenon arc weathering machine at 90 C	500, 1,000 and 2,000
Solar Simulator	a) Tungsten b) Xenon simulators with irradiance of 950 W/m ² and 130 C	30, 60 and 120 cycles*
"Real Time" Outdoor	1 sun at 140 C and 160 C	80, 160, 240 and 480 days**
Accelerated Outdoor	6 suns at 150 C	6, 12 and 24 equivalent months***

*Each cycle consists of 5 irradiation and 1 cooling, as defined in Tables 2-6 and 2-7.

**Radiant exposure must exceed 17,100 kJ/m² for each day.

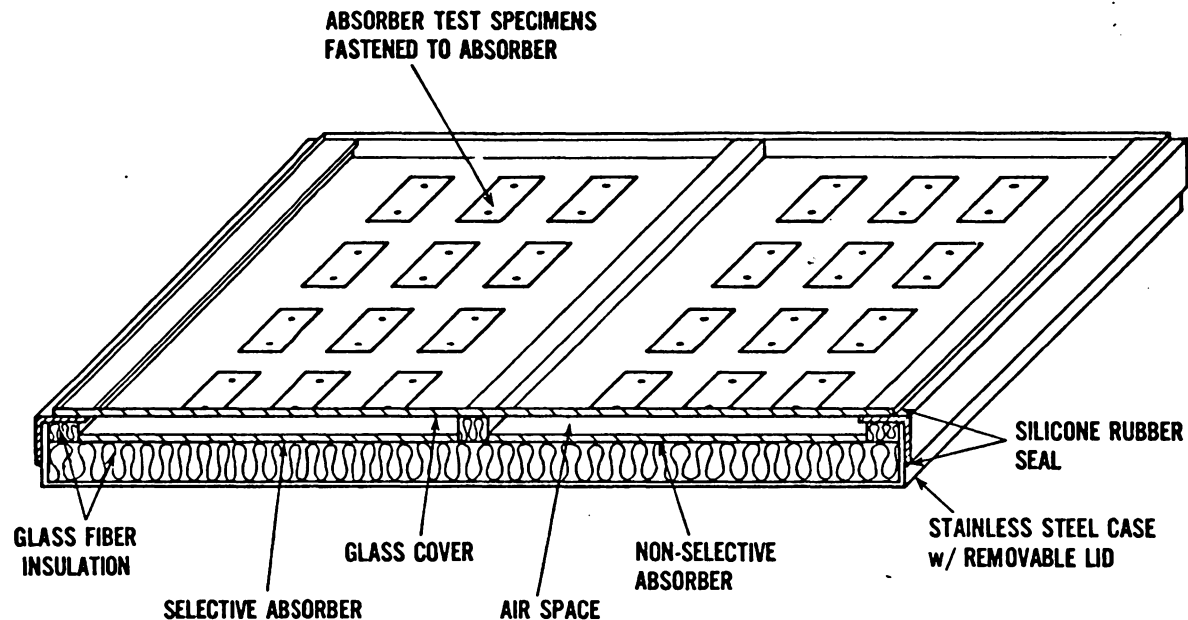
***One equivalent month equals 6.625×10^8 J/m².

The outdoor samples were placed in an exposure box to simulate temperatures and thermal cycling experienced in actual service. A schematic of this apparatus is shown in Fig. 2.2. Real time and accelerated exposures were conducted using five coupons. One was used for control and one each was removed from exposure at 80 day intervals up to 480 exposure days. Solar absorptance was measured using ASTM E424, Method A and emittance was measured using ASTM E408, Method A [19].

Indoor samples were exposed as outlined in Table 2.5. Samples were removed from exposure and properties measured in accordance with the schedule in Table 2.5.

2.3 Results of Material Tests

The measurements taken on the 14 types of cover samples and 13 types of absorber samples provided a large data base on material property degradation. A number of samples showed no change greater than 6 percent of the original value in any measured property. Other samples produced inconclusive data since the measured properties would alternate between decreasing and increasing in value. Therefore, six representative absorber samples and six cover samples were selected for detailed analysis. These samples were chosen because they exhibited either consistent degradation of property values or a significant change from the original value or both. A more complete listing of the measured properties of all samples is presented in Appendix B.



Notes:

Absorber Test Specimens	7.6 x 5.1 cm
Stainless Steel Case	190 x 84 x 9 cm
Glass Fiber Insulation	64 kg/m ³ density
	Baked out at 230 C for 24 hours
	Edges and center 1.3 cm thick
	Bottom 10 cm thick
Air Space	1.3 cm
Cover	Water white glass
Absorber	Selective side -- Black chrome on copper
	Non-selective side -- Black porcelain enamel on steel

Type T Thermocouples attached to center of each absorber

Fig. 2.2. Absorber Sample Exposure Apparatus Schematic Diagram (From Reference 2)

2.3.1 Cover Sample Exposure Results

The samples studied represent a variety of materials ranging from acrylic sheet to four types of FRP. The degradation tests which appeared to be most severe and the transmittances measured after these tests are shown in Table 2.6.

Several observations can be made from the table. The cover system for collector H consists of a polyester film outer cover and a teflon film inner cover. This cover assembly is extremely stable. The tabulated data show that changes in all test parameters measured were always less than 0.03. Sample N, acrylic sheet, also proved to be stable, changing less than 0.02 in all tests but temperature and humidity exposure. In the 90 C and 95 percent relative humidity test, the transmittance of Sample N decreased from 0.90 to 0.64 in 2000 hours of exposure. The FRP samples, on the other hand, were much less stable. Sample L, FRP-type 1B, appeared to be the most stable of the four types of FRP. There are, however, no other clear-cut conclusions which can be drawn from the available data.

Figures 2.3 through 2.8 provide a visual representation of the data in Table 2.6. It should be noted that the lines are simply drawn from point to point and are not necessarily indicative of trends between the individual points. Each figure shows six plots grouped by test type. This grouping allows a comparison of how each sample withstood the different environments relative to the other samples. The high temperature-high

Table 2.6
Cover Sample Transmittance Degradation in Selected Exposure Tests

Test	Actual Outdoor (Days)					90 C & 95% RH (Hours)				90 C & Xenon Rad. (Hours)				70 C (Hours)				90 C (Hours)				125 C (Hours)			
Sample	0	80	160	240	480	0	500	1000	2000	0	500	1000	2000	0	500	1000	2000	0	500	1000	2000	0	500	1000	2000
E	0.83	0.84	0.82	0.80	0.84	0.85	0.50	0.46	0.30	0.85	0.78	0.79	0.77	0.85	0.83	0.85	0.81	0.85	0.84	0.84	0.82	0.85	0.82	0.81	0.79
G	0.84	0.81	0.79	0.80	0.66	0.84	0.10	0.08	0.07	0.84	0.78	0.78	0.74	0.84	0.82	0.80	0.79	0.84	0.73	0.73	0.78	0.84	0.70	0.66	0.64
H	0.85	0.84	0.85	0.85	0.82	0.85	0.84	0.83	---	0.85	0.86	0.86	0.85	0.85	0.84	0.85	0.84	0.85	0.84	0.84	0.85	0.85	0.85	0.85	0.84
L	0.84	0.84	0.84	0.83	0.84	0.84	0.31	0.25	0.21	0.85	0.83	0.83	0.80	0.84	0.83	0.81	0.83	0.84	0.83	0.80	0.83	0.84	0.81	0.80	0.80
M	0.82	0.78	0.77	0.75	0.77	0.78	0.24	0.23	0.18	0.78	0.74	0.73	0.70	0.78	0.81	0.79	0.80	0.78	0.75	0.64	0.66	0.78	0.68	0.63	0.55
N	0.91	0.89	0.89	0.89	0.90	0.90	0.76	0.82	0.64	0.90	0.89	0.88	0.88	0.90	0.89	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.89	0.90	0.91

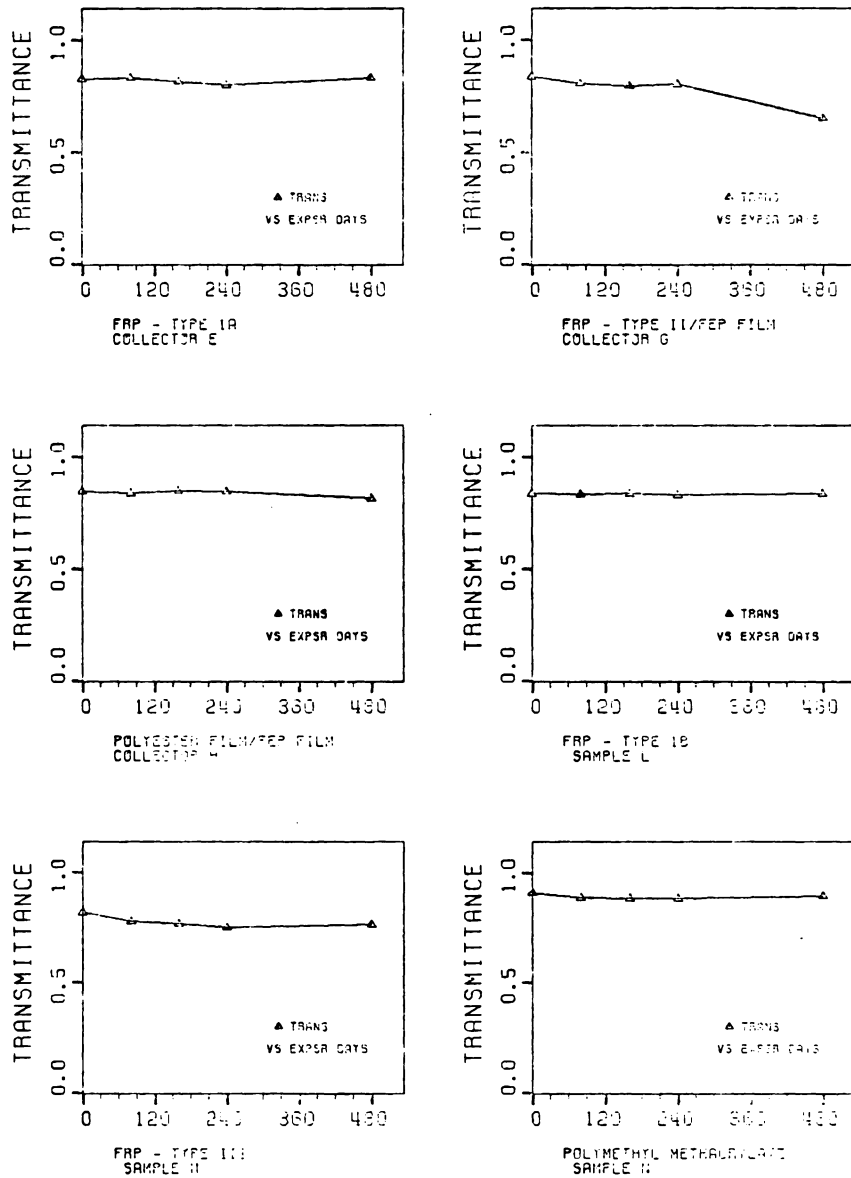


Fig. 2.3. Cover Sample Transmittance vs Exposure Days for Actual Outdoor Tests

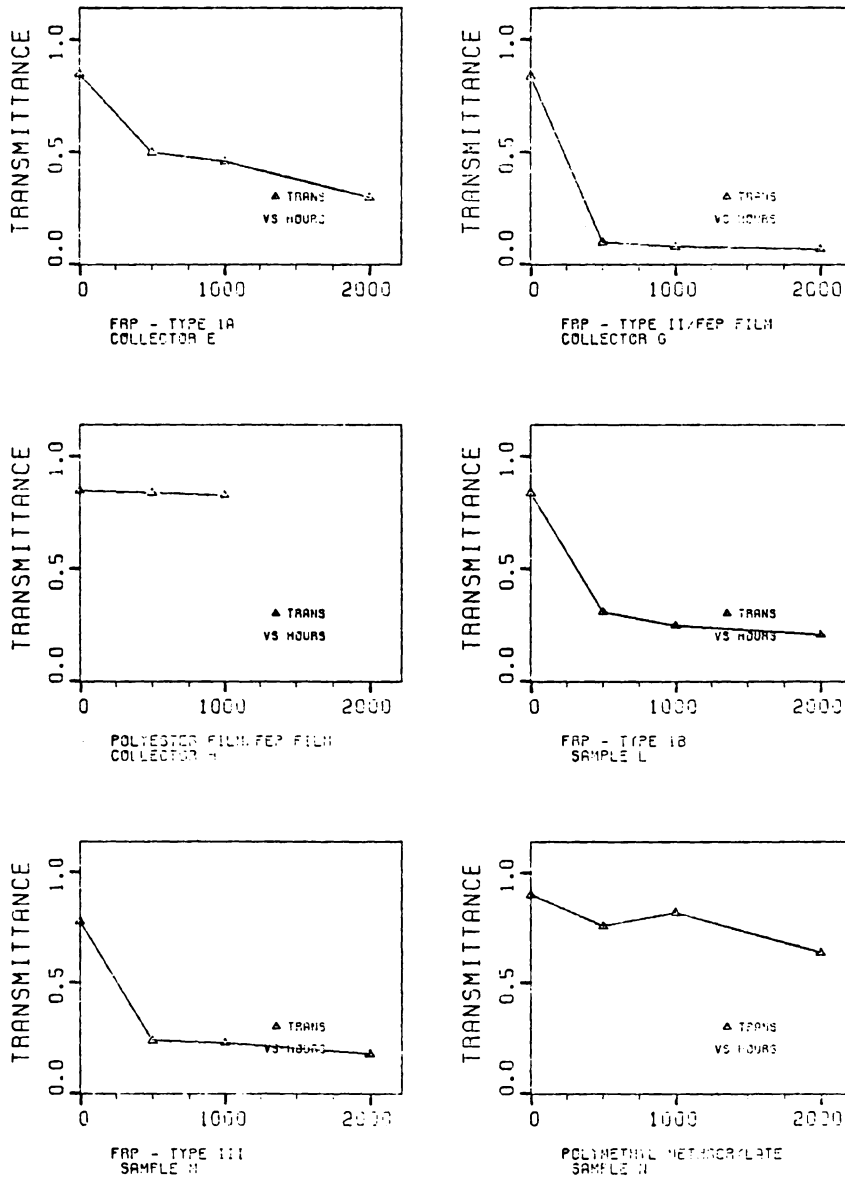


Fig. 2.4. Cover Sample Transmittance vs Exposure Hours for 90 C and 95 percent Relative Humidity Tests

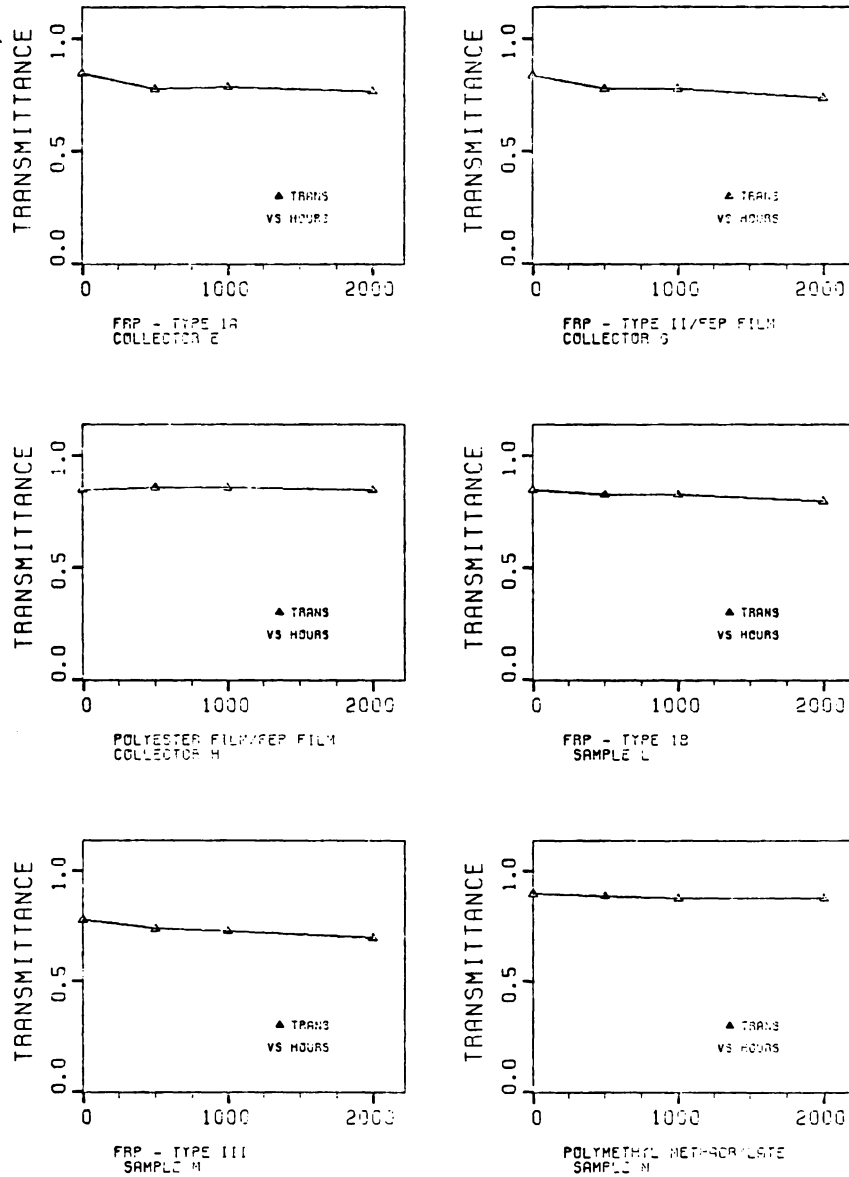


Fig. 2.5. Cover Sample Transmittance vs Exposure Hours for 90 C and Xenon Radiation Tests

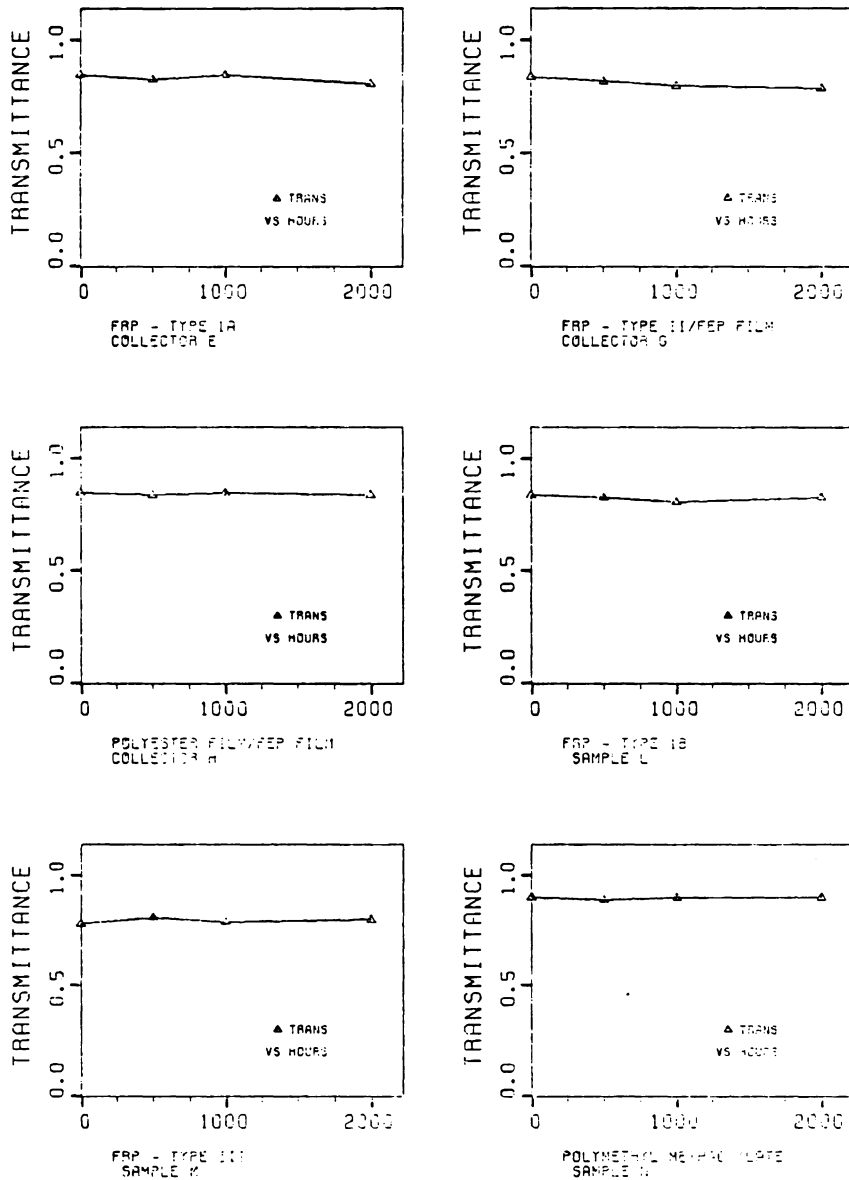


Fig. 2.6. Cover Sample Transmittance vs Exposure Hours for 70 C Tests

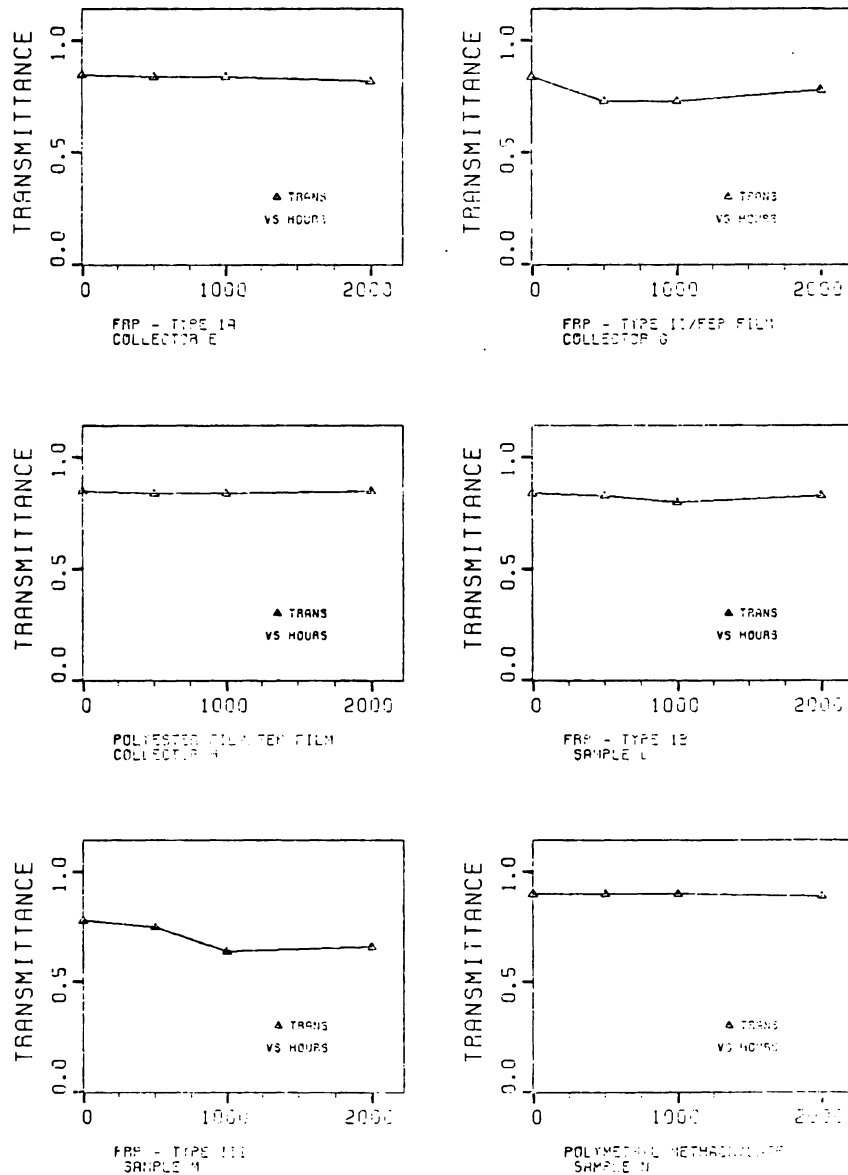


Fig. 2.7. Cover Sample Transmittance vs Exposure Hours for 90 C Tests

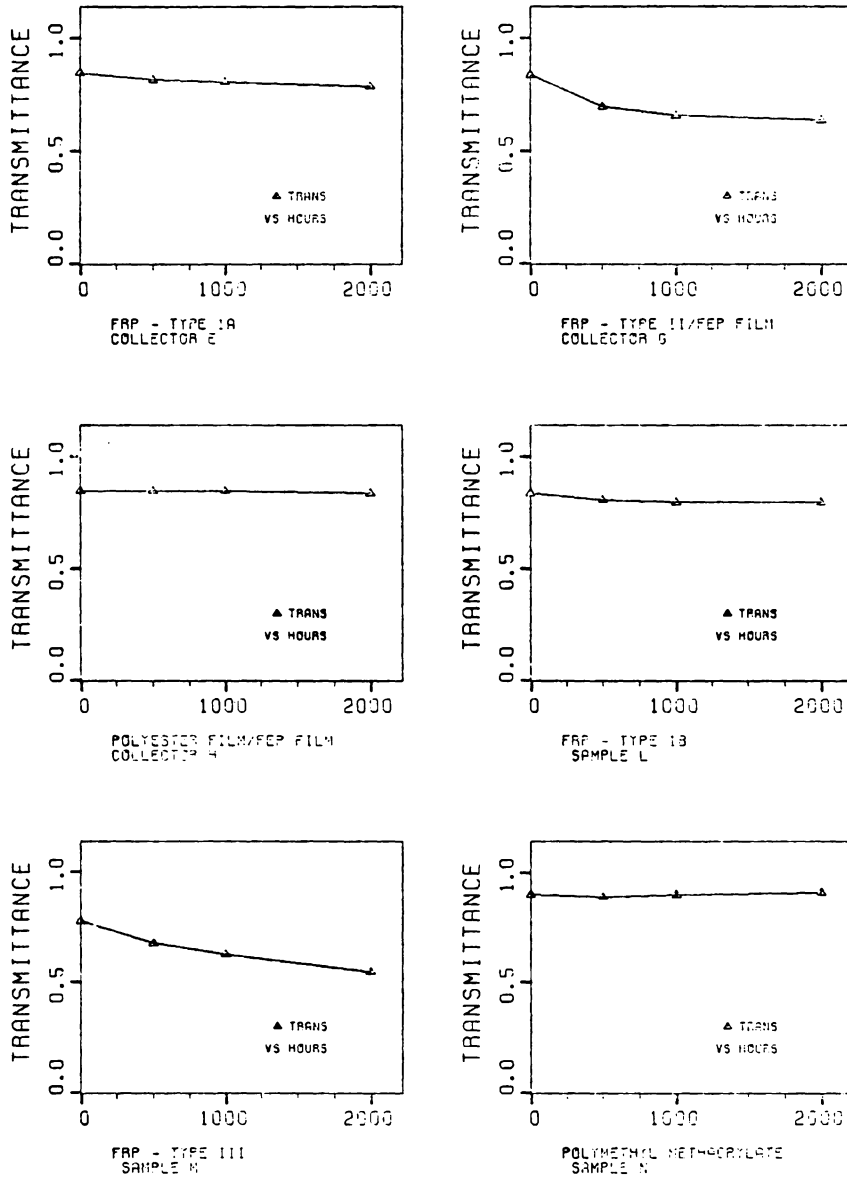


Fig. 2.8. Cover Sample Transmittance vs Exposure Hours for 125 C Tests

humidity test had the strongest effects on transmittance changes. All other tests provided results that follow the basic trend of the actual outdoor exposure.

2.3.2 Arrhenius Analysis of Cover Samples

A more detailed analysis of the degradation mechanism in the cover samples can be performed using the method suggested by Thomas [20]. His method is based on the Arrhenius model of temperature dependence of a chemical reaction applied to material degradation. The physical significance of this model lies in the relation between sample temperature and property degradation. If the dominant mode of degradation is thermally driven, the Arrhenius model can be used to predict changes in properties based on operating temperature.

The Arrhenius equation

$$\log m = A + B/t \quad (2.1)$$

provides a functional relationship between the slope of an experimental degradation curve, m , and the absolute temperature at which the test was performed, t . The property of interest can then be predicted, if the operating temperature is known, using the relationship

$$P = P_o - m\theta \quad (2.2)$$

where P is the value of the property of interest, P_0 is the initial value, θ is the exposure time, and m is the slope obtained in Eq. 2.1 above.

The constants in Eq. 2.1 are determined experimentally by exposing a material to a constant high temperature and measuring the property of interest at regular intervals of time. If the material being tested obeys the Arrhenius model, i.e., if the dominant mode of degradation is thermally driven, the property of interest will degrade in a relatively linear fashion. The slope of the property versus time line will be different for each temperature. By fitting a least-squares linear curve to the measured data, the slope, m , can be determined for a specific temperature. Repeating this procedure at different temperatures provides data for the Arrhenius plot.

To produce the Arrhenius plot, the logarithm of the measured slope is plotted versus the reciprocal of the absolute temperature at which the test was performed. The resulting graph will be a semilog plot linear in $1/t$, where t is the absolute temperature at which the test was performed. Each temperature provides one point on the Arrhenius plot. The data points on the Arrhenius plot are then fitted with a least-squares linear curve to determine the constants A (intercept) and B (slope) of the resulting line. The closer the data points fall to a straight line, the better the assumption of Arrhenius-type degradation.

Figure 2.9 shows the results of the process described using the data from the three temperature tests shown in Table 2.6. When a linear curve was fitted to the property versus time data, a net positive slope was observed in several test samples. In other words, the measured transmittance apparently improved. The three places where this anomaly occurred are in Sample M at 70 C and Sample N at 70 C and 125 C. Since the Arrhenius theory is based on decreasing property values, the points which gave positive slopes are not considered and are not plotted on Fig. 2.9. Finally, the limitations on all the plots should be noted since the curve fits are based on only three data points.

Accepting the limitations of the graphs as noted, Collector E and Sample L fit the Arrhenius model best. On the other hand, Sample H shows the worst fit to the model.

2.3.3 Absorber Sample Test Results

Table 2.7 shows the results of the representative absorber samples. As in the cover sample tests, little change is observed for many of the measured properties in the tests. Emittance is generally more susceptible to change than absorptance in many samples. For example, the emittance of Sample L increased to at least 1.4 times the original value in every test shown. The absorptance of this sample, on the other hand, changed by more than 3 percentage points in only one of the four tests shown. In fact, only the sample L specimens exposed to the solar simulator

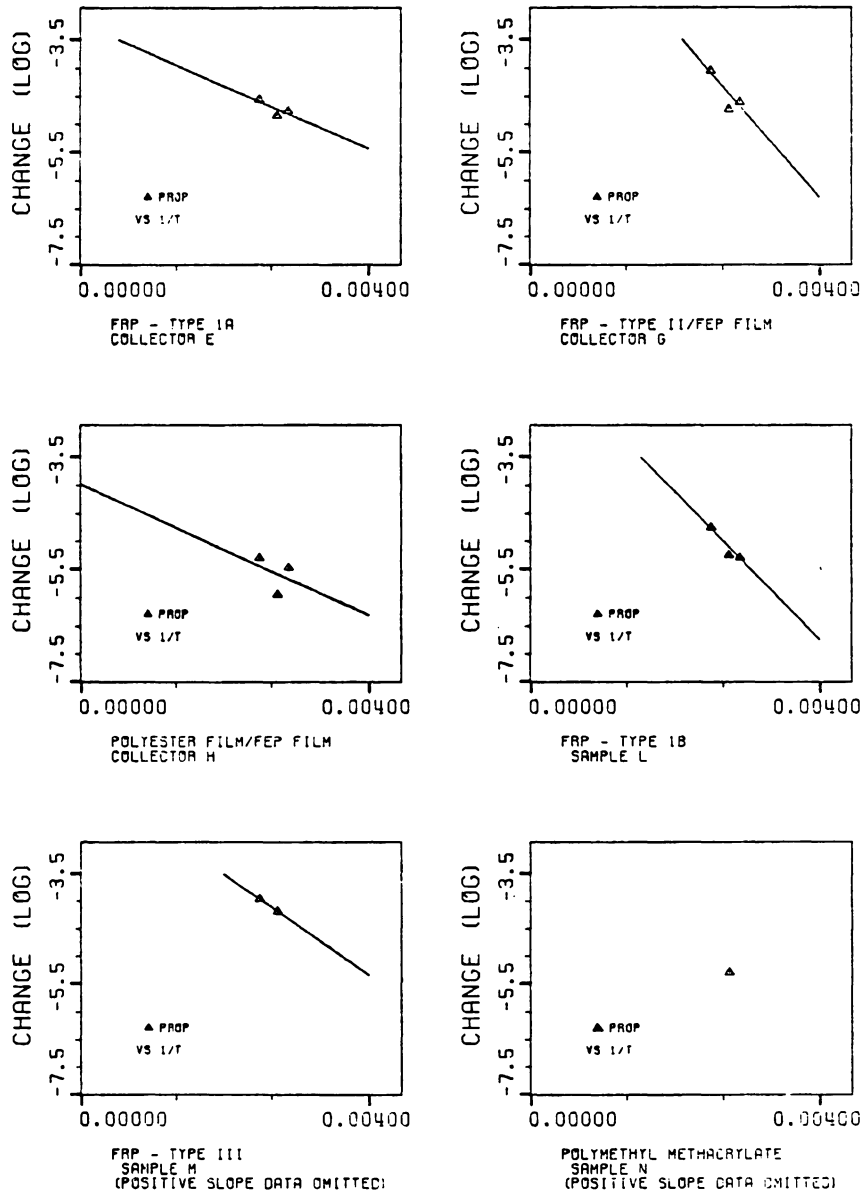


Fig. 2.9. Arrhenius Plot of Cover Sample Transmittance

Table 2.7

Absorber Sample Absorptance and Emittance Degradation in Selected Exposure Tests

Test	Actual Outdoor (Days)					Accelerated Outdoor (Equivalent Days)				90 C & 95 Percent RH (Hours)			Solar Simulator (Daily Cycles)			
Sample	0	80	160	240	480	0	36	60	120	0	1000	2000	0	30	60	120
B	0.98 0.92	0.97 0.91	0.97 0.91	0.97 0.91	0.97 --	0.97 0.92	0.96 --	0.98 --	0.97 0.91	0.98 0.92	0.97 0.91	0.97 0.91	-- --	-- --	-- --	-- --
D	0.97 0.07	0.96 0.05	0.96 0.10	0.96 0.06	0.94 --	0.96 0.07	0.95 --	0.95 --	0.94 0.07	0.97 0.07	0.95 0.13	0.95 0.19	0.95 0.07	0.97 0.06	0.96 0.06	0.96 0.06
E	0.95 0.87	0.96 0.89	0.96 0.90	0.96 0.90	0.96 --	-- --	-- --	-- --	-- --	0.95 0.87	0.92 0.88	0.92 0.89	-- --	-- --	-- --	-- --
F	0.96 0.75	0.93 0.66	0.91 0.66	0.91 0.62	0.89 --	0.94 0.75	0.93 --	0.92 --	0.90 0.64	0.96 0.75	0.93 0.76	0.93 0.77	0.96 0.75	0.94 0.68	0.93 0.68	0.91 0.69
L	0.99 0.29	0.99 0.39	0.98 0.42	0.98 0.36	0.96 --	0.97 0.29	0.97 --	0.97 --	0.96 0.47	0.99 0.29	0.85 0.81	0.81 0.85	0.98 0.35	0.98 0.52	0.98 0.56	0.98 0.62
N	0.92 0.49	-- 0.45	0.76 --	0.77 0.47	-- --	0.92 0.49	0.78 --	0.76 --	0.74 0.43	0.92 0.49	0.50 0.81	-- --	0.92 0.49	0.77 0.48	0.77 0.48	0.77 0.45

experienced a change in absorptance greater (in a percent of original value sense) than the corresponding change in emittance.

Individual sample performance over the spectrum of tests provides information on the severity of each test type. Sample N exhibited consistent decreases in absorptance in all tests shown, but the emittance results varied from test to test. In the 90 C - 95 percent relative humidity test, the emittance of Sample N nearly doubled after 1000 hours of exposure. In all other tests, the emittance of this sample decreased slowly by a maximum of 14 percent of the original value during accelerated outdoor exposure. The absorptance of Sample F exhibits significant change in the actual outdoor tests but change of less than 5.5 percent of the original value in all other tests. The absorptance of the other selected samples remain essentially unchanged regardless of the exposure conditions. The emittance of the samples experiences significant change in Sample D exposed to actual outdoor conditions, Sample F exposed to actual and accelerated outdoor, and Sample L in all tests performed. All other emittances are relatively stable, except for Sample N as noted before. Figures 2.10 through 2.13 provide a visual representation of the data in Table 2.7. Once again, the lines are not necessarily indicative of the measurements between points.

In summary, many of the materials did not degrade significantly after 480 days of exposure to outdoor conditions. Cover samples of acrylic and FEP were stable, as were absorber samples

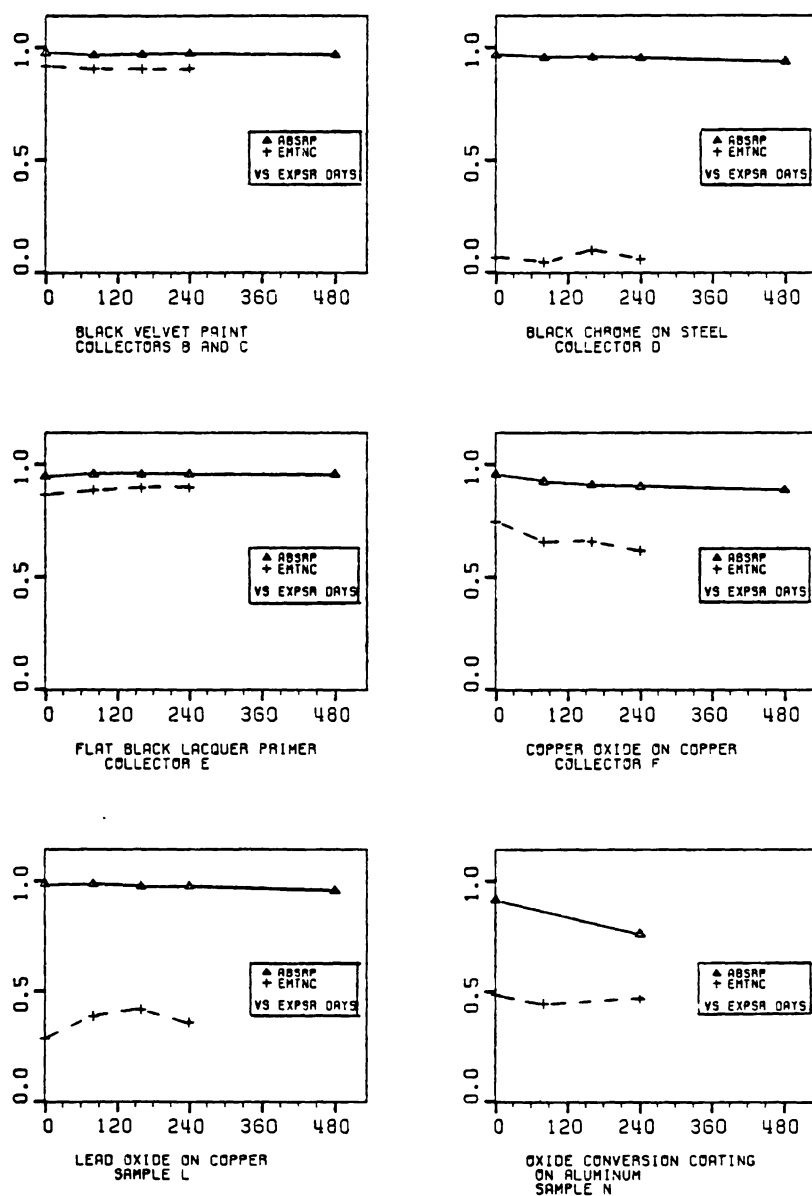


Fig. 2.10. Absorptance and Emittance of Material Samples vs Exposure Days for Actual Outdoor Tests

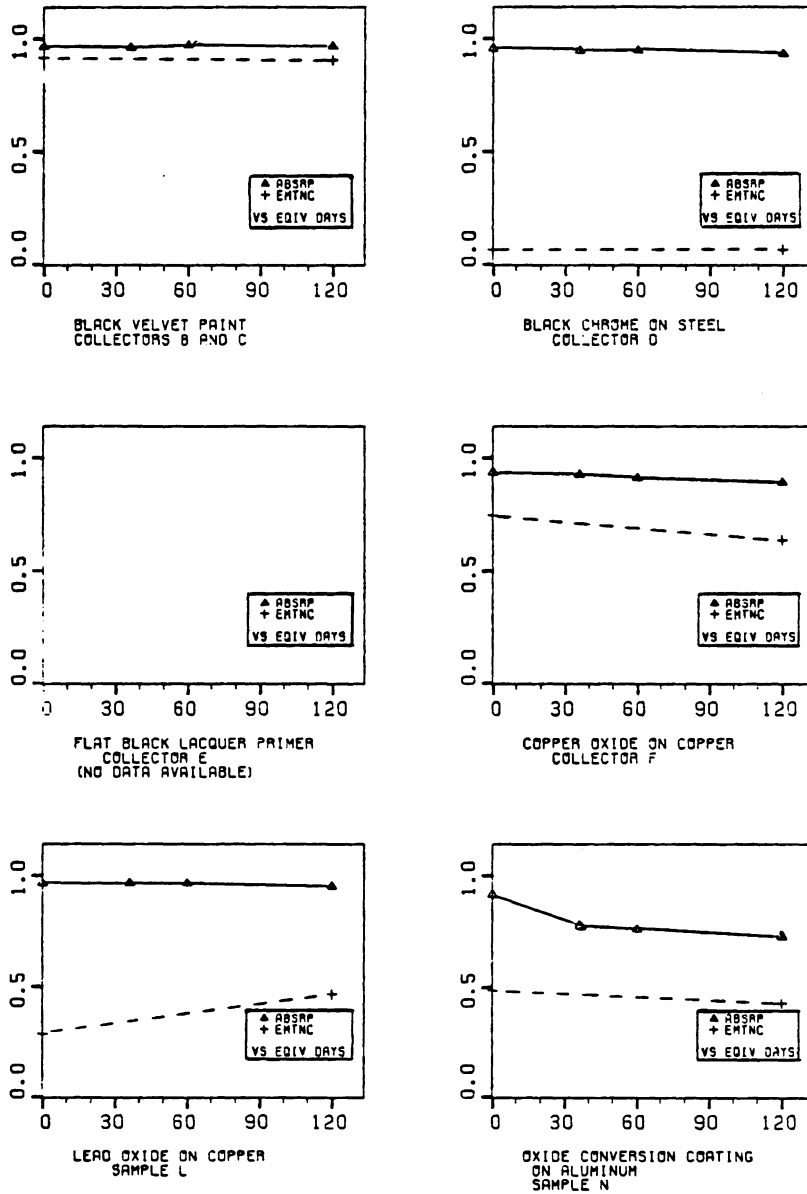


Fig. 2.11. Absorptance and Emittance of Material Samples vs Exposure Days for Accelerated Outdoor Exposure Tests

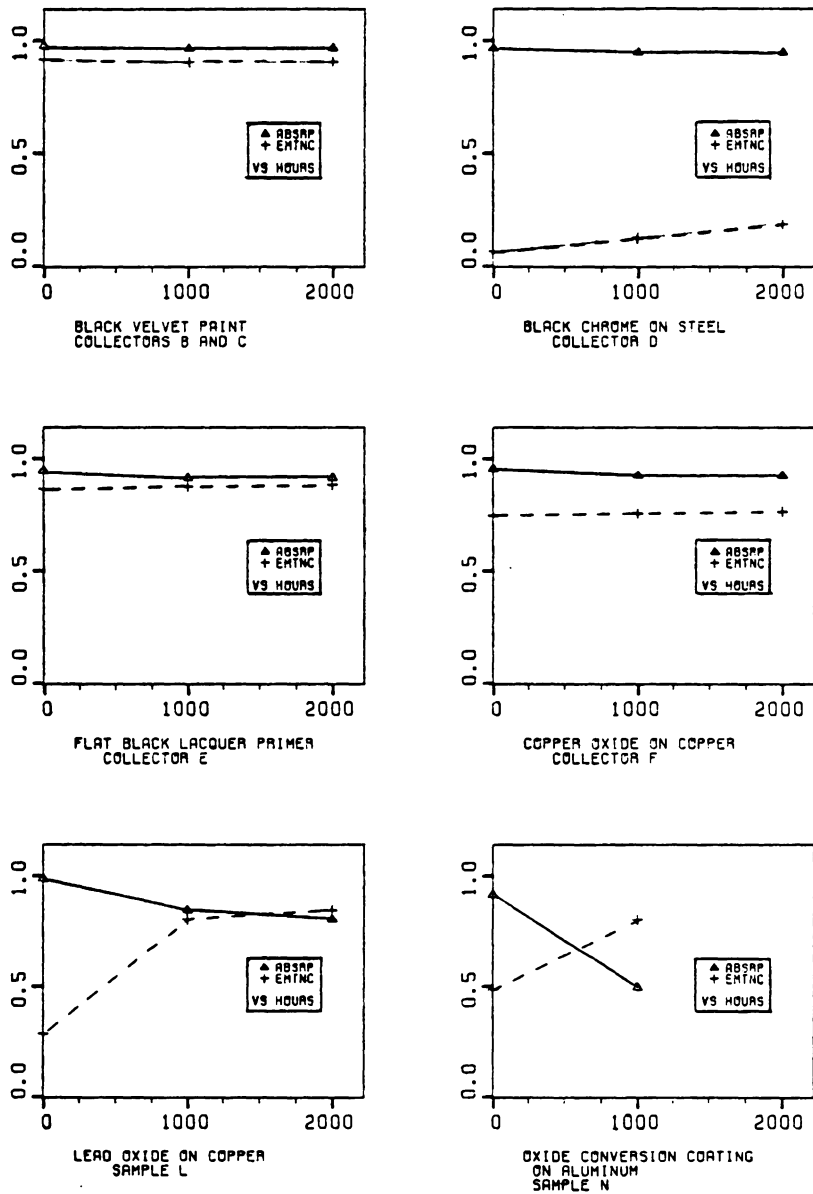


Fig. 2.12. Absorptance and Emittance of Material Samples vs. Exposure Days for 90 C and 95 Percent Relative Humidity Tests

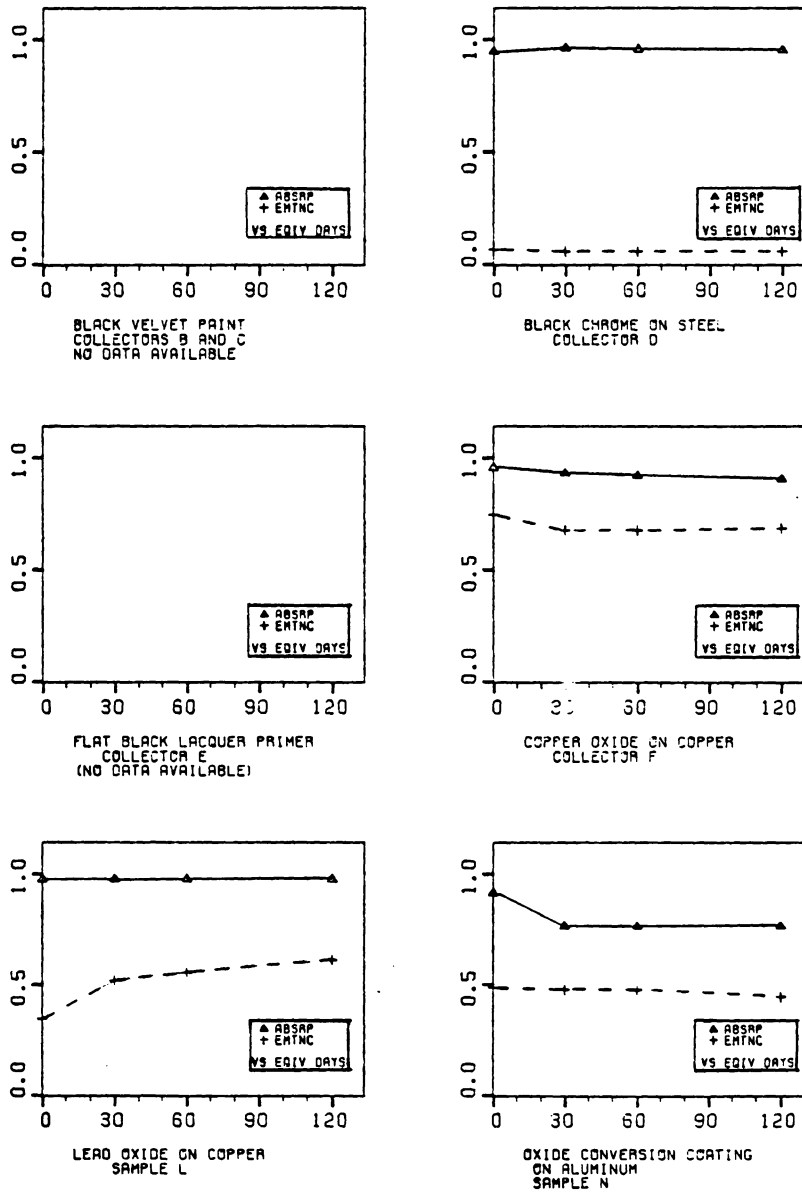


Fig. 2.13. Absorptance and Emittance of Material Samples vs Equivalent Daily Cycles for Solar Simulator Tests

coated with black paint or black chrome. These results were more or less anticipated from the literature review. High temperature seemed to be the most damaging isolated effect tested, but it did not appear that UV radiation added significantly to the degradation. Generally, it appeared that all tests needed to be run for longer periods of time to provide a greater change in properties.

Chapter 3

COLLECTOR ANALYSIS

In the last chapter, data was presented on the degradation of individual materials when exposed to outdoor and laboratory aging tests. In order to find relationships between the degradation of material samples and the degradation of full scale collectors, exposure tests of collectors must be performed simultaneously with the material sample tests. This chapter will describe a mathematical model of collector thermal performance and how the model is used to predict changes in efficiency caused by changes in material properties. Next, procedures used in the NBS Durability/Reliability Program [2] to perform exposure tests on collectors will be described. A method for predicting the actual degradation of collector performance using measured material property changes will also be discussed. Finally, results of all the procedures will be presented and compared for agreement.

It was difficult to find trends among the data from the NBS program. The measurements exhibited considerable scatter in the values of $F_R(\tau\alpha)$ and F_{RU_L} , and it did not appear beneficial to analyze all the collector results in-depth. Therefore, three collectors which span a number of typical cases were chosen for in-depth analysis. Collector B was chosen because it exhibited stability in thermal performance during exposure. Note the tight spacing of the efficiency curves in Fig. 3.1(a). This spacing

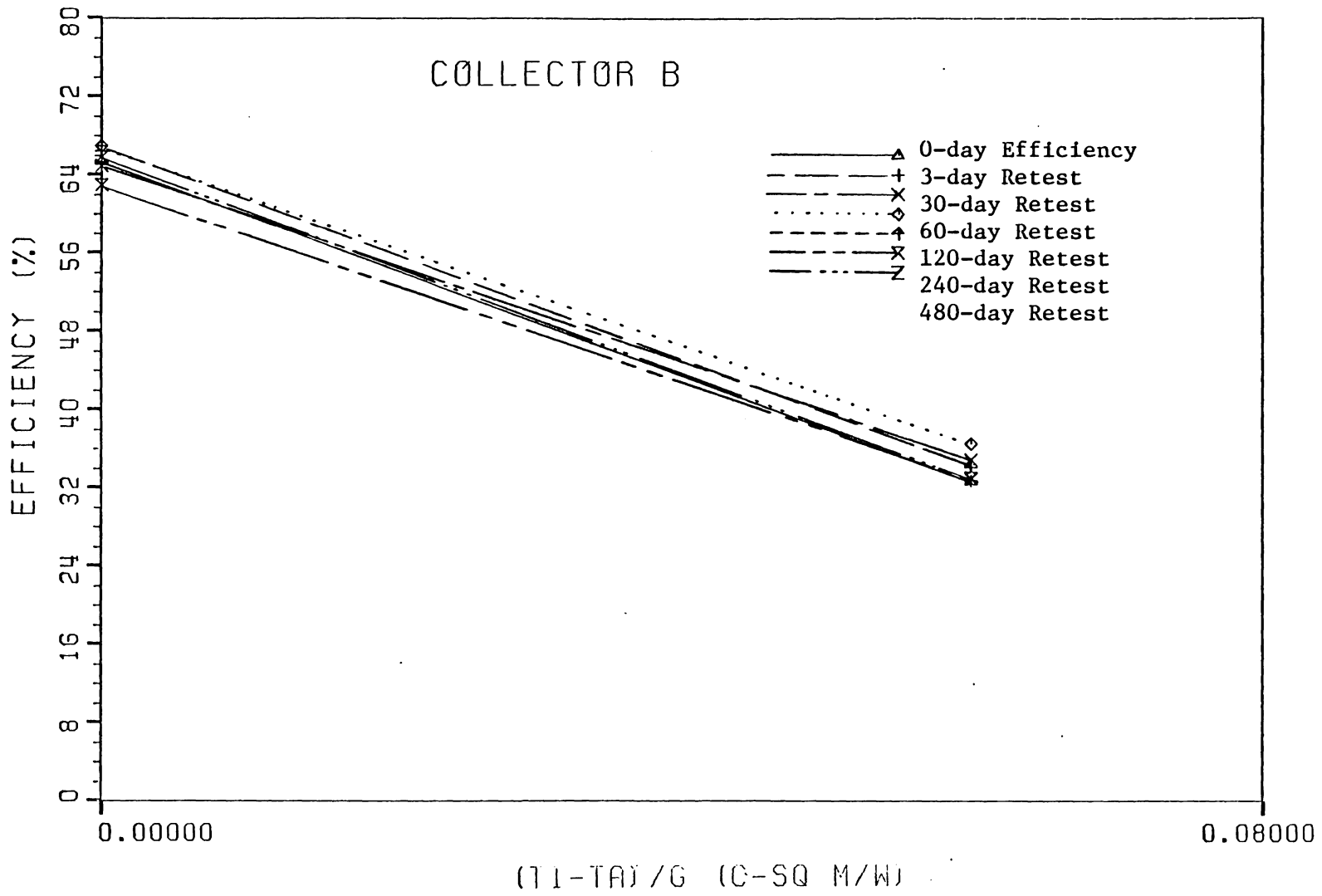


Fig. 3.1(a). Aggregate Plot of All Measured Efficiency Curves for Collector B

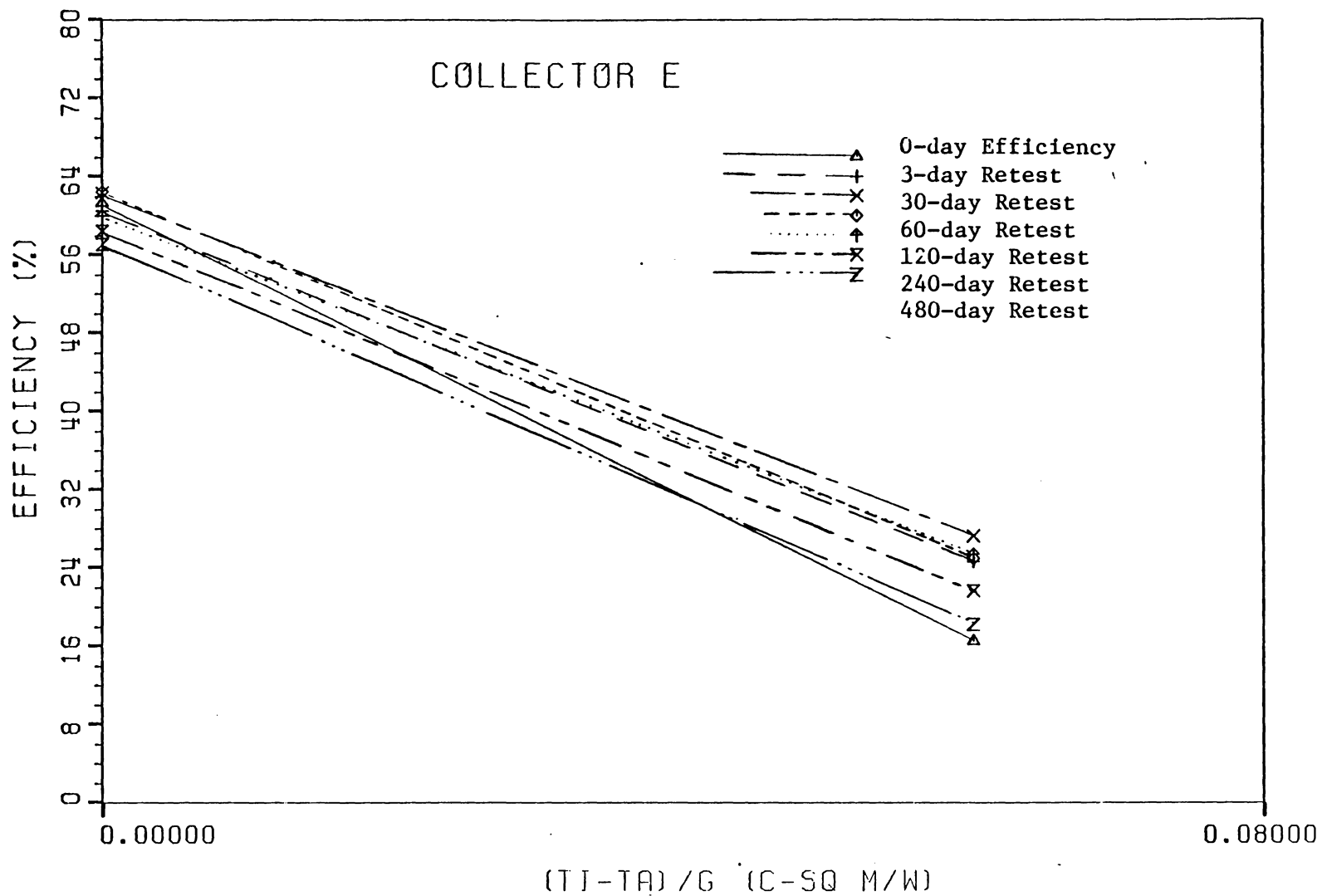


Fig. 3.1(b). Aggregate Plot of All Measured Efficiencies for Collector E

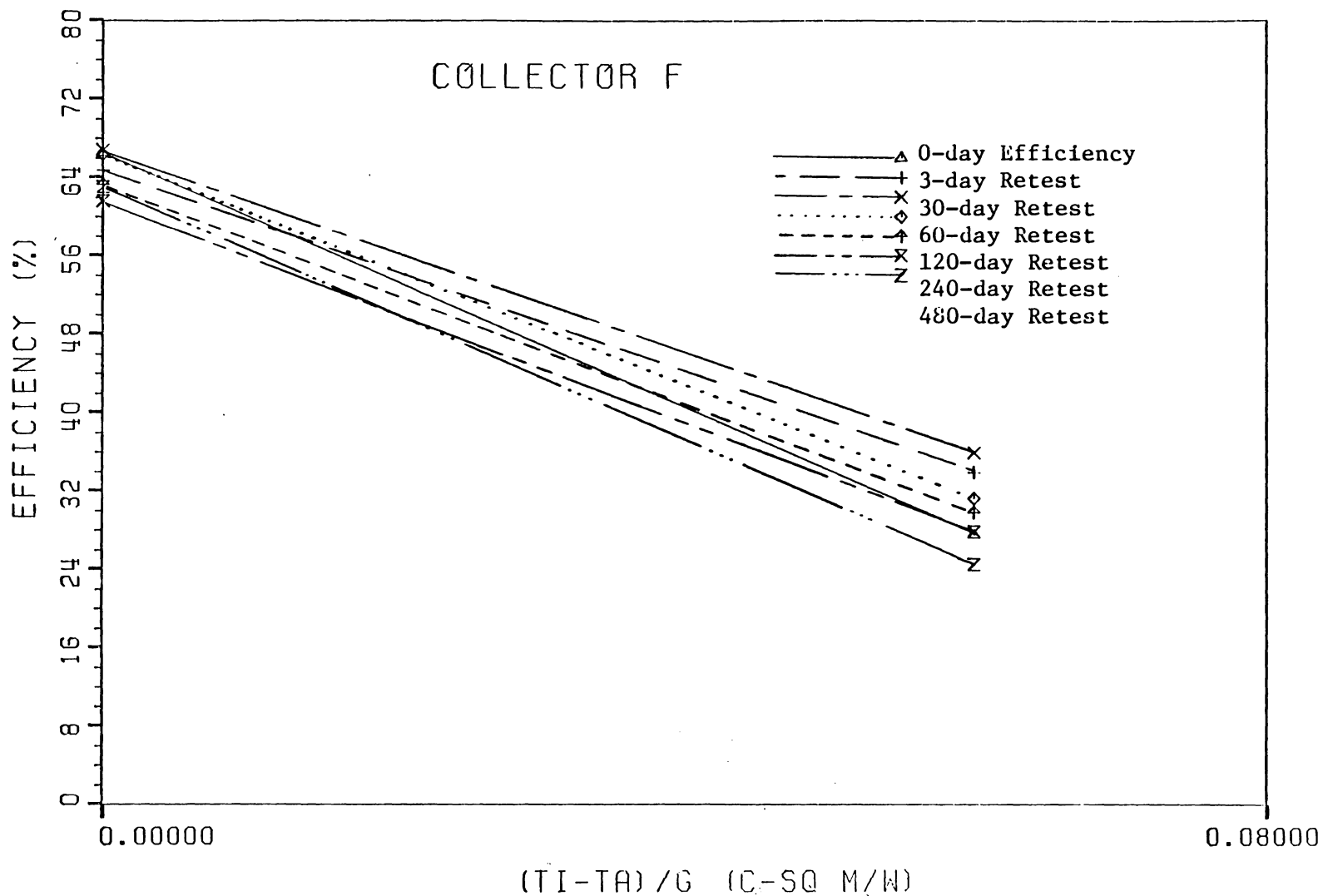


Fig. 3.1(c). Aggregate Plot of All Measured Efficiency Curves for Collector F

shows that the collector did not exhibit significant measured change in efficiency during any of the retests. Collector E was chosen for this study because it exhibited significant degradation of thermal performance after an initial break-in period of approximately 30 days. Figure 3.1(b) shows plots of the measured thermal performance of collector E for all retest days. Note that the 30-day curve is the highest and that all curves after 30 days exhibit a decrease in overall thermal performance. Finally, collector F was chosen because the absorber samples tested exhibited consistent degradation in property values as was shown in Figs. 2.10-2.13. A similar decline in thermal performance is noted in Fig. 3.1(c). Correlations between the material sample results and collector test results will be discussed in the section on calculated efficiency change.

3.1 Analysis Using the Governing Equation

Using the linear approximation of the HWB equation described in Section 1.1, it can be shown that the effect of a change in optical or heat transfer characteristics of collector materials should be a change in $F_R(\tau\alpha)$ or $F_R U_L$, respectively. Degradation in cover transmittance or plate absorptance would be evidenced by a fractional decrease, δ_1 , in the intercept of the efficiency curve according to the relationships defining $F_R(\tau\alpha)$. Likewise, a decrease in the insulation conductivity should result in a fractional increase, δ_2 , in the magnitude of the slope of the efficiency curve. In general, both δ_1 and δ_2 will be nonzero, so

the slope and intercept of the degraded efficiency curve could be written as $(1+\delta_2)F_R U_L$ and $(1-\delta_1)F_R(\tau\alpha)$, respectively. To observe the combined effect of these changes, let the degraded efficiency be η_2 and the unexposed, or reference efficiency, be η_1 . The change in efficiency caused by material property changes may then be written as

$$\eta_1 - \eta_2 = \delta_1 F_R(\tau\alpha) + \delta_2 F_R U_L \left[\frac{t_{f,i} - t_a}{G} \right] \quad (3.1)$$

Note the dependence of the change in efficiency upon $\Delta t/G$. If the linearity assumption of the model holds, that is, if $F_R(\tau\alpha)$ and $F_R U_L$ are independent of $\Delta t/G$, the difference between the degraded and the reference efficiency should increase with increasing $\Delta t/G$ if $\delta_2 \geq 0$. If $\delta_1 \geq 0$, the difference between the two efficiencies should be some constant fraction of the original maximum efficiency which will not change with inlet temperature.

The changes in efficiency resulting from specific changes in material properties are observable by manipulation of the governing equations using the digital computer. The next section describes a mathematical model which allows easy substitution of degraded material properties to observe the effects of changes in property values on collector efficiency.

3.1.1 Mathematical Model of Collector Thermal Performance

There are several available computer routines for carrying out calculations based on the HWB mathematical model. In the

present analysis, a program developed at VPI&SU entitled CPI FORTRAN [21] was used to carry out the calculations. A detailed description of the origins and mathematical methods used in this program would be lengthy and is not repeated in this paper. The reader is referred to reference 21 for additional information on the VPI computer model.

The input parameters determine the specific situation simulated as in any model. The model is made collector-specific by changing the physical dimensions and material properties input to the program. The necessary dimensions and the values corresponding to the three collectors selected from the NBS Durability/Reliability Program are listed in Table 3.1. Most of the values are measured from actual collectors. Cover solar extinction coefficient and back loss coefficient are adjusted initially to provide the model with the best fit to 0-day measured efficiency data. All other calculations are then made using these adjusted parameters or measured material property values. Since there is considerable uncertainty in the measured values of these parameters, the adjustments are justifiable to improve the fit of the model.

The other group of input parameters which specify the situation are the prevailing weather conditions. Differences resulting from weather conditions may mask the desired changes in efficiency caused by material property changes. Therefore, a standard set of weather conditions was used in the calculation of

Table 3.1

Collector Parameters Used in Mathematical Model

Description	Collector B	Value Collector E	Collector F
Heat transfer fluid	Water	Water	Water
Flow Rate (kg/s-sq m)	0.02	0.02	0.02
Width (m)	0.838	0.559	0.880
Length in Flow Direction (m)	1.911	2.915	2.010
Flow Configuration	Parallel	Parallel	Parallel
Number of Tubes	6	5	6
Tube Outside Diameter (mm)	10.39	16.06	11.11
Inside Diameter (mm)	9.58	12.70	7.94
Absorber Plate Material	Copper	Copper	Copper
Thickness (mm)	0.813	0.406	0.241
Thermal Conductivity (W/m-C)	360	360	360
Bond Conductance (Tube-Plate) (W/m-C)	1.0E+20	1.0E+20	1.0E+20
Plate Absorptance	0.98	0.95	0.96
Plate Emittance	0.07	0.87	0.75
Insulation Thickness (mm)	76.2	25.4	38.1
Conductivity (W/m-C)	0.04	0.02	0.024
Derived Back Loss Coefficient (From Model to Measured Fit)	1.55	2.27	0.925
Number of Covers	2*	1	1
Cover Material	Low Iron Glass	FRP Type-1A	Low Iron Glass
Thickness (mm)	3.175	0.965	4.70
Infrared Transmittance	0.02	0.07	0.02
Index of Refraction	1.52	1.54	1.52
Extinction Coefficient (1/m)	0.0095	0.0565	0.003
Spacing, Plate-Cover (mm)	25.4	60.0	19.1
Cover-Cover (mm)	6.35	n/a	n/a

* Note: Both covers on collector B are made of the same material.

all theoretical efficiencies, so that weather-related effects would be minimized. Thomas [21] recommends a set of standard weather conditions which are in the middle of the ranges of allowable conditions specified by ASHRAE standard 93-77. The recommended weather conditions are listed in Table 3.2. Later in this investigation, measured efficiencies will be referenced to these same weather conditions to minimize weather effects in experimental results (see Section 3.4.2).

The model has been shown to represent measured results accurately. Figure 3.2 shows how the calculated results compare to the 0-day measured results for the collectors in this investigation. The figure shows that the predictions are always within a few percentage points of the measured values. If the model and measurements were free from error, all the points would lie on the 45 degree line shown. Some error is introduced by the simplifying assumptions of the mathematical model and by experimental uncertainty in the measured values. Possible sources of experimental error include experimental measurement procedure, instrumentation, and recorders. In order to establish the accuracy of the data, an uncertainty analysis on the efficiency measurements was performed in reference 21. Several plots similar to Fig. 3.2, with the addition of an uncertainty band around the 45 degree line, are presented. Based on some 80 points plotted of calculated versus measured data, only one point was found to be outside the measurement uncertainty band.

Table 3.2
Standard Weather Conditions Used
in Collector Model

Ambient Temperature	20 C
Wind Speed	3.0 m/s
Total Solar Radiation (in collector plane)	1000 W/m ²
Collector Slope	45 degrees
Incidence Angle	0 degrees
Diffuse Fraction	0.15
Fluid Flow Rate	0.02 kg/s-m ²
Heat Transfer Fluid	water

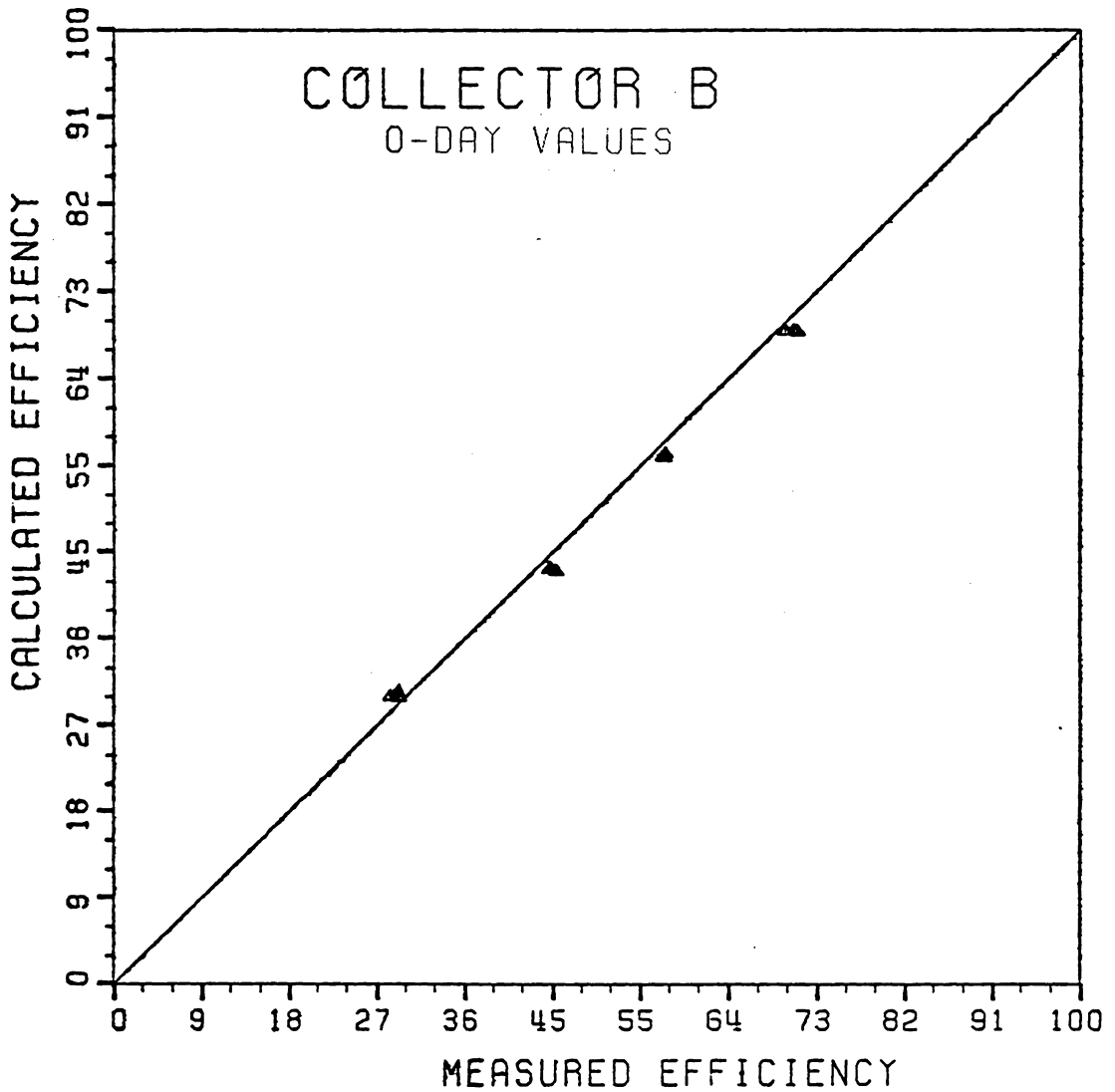


Fig. 3.2(a). Accuracy of Mathematical Model as Shown by Calculated Efficiency vs Measured Efficiency, Collector B

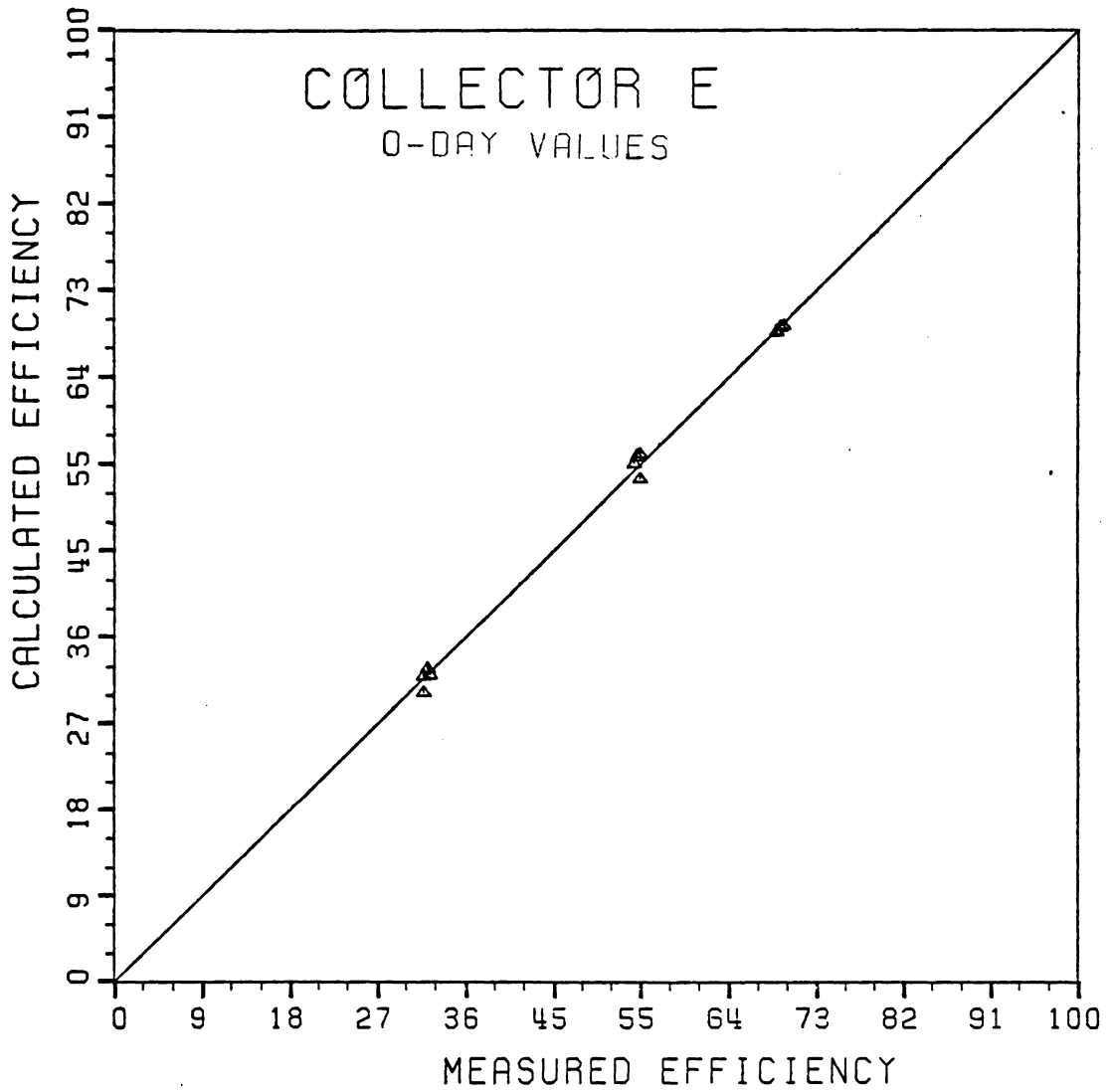


Fig. 3.2(b). Accuracy of Mathematical Model as Shown by Calculated Efficiency vs Measured Efficiency, Collector E

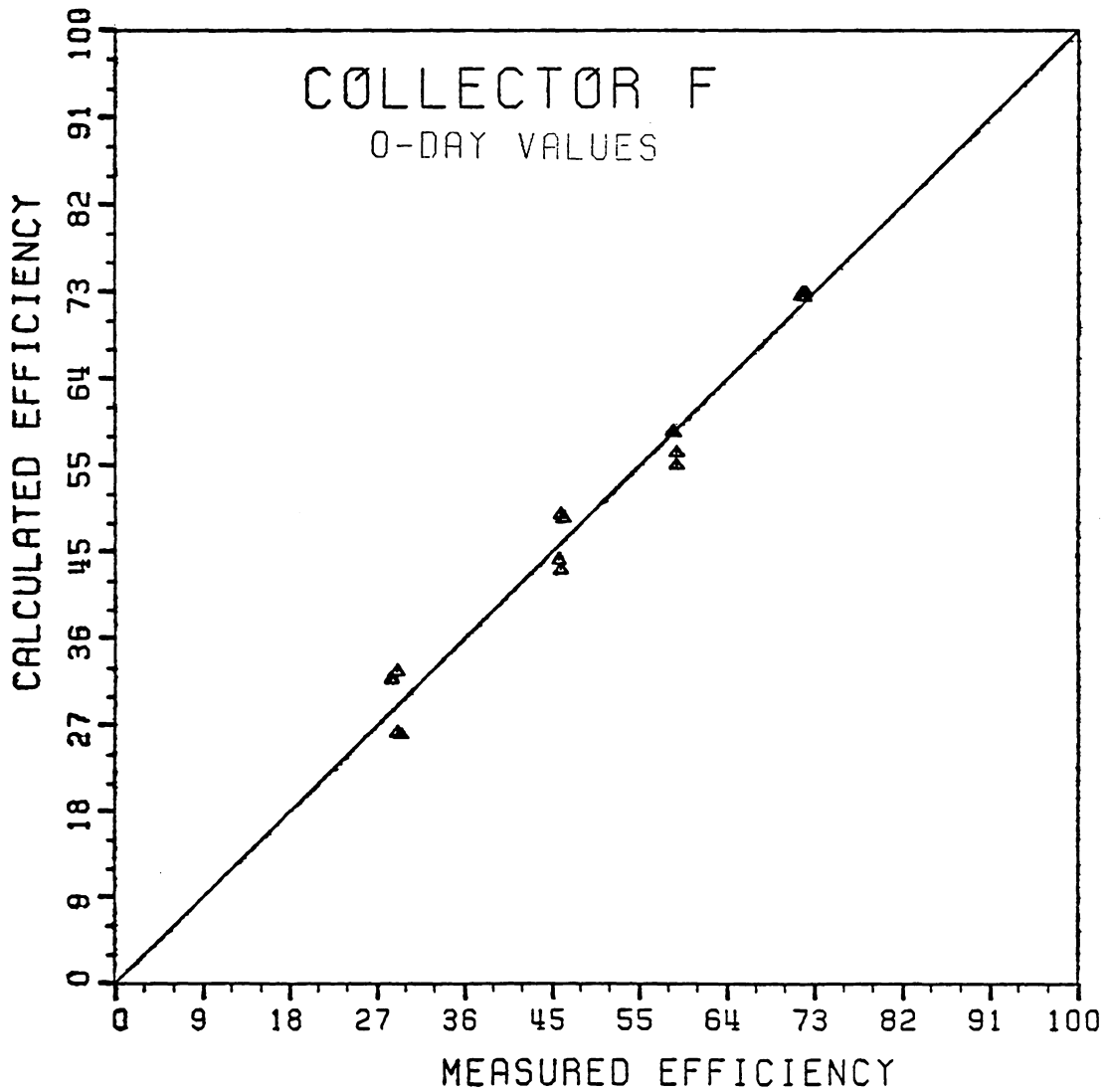


Fig. 3.2(c). Accuracy of Mathematical Model as Shown by Calculated Efficiency vs Measured Efficiency, Collector F

3.2 Theoretical Performance Degradation

Before presenting actual collector exposure procedures and results, it is of value to use the mathematical model to observe the effect of changes in material property values on thermal performance. To this end, two procedures were followed in this investigation. The first procedure is designed to show whether efficiency is a strong or weak function of individual properties with all other input parameters held constant. The second procedure shows the effect of temperature as well as property value changes by varying inlet temperature and material properties input to the model.

In both cases, the efficiencies calculated using degraded material properties are compared to a reference efficiency. The reference efficiency, η_{ref} , is calculated using values of collector dimensions and material properties which characterize an unexposed collector. Weather-related differences are minimized by using the recommended weather conditions listed in Table 3.2 for all calculations. Reference efficiency curves are shown for collectors B, E, and F in Fig. 3.3.

3.2.1 Property Dependence

A typical inlet temperature for the following calculations was selected halfway between ambient and stagnation temperature. Several runs were required to determine theoretical stagnation temperature. These initial runs give the theoretical stagnation temperatures as 140 C, 110 C, and 115 C for collectors B, E, and

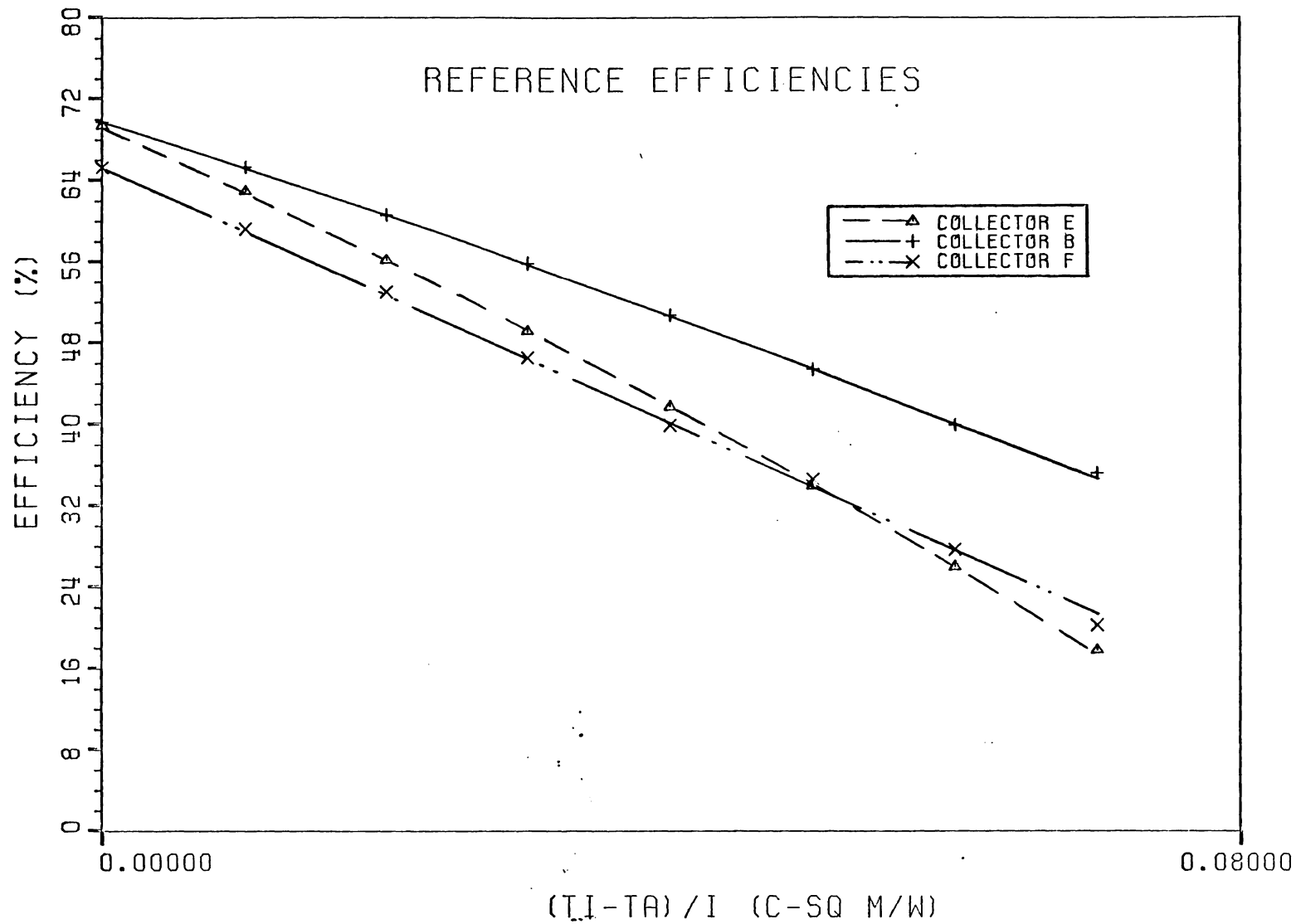


Fig. 3.3. Reference Efficiency Curves (No Degradation) for Collectors B, E, and F

F, respectively. While results varied from collector to collector, an inlet temperature of 50 C is typical for those collectors considered. Since the results are similar for all three collectors, Collector E will be presented as typical in all remaining theoretical comparisons.

The strength of the functional dependence of efficiency upon individual material properties can now be determined. Material properties input to the model were varied one by one to produce an efficiency versus property value plot. Degraded efficiencies were normalized by the reference efficiency, so the curve for each property would pass through 1.0 at the reference value of the property.

3.2.2 Property and Temperature Dependence

Functional dependence of efficiency upon both material properties and temperature is now investigated. A property which affects collector thermal performances is changed to simulate a deviation of 10 percent from the original value. A degraded theoretical efficiency curve is then generated by varying inlet temperature from ambient to stagnation. The property is reset to the original value and a second property changed. The process is repeated until the four properties investigated have been changed individually. Finally, all four properties are changed simultaneously to observe any synergistic effects which occur. Inlet temperature is varied from ambient to stagnation and resulting

efficiencies plotted to show the results. The results of these calculations are given in Section 3.4.1.

3.2.3 Prediction of Degradation

Prediction of the effects of actual material property changes is accomplished using the mathematical model. The input information is divided into two categories: 1) invariant parameters, which include physical dimensions, mechanical properties, weather conditions, and properties which were not monitored during exposure, and 2) variable parameters, including optical property data obtained from material tests.

Measured efficiencies and experimental test conditions are input to the model. At each measured $\Delta t/G$, the model is used to calculate two theoretical efficiencies--one using the 0-day measured properties and the other using the 480-day measured properties. The difference between these two calculated efficiencies is taken to be the change in efficiency attributable to the changes in the material properties of the collector. The difference is then subtracted from the measured efficiency at 0-days to give the 480-day predicted efficiency. A comparison is made between the predicted results and the measured thermal performance degradation by plotting the predicted and measured 480-day efficiencies on the same graph.

3.3 Collector Exposure Test Procedures

This section describes one of the methods used in the NBS Durability/Reliability Program to measure actual collector thermal performance degradation. Although four series of tests were performed at four different laboratories for each type of collector, only dry stagnation (series 1) at Laboratory site 1 (Phoenix) will be described. The results of this test series are typical of all others, and the greatest amount of data about the tests was available from site 1. A parallel study by Douro is underway to determine the statistical variation between sites and series of tests in the program [22]. The results presented here may be extended to other collector-site-series combinations dependent on Douro's results.

In the series 1 exposure test, the collectors are tested per ASHRAE standard 93-77 except without the recommended three-day pre-exposure. The results obtained for $F_R(\tau\alpha)$ and F_{R,U_L} are taken as the 0-day values. Collectors with no fluid flow are then placed on test racks and exposed to natural weather conditions. Exposure days are tallied as any calendar day with a daily solar radiation of at least 17.1 MJ/sq m (1500 BTU/sq ft) in the plane of the collector. Performance retests are performed in accordance with ASHRAE standard 93-77 at intervals of 3, 30, 60, 120, 240, and 480 exposure days. Values of $F_R(\tau\alpha)$ and F_{R,U_L} calculated from the efficiency measurements at each retest are plotted to allow comparison to the 0-day values.

In addition, meteorological data and maximum daily absorber plate temperature data are tabulated during exposure. The meteorological data provides information about the total radiation on the collector. The maximum daily stagnation temperature is analyzed as another means of measuring performance degradation in the next section.

3.3.1 Stagnation Temperature Analysis

Stagnation temperature has been investigated by several authors [23,24] as a possible means of indicating changes in thermal performance. Since the useful heat collected at stagnation is zero, Eq. 1.2 can be rearranged as

$$t_s - t_a = \frac{(\tau\alpha)G}{U_L} \quad (3.2)$$

The temperature difference between stagnation and ambient is then a function of optical $(\tau\alpha)$ and heat transfer (U_L) characteristics. By dividing both sides by G , the quantity on the left hand side, $[t_s - t_a]/G$, will be a function of property value only. For convenience, $[t_s - t_a]/G$ will be called the stagnation parameter. It is possible that changes in material properties will be evidenced by changes in stagnation temperature or the stagnation parameter for a particular collector.

This method of observing property changes is tested by monitoring the maximum stagnation temperature during the entire exposure period. Values of stagnation temperature are selected from the test data at approximately 15-day intervals. The

weather conditions prevailing at the time of the stagnation temperature measurement are recorded. Finally, $[t_s - t_a]$ and $[t_s - t_a]/G$ are plotted versus exposure days to observe possible property changes. A decrease in $(\tau\alpha)$ or an increase in U_L should result in a decrease in maximum daily stagnation temperature. However, since the optical and heat transfer characteristics are lumped into one parameter, it will be difficult to say which property caused the change in stagnation temperature.

By using the mathematical model, 0-day and 480-day stagnation temperatures can be estimated from measured properties. First, 0-day properties are substituted into the model. Inlet temperature is then varied until stagnation temperature is found. The model provides values of $(\tau\alpha)$ and U_L , so these can be compared to calculated values of stagnation temperature. Next, 480-day properties are substituted into the model and stagnation temperature, $(\tau\alpha)$ and U_L recalculated. These values can be compared to measured results by plotting both on the same graph.

3.4 Results of Collector Analysis and Testing

The analytical and experimental results are presented in this section. As expected, the analytical results show clear trends that can be predicted from the methods used. The experimental results, on the other hand, show considerable scatter because of experimental uncertainty, variations in weather conditions, and other unexplained phenomena. Some of these variations will be accounted for later on.

3.4.1 Analytical Results

Figure 3.4 shows the results of the method described in Section 3.2.1. The variation of efficiency with respect to individual property changes is shown clearly. It is interesting to note how closely the points are fit by a straight line. This correlation suggests that efficiency changes may be linearly related to changes in individual property values at midrange temperatures. Culkin [25] shows plots of a similar nature, but at the extreme ends of the temperature scale. Based on the plots in Reference 25 and Fig. 3.4, the linear relationship between property value change and efficiency change appears to hold over a wide temperature range. However, the slope of the individual lines varies at each specific temperature.

Figure 3.5 shows the dependence of efficiency on both temperature and property values. Degradation of property values is evident by the effect on $F_R(\tau\alpha)$ and $F_R U_L$. Changes in plate absorptance and cover transmittance decrease $F_R(\tau\alpha)$ almost directly proportional to the magnitude of the property change. The value of $F_R U_L$, however, is relatively insensitive to changes in α_p or τ_{sb} , so the curves appear to be parallel. Changes in insulation conductivity and plate emittance, suprisingly, affect $F_R(\tau\alpha)$ almost as much as $F_R U_L$. Upon examination of the governing relationships, it becomes evident that F_R is functionally dependent on $1/U_L$. This dependence causes the product of F_R and $(\tau\alpha)$ to be a function of both optical and heat transfer

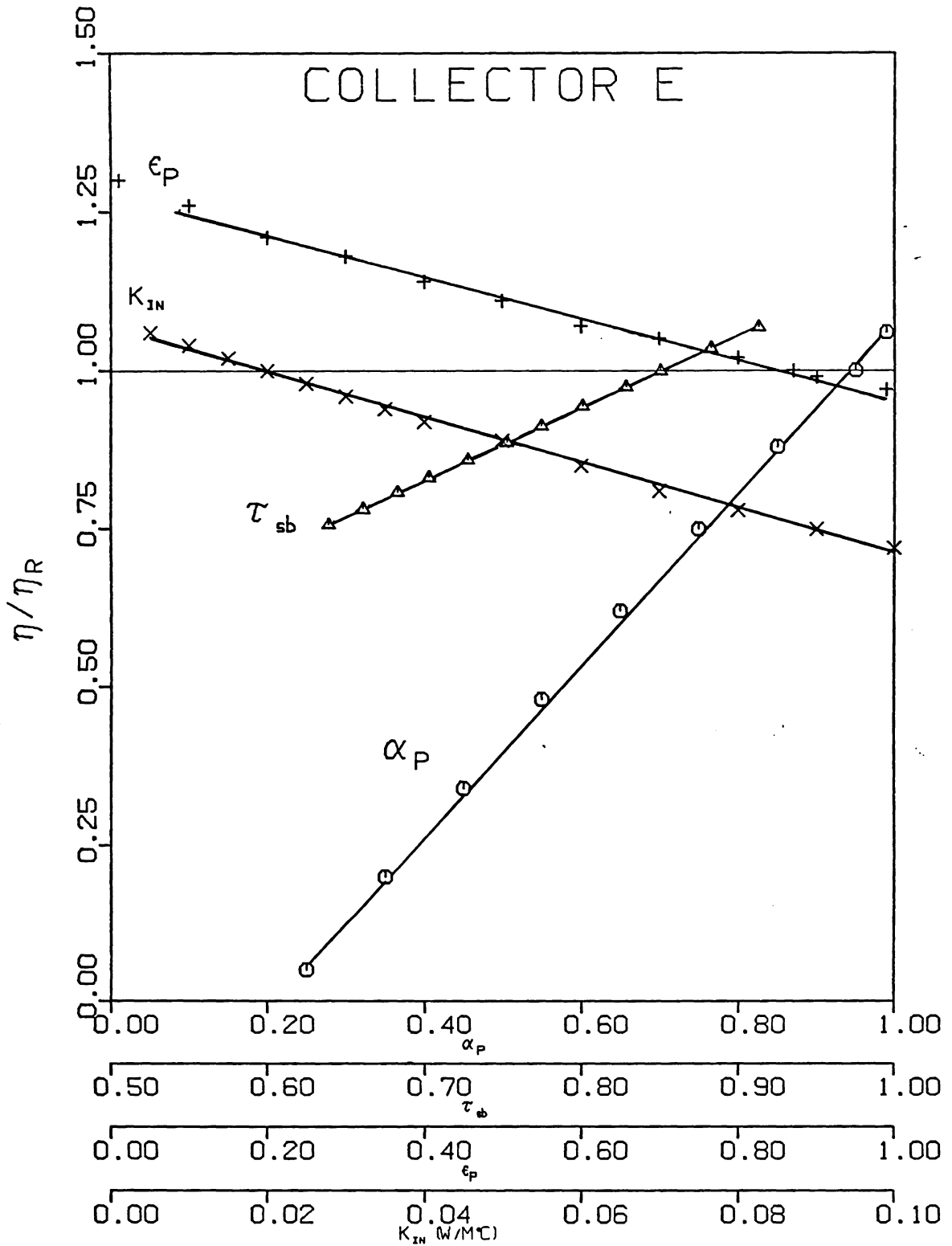


Fig. 3.4. Variations in Theoretical Efficiency with Respect to Changes in Material Property Values

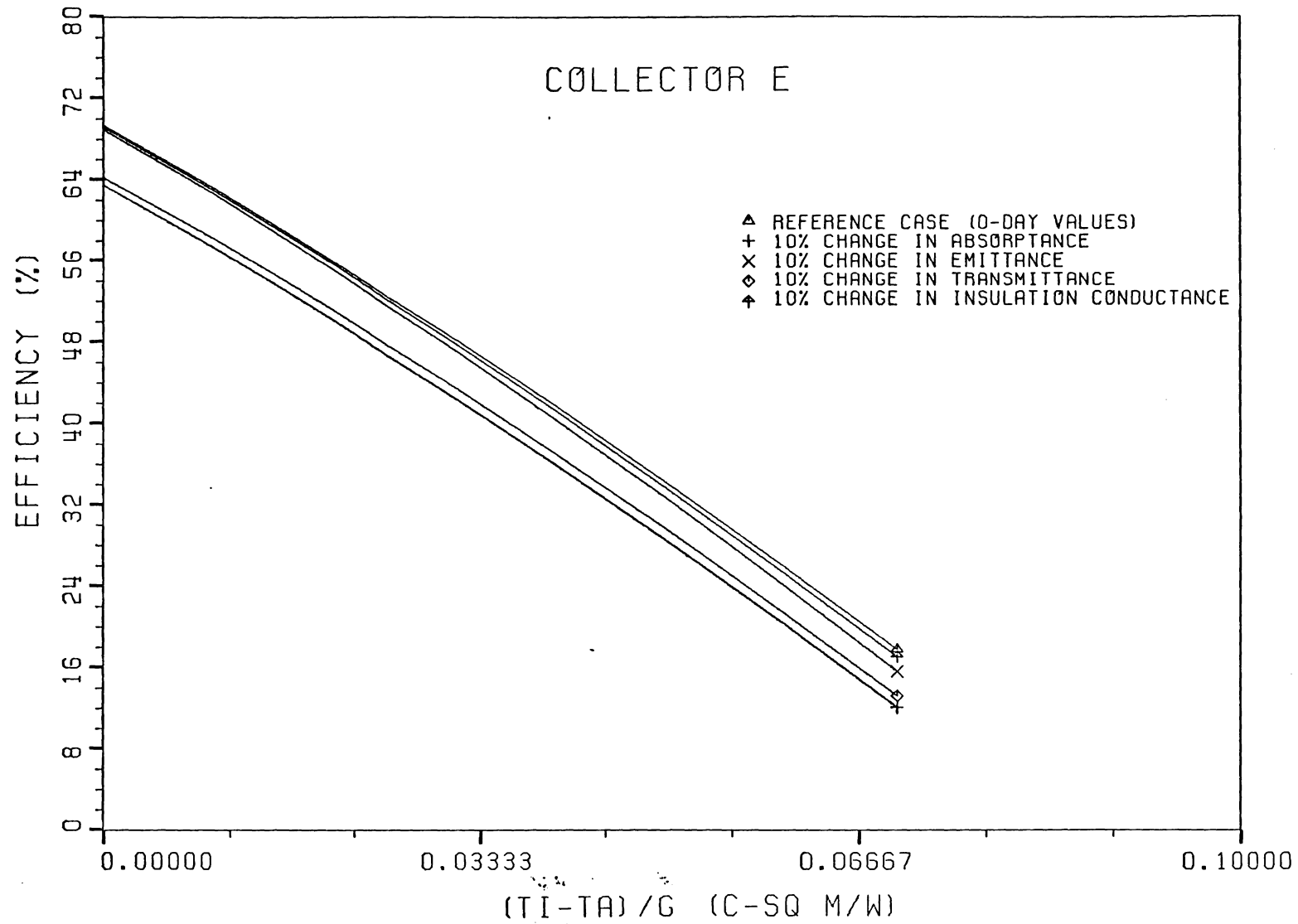


Fig. 3.5. Variation of Theoretical Efficiency with Variable Property Values and Inlet temperature.

characteristics, rather than just optical properties as stated previously.

The magnitude of the changes shown in Fig. 3.5 is a little misleading. It appears in Fig. 3.5 that a 10 percent change in plate absorptance has a much greater effect than the same percentage change in emittance or insulation conductivity. In performing the calculations, the degraded property value was taken to be $(1 \pm \delta)P_0$, where δ is the fractional change used and P_0 is the 0-day value of the property. The plus sign is used for emittance and insulation conductivity since a decrease in these properties would be a desirable effect, rather than an effect regarded as degradation. As such, the original values of these properties are small and a 10 percent change has little effect in absolute terms.

The materials sample tests presented in Chapter 2 show that the 10 percent change chosen as typical lies in the range of observed changes in measured properties. Absorber samples exposed outdoors exhibited changes in absorptance and emittance between 1 and 19 percent of the original value after 480 days of exposure. Cover sample transmittances changed between 0 and 27 percent after the same exposure to outdoor conditions. No information was available for typical insulation changes.

The purpose of changing all four property values simultaneously is to observe any synergistic effects. Figure 3.6 shows the results of a theoretical efficiency calculation using all

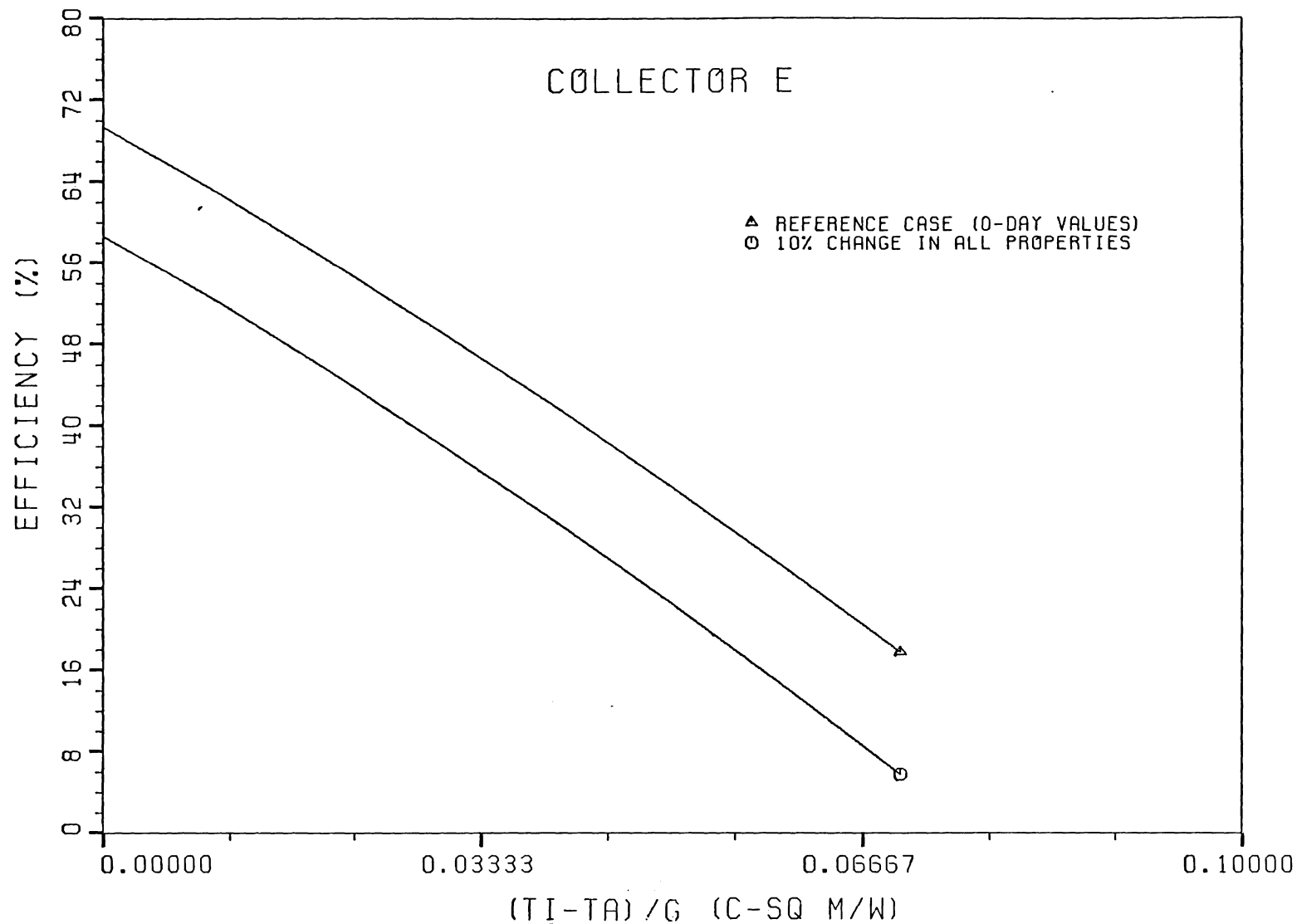


Fig. 3.6. Variation of Theoretical Efficiency when Multiple Property Value Changes Occur Simultaneously

degraded properties. No synergism is observed in this plot when compared to Fig. 3.5. In fact, the efficiency at any $\Delta t_1/G$ in Fig. 3.6 can be found using the efficiencies of Fig. 3.5 by

$$\eta_{rel,i}(\text{Fig. 3.5}, t_1/G) = \frac{\eta_i}{\eta_{ref}} ; \quad i = 1,2,3,4 \text{ for } \alpha_p, \epsilon_p, \tau_{sb}, \text{ and } k_{in} \quad (3.3)$$

$$\eta(\text{Fig. 3.6}, t_1/G) = \eta_{ref}(t_1/G) \prod_{i=1}^4 \eta_{rel,i} \quad (3.4)$$

The error generated by using Eq. 3.3 and 3.4 is always less than 2 percentage points.

3.4.2 Experimental Results

Collector thermal performance measurements obtained by laboratory site 1 are now presented in this section. The exposure schedule sheets for collectors B, E, and F are shown in Table 3.3. These sheets show the tests performed and the dates of completion. The total solar radiation on the collector is summed and presented in Table 3.4. The values in this table represent the total amount of solar radiation on the plane of the collector while the collectors were outdoors including calendar days which did not qualify as exposure days.

Before presenting the measured efficiency changes, weather induced differences must be accounted for. Thomas [21] has shown that efficiency variation as a result of weather conditions can be significant. Therefore, the correction procedure developed in Reference 21 is used to refer measured efficiency values to

Table 3.3
Collector B, Site 1, Series 1
Exposure Log Sheet

Step	Test Procedure	Date
1	Initial Performance Test	10-04-78
2	3 Day Exposure	6-05-79 to 6-07-79
3	3-Day* Performance Retest	7-06-79
4	12 Day Exposure	7-16-79 to 7-29-79
5	15-Day* Performance Retest	N/A
6	15 Day Exposure	9-10-79 to 9-26-79
7	30-Day* Performance Retest	10-16-79
8	30 Day Exposure	10-19-79 to 11-26-79
9	60-Day* Performance Retest	12-10-79
10	60 Day Exposure	12-14-79 to 3-21-80
11	120-Day* Performance Retest	4-13-80
12	120 Day Exposure	5-02-80 to 8-31-80
13	240-Day* Performance Retest	9-16-80
14	240 Day Exposure	10-29-80 to 8-05-81
15	480-Day* Performance Retest	9-13-81

*Total number of days of exposure, following purging with dry air, with daily solar radiation 17.1 MJ/m^2 (1500 BTU/ft^2)

Table 3.3 (continued)
Collector E, Site 1, Series 1
Exposure Log Sheet

Step	Test Procedure	Date
1	Initial Performance Test	6-19-79
2	3 Day Exposure	6-21-79 to 6-24-79
3	3-Day* Performance Retest	7-07-79
4	12 Day Exposure	7-17-79 to 7-29-79
5	15-Day* Performance Retest	N/A
6	15 Day Exposure	9-11-79 to 9-26-79
7	30-Day* Performance Retest	10-16-79
8	30 Day Exposure	10-18-79 to 11-24-79
9	60-Day* Performance Retest	12-07-79
10	60 Day Exposure	12-14-79 to 3-21-80
11	120-Day* Performance Retest	4-08-80
12	120 Day Exposure	5-02-80 to 8-31-80
13	240-Day* Performance Retest	9-22-80
14	240 Day Exposure	10-29-80 to 8-31-81
15	480-Day* Performance Retest	9-13-81

*Total number of days of exposure, following purging with dry air, with daily solar radiation 17.1 MJ/m^2 (1500 BTU/ft^2)

Table 3.3 (continued)
 Collector F, Site 1, Series 1
 Exposure Log Sheet

Step	Test Procedure	Date
1	Initial Performance Test	6-19-79
2	3 Day Exposure	6-21-79 to 6-24-79
3	3-Day* Performance Retest	7-09-79
4	12 Day Exposure	7-17-79 to 7-29-79
5	15-Day* Performance Retest	N/A
6	15 Day Exposure	9-10-79 to 9-26-79
7	30-Day* Performance Retest	10-21-79
8	30 Day Exposure	10-23-79 to 11-26-79
9	60-Day* Performance Retest	12-09-79
10	60 Day Exposure	12-14-79 to 3-21-80
11	120-Day* Performance Retest	4-15-80
12	120 Day Exposure	5-02-80 to 8-31-80
13	240-Day* Performance Retest	9-20-80
14	240 Day Exposure	10-29-80 to 8-03-81
15	480-Day* Performance Retest	8-31-81

*Total number of days of exposure, following purging with dry air, with daily solar radiation 17.1 MJ/m^2 (1500 BTU/ft^2)

Table 3.4
Total Solar Radiation Exposure Summations for Site 1, Series 1

Collector ID	(All Exposures Are MJ/sq m)							Total Days Exposed	Total Irradiation
	3	15	30	Exposure 60	Days 120	240	480		
B-1-1	81	439	813	1690	3428	6732	13087	480	13087
E-1-1	83	414	786	1641	3379	6683	13038	480	13038
F-1-1	83	414	750	1547	3285	6589	12944	480	12944

standard weather conditions. The procedure involves calculating the change in efficiency attributable to test and environmental conditions and adding or subtracting this change to the measured efficiency. The reader is referred to Reference 21 for further details of the correction procedure.

The relevant point here is that comparisons between efficiencies measured at 0 days and 480 days, and between measured and calculated efficiencies, can be made with the complications of differing test conditions minimized. Figure 3.7 shows plots of the 0-day and 480-day measured efficiencies after weather effects have been taken into account. Note that collector B shows the 480-day efficiency as higher than the 0-day efficiency, but only by a maximum of 2 percentage points. Degradation in collector E appears as a decrease in $F_R(\tau\alpha)$, but an increase (less negative) in F_{RUL} . Collector F shows a trend similar to collector E, except that the change in $F_R(\tau\alpha)$ is smaller.

3.4.3 Stagnation Temperature Results

Figures 3.8 and 3.9 shows the measured data and calculated values of stagnation temperature for collectors E and F. The experimental measurements show scatter which may be caused by variations in weather conditions, measurement uncertainties, and other unexplained sources. Linear curves fitted to the data showed positive slopes for all cases except for Fig. 3.9(a). The negative slope is for the curve of $[t_s - t_a]/G$ for collector E. However, the trend of a slight increase in t_s is in agreement

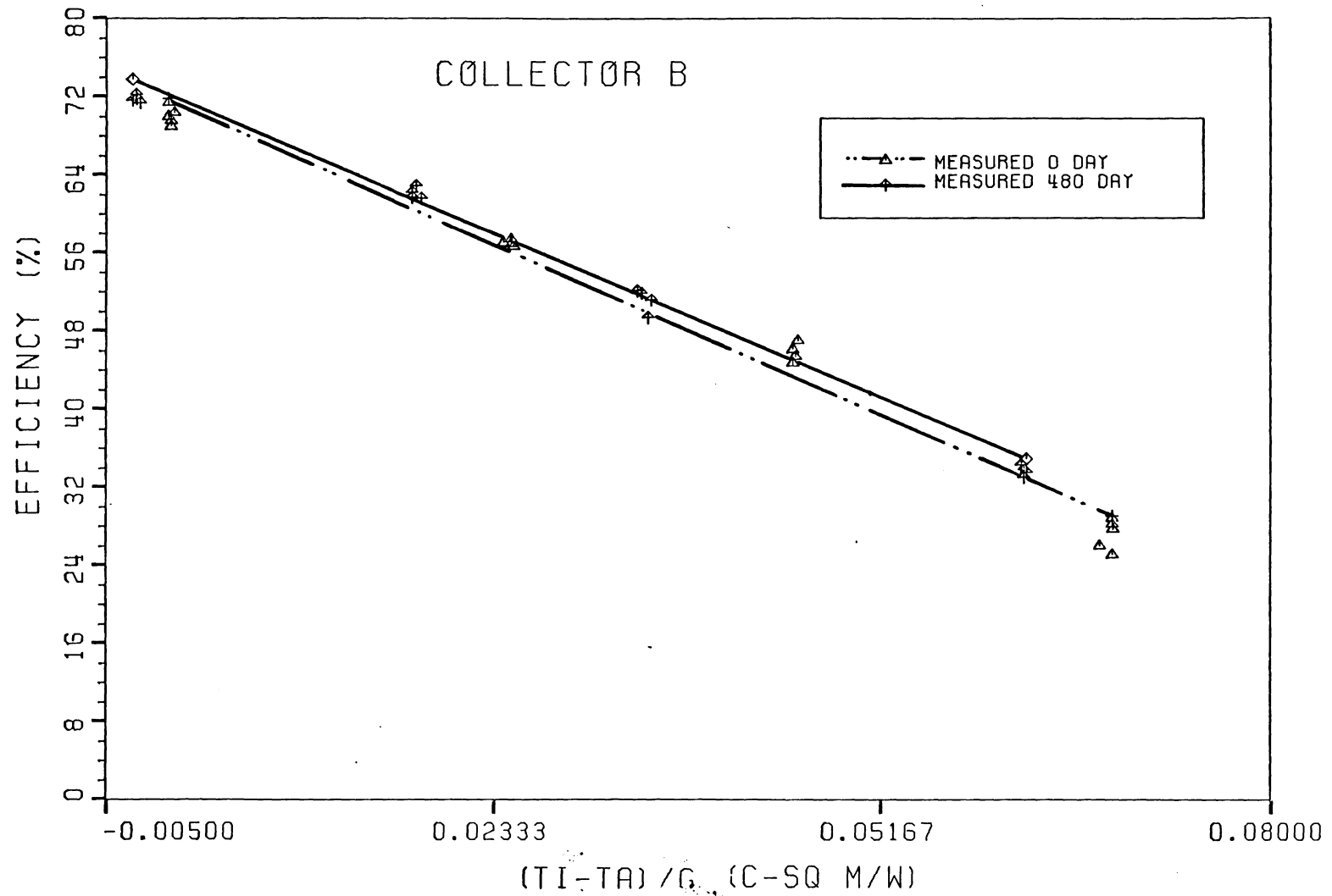


Fig. 3.7(a). 0-day and 480-day Efficiency Curves Showing Measured Degradation-Collector B

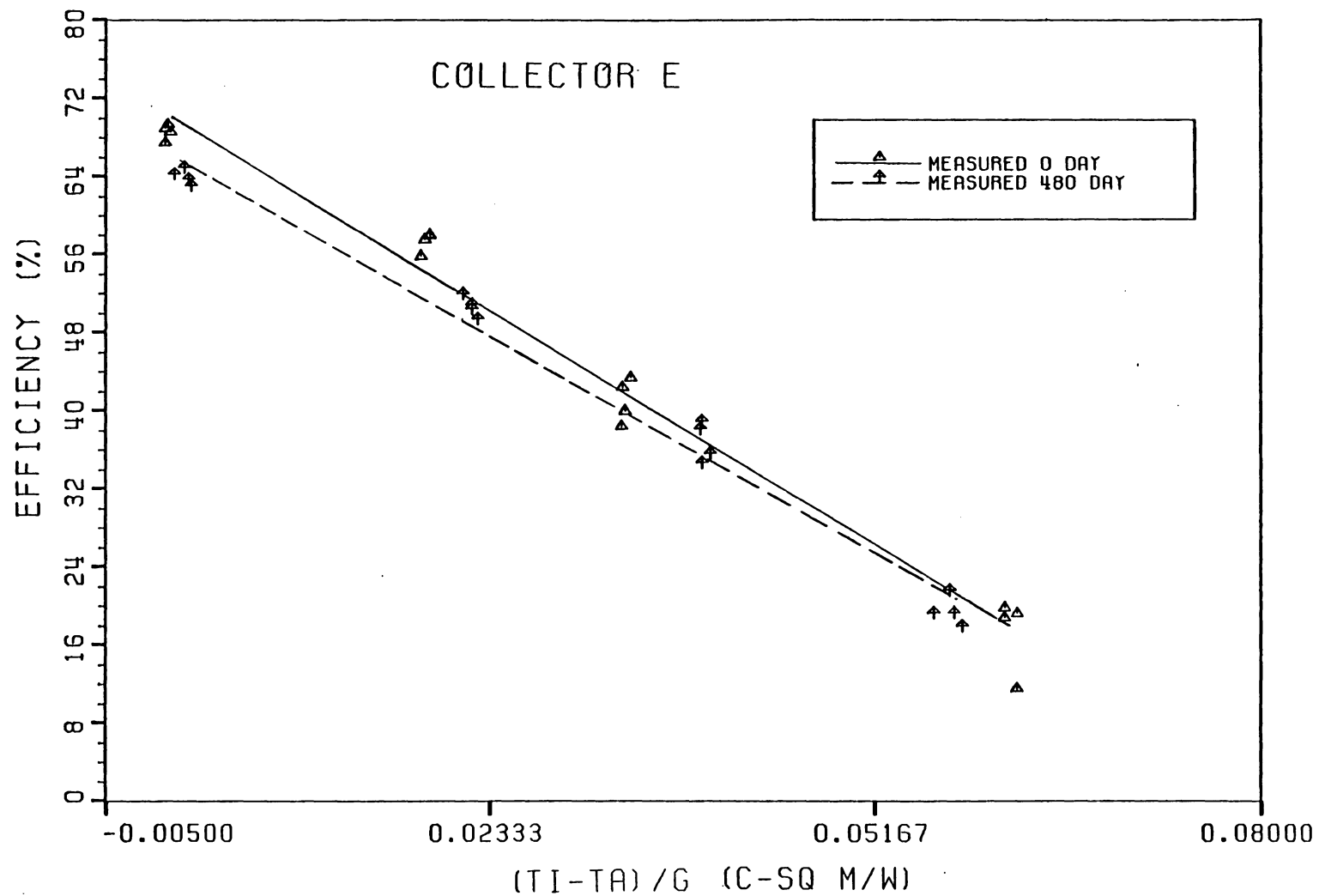


Fig. 3.7(b). 0-Day and 480-Day Efficiency Curves Showing Measured Degradation, Collector E

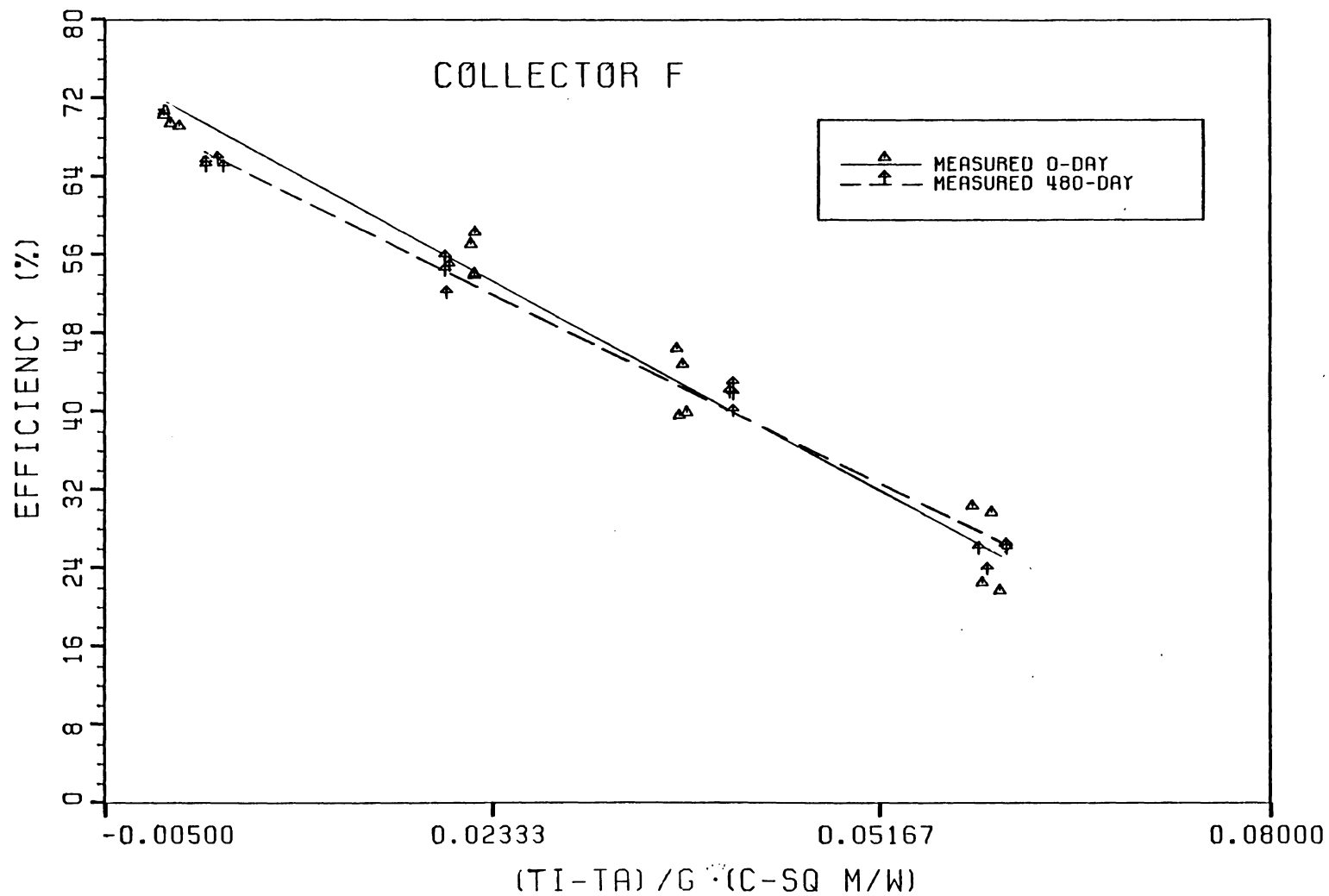


Fig. 3.7(c). 0-Day and 480-Day Efficiency Curves Showing Measured Degradation, Collector F

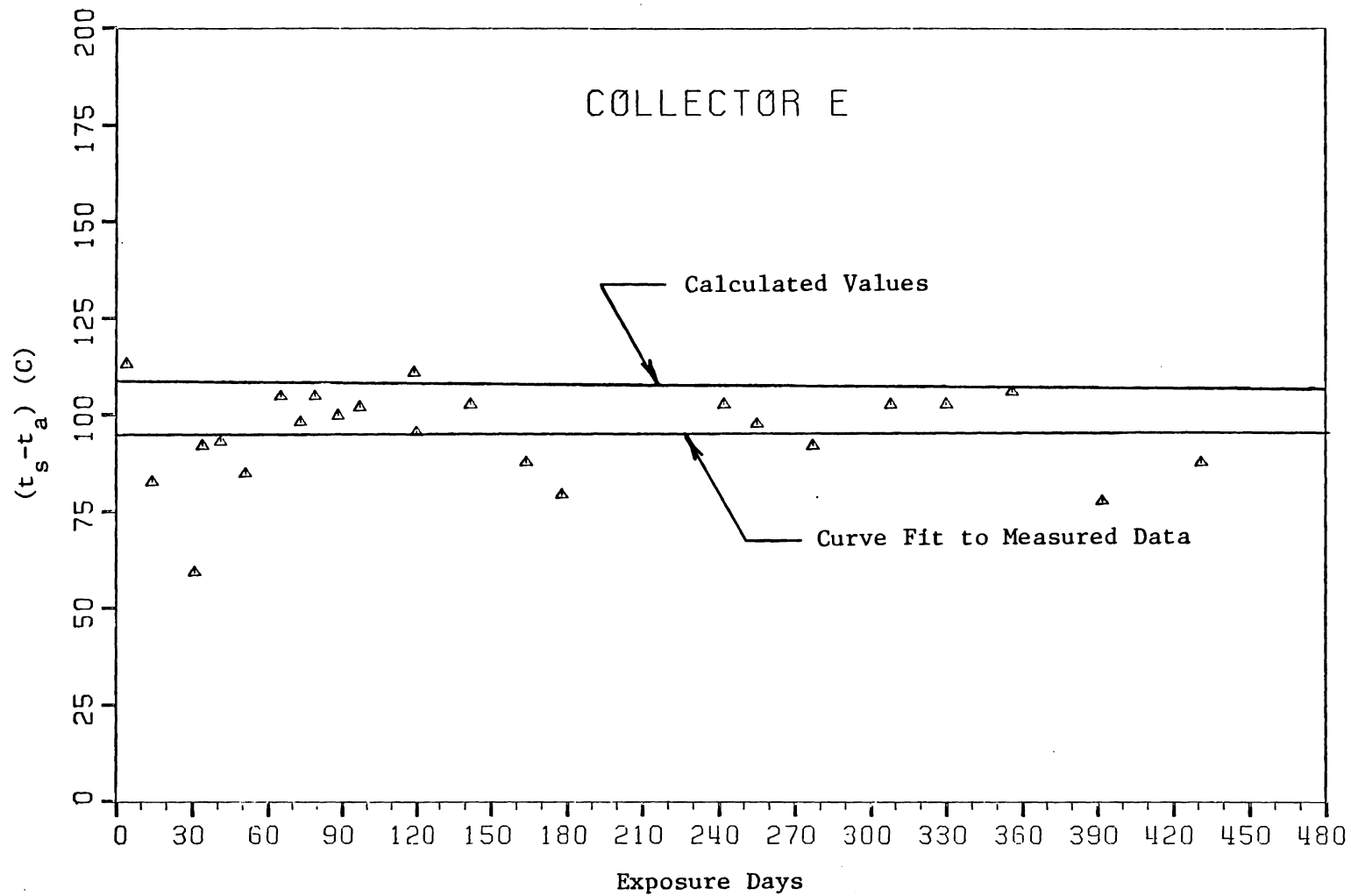


Fig. 3.8(a). Stagnation Temperature Normalized by Ambient Temperature for Collector E

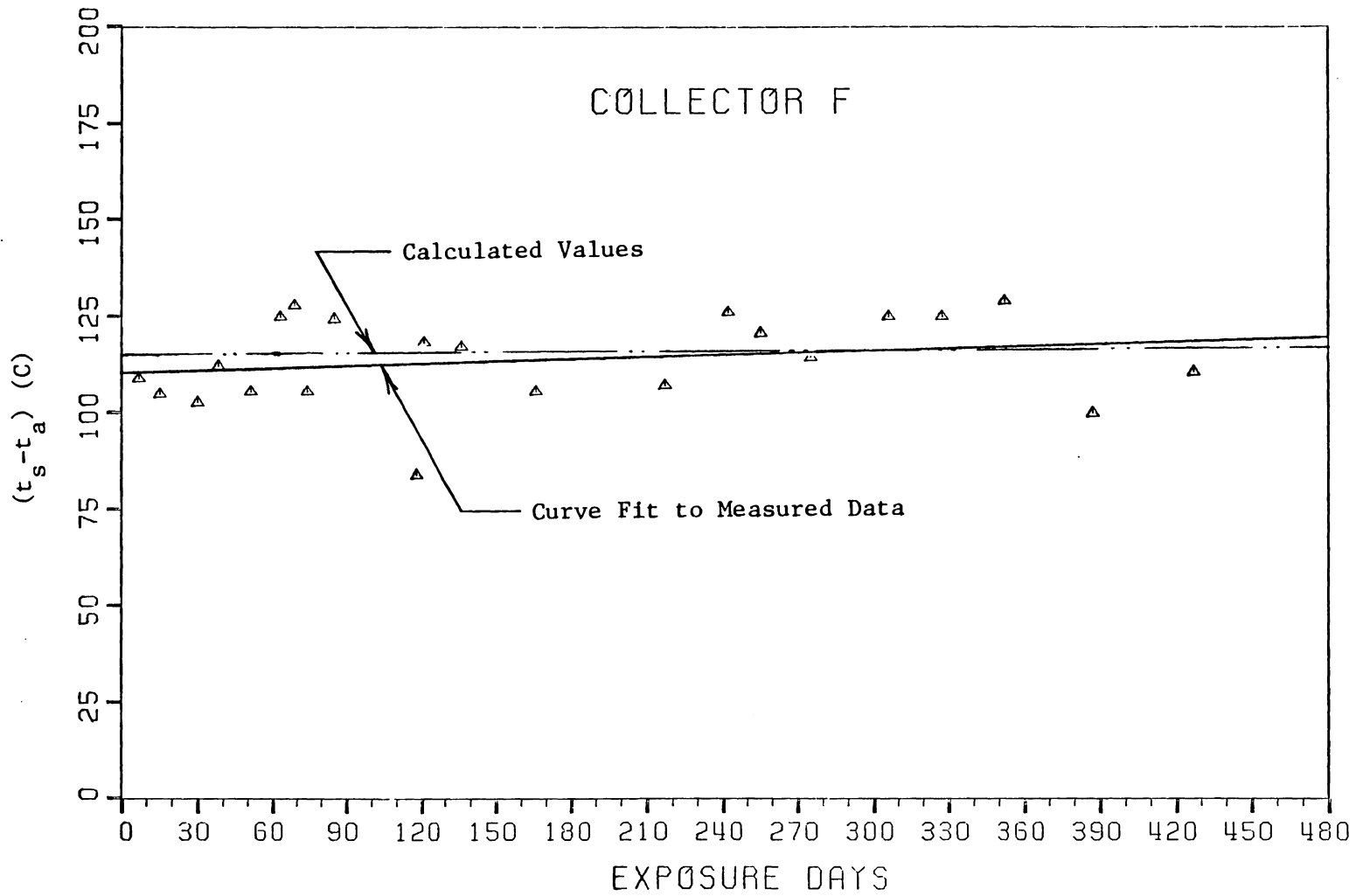


Fig. 3.8(b). Stagnation Temperature Normalized by Ambient Temperature for Collector F

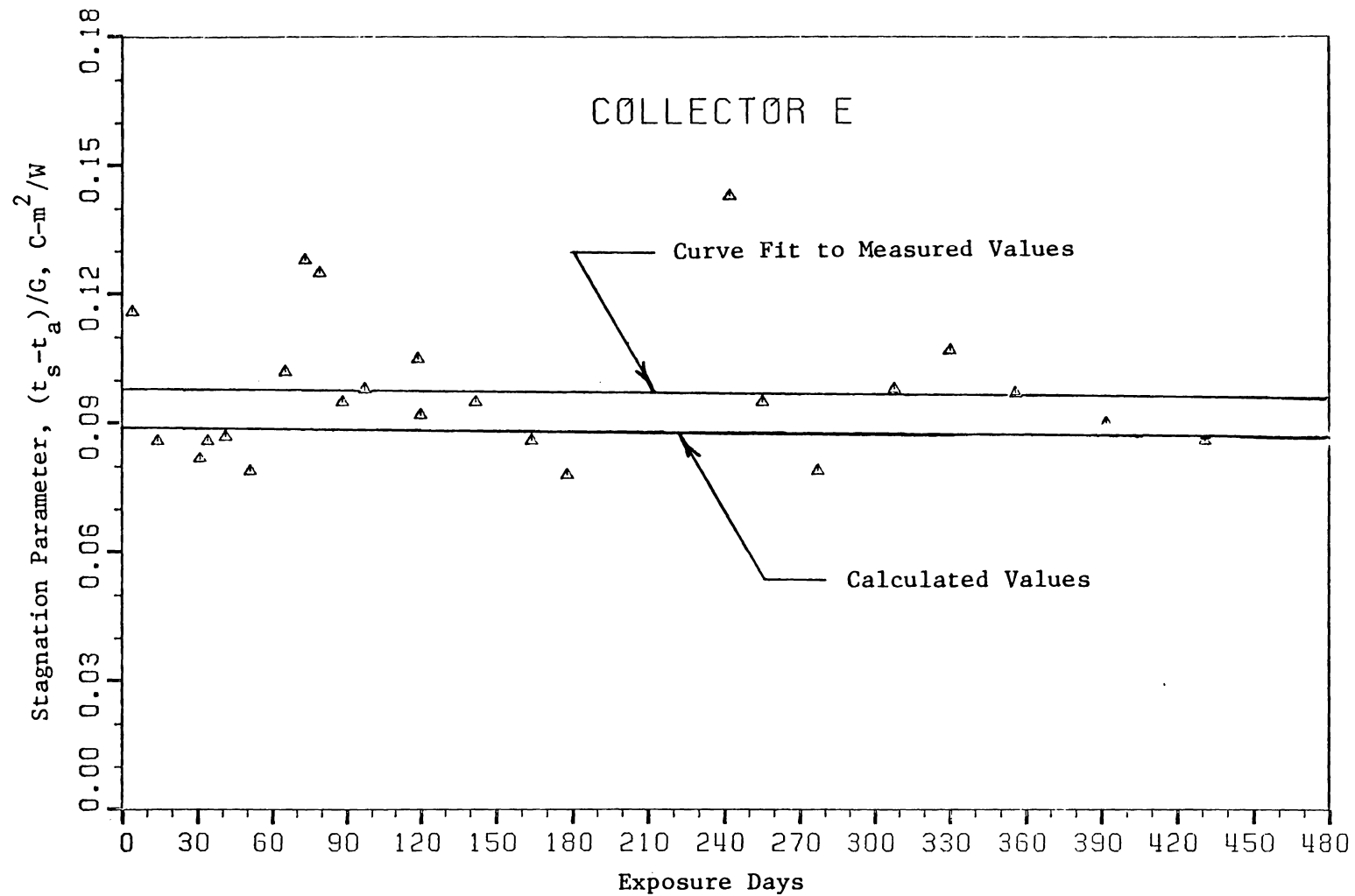


Fig. 3.9(a). Stagnation Parameter Variation with Exposure Time for Collector E

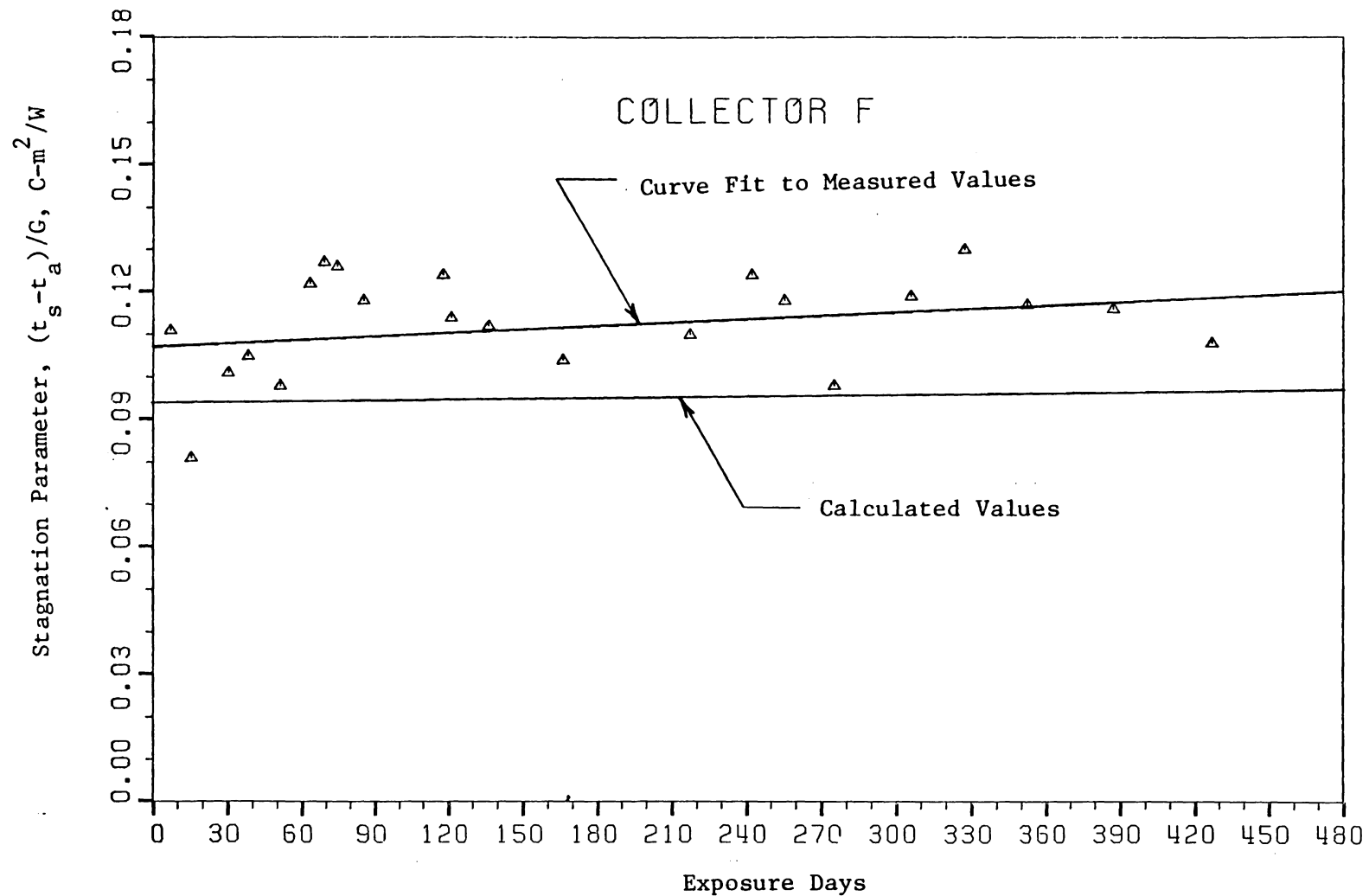


Fig. 3.9(b). Stagnation Parameter Variation with Exposure Time for Collector F

with the measured efficiency changes for these two collectors. Notice on Fig. 3.7(b) and (c) that the 480-day curves are above or nearly above the 0-day curves at high inlet temperatures. As inlet temperature continued to increase towards stagnation, the 480-day stagnation temperature given by the efficiency curve would be higher than the 0-day for both collectors E and F. This result agrees with the trends in measured stagnation temperature.

Calculations of stagnation parameter and stagnation temperature using the material property changes provided mixed results when compared to measurements. The calculated values of stagnation temperature for Collector E were approximately 10 percent higher than the measured values. The calculated values of t_s for Collector F were always within 3.6 percent of the measured values and showed the same trend as the measurements of increasing with exposure time. However, calculated values of stagnation parameter were considerably lower than measured values for both cases. Collector E calculated values, instead of 10 percent higher than measurements as in $t_s - t_a$ calculations, were approximately 10 percent lower than measured values of stagnation parameter. Calculated values of stagnation parameter for Collector F are 14 percent lower than measurements made at 0-days, and 24 percent lower than measured values at 480 days. There are no reasons immediately apparent for these differences.

3.4.4 Results of Calculated Efficiency Change

Although the results varied from one collector to another, the prediction method was generally successful in predicting thermal performance degradation based upon measured property value changes. The collectors presented here proved to be so stable that nearly two years of outdoor exposure produced changes in measured efficiencies of less than 6 percentage points. The predictions match measured results as far as general trends are concerned. For example, if the 480-day measured results reveal that the intercept of the efficiency curve decreased, in general so does the model. However, the magnitude of the change is usually predicted to be less than that corresponding to the measurements.

Table 3.5 gives the results of the degradation prediction for collectors B, E, and F. The values for 0-day measured, 480-day predicted, and 480-day measured efficiency are fitted with least-squares linear curves and plotted to provide a visual comparison in Fig. 3.10. Note that the 480-day prediction and the 0-day measurements are close together for collector B. Yet, the predicted curve is above the 0-day curve, as are the 480-day measurements. The magnitude of the change in efficiency is less for the prediction than for the measurements, but the prediction is still within 2 percentage points of the measured 480-day efficiency anywhere along the curve. So, in terms of general

Table 3.5
Values and Curve Fits for 0-day Measured, 480-day Predicted
and 480-day Measured Efficiency

Collector B					
$\Delta t/G$ (0-day)	0-Day Efficiency	Change	Predicted Efficiency	$\Delta t/G$ (480-day)	480-Day Efficiency
-0.00030	69.60	-0.40	70.00	-0.00260	71.41
-0.00030	69.00	-0.50	69.50	-0.00310	71.64
-0.00050	70.00	-0.40	70.40	-0.00290	72.26
-0.00010	70.40	-0.50	70.90	-0.00280	71.81
0.02410	57.00	-0.40	57.40	0.01740	61.71
0.02480	56.60	-0.40	57.00	0.01810	61.64
0.02460	56.90	-0.40	57.30	0.01740	62.19
0.02460	57.40	-0.40	57.80	0.01770	62.91
0.04520	44.70	-0.40	45.10	0.03460	49.37
0.04540	45.40	-0.40	45.80	0.03380	52.10
0.04520	46.10	-0.30	46.40	0.03480	51.14
0.04560	47.00	-0.30	47.30	0.03410	51.83
0.06760	26.00	-0.40	26.40	0.06210	33.05
0.06850	25.10	-0.30	25.40	0.06210	33.75
0.06860	27.70	-0.40	28.10	0.06230	33.54
0.06850	28.20	-0.30	28.50	0.06190	34.31

Least Squares Linear Curve Fit

0-day Measured $\eta = 71.11 - 617.7(\Delta t/G)$

480-day Predicted $\eta = 71.55 - 619.2(\Delta t/G)$

480-day Measured $\eta = 71.91 - 594.3(\Delta t/G)$

Table 3.5
Values and Curve Fits for 0-day Measured, 480-day Predicted
and 480-day Measured Efficiency (cont'd)

Collector E					
$\Delta t/G$ (0-day)	0-Day Efficiency	Change	Predicted Efficiency	$\Delta t/G$ (480-day)	480-Day Efficiency
-0.00070	67.50	1.60	65.90	0.00000	64.31
-0.00050	69.40	2.00	67.40	0.00100	63.81
-0.00070	69.00	2.10	66.90	0.00120	63.19
-0.00030	68.60	2.00	66.60	0.00070	64.98
0.01830	55.80	1.70	54.10	0.02250	49.41
0.01860	57.50	2.20	55.30	0.02210	50.43
0.01900	57.90	2.20	55.70	0.02210	50.90
0.01900	58.00	2.30	55.70	0.02140	51.98
0.03310	38.40	1.70	36.70	0.03900	34.75
0.03340	40.00	2.00	38.00	0.03960	35.66
0.03320	42.40	2.20	40.20	0.03890	38.23
0.03380	43.40	2.30	41.10	0.03900	38.95
0.06210	11.50	1.80	9.70	0.05600	19.29
0.06120	19.80	2.40	17.40	0.05810	17.99
0.06120	18.80	2.50	16.30	0.05750	19.35
0.06210	19.20	2.70	16.50	0.05720	21.64

Least Squares Linear Curve Fit

0-day Measured $\eta = 69.99 - 845.0(\Delta t/G)$

480-day Predicted $\eta = 68.06 - 851.4(\Delta t/G)$

480-day Measured $\eta = 66.22 - 786.7(\Delta t/G)$

Table 3.5

Values and Curve Fits for 0-day Measured, 480-day Predicted
and 480-day Measured Efficiency (cont'd)

Collector F					
$\Delta t/G$ (0-day)	0-Day Efficiency	Change	Predicted Efficiency	$\Delta t/G$ (480-day)	480-Day Efficiency
-0.00030	69.50	3.60	65.90	0.00220	65.22
-0.00080	70.30	3.60	66.70	0.00220	65.62
0.00030	69.20	3.60	65.60	0.00310	66.02
-0.00080	70.80	3.50	67.30	0.00350	65.19
0.02200	53.90	3.00	50.90	0.02000	52.16
0.02200	54.10	3.10	51.00	0.01990	54.48
0.02180	57.10	2.80	54.30	0.02020	54.87
0.02210	58.30	2.60	55.70	0.01990	55.81
0.03710	39.60	2.90	36.70	0.04100	40.12
0.03760	39.90	2.80	37.10	0.04100	41.86
0.03730	44.80	2.30	42.50	0.04080	42.03
0.03690	46.40	2.10	44.30	0.04100	42.89
0.05910	22.50	2.20	20.30	0.05950	23.94
0.06040	21.70	2.20	19.50	0.05890	26.03
0.05980	29.70	1.50	28.20	0.06090	26.39
0.05840	30.30	1.60	28.70	0.06090	25.97

Least Squares Linear Curve Fit

0-day Measured $\eta = 70.58 - 742.5(\Delta t/G)$

480-day Predicted $\eta = 67.04 - 714.2(\Delta t/G)$

480-day Measured $\eta = 68.00 - 685.0(\Delta t/G)$

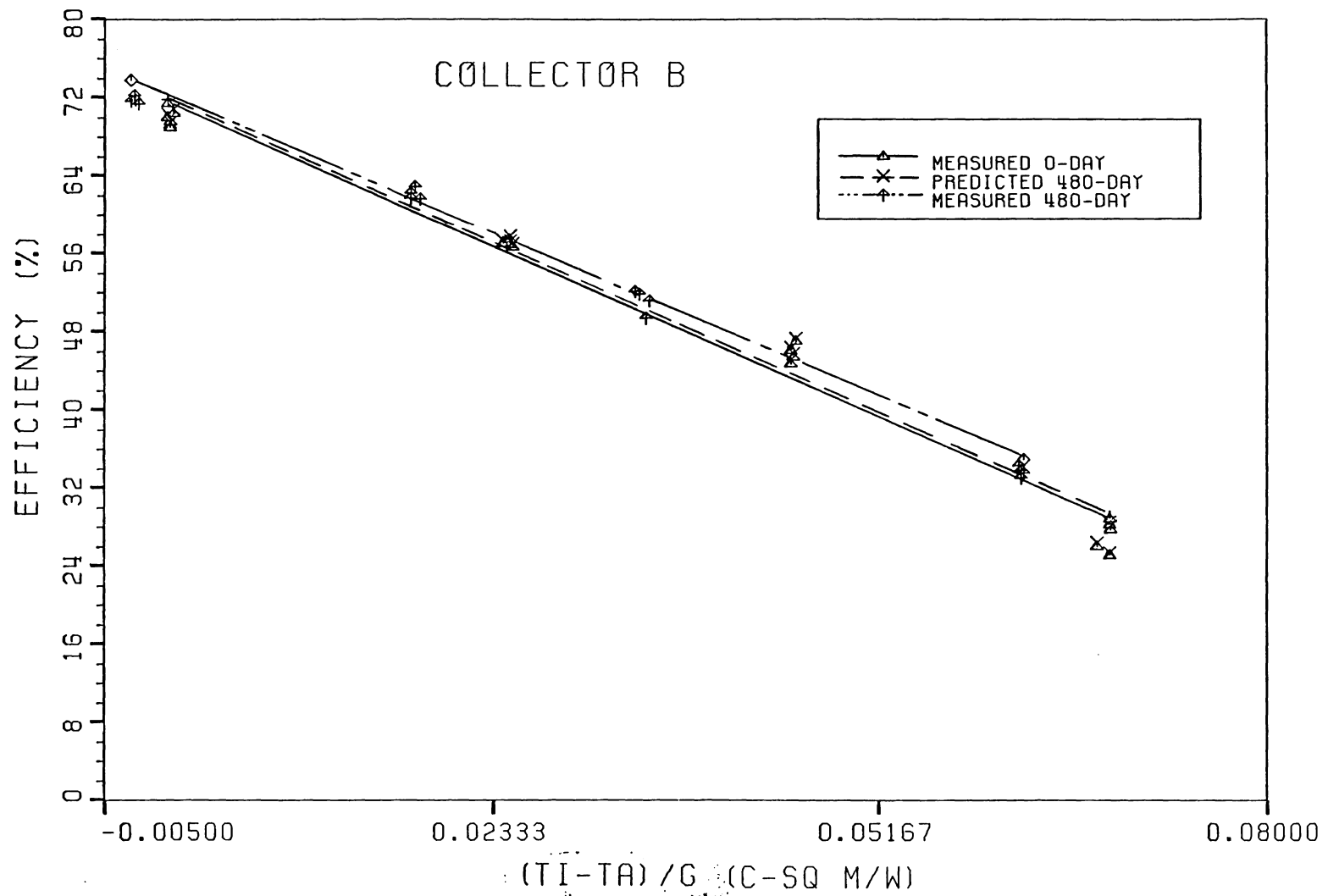


Fig. 3.10(a). Predicted 480-day Performance Compared to Measured 0-day and 480-day Performance

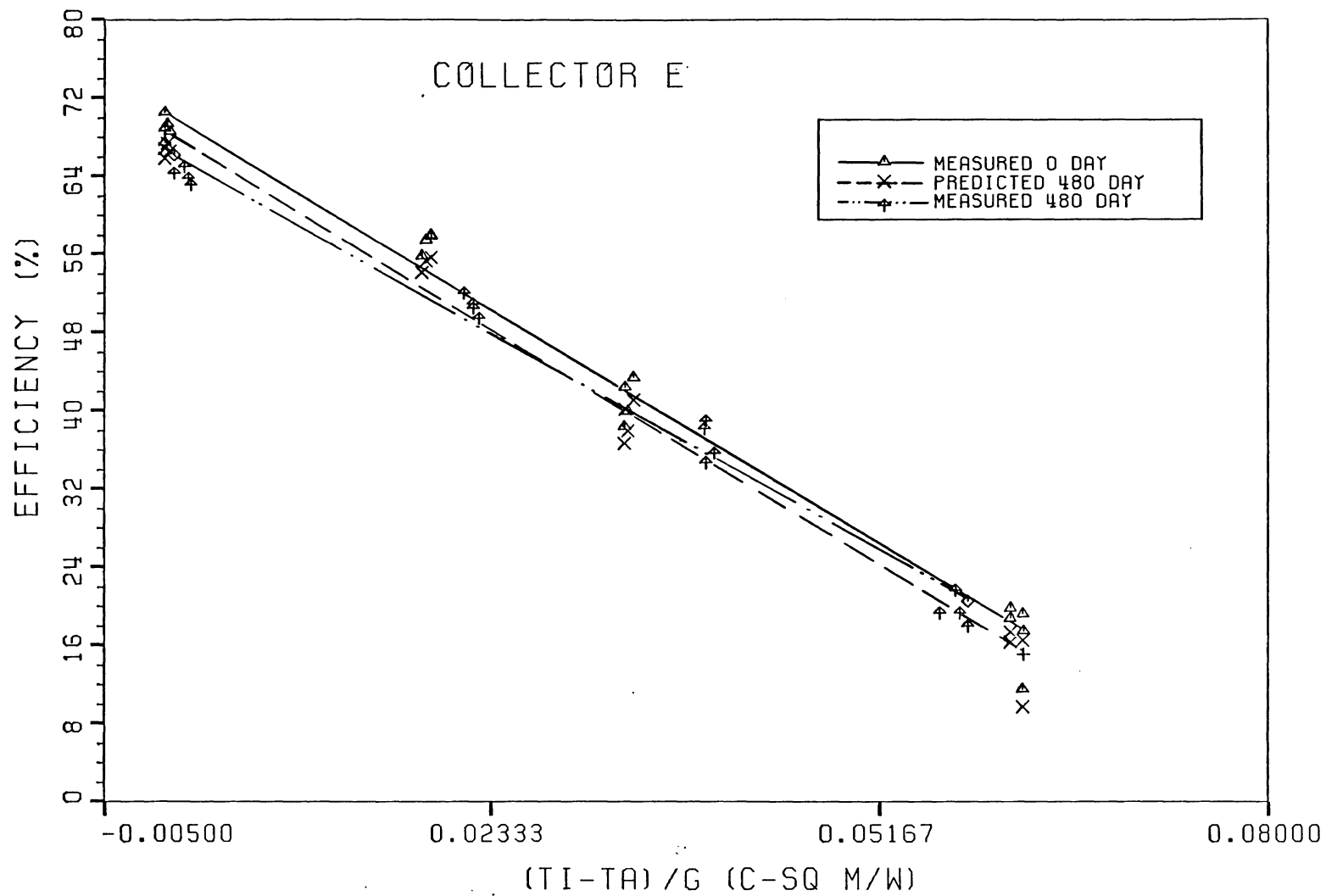


Fig. 3.10(b). Predicted 480-day Performance Compared to Measured 0-day and 480-day Performance- Collector E

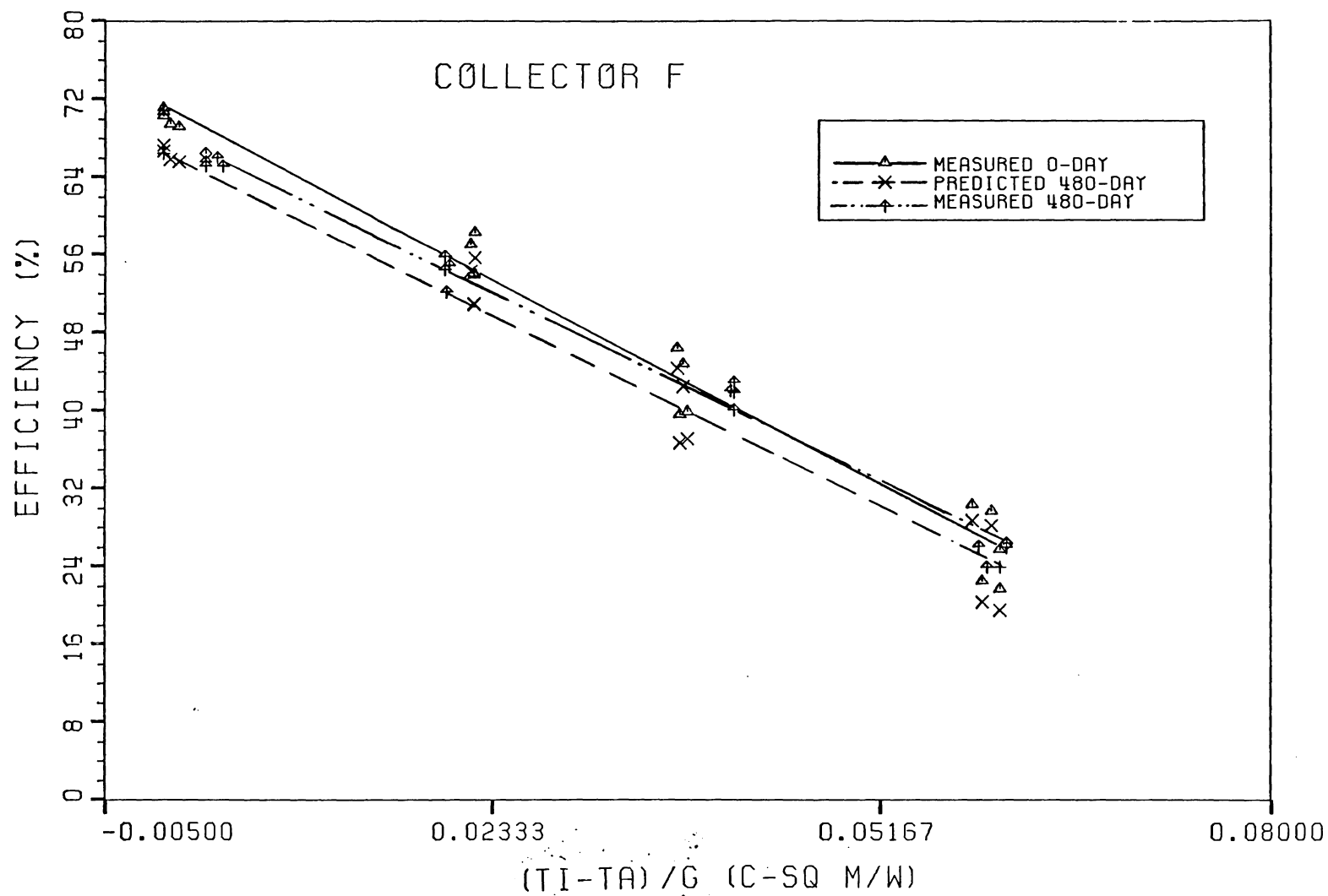


Fig. 3.10 (c). Predicted 480-day Performance Compared to Measured 0-day and 480-day Performance - Collector F

trends, the prediction of efficiency change seems to be good for collector B based on the limited data available.

The predictions for collectors E and F are always within 2.7 percentage points of the measured efficiency. The most significant differences between the measurements and the predictions seems to be caused by the randomness in $F_{R U_L}$. Using the values of slope and intercept for the curve-fits in Table 3.5, the difference between the measured and predicted $F_R(\tau\alpha)$ is 3.1 percent of the measured value (percent of percent efficiency) for collector E and 1.4 percent for collector F. The difference between the measured and predicted $F_{R U_L}$, on the other hand, is 8.2 percent for collector E and 4.3 percent for collector F. These errors in $F_{R U_L}$ are almost three times as large as the error in $F_R(\tau\alpha)$.

A possible explanation of the larger error in $F_{R U_L}$ comes from consideration of the methods used in the prediction. The property values changed to generate the efficiency changes were plate absorptance, cover transmittance, and plate emittance. The former two properties primarily affect the value of $F_R(\tau\alpha)$, while the latter also affects heat losses. However, no information was available on how insulation conductivity changed with exposure time, either from tests or literature study, so the value of conductivity was not changed in the prediction. Reference 6 considered the various effects of high temperature exposure on insulation and noted that outgassing occurred in a number of

insulation types used in solar collectors. Most studies on outgassing consider it in terms of the effect on cover transmittance of outgassing products condensing or precipitating on the cover plates. In the NBS study, weekly inspection reports noted that outgassing products were observed, but no follow up tests were conducted to determine if the thermal conductivity of the insulation was affected.

If outgassing results from insulation binders, trapped moisture, and other volatile substances evaporating, the overall effect would decrease the thermal conductivity. This decrease would, in turn, affect the efficiency curve by decreasing $F_R U_L$ and increasing $F_R(\tau\alpha)$. (In fact, this trend of a lesser curve slope was observed in collectors E and F, but the reason for the increase is not known with certainty.) Figure 3.11 shows the effect of decreasing the insulation conductivity of collector F by 0.005 W/m C, or 21 percent of the original value. Note that the slope of the degraded efficiency curve now appears less negative than the reference efficiency. The intercept is also affected, but not as much as the slope. The degraded slope is 1.11 times the reference value of $F_R U_L$ whereas the degraded intercept is only 1.04 times the reference value of $F_R(\tau\alpha)$.

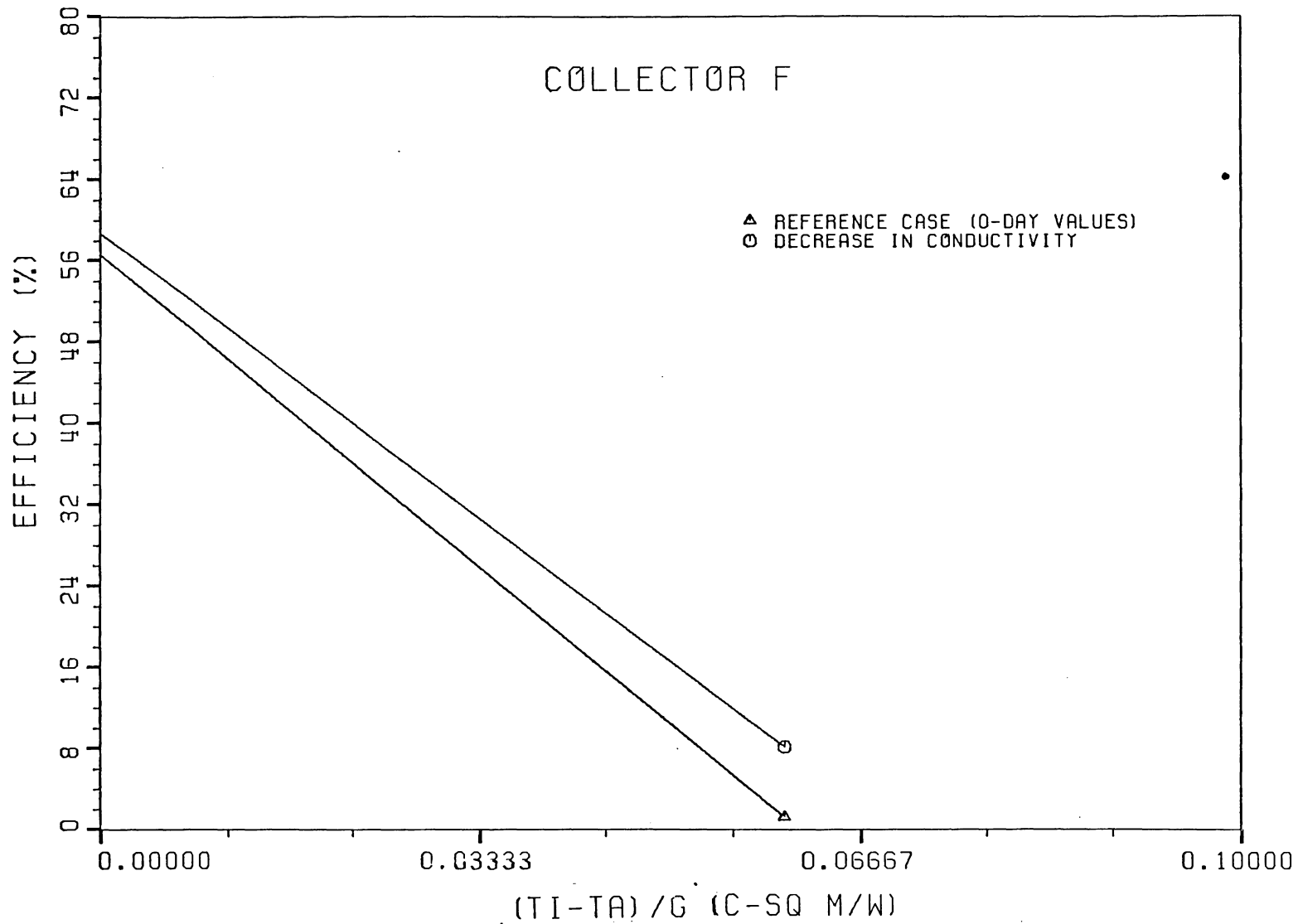


Fig. 3.11. Effect of a Decrease in Insulation Conductivity on Theoretical Efficiency

Chapter 4

DISCUSSION

The primary objective of this investigation has been directed at assuring solar collector long term thermal performance stability. It is asserted that, by analyzing the data collected in the NBS Durability/Reliability Program, correlations between exposure conditions and collector degradation can be found. Such correlations may relate performance changes to exposure time, incident radiation, UV exposure, thermally activated processes, etc. The best possible correlations that could result would use data from tests which are performed on small samples in an accelerated manner. Thus, the size of the test apparatus and cost of performing the tests would be reduced, and data concerning the 20-year performance of solar collectors could be obtained in shorter periods of time. The data presented and analyzed in this paper has been primarily for the purpose of supporting the development of degradation correlations.

Two means of accelerating degradation in solar collectors and material samples were used in the Durability/Reliability Program. The first method used concentrated solar radiation to increase the rate at which degradation occurred in test specimens. The samples and collectors were placed in an apparatus which used reflective panels to produce an incident solar flux approximately six times the ambient value. The concentrated radiation caused higher operating temperatures than would be

experienced normally as well as increasing the Ultraviolet (UV) flux on the specimens. According to theories dealing with acceleration of property changes, any problems which were either radiation or thermally induced would occur more quickly. Since the collectors were outdoors during exposure, they experienced other natural conditions which may cause degradation such as wind, thermal shock from rain, thermal cycling, abrasion from airborne particles, etc. The end result is that long term tests can be performed in relatively short times since the rates of decay are increased.

An example of the success of concentrating the solar radiation at decreasing the time required to obtain data was shown in Chapter 2. The accelerated outdoor material samples exhibit the same behavior after 120 equivalent days as the real time outdoor samples do at approximately 160 days. The real time data required 171 calendar days to obtain while the accelerated data was obtained in 37 calendar days. It remains to be seen whether the extra cost of performing concentrated radiation testing outweighs benefits of quick response times.

The second method of accelerating material degradation involved exposing samples to carefully controlled environments indoors and measuring property changes with time. These tests are performed to isolate specific degradation mechanisms and observe the severity of each. By testing the effects of high temperature, high UV radiation, thermal cycling, and a solar

simulator individually, it may be possible to determine which combinations of natural elements are most destructive to solar collector performance. The results of these tests may also be useful in determining the dominant failure modes in outdoor exposure by comparing the indoor and outdoor tests results and noting similarities. From the data presented in Chapter 2, the high temperature-high humidity tests were the most severe, causing the greatest amount of change in the widest variety of samples tested. Temperatures above 90 C appear to have a significant effect on cover materials, but radiation damage does not appear to be a severe problem in any of the samples presented. This last observation points toward the possibility that the high temperatures which result from the concentrated solar radiation may be more important than the radiation itself.

The material sample tests, in general, showed that many of the materials used in solar collectors today appear to be insensitive to environmental exposure over the time period tested. Some of the samples, such as absorbers made of black nickel or flat-black paint, or covers made of FEP and PVF, showed so little change that experimental uncertainty could not be eliminated as a possible cause of the differences. Other samples, such as lead oxide absorber coatings and certain FRP's, showed considerable change in property values when exposed to harsh operating conditions. Based on the data presented, the most severe tests seem

to be temperature and humidity, high temperature alone, and concentrated solar radiation.

In order for the material tests to be used to the fullest value, correlations between laboratory or accelerated time frames and actual operation must be developed. One method of equating accelerated time to real time used in this investigation is based on the amount of radiation which strikes a surface during outdoor exposure. It appears that data obtained in this manner provide degradation data similar to actual exposure but in significantly reduced times. Tests are still required to minimize the possible statistical differences between samples.

Since the methods used for measuring property changes are well established and standardized, the results are expected to be indicative of actual changes in property values. On the other hand, the methods used to measure the thermal performance of full scale collectors are relatively new and not as well tested. As such, the results of efficiency tests are subject to rather rigorous uncertainty analysis which reveal experimental uncertainties of three to four percent in measuring thermal efficiency [26]. The point here is that degradation may occur in the thermal performance of solar collectors, but the change after two years of exposure is not detectable by methods which are based on thermal performance measurement. The collectors used in this program have exhibited slight changes in measured thermal

efficiency, but not enough for the changes to be identified as performance degradation with any certainty.

Collector B exhibited the most stable behavior of any collector analyzed in depth. Other collectors which exhibited little sensitivity to environmental exposure are collectors A and D. Figure 4.1 shows the highest and lowest measured efficiency curves for these two collectors. All other measured efficiency curves fall between the two lines shown, which are separated at the most by 4.7 percentage points for collector A and 5.0 points for collector D. The behavior shown by Fig. 4.1 and Fig. 3.1 for collectors B, E, and F span the range of responses observed. Since changes in efficiency which were clearly outside of the uncertainty bands were not observed, the results remain inconclusive as to whether thermal performance degradation actually occurred.

Although only series 1 test results were analyzed in detail, the other three series of test gave similar results. Again, the data collected showed no clear conclusions about the degradation of actual collectors.

Series 1, as described before, was characterized by dry stagnation. No fluid was in the collector at any time except during performance retests. Series 2 added thermal shock to series 1 through periodic water-spray and the boil-out of fluid from the collector at the beginning of each exposure period. Series 3 provided for one-quarter of the normal operational fluid

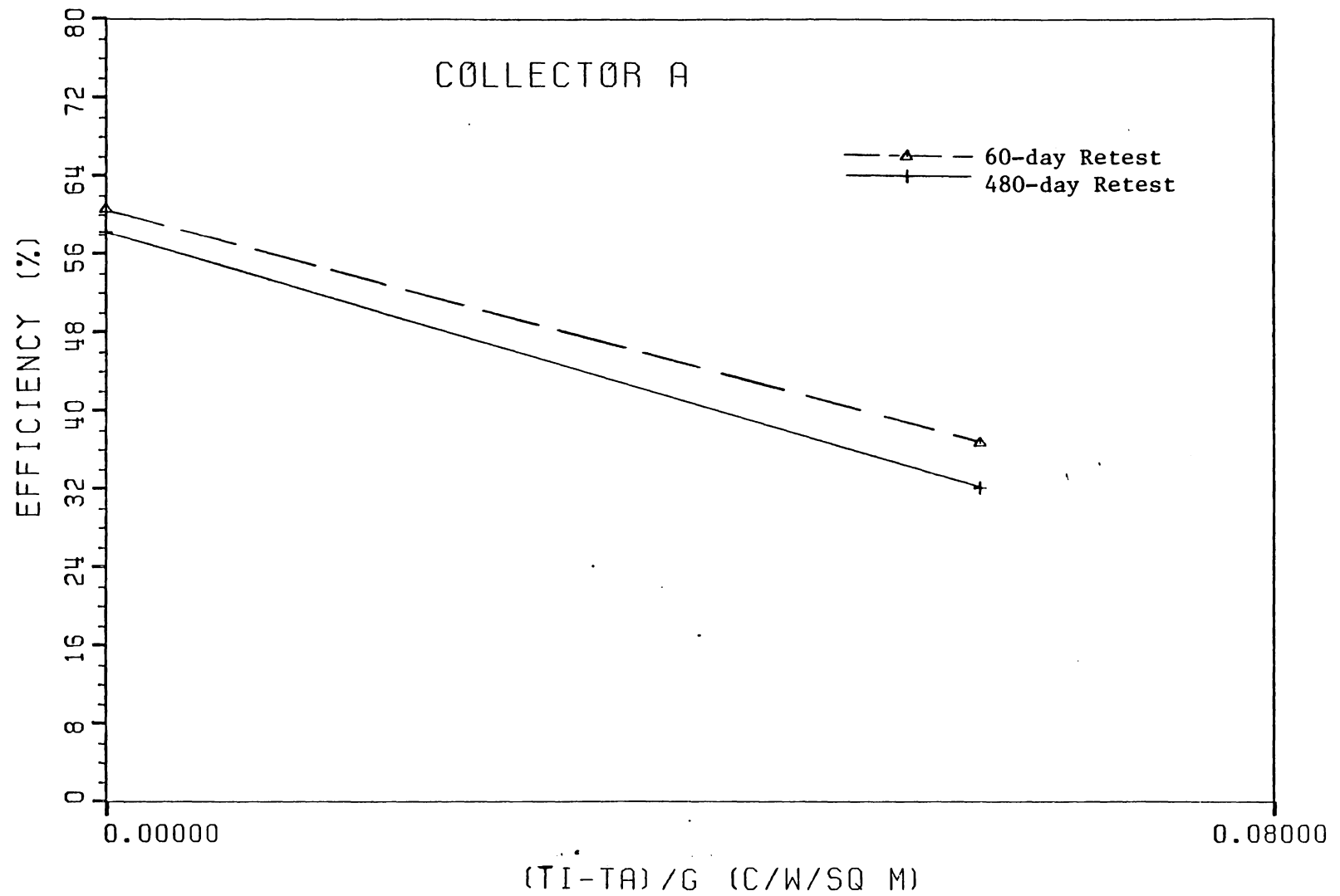


Fig. 4.1(a). Maximum and Minimum Measured Efficiency for Collector A

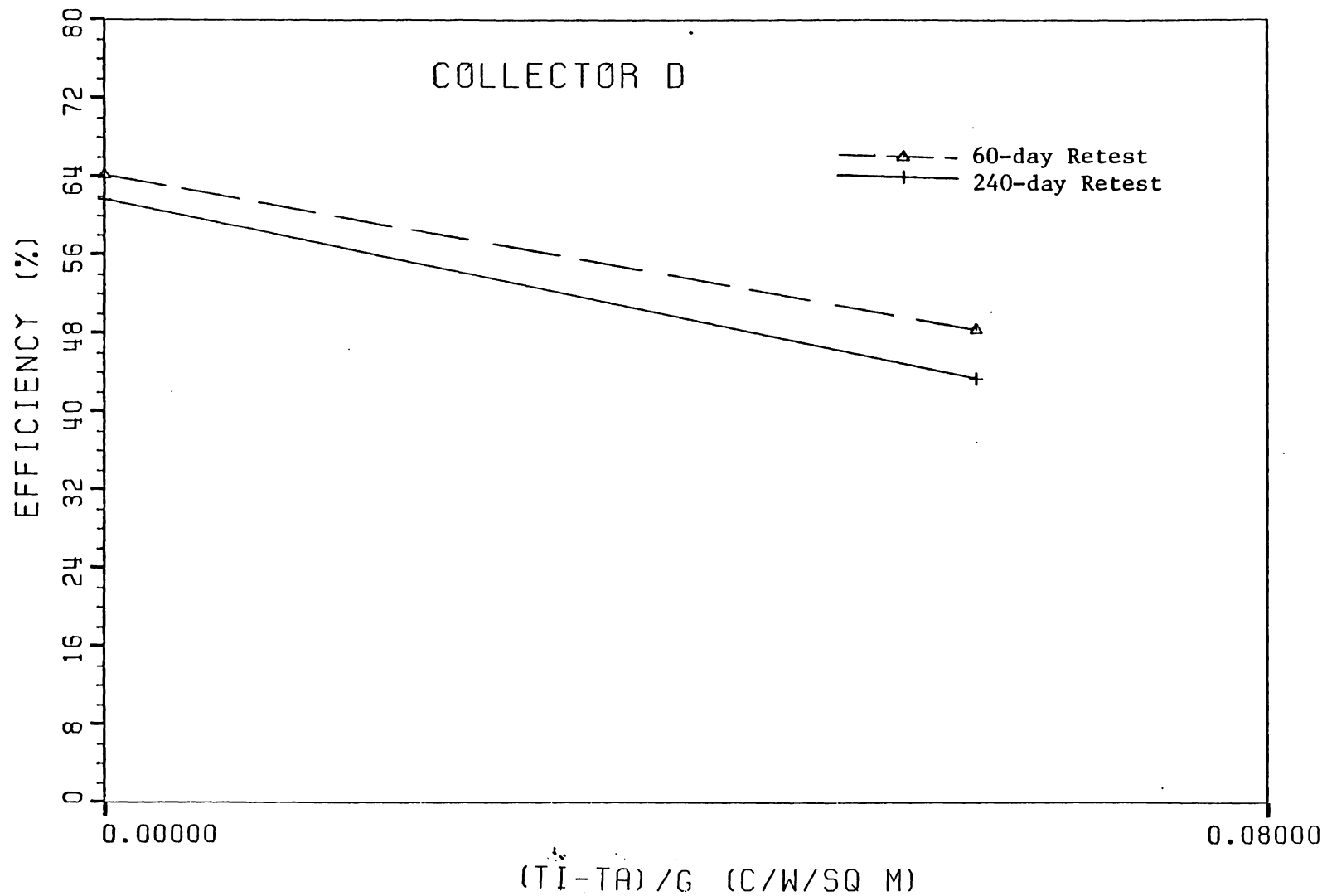


Fig. 4.1(b) Maximum and Minimum Measured Efficiency for Collector D

flow rate to be circulated throughout the exposure tests. Series 4 required placement of the collectors in a solar concentrating apparatus to provide an incident flux of six times the normal value. Figure 4.2 shows a set of plots comparing series 1 through 4 at lab site 1. As when observing a single collector and series, it is difficult to discern any trends from the data because of the unaccountable scatter in the test results. On the whole, series 4 appears to be the most severe test, producing the most degradation in the shortest time until exposure was halted after 120 days. In the absence of concentrating apparatus, however, the results of the other three test types do not show enough difference to justify the additional expense and effort of adding thermal shock to dry stagnation or running one-quarter flow tests to measure degradation.

Note that the plots in Fig. 4.2 exhibit a peak in $F_R(\tau\alpha)$ after approximately 30 to 60 days. The reason for this increase is unaccountable in the present investigation. The effect appears in enough plots for it to be real and not a result of measurement error. It may result from absorber plate coatings becoming more conductive as volatiles are driven off during operation. The absorptance of the coating may also increase due to wrinkling as volatiles are removed. Insulation binders and trapped moisture may evaporate during this period, leaving the insulation less conductive than when brand new. Gilligan [11] has shown that certain polymer cover materials exhibit a peak in

COLLECTOR B

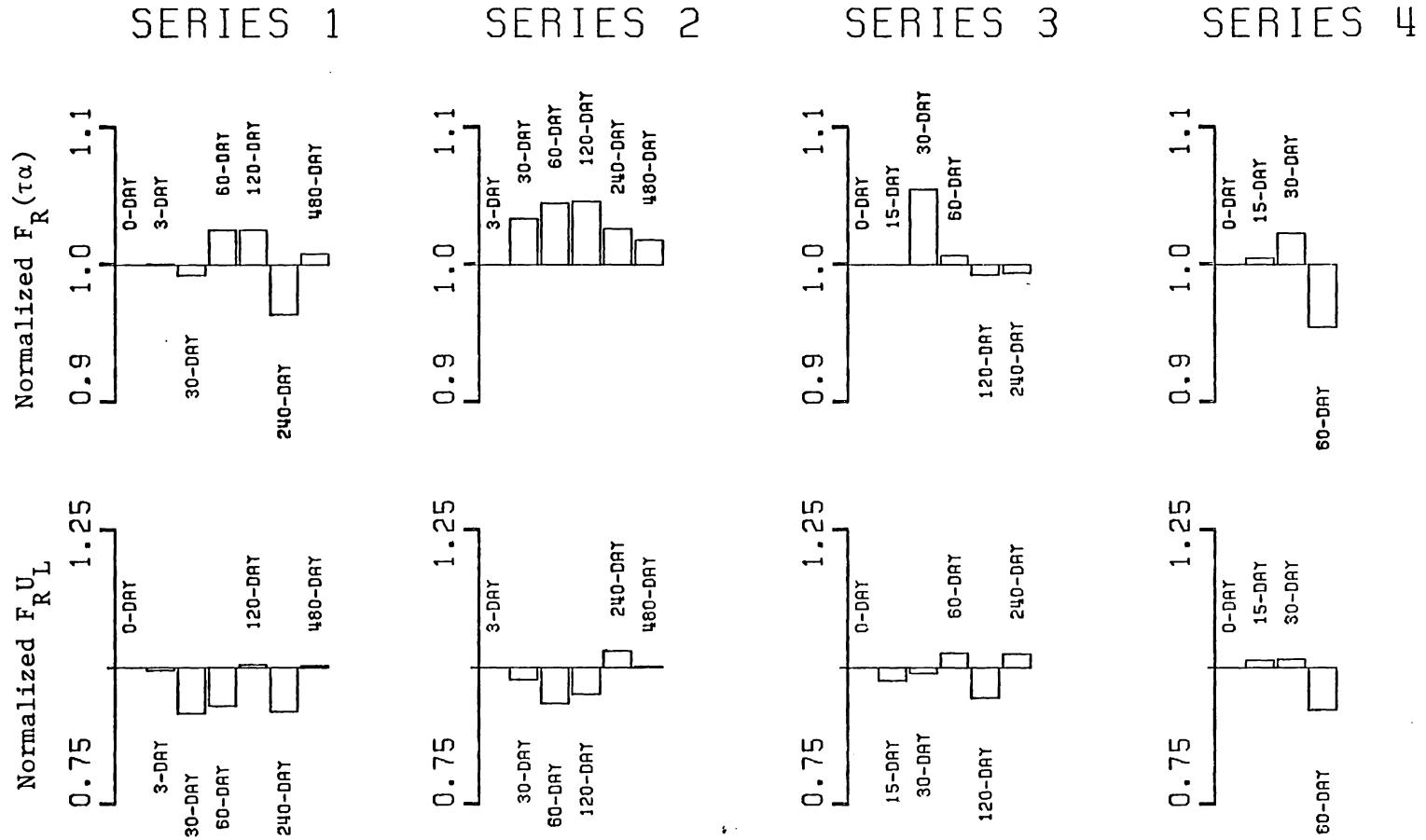


Fig. 4.2(a) Comparison of Series 1 through 4 Measured $F_R(\tau_\alpha)$ and $F_R^U_L$ at all Retest Days Collector B

COLLECTOR E

SERIES 1

SERIES 2

SERIES 3

SERIES 4

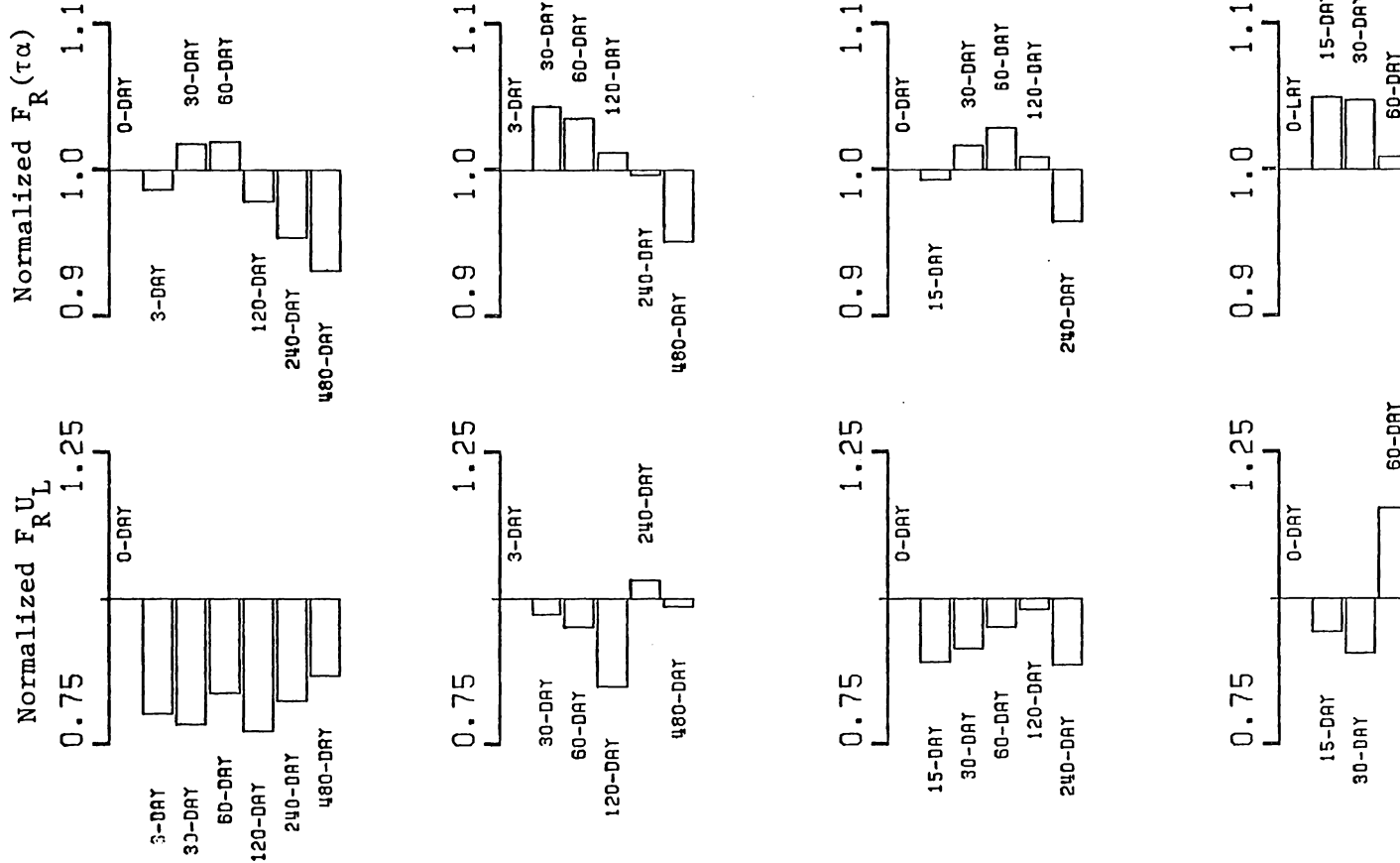


Fig. 4.2(b). Comparison of Series 1 through 4 Measured $F_R(\tau)$ and $F_R U_L$ at all Retests Days Collector E

COLLECTOR F

SERIES 1

SERIES 2

SERIES 3

SERIES 4

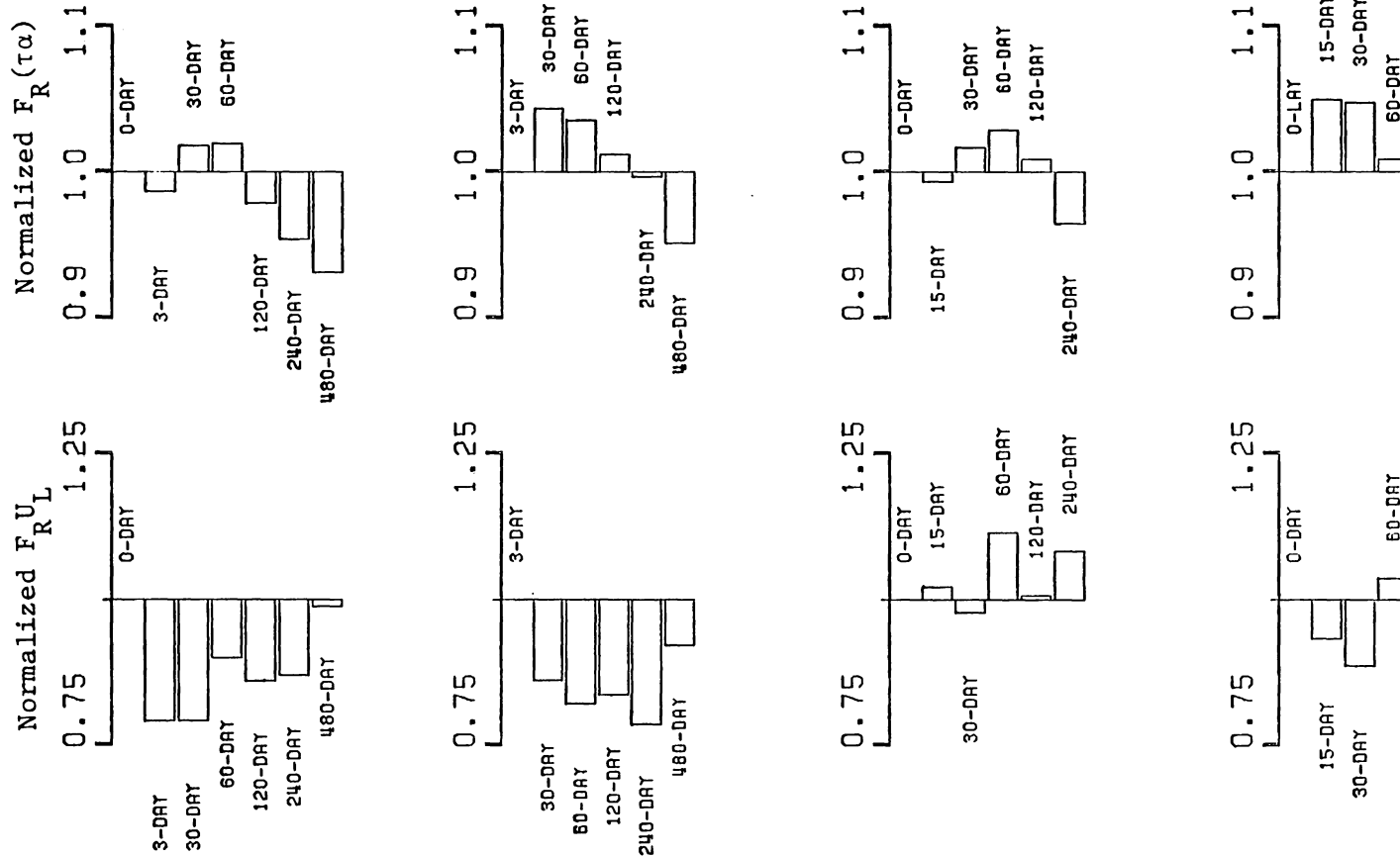


Fig. 4.2(c) Comparison of Series 1 through 4 Measured $F_R(\tau_\alpha)$ and $F_R U_L$ at all Retests Days - Collector F

transmittance at approximately 30-90 days. He estimates the increase is caused by a solar-absorbing component being driven from the polymer, leaving the remaining sheet more transparent to solar energy. At this time, however, no one has performed tests to determine the actual causes of this apparent "break-in" phenomenon.

The stagnation temperature analysis data was scattered and revealed little additional information on collector degradation. In general, the trends exhibited by the stagnation parameter, $[t_s - t_a]/G$, were the same as those exhibited by collector efficiency. For example, when the 480-day measured efficiency at high inlet temperature increased when compared to 0-day values, so did the stagnation temperature in the two cases presented. Analytical results, on the other hand, were not in agreement with the trends or measurements for either collector E or collector F. The analytical results predicted that stagnation temperature would decrease over time, while measurements show a slight increase.

The prediction of efficiency change using measured property change and the mathematical model produced good results in general. The predictions were always within 3 percentage points of the measured 480-day values but never quite matched the degraded efficiency curve exactly. As noted before, the most error appears to be introduced by uncertainty in $F_{R U_L}$. This appears to be a result of the lack of good data on insulation

conductivity changes. The points plotted in Fig. 3.9 showed the effects that insulation changes could have upon efficiency curves, and the measured results seem to point towards a change in insulation conductivity as a means of improving the prediction accuracy.

It should be noted that even if the predictions agreed with the measured curve more closely, the experimental uncertainty of the measurements would leave a considerable amount of doubt as to the actual location of the measured curve. Adams [26] and Thomas [21] have performed detailed uncertainty analysis on the efficiency test procedure and found the experimental error in thermal performance measurements for these type collectors to be between 3 and 4 percentage points. Figure 4.3 shows the 480-day efficiency curves for collector E with uncertainty bands of 3.5 percentage points added to each curve. The area where the uncertainty bands overlap shows that there is not enough separation between the two curves to say for certain that there was a change in material properties which resulted in a change in efficiency. In other words, the efficiency change measured after 480-days of exposure was not enough to verify the theories about changes in material properties with certainty.

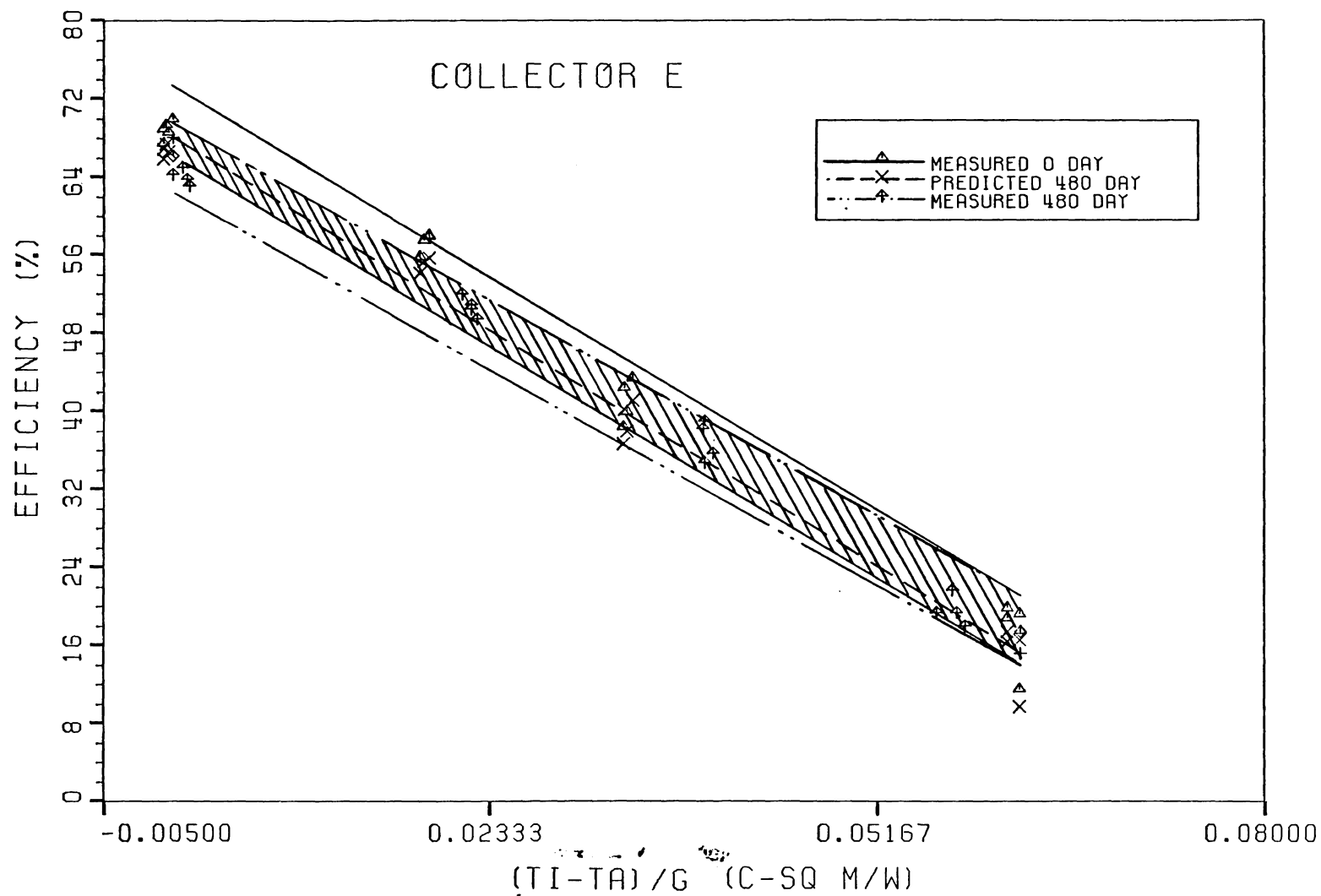


Fig. 4.3. Measured 0-day and 480-day Efficiency for Collector E with Uncertainty Bands Added to Measured Values

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The results presented in this paper support the following conclusions:

1. On the basis of the limited data available, material samples subjected to concentrated solar radiation for 120 equivalent days, based on equivalent irradiation, appear to degrade in the same manner as samples exposed to natural weathering for 120 days.
2. The optical properties of typical materials currently used in commercially available solar collectors are insensitive to exposures of 12,000 to 13,000 MJ/m² as evidenced by insignificant changes in the plate absorptance, plate emittance, and cover transmittance of small scale material samples.
3. Based on the data presented, it does not appear to be possible to determine the change in collector performance caused by 480 days of outdoor exposure by measuring the thermal efficiency because of the small magnitude of the change and the inherent uncertainty associated with the thermal output of a solar collector.
4. Since the measurements of collector degradation have no apparent advantage, it seems that calculated methods of determining performance degradation are as good and

considerably less expensive than methods based on experimental measurement of efficiency, provided the material properties are known for the collector.

5.2 Recommendations

Several recommendations for further research have developed during the present investigation. First, careful testing of insulation materials should be performed to provide data on the change of insulation conductivity with exposure time. Information on insulation conductivity change is needed to make the predictions more accurate when larger changes in efficiency (i.e., longer exposure times) are involved. Since the insulation in a solar collector is completely contained within the outer box of the collector, the only environmental effects which are experienced are a result of high absorber plate temperature. Therefore, high temperature laboratory tests could be performed on insulation samples to measure the changes in conductivity. Parameters measured versus exposure time should include weight loss resulting from outgassing, conductivity, and physical dimensions if possible. A correlation between weight loss caused by outgassing and conductivity would allow the results to be extended to other materials for which weight loss has been measured. Reference 6 is one source of weight loss versus exposure time data for several types of insulation, but the authors do not provide data on conductivity changes.

The second recommendation also deals with material properties. The data from the NBS Program has all been assimilated, but there is much room for different analysis of this data base. One possible means of analysis could be to develop exposure time transfer functions between the actual outdoor exposure tests performed on material samples and the various accelerated methods tested. The basis of the transfer function should be equivalent degradation. For example, suppose the absorptance of a sample changes 5 percentage points after an average of 300 days of outdoor exposure. The same change occurred in samples exposed to 125 C for an average of 1400 hours. A simple time transfer function might suggest that 1 hour in the temperature exposure is equivalent to 0.21 days of actual exposure. Enough samples would have to be analyzed for statistical variations to be smoothed and differences between different sample types considered. However, there appears to be sufficient data to develop approximate transfer functions for most of the tests performed.

A third recommendation deals with the pre-exposure period called for by ASHRAE standard 93-77. As shown by Fig. 31.(a)-(c) there is a change in measured efficiency as a result of the 3-day pre-exposure in most collectors. Some collectors experience only a slight change, such as collector B, but every collector discussed in this investigation experienced some increase in efficiency between 0 and 3 days of exposure. However, these same collectors appeared to continue to increase in efficiency until

between 30 and 60 days of exposure. The reason for this increase is unaccountable in the present investigation, but appears often enough in the retest measurements to be genuine, and not a measurement error. Therefore, it is recommended that the collectors be exposed for 30 days before the initial test to allow transient reliability effects to die out and influence the measurement less.

Another recommendation would be to restart some form of concentrated solar radiation testing of full scale collectors. These tests, when performed in the NBS Program, showed promise of giving long term data that matched real time exposure data in relatively short exposure periods. The series 4 collectors were exposed for only 60 days, yet in Fig. 4.2 they appeared to exhibit trends similar to those observed in series 1 over the 480-day test period. Thus, further testing of collectors using concentrated solar radiation would appear to be justifiable. These tests would have to be carefully monitored during the initial exposures, because the peak in performance mentioned previously would occur quickly, perhaps within 5 to 10 days. The best way to run the test would be to mount movable reflectors on a test stand with the collector in position for an efficiency test. Stagnation exposure could then be accomplished by moving the reflectors into position, purging the collector with air, and recording the weather conditions and collector temperatures needed for analysis. Efficiency tests should be performed

initially every 2 days by moving the reflectors out of the way and performing the test. In this manner, the performance could be closely monitored and significant changes in efficiency noted immediately. After the transient reliability effects decrease, efficiency measurements could be moved to once a week to monitor long term changes. A schematic diagram of a suggested test stand is shown in Fig. 5.1. Using this stand and the procedure above, it is possible that large changes in efficiency could be observed in a relatively short measurement period.

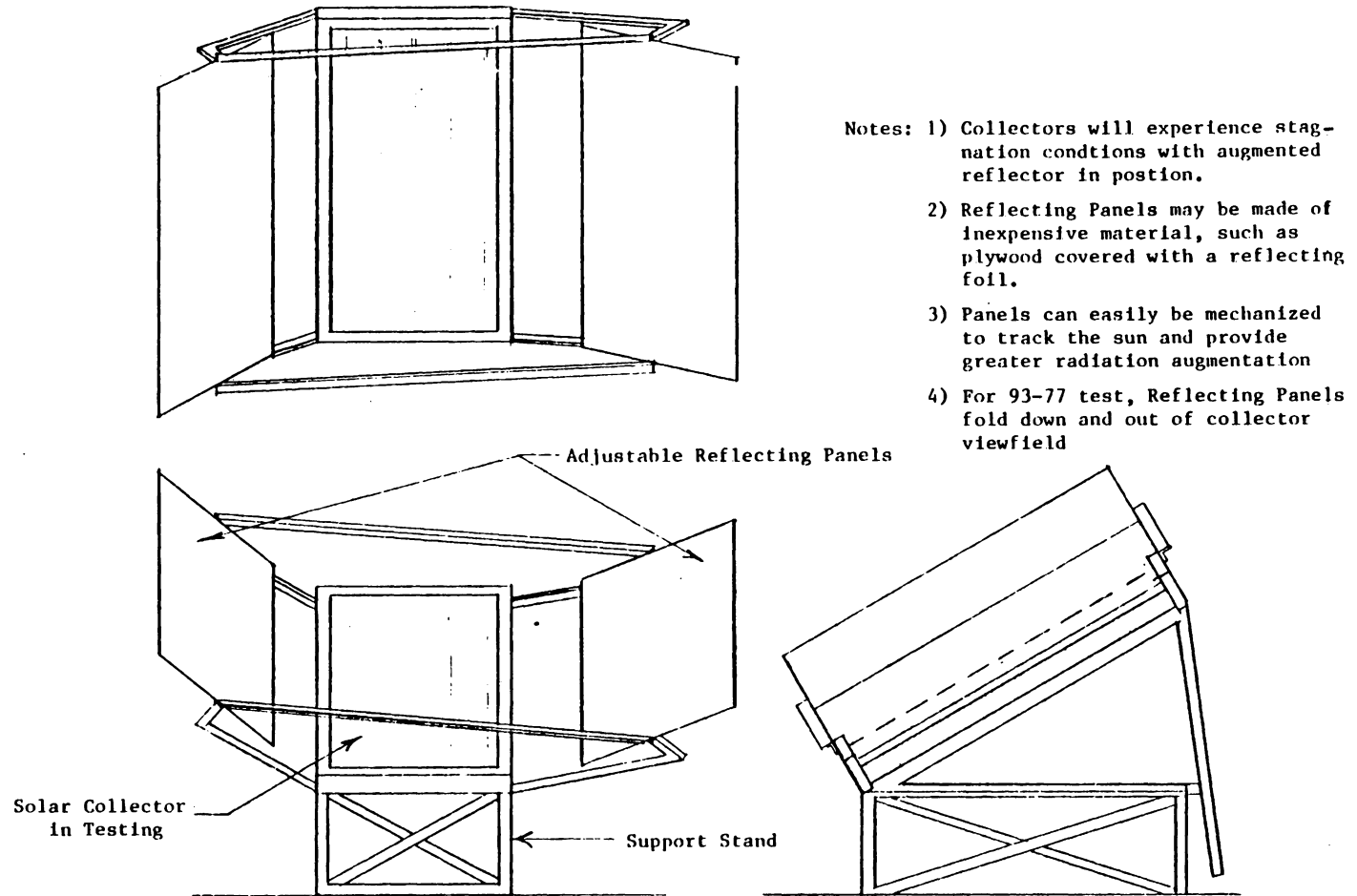


Fig. 5.1. Schematic Diagram of Concentrated Radiation/Efficiency Test Exposure Rack

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APPENDIX A

AUTOMATIC DATA LOGGER DESIGN

During the research associated with the R/D program, it became apparent that some form of automatic data acquisition system would be needed at VPI. The reasons behind this fact are as follows: first, it was desired to monitor meteorological data continuously to provide a database of this information on the computer. This database could then be used to correlate thermal performance degradation to various weather conditions experienced in operation. Second, the possible use of stagnation temperature as an indicator of thermal performance change requires careful monitoring of collector temperatures to observe change. Also, the possibility of Series 4 tests being reinstated would increase the amount of continuous data required to monitor the aging process. Consequently, a data acquisition system was designed which, with a minimum of operator supervision, could monitor collector stagnation temperatures and meteorological data, as well as record data required for ASHRAE standard 93-77 efficiency tests. The system is to record data from the present instrumentation at VPI&SU solar collector test facility. At intervals as long as one week, the data is to be sent to the University's IBM 370/65 computer for permanent storage and manipulation.

Several possibilities existed for designing microprocessor-controlled devices of this type. The first considered was a dedicated system which would convert Binary Coded Decimal (BCD)

data into an ASCII (American National Standard Code for Information Interchange) code and send the codes directly to the IBM 370/165. This idea was discarded because of lack of system flexibility, expense in components, and time required to design such a device.

The design selected provides flexibility, ease of application, and minimal modifications to the instrumentation in the Solar Test Facility. Presently, the data signals from the transducers are sent to electrical integrators on a five-minute reset cycle. The voltage from the transducer is integrated into a ramp function which represents the integrated average value from the last reset. After five minutes, the average value is reset to zero and the integration started again. The peak value of the ramp for each integration is recorded on an Analogic AN2570 digital panel instrument. These panel meters latch the input signal and display the five-minute average. The meters provide three and one-half digits of display with the decimal point fixed after the second digit (i.e., the range of displayable values is ± 19.99). The AN2570 also provides a 14-bit BCD signal which corresponds to the value displayed.

A system based on the Radio Shack TRS-80 Microcomputer was selected. A schematic of the system is shown in Fig. A.1. System flexibility is achieved through software design, rather than hardware, so adaptation to different tasks is easily performed. Because only 12 readings are required once every five

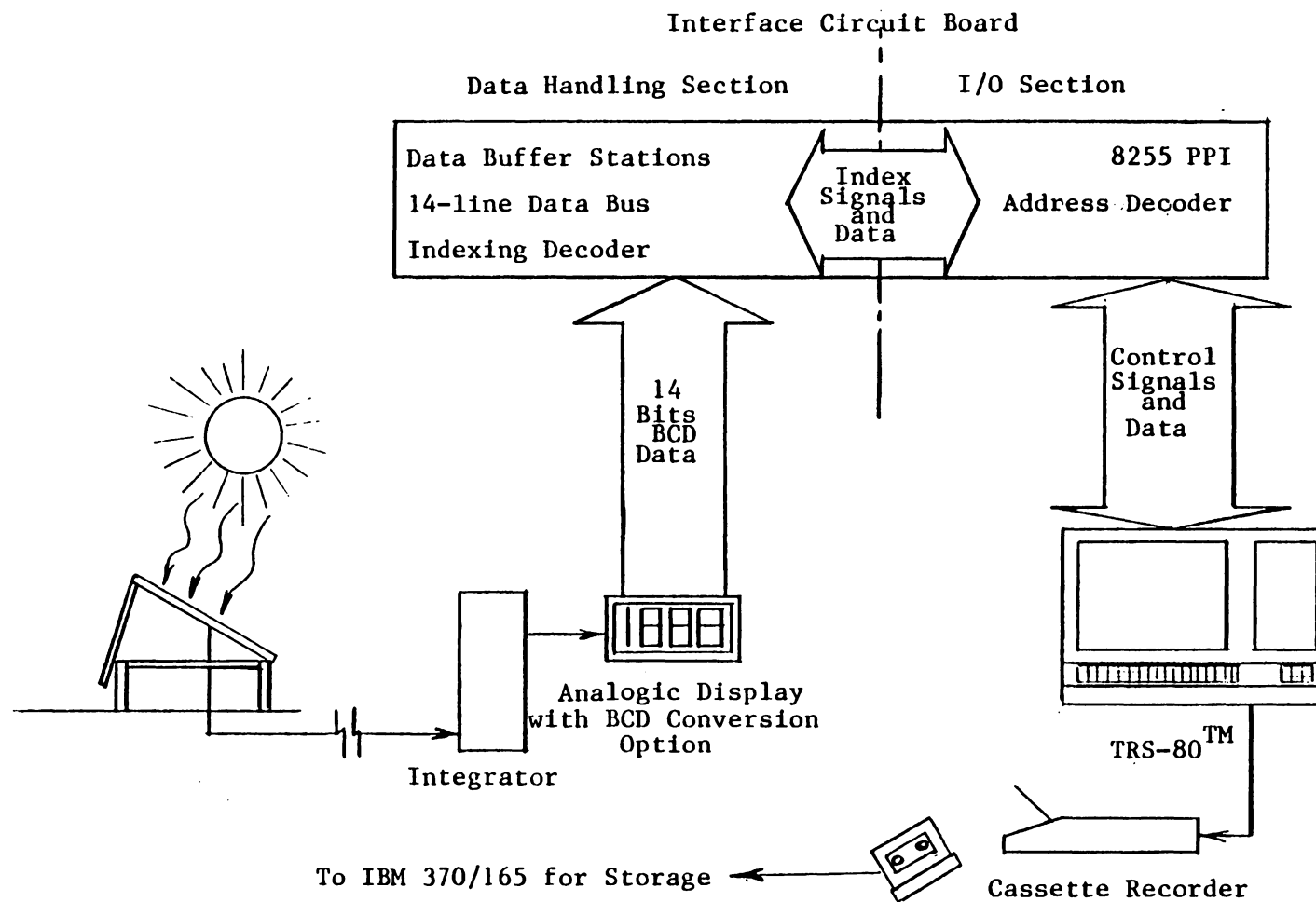


Fig. A.1. Schematic Representation of Automatic Data Logger System

minutes, the high processing speed of machine language is not necessary and all the programming can be done in BASIC. All conversion of BCD data to ASCII data and all input/output functions are controlled through software. The data is directed from the displays into the computer by a peripheral interface circuit, the heart of which is an Intel 8255 Programmable Peripheral Interface (PPI) chip. The PPI is controlled by software to provide data to the TRS-80 in a compatible format.

The peripheral interface circuit serves two major functions: (1) to latch and buffer the BCD signal from the display meters and index the readings one at a time onto a data bus and (2) transfer signals from the 14-line data bus of the interface circuit to the 8-line data bus of the TRS-80 in the proper sequence so they may be interpreted in the microcomputer. Therefore, the circuit can be divided logically into two sections, the data handling section and the Input/Output (I/O) section.

A schematic diagram of the data handling section is shown in Fig. A.2. The section has three major components. These are the decoder, the 14-line data bus, and the 12 data stations. A typical data station is shown in Fig. A.2 for simplicity. The decoder receives a four bit binary signal from the I/O section and translates it into an enable signal for one of the data stations. There is a direct correspondence between the binary code input and the data station selected. For example, if the

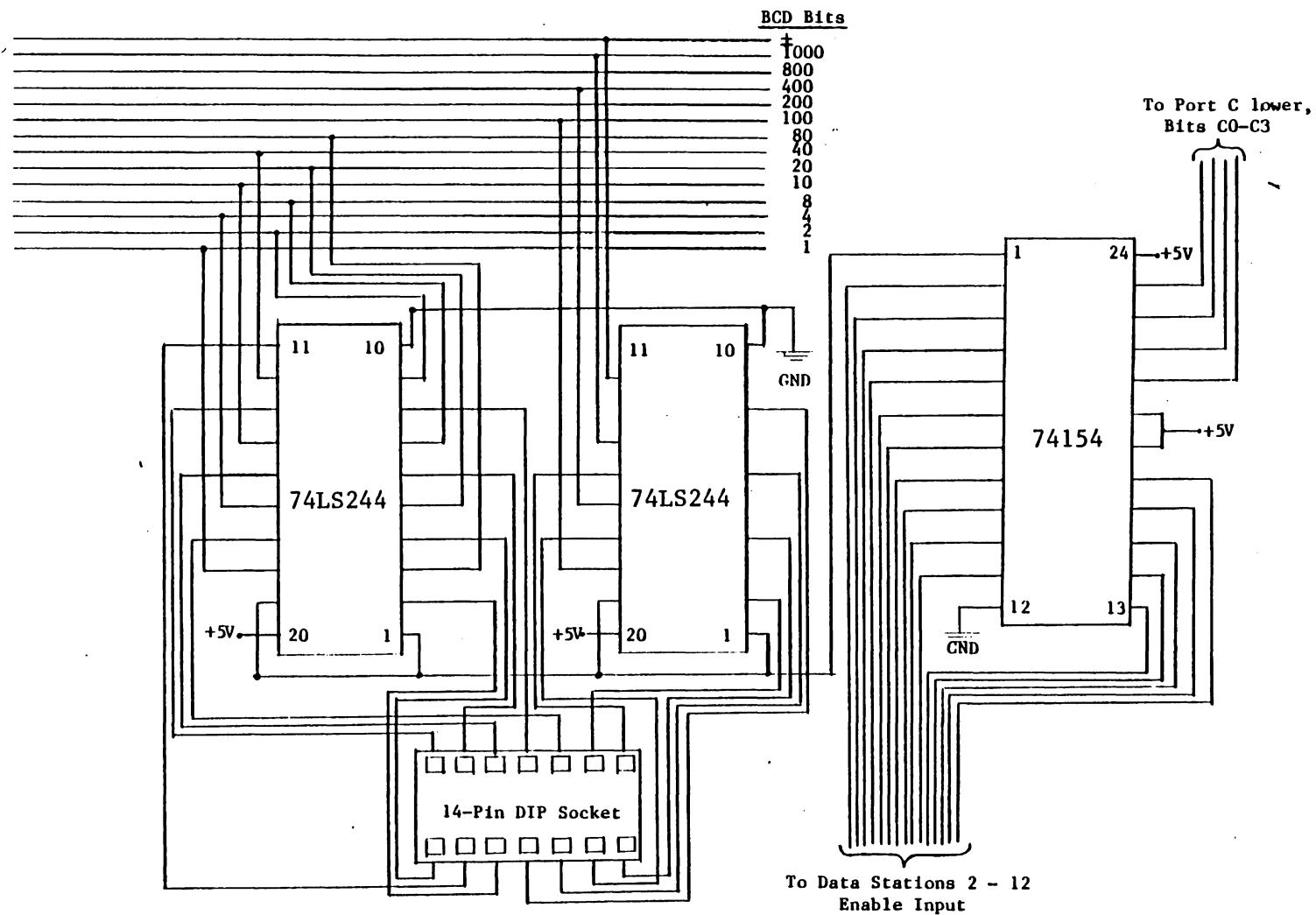


Fig. A.2. Schematic Diagram of Automatic Data Logger Data Handling Section, Including Typical Data Station and Decoder Circuit

four bits received by the decoder are 0101, the data station enabled is station number five.

The data stations provide a tristate buffer for the input signal from the display meters. The 14-bit signal is held in the two 8-bit buffers until an enable signal is received from the decoder. At that time, the tristate buffers allow all 14 bits to pass through the data station and onto the interface data bus. The signals are taken off of the data bus by the I/O section and sent to the microcomputer.

The I/O section consists of the address decoder (separate from the data station decoder) and the PPI chip. A schematic of the I/O Section is shown in Fig. A.3. The TRS-80 addresses peripheral devices through an 8-bit address bus within the microcomputer. The bits of this bus are normally referred to as bits A0-A7. Each peripheral device has a logic circuit to decode the particular address reserved for that function. The PPI chip has four addressable registers. Consequently, the address is divided into a device address using bits A2-A7 and a register address using bits A0-A1. These addresses, though discussed separately, are combined into one 8-bit binary number in the programming so that an 8-bit code which is output to lines A0 to A7 first selects the PPI (by virtue of the device address) and then a specific register (using the register address). The device address is the same for all ports within the PPI. It is chosen to be 01100000_2 , or 96_{10} . The four possible combinations



of the two Least Significant Bits (LSB) result in the register addresses shown in Table A.1. To call Port A from the software, the address called is 96_{10} in a BASIC program.

The three I/O ports in the PPI are controlled by the word output from the software to the control register in the PPI. This word is shown at the bottom of Table A.1, along with the register configuration of the I/O Ports which results. The control word is output to the PPI as part of the initialization routine in the beginning of the software. For example, the lines

```

10  CLS
20  OUT(99), 154
30  X = INP(96)
40  ---

```

in a BASIC program clear the display of the microcomputer and then output to the control register (address 99_{10}) the configuration control word (154_{10} , 10011010_2). The variable X is then set equal to the 8-bit binary number which is present at Port A (address 96_{10}).

The physical layout of the interface circuit board is shown in Fig. A.4. The schematic of the power supply is shown in Fig. A.5. The interface board and microcomputer are connected by a 50-line ribbon cable. The cable provides connections to the internal address and data busses of the microcomputer. The connections necessary between the 50-line cable and a 40-pin

Table A.1. Device Address and Control Words for
Automatic Data Logger

<u>A7</u>	<u>A6</u>	<u>A5</u>	<u>A4</u>	<u>A3</u>	<u>A2</u>	<u>A1</u>	<u>A0</u>	<u>Octal</u>	<u>Decimal</u>	<u>Register</u>
0	1	1	0	0	0	0	0	140	96	Port A
0	1	1	0	0	0	0	1	141	97	Port B
0	1	1	0	0	0	1	0	142	98	Port C
0	1	1	0	0	0	1	1	143	99	Control Register

Port C Lower will be used for output of the indexing number, 1 - 12. Port A will be used for inputting BCD bits 1-200 and Port B will be used for inputting BCD bits 400-1000 and the polarity. Therefore the Control Register must be loaded as follows

<u>D7</u>	<u>D6</u>	<u>D5</u>	<u>D4</u>	<u>D3</u>	<u>D2</u>	<u>D1</u>	<u>D0</u>	<u>Port A</u>	<u>Port B</u>	<u>Port C</u>	
1	0	0	1	1	0	1	0	Input	Input	<u>Upper</u>	<u>Lower</u>
										Input	Output

Octal -- 232
Decimal -- 154

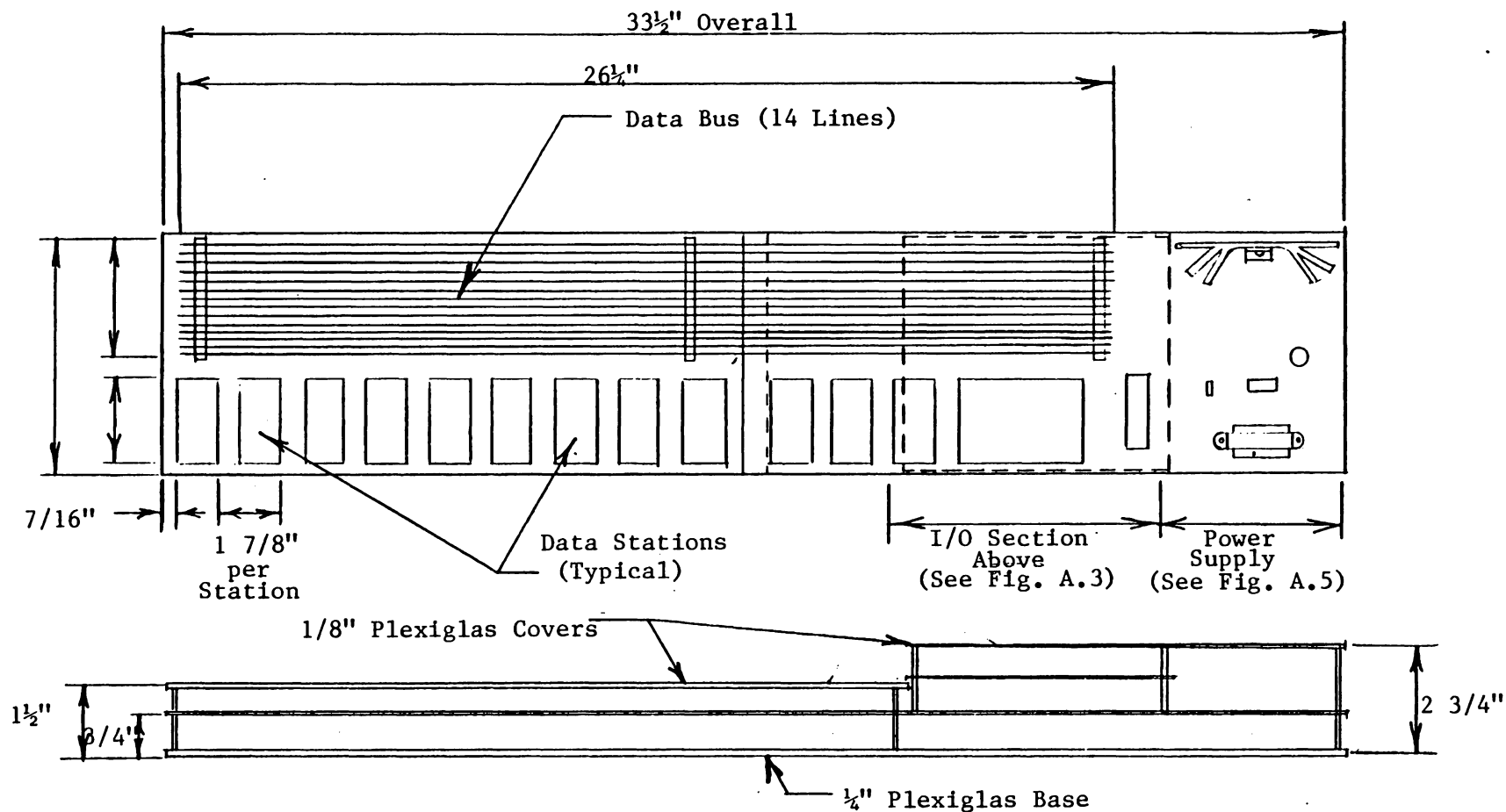


Fig. A.4. Physical Layout of Automatic Data Logger

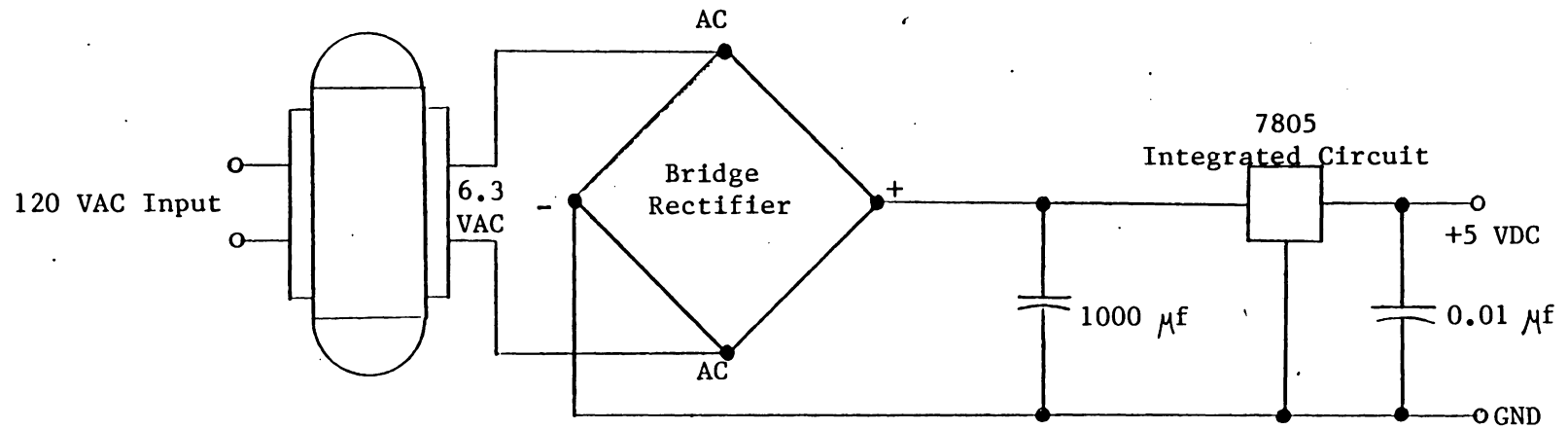


Fig. A.5. Schematic Diagram of Automatic Data Logger Power Supply

jumper header on the I/O section of the interface board are shown in Table A.2.

The logic diagram for the software is shown in Fig. A.6. This software initializes the PPI ports as shown earlier, queries the operator about the data stations to be displayed, and sets up the screen of the microcomputer so that readings may be properly interpreted. A data acquisition loop then begins. There are actually four nested loops which provide data acquisition capability. The innermost loop increments the data station decoder on the interface board and stores the values of each station in internal memory of the microcomputer. After all data stations have been read, the microcomputer goes into a delay routine for five minutes (while the integrators average the next five-minute values). After twelve cycles of this loop, one hour is completed and the program averages all the five minute data to produce an hourly average value. When 24 hourly loops have been completed, daily averages are produced and stored on cassette tape along with all of the hourly averages. The program then resets all parameters and begins taking data again for the next 24-hour period. A listing of the program is provided at the end of the Appendix.

Table A.2. Pin Connections Between TRS-80TM and Peripheral
Interface Board for Automatic Data Logger

Pin on J1	Function	Pin on J2

1	D0	40
3	D1	38
5	D2	39
7	D3	37
9	D4	35
11	D5	36
13	D6	34
15	D7	32
17	A0	30
19	A1	28
21	A2	20
23	A3	18
25	A4	16
27	A5	26
29	A6	24
31	A7	22
43	<u>EXTIOSEL</u>	7
37	<u>RESET</u>	6
35	<u>OUT</u>	13
33	<u>IN</u>	11
N/C	GND	1 and/or 2
N/C	+5	3 and/or 4

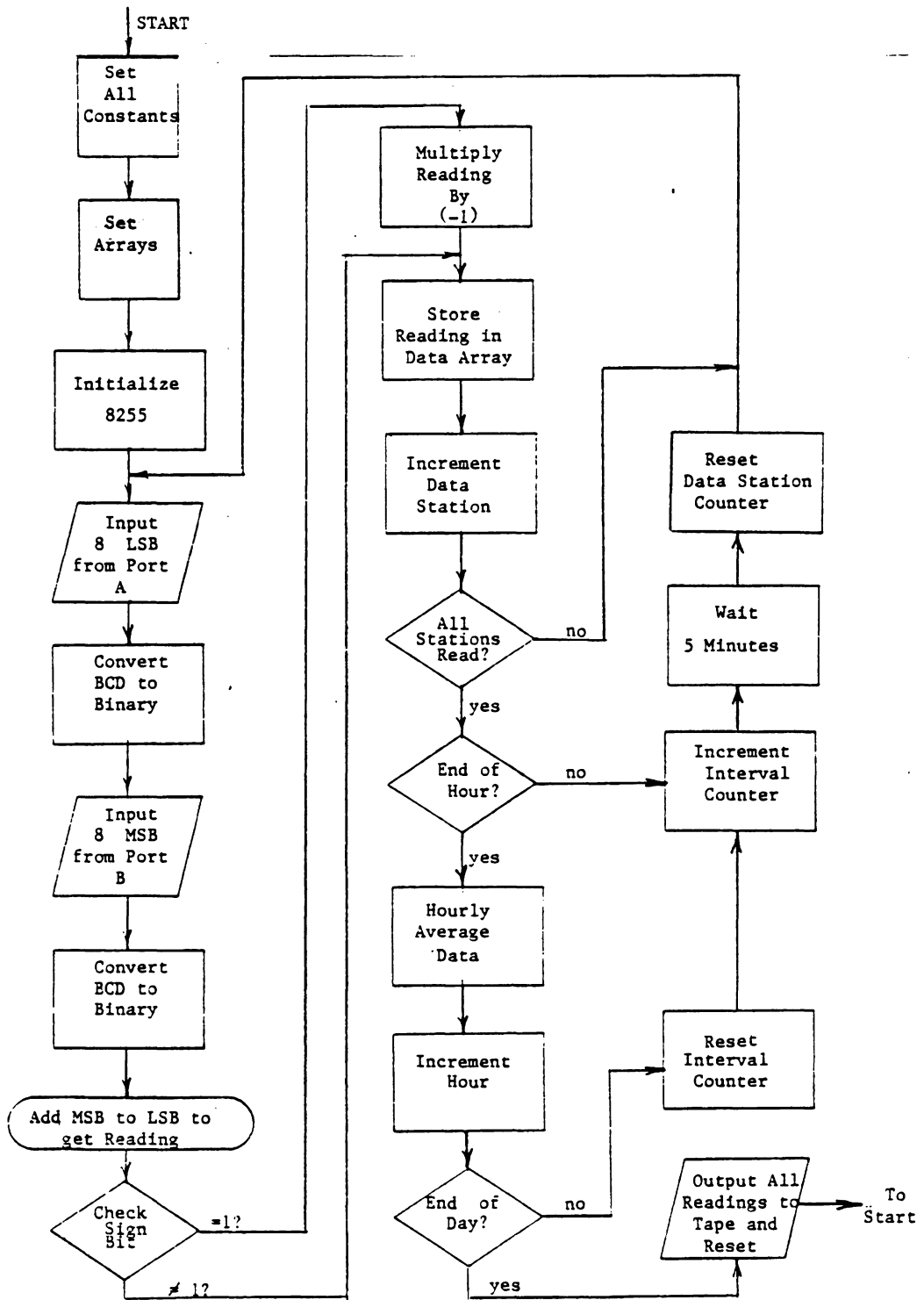


Fig. A.6. Flow Chart of Programming Logic for Automatic Data Logger

Table A.3. Program Listing for Data Logger Software

```

1 A=INP(252) OR 16
5 OUT 236,A
10 CLS:PRINT "ENTER THE DATA STATIONS YOU WOULD LIKE
  DISPLAYED"
20 INPUT "ENTER UP TO 10 STATIONS BETWEEN 1 AND 12)
  ";S1,S2,S3,S4,S5,S6,S7,S8,S9,S0
30 CLS:POKE 16916,3:PRINT @ 25,"DATA STATION"
40 A$="  %  %  #  #  #  #  #  #  #  #
  ##  ##  ##"
50 PRINT USING A$;"TIME";S1;S2;S3;S4;S5;S6;S7;S8;S9;
  S0
60 FOR I=128 TO 191:PRINT @ I,CHR$(131):NEXT I
70 E$="##  ##.## ##.## ##.## ##.## ##.## ##.##
  ##.## ##.####.##"
80 DIM D(12,13),HA(12,25),DA(12,12)
90 FOR I=0 TO 2:POKE 16919+I,0:NEXT I
100 POKE 16526,152:POKE 16527,2:X=USR(0)
110 OUT 99,154
120 S=0:HOUE=0:T=0
130 T=T+1
140 S=S+1
150 OUT 98,S
160 A=INP(95)
170 REM CONVERT LSB TO BINARY
180 GOSUB 530
190 X=A1/100+A2/10
200 E=INP(97)
210 A=INP(252) AND 239
215 OUT 236,A
220 A=(E AND 95)
230 GOSUB 530
240 X=X+A1+A2*10
250 SIGN=(E AND 32)
260 IF SIGN <> 0 THEN X=(-1)*X
270 D(S,T)=X
280 IF S >= 12 THEN GOTO 300
290 GOTO 140
300 IF T >= 12 THEN GOTO 350
310 LI=1+(3+T)*63:PRINT @ LI,CHR$(27)
320 PRINT USING E$;T,D(S1,T),D(S2,T),D(S3,T),D(S4,T),
  ,D(S5,T),D(S6,T),D(S7,T),D(S8,T),D(S9,T),D(S0,T)
330 IF FLG =1 THEN GOSUB 610:ELSE GOSUB 570
340 S=0:GOTO 130
350 POKE 16916,1:PRINT @ 64,"HOUR";CHR$(26);CHR$(26)
  :POKE 16916,3

```

Table A.3. Program Listing for Data Logger
Software (Continued)

```

360 FOR DS=1 TO 12
370 SUM=0
380 FOR TM=1 TO 12
390 SUM=SUM+D(DS, TM)
400 NEXT TM
410 HA(DS, TM)=SUM/12
420 NEXT DS
430 PRINT @ 192, CHR$(27)
440 FOR NUM=0 TO HOUR:PRINT USING B$;NUM;HA(S1, NUM),
HA(S2, NUM), HA(S3, NUM), HA(S4, NUM), HA(S5, NUM), HA(S6, NU
M), HA(S7, NUM), HA(S8, NUM), HA(S9, NUM), HA(S0, NUM)
450 NEXT NUM
460 HOUR=HOUR+1
470 IF HOUR=24 THEN GOSUB 800
480 T=0
490 POKE 16916,0:PRINT @ 0,"HOUR =":HOUR::PRINT @ 64
,"TIME":CHR$(26):CHR$(26):POKE 16916,3
500 REM
510 IF FLAG=2 THEN GOTO 90:ELSE GOTO 330
520 END
530 REM -- BCD TO BINARY CONVERSION SUBROUTINE
540 A1=(A AND 15)
550 A2=(A AND 240)/16
560 RETURN
570 REM -- DELAY SUBROUTINE
580 MIN#=MID$(TIME$,10,8)
590 TM1=VAL(MID$(MIN$,1,2)+MID$(MIN$,4,2)+MID$(MIN$,
7,2))
600 TT=TM1
610 PRINT @ 896,"IN DELAY SUBROUTINE -- START TIME "
;MIN$
620 MIN1#=MID$(TIME$,10,8)
630 TM=VAL(MID$(MIN$,1,2)+MID$(MIN$,4,2)+MID$(MIN$,7
,2))
640 T1=TM
650 IF (T1=1) AND (TT=235501) THEN GOTO 690
660 DFF=TM-TT
670 IF DFF=500 OR DFF=4500 THEN GOTO 690
680 GOTO 620
690 FLAG=1
700 TT=T1
710 RETURN
800 REM CALCULATE AND DISPLAY AND STORE DAILY AVG FO
RM HOURLY          AVG READING
810 FOR I1=1 TO 12

```

Table A.3. Program Listing for Data Logger
Software (Continued)

```
820 SUM2=0
830 FOR J1=0 TO 25
840 SUM2=SUM2+HA(I1,J1)
850 NEXT J1
860 HA(I1,25)=SUM2/24
870 NEXT I1
880 FLAG=2
890 RETURN
```

APPENDIX B

Listing of Material Property Measurements

Table B.1

ABSORBER COATINGS - SELECTIVE EXPOSURE SIDE																				
Sample	Control	DSET Absorptance				Control	FSEC Absorptance				Control	LMSC Absorptance				Control	NBS Absorptance			
		80	160	240	480		80	160	240	480		80	160	240	480		80	160	240	480
A	0.89	0.87	0.86	0.88	--	0.87	0.88	0.85	0.86	--	0.87	0.88	0.86	0.87	--	0.87	0.87	0.89	0.87	--
B	0.98	0.97	0.97	0.97	0.97	0.98	0.97	0.98	0.98	--	0.98	0.97	0.97	0.98	--	0.98	0.97	0.97	0.97	--
D	0.97	0.96	0.95	0.94	0.94	0.97	0.95	0.96	0.96	--	0.97	0.96	0.96	0.96	--	0.97	0.96	0.96	0.96	--
E	0.95	0.96	0.96	0.96	0.96	0.95	0.96	0.96	0.96	--	0.95	0.96	0.96	0.96	--	0.95	0.96	0.96	0.96	--
F	0.96	0.92	0.92	0.90	0.89	0.96	0.93	0.91	0.91	--	0.96	0.93	0.90	0.90	--	0.96	0.93	0.92	0.91	--
G	0.93	0.92	0.90	0.92	0.93	0.93	0.93	0.93	0.93	--	0.93	0.93	0.93	0.93	--	0.93	0.93	0.93	0.93	--
H	0.95	0.96	0.95	0.96	0.94	0.95	0.95	0.96	0.96	--	0.95	0.95	0.96	--	--	0.95	0.95	0.96	0.96	--
I	0.88	--	--	0.87	--	0.88	--	--	0.88	--	0.88	--	--	0.88	--	0.88	--	--	0.87	--
J	0.98	0.97	0.97	0.97	0.96	0.98	0.97	0.97	0.98	--	0.98	0.97	0.97	0.97	--	0.98	0.97	0.98	0.97	--
L	0.99	0.98	0.97	0.97	0.96	0.99	0.98	0.98	0.99	--	0.99	0.99	0.99	--	--	0.99	0.99	0.98	--	--
M	0.92	0.94	0.92	0.91	--	0.94	0.96	0.93	0.96	--	0.94	0.91	0.96	0.92	--	0.94	0.94	0.93	0.93	--
N	0.92	0.76	--	0.77	--	--	0.74	--	0.74	--	--	0.76	--	0.78	--	--	0.77	--	0.77	--
P	0.96	0.95	0.95	0.94	0.94	0.96	0.95	0.95	0.95	--	0.96	0.95	0.94	0.95	--	0.96	0.95	0.95	0.95	--

Table B.2

ABSORBER COATINGS - SELECTIVE EXPOSURE SIDE																				
Sample Control		DSET				FSEC				LMSC				NBS						
		Emittance				Emittance				Emittance				Emittance						
		80	160	240	480	Control	80	160	240	480	Control	80	160	240	480	Control	80	160	240	480
A	0.12	0.10	0.11	0.18	--	0.15	0.10	0.12	0.11	--	0.15	0.11	0.13	0.14	--	0.13	0.14	0.11	0.11	--
C	0.92	0.91	0.92	--	--	0.92	0.91	0.91	0.91	--	0.92	0.91	0.91	0.91	--	0.92	0.91	0.91	0.91	--
D	0.07	0.05	0.10	--	--	0.07	0.06	0.09	0.06	--	0.07	0.05	0.07	0.08	--	0.07	0.06	0.06	0.06	--
E	0.87	0.89	0.85	--	--	0.87	0.89	0.90	0.90	--	0.87	0.88	0.89	0.89	--	0.87	0.88	0.89	0.89	--
F	0.75	0.65	0.61	--	--	0.75	0.66	0.66	0.62	--	0.75	0.67	0.63	0.62	--	0.75	0.68	0.65	0.63	--
G	0.86	0.86	0.86	--	--	0.86	0.85	0.85	0.15	--	0.86	0.85	0.85	0.85	--	0.86	0.85	0.85	0.85	--
H	0.89	0.87	--	--	--	0.89	0.88	0.85	0.86	--	0.89	0.88	0.89	0.86	--	0.89	0.88	0.88	0.87	--
I	0.19	--	--	0.17	--	0.19	--	--	0.18	--	0.19	--	--	--	--	0.19	--	--	0.17	--
J	0.14	0.13	0.15	--	--	0.14	0.10	0.11	0.11	--	0.14	0.12	0.12	0.10	--	0.14	0.12	0.11	0.13	--
L	0.29	0.39	--	--	--	0.29	0.39	0.42	0.36	--	0.29	0.27	0.35	0.30	--	0.29	0.29	0.35	--	--
M	0.10	0.11	0.08	0.08	--	0.10	0.12	0.10	0.13	--	0.10	0.08	0.13	0.11	--	0.10	0.09	--	0.09	--
N	0.49	0.48	--	0.49	--	--	0.45	--	0.47	--	--	0.47	--	0.47	--	--	0.46	--	0.48	--
P	0.08	0.07	0.10	--	--	0.08	0.07	0.07	0.07	--	0.08	0.08	0.08	0.09	--	0.08	0.07	0.08	0.06	--

Table B.3

ABSORBER COATINGS - NON-SELECTIVE EXPOSURE SIDE																				
Sample	Control	DSET Absorptance				Control	FSEC Absorptance				Control	LMSC Absorptance				Control	NBS Absorptance			
		80	160	240	480		80	160	240	480		80	160	240	480		80	160	240	480
A	0.89	0.87	0.87	0.87	--	0.87	0.87	0.87	0.88	--	0.87	0.87	0.86	0.87	--	0.87	0.88	0.87	0.86	--
B	0.97	0.97	0.97	0.98	--	0.98	0.97	0.97	0.97	--	0.97	0.96	0.96	0.96	--	0.98	0.97	0.97	0.97	--
D	0.97	0.96	0.96	0.96	--	0.97	0.96	0.95	0.96	--	0.97	0.96	0.96	0.96	--	0.97	0.96	0.96	0.94	--
E	0.95	0.96	0.96	0.96	--	0.95	0.96	0.96	0.96	--	0.95	0.96	0.96	0.96	--	0.95	0.96	0.96	0.96	--
F	0.96	0.93	0.93	0.93	--	0.96	0.93	0.92	0.93	--	0.96	0.93	0.92	0.93	--	0.96	0.94	0.93	0.93	--
G	0.93	0.92	0.93	0.92	--	0.93	0.93	0.93	0.93	--	0.93	0.93	0.93	0.93	--	0.93	0.93	0.93	0.93	--
H	0.95	0.96	0.95	0.96	--	0.95	0.95	0.95	0.96	--	0.95	0.95	0.95	--	--	0.95	0.95	0.95	0.95	--
I	0.88	--	--	--	--	0.88	--	--	--	--	0.88	--	--	--	--	0.88	--	--	--	--
J	0.98	--	--	--	--	0.98	0.97	--	--	--	0.98	--	--	--	--	0.98	--	--	--	--
L	0.99	0.99	0.99	0.99	--	0.99	0.98	0.97	0.97	--	0.99	0.99	0.98	--	--	0.99	0.98	0.98	0.98	--
M	--	0.91	0.95	0.95	--	--	0.94	0.91	0.92	--	--	0.96	0.94	0.94	--	--	0.95	0.95	0.94	--
N	--	--	--	0.77	--	--	--	--	0.75	--	--	--	--	0.78	--	--	--	--	0.78	--
P	0.96	0.95	0.95	0.95	--	0.96	0.95	0.95	0.96	--	0.96	0.96	0.95	0.95	--	0.96	0.95	0.95	0.95	--

Table B.4

ABSORBER COATINGS - SELECTIVE EXPOSURE SIDE																				
Sample	Control	DSET				Control	FSEC				Control	LMSC				Control	NBS			
		Absorptance	80	160	240		480	Absorptance	80	160		240	480	Absorptance	80		160	240	480	Absorptance
A	--	0.14	0.11	0.11	--	--	0.14	0.10	0.13	--	0.15	0.14	0.14	0.15	--	--	0.11	0.11	0.10	--
B	0.92	0.91	0.91	0.91	--	0.92	0.91	0.91	0.91	--	0.92	0.91	0.91	0.90	--	0.92	0.91	0.91	0.91	--
D	0.07	0.09	0.07	0.06	--	0.07	0.07	0.05	0.06	--	0.07	0.07	0.06	0.08	--	0.07	0.06	0.06	0.06	--
E	0.87	0.88	0.89	0.89	--	0.87	0.87	0.89	0.89	--	0.87	0.87	0.89	0.89	--	0.87	0.87	0.89	0.89	--
F	0.75	0.66	0.66	0.66	--	0.75	0.66	0.65	0.66	--	0.75	0.67	0.66	0.67	--	0.75	0.68	0.67	0.67	--
G	0.86	0.85	0.85	0.85	--	0.86	0.85	0.85	0.85	--	0.86	0.85	0.85	0.85	--	0.86	0.85	0.85	0.85	--
H	0.89	0.88	0.88	0.88	--	0.89	0.88	0.88	0.88	--	0.89	0.88	0.88	0.88	--	0.89	0.88	0.88	0.88	--
I	0.19	--	--	--	--	0.19	--	--	--	--	0.19	--	--	--	--	0.19	--	--	--	--
J	0.14	--	--	--	--	0.14	--	--	--	--	0.14	--	--	--	--	0.14	--	--	--	--
L	0.29	0.29	0.32	0.31	--	0.29	0.44	0.42	0.46	--	0.29	0.33	0.38	0.34	--	0.29	0.32	0.30	0.30	--
M	--	0.08	0.11	0.10	--	--	0.10	0.08	0.09	--	--	0.13	0.12	0.11	--	--	0.11	0.10	0.09	--
N	--	--	--	0.49	--	--	--	--	0.46	--	--	--	--	0.48	--	--	--	--	0.47	--
P	0.08	0.07	0.07	0.07	--	0.08	0.07	0.08	0.07	--	0.08	0.07	0.07	0.09	--	0.08	0.07	0.07	0.07	--

Table B.5

ABSORBER COATINGS - TEMPERATURE EXPOSURE																
Sample	150 C								175 C							
	Control	Absorptance			Control	Emittance			Control	Absorptance			Control	Emittance		
		500	1000	2000		500	1000	2000		500	1000	2000		500	1000	2000
A	--	0.86	0.86	0.86	--	0.13	0.09	0.13	--	0.88	0.87	0.91	--	0.13	0.13	0.12
C	--	--	0.97	0.97	--	--	0.91	0.92	0.97	--	0.95	0.96	0.07	--	0.07	0.07
D	0.97	--	0.96	0.96	--	--	0.06	0.06	0.97	--	0.95	0.96	0.07	--	0.07	0.07
E	0.95	--	0.96	0.96	--	--	0.86	0.87	0.95	--	0.96	0.96	0.87	--	0.89	0.89
F	0.96	--	0.91	0.90	--	--	0.66	0.65	0.96	--	0.89	0.89	0.75	--	0.67	0.70
G	0.93	--	0.93	0.93	--	--	0.85	0.85	0.93	--	0.94	0.95	0.86	--	0.86	0.82
H	0.95	--	0.96	0.96	--	--	0.88	0.88	0.95	--	0.95	0.95	0.89	--	0.88	0.87
I	0.88	--	--	--	--	--	--	--	0.88	--	0.87	--	0.19	--	0.18	--
J	0.98	--	0.98	0.98	--	--	0.12	0.12	0.98	--	0.97	0.97	0.14	--	0.13	0.13
L	0.99	--	0.99	0.99	--	--	0.37	0.35	0.99	--	0.98	0.99	0.29	--	0.41	0.38
M	--	0.94	0.95	0.91	--	0.10	0.12	0.08	--	0.93	0.93	0.92	--	0.09	0.12	0.12
N	--	--	0.85	--	--	--	0.49	--	--	--	0.80	--	--	--	0.50	--
P	0.96	--	0.95	0.95	--	--	0.07	0.06	0.96	--	0.95	0.95	0.08	--	0.10	0.08

Table B.6

Sample	ABSORBER COATINGS															
	Temperature and Humidity, 90 C and 95 Percent RH								Temperature and Radiation, 90 C and Xenon Arc Lamp							
	Absorptance				Emittance				Absorptance				Emittance			
	Control	500	1000	2000	Control	500	1000	2000	Control	500	1000	2000	Control	500	1000	2000
A	--	--	0.73	0.84	--	--	0.70	0.53	--	--	0.86	0.87	--	--	0.10	0.11
C	0.98	--	0.97	0.97	0.92	--	0.91	0.91	0.97	--	0.96	0.96	0.92	--	0.91	0.91
D	0.97	--	0.95	0.95	0.07	--	0.13	0.19	0.97	--	0.96	0.96	0.07	--	0.06	0.06
E	0.95	--	0.92	0.92	0.87	--	0.88	0.89	0.95	--	0.96	0.97	0.87	--	0.89	0.89
F	0.96	--	0.93	0.93	0.75	--	0.76	0.77	0.96	--	0.90	0.89	0.75	--	0.73	0.71
G	0.93	--	0.94	0.93	0.86	--	0.89	0.87	0.93	--	0.94	0.94	0.86	--	0.86	0.86
H	0.95	--	0.94	0.94	0.89	--	0.90	0.90	0.95	--	0.95	0.96	0.89	--	0.87	0.87
I	0.88	--	0.88	--	0.19	--	0.17	--	0.88	--	0.85	--	0.19	--	0.15	--
J	0.98	--	0.96	0.96	0.14	--	0.22	0.26	0.98	--	0.98	0.98	0.14	--	0.12	0.11
L	0.99	--	0.85	0.81	0.29	--	0.81	0.85	0.99	--	0.98	0.90	0.29	--	0.37	0.39
M	--	--	0.59	0.54	--	--	0.62	0.65	--	--	0.94	0.95	--	--	0.10	0.11
N	0.92	--	0.50	--	0.49	--	0.81	--	0.92	--	0.79	--	0.49	--	0.45	--
P	0.96	--	0.95	0.95	0.08	--	0.12	0.14	0.96	--	0.95	0.96	0.08	--	0.11	0.32

Table B.7

Sample	ABSORBER COATINGS							
	Thermal Cycling (Simulated Daily Cycles)							
	Absorptance				Emittance			
	Control	5	15	30	Control	5	15	30
A	--	--	0.87	0.87	--	--	0.16	0.25
C	0.98	--	0.97	0.97	0.92	--	0.91	0.91
D	0.97	--	0.95	0.96	0.07	--	0.06	0.06
E	0.95	--	0.96	0.96	0.87	--	0.86	0.85
F	0.96	--	0.91	0.91	0.75	--	0.64	0.65
G	0.93	--	0.92	0.93	0.86	--	0.85	0.85
H	0.95	--	0.95	0.95	0.89	--	0.88	0.88
I	0.88	--	0.88	--	0.19	--	0.17	--
J	0.98	--	0.97	0.97	0.14	--	0.16	0.12
L	0.99	--	0.95	0.94	0.29	--	0.45	0.43
M	--	--	--	0.94	--	--	--	0.14
N	--	--	--	--	--	--	--	--
P	0.96	--	0.95	0.95	0.08	--	0.09	0.09

Table B.8

ABSORBER COATINGS - ACCELERATED OUTDOOR																
Sample	Sample 1								Sample 2							
	Control	Absorptance			Control	Emittance			Control	Absorptance			Control	Emittance		
		36	60	120		36	60	120		36	60	120		36	60	120
A	0.87	0.87	0.87	0.88	0.15	--	--	--	0.87	0.87	0.87	0.86	0.14	--	--	0.12
C	--	0.96	0.97	0.97	--	--	--	--	0.97	0.97	0.98	0.97	--	--	--	--
D	--	0.96	0.97	0.97	--	--	--	--	0.96	0.95	0.95	0.94	--	--	--	--
E	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
F	--	0.95	0.92	0.88	--	--	--	--	0.94	0.91	0.91	0.91	--	--	--	--
G	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
H	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
I	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
J	--	0.97	0.97	0.96	--	--	--	--	0.97	0.97	0.97	0.96	--	--	--	--
L	--	0.97	0.97	0.95	--	--	--	--	0.97	0.97	0.97	0.96	--	--	--	--
M	--	0.93	0.94	0.93	0.11	--	--	--	0.94	0.94	0.94	0.93	0.49	--	--	--
N	0.92	0.78	0.77	0.73	0.49	--	--	--	0.91	0.78	0.76	0.74	--	--	--	--
P	--	0.95	0.95	0.94	--	--	--	--	0.94	.94	0.94	0.94	--	--	--	--

Table B.9

ABSORBER COATINGS - SOLAR SIMULATOR																
Sample	Selective Side								Non-Selective Side							
	Control	Absorptance			Control	Emittance			Control	Absorptance			Control	Emittance		
		30	60	120			30	60	120		30	60		120		30
A	--	--	0.87	0.87	--	--	0.10	0.22	--	0.87	0.87	0.86	--	0.12	0.11	0.10
C	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
D	0.95	0.96	0.96	0.96	0.07	0.06	0.06	0.06	0.97	0.97	0.96	0.95	0.07	0.06	0.06	0.06
E	--	--	--	--	--	--	--	--	--	0.96	0.96	--	--	0.86	0.87	--
F	--	0.93	0.92	0.91	--	0.68	0.68	0.69	--	0.94	0.93	--	--	0.71	0.68	--
G	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
H	0.95	0.96	0.96	0.96	0.88	0.87	0.87	0.87	--	0.96	0.96	0.96	--	0.86	0.86	0.86
I	--	--	--	0.88	--	--	--	0.17	--	--	--	--	--	--	--	--
J	--	0.98	0.97	0.98	--	0.12	0.11	0.12	--	0.97	0.98	0.98	--	0.13	0.13	0.12
L	0.98	0.98	0.98	0.98	0.35	0.52	0.56	0.62	--	--	--	--	--	--	--	--
M	--	--	0.94	0.91	--	--	0.11	0.08	--	0.91	0.91	0.94	--	0.09	0.08	0.10
N	--	0.77	0.77	0.77	--	0.48	0.48	0.48	0.45	--	--	--	--	--	--	--
P	--	--	0.96	0.95	--	--	0.07	0.08	--	--	--	--	--	--	--	--

Table B.10

COVER SAMPLES - ACCELERATED OUTDOOR																
Sample	Sample 1, Mini-box				Sample 2, Mini-box				Sample 1, Board Mount				Sample 2, Board Mount			
	Control	36	60	120	Control	36	60	120	Control	36	60	120	Control	36	60	120
E	--	0.83	0.84	0.88	--	0.83	0.83	0.83	--	0.82	0.85	0.83	0.83	0.83	0.87	0.86
G	--	0.83	0.83	0.78	--	0.81	0.82	0.74	--	0.82	0.83	0.82	0.84	0.81	0.83	0.83
H	--	0.84	0.85	0.71	--	0.84	0.85	0.81	--	0.84	0.85	0.86	0.85	0.84	0.86	0.86
J	--	0.86	0.86	0.84	--	0.84	0.86	0.85	--	0.86	0.87	0.86	0.87	0.85	0.87	0.86
L	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
M	--	0.77	0.79	0.76	--	0.81	0.79	0.80	--	0.82	0.82	0.80	0.82	0.80	0.81	0.82
N	--	0.89	0.89	0.89	--	0.89	0.89	0.89	--	0.89	0.89	0.89	0.91	0.89	0.88	0.88

Table B.11

COVER SAMPLES - TEMPERATURE EXPOSURE												
Sample	70 C				90 C				125 C			
	Control	Transmittance			Control	Transmittance			Control	Transmittance		
		500	1000	2000		500	1000	2000		500	1000	2000
E	--	0.83	0.85	0.81	--	0.84	0.84	0.82	--	0.82	0.81	0.79
G	--	0.82	0.80	0.79	--	0.73	0.73	0.78	--	0.70	0.66	0.64
H	--	0.84	0.85	0.84	--	0.84	0.84	0.85	--	0.85	0.85	0.84
J	--	0.87	0.87	0.87	--	0.87	0.87	0.87	--	0.87	0.87	0.86
L	--	0.83	0.81	0.83	--	0.83	0.80	0.83	--	0.81	0.80	0.80
M	--	0.81	0.79	0.80	--	0.75	0.64	0.66	--	0.68	0.63	0.55
N	--	0.89	0.90	0.90	--	0.90	0.90	0.89	--	0.89	0.90	0.91

Table B.12

COVER SAMPLES - TEMPERATURE AND HUMIDITY												
Sample	50C and 95% RH Transmittance				70C and 95% RH Transmittance				90 C and 95% RH Transmittance			
	Control	500	1000	2000	Control	500	1000	2000	Control	500	1000	2000
E	--	--	--	--	--	0.72	0.64	--	--	0.50	0.46	0.30
G	--	--	--	--	--	0.15	0.13	--	--	0.10	0.08	0.07
H	--	--	--	--	--	0.85	0.85	--	--	0.84	0.83	--
J	--	--	--	--	--	0.87	0.87	--	--	0.86	0.84	0.74
L	--	--	--	--	--	0.54	0.51	--	--	0.31	0.25	0.21
M	--	--	--	--	--	0.35	0.31	--	--	0.24	0.23	0.18
N	--	--	--	--	--	0.88	0.89	--	--	0.76	0.82	0.64

Table B.13

COVER SAMPLES - TEMPERATURE AND RADIATION								
Sample	70C and Xenon Arc Transmittance				90C and Xenon Arc Transmittance			
	Control	500	1000	2000	Control	500	1000	2000
E	--	0.85	0.85	0.84	--	0.78	0.79	0.77
G	--	0.80	0.78	0.81	--	0.78	0.78	0.74
H	--	0.85	0.85	0.85	--	0.86	0.86	0.85
J	--	0.86	0.86	0.86	--	0.85	0.85	0.84
L	--	0.82	0.84	0.83	--	0.83	0.83	0.80
M	--	0.79	0.78	0.80	--	0.74	0.73	0.70
N	--	0.89	0.89	0.90	--	0.89	0.88	0.88
O	--	0.91	0.92	0.92	--	0.91	0.96	0.88

Table B.14

COVER SAMPLES - ACTUAL OUTDOOR

Sample	Control	DSET Transmittance				Control	FSEC Transmittance				Control	LMSC Transmittance				Control	NBS Transmittance			
		80	160	240	480		80	160	240	480		80	160	240	480		80	160	240	480
E	--	0.83	0.83	0.80	0.84	--	0.84	0.81	0.81	0.83	--	0.85	0.82	0.80	--	--	0.82	0.81	0.80	--
G	--	0.80	0.80	0.83	0.62	--	0.81	0.79	0.79	0.63	--	0.81	0.80	0.80	--	--	0.82	0.80	0.80	--
H	--	0.85	0.85	0.85	0.88	--	0.84	0.85	0.85	0.79	--	0.84	0.85	0.83	--	--	0.84	0.86	0.87	--
J	--	0.87	0.86	0.86	0.85	--	0.85	0.85	0.84	0.84	--	0.84	0.85	0.83	--	--	0.86	0.86	0.85	--
K	--	0.89	0.90	0.90	0.90	--	0.90	0.90	0.84	0.90	--	0.90	0.89	0.91	--	--	0.90	0.90	0.90	--
L	--	0.83	0.83	0.83	0.84	--	--	--	--	0.84	--	8.84	0.85	0.85	--	--	0.84	0.84	0.82	--
M	--	0.80	0.74	0.78	0.78	--	0.78	0.77	0.73	0.75	--	0.80	0.81	0.74	--	--	0.74	0.75	0.76	--
N	--	0.89	0.88	0.89	0.89	--	0.88	0.88	0.88	0.90	--	0.89	0.89	0.88	--	--	0.89	0.89	0.89	--
O	--	0.89	--	--	0.89	--	--	--	--	0.89	--	--	--	--	--	--	--	--	--	--

Table B.15

COVER SAMPLES - SOLAR SIMULATOR								
Sample	Control	Xenon Arc Transmittance			Control	Tungsten Arc Transmittance		
		30	60	120		30	60	120
E	--	0.52	0.74	0.84	--	--	0.77	--
G	--	--	--	--	--	--	--	--
H	--	0.78	0.74	0.86	--	--	0.85	--
J	--	0.76	0.71	0.85	--	0.87	0.87	--
K	--	0.64	0.77	0.91	--	0.92	--	--
L	--	--	--	--	--	--	0.83	--
M	--	0.26	0.36	0.74	--	--	--	--
N	--	0.78	0.73	0.86	--	0.90	--	--
O	--	--	--	--	--	--	0.92	--

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THE EFFECTS OF MATERIAL PROPERTY CHANGES
ON SIMILAR COLLECTOR THERMAL PERFORMANCE

by

Mark Alan Monroe

(ABSTRACT)

Data taken during the National Bureau of Standards Durability/Reliability (NBS D/R) Program is analyzed in depth in this report. The main thrust of the analysis is to develop methods of relating material property changes to full scale collector efficiency changes after exposure to environmental and operational conditions. To this end, results of material sample and full scale collector tests are discussed separately and then related to each other. Many of the materials tested showed no measurable change in optical properties after 480 days of exposure. Therefore, the results of six representative samples which span the range of responses observed are presented in detail. Next, a mathematical model of collector thermal performance is used to show the theoretical dependence of efficiency on property values. Actual degradation measurements of three typical collectors in the NBS D/R Program are presented. These measurements, based on ASHRAE standard 93-77 tests, show degradation between 0 and 4 percent of the original value of efficiency. Also presented is an analysis of the stagnation temperature variation with exposure time. No conclusive data resulted from

the stagnation temperature analysis. Finally, the mathematical model is used with results from the material tests to predict the change in efficiency. The predictions are always within ± 3 percent of the measured 480-day efficiency. Error is estimated to be a result of uncertainty in insulation conductivity values used and other unexplained sources of error.