INVESTIGATION OF PERFORMANCE DEGRADATION AND TEST METHODS FOR FLAT-PLATE SOLAR COLLECTORS

by

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NOMENCLATURE

A_a = transparent frontal area of a flat plate collector (aperture area), sq m

A_g = surface area of collector, sq m

C_p = specific heat of the transfer fluid, kJ/kg-C

F_R = heat removal factor, dimensionless

H_T = total solar radiation incident in the aperture plane of the collector, W/sq m-C

$\dot{m}$ = mass flow rate of the transfer fluid, kg/s

$\dot{q}''_u$ = rate of useful energy extraction per unit aperture area of collector, W/sq m-C

t_a = ambient air temperature, C

t_e = temperature of transfer fluid leaving the collector, C

t_i = temperature of transfer fluid entering the collector, C

t_{pm} = average temperature of the absorber plate, C

U_L = overall heat loss coefficient, W/sq m-C

U_{top} = collector top less coefficient, W/sq m-C

α = absorptance of the absorber plate for solar radiation, dimensionless

ε = emittance of the absorber plate for long-wave radiation, dimensionless

η = collector efficiency, per cent

θ = time, days

σ = standard deviation, units/measurement

τ = transmittance of the cover for solar radiation, dimensionless

Chapter 1

Introduction

1.1 General Background

In order to support the development of a large scale commercial market for flat-plate solar collectors, long term reliability and durability must be demonstrated. Collectors should have long lifetimes (in excess of 20 years) with minimal performance degradation. While application of current flat-plate collector theory has resulted in collectors which compete favorably with conventional energy systems in many applications, the economic feasibility is dictated by the life-cycle cost/benefit ratio. As such, there is a need for information concerning collector life-cycle performance characteristics.

At present, there is little accurate performance data from collectors which have been in service for an extended period of time. Of the data available, there is evidence that significant performance degradation with service time may be expected. Decreases in thermal efficiency of nearly 30 percent have been reported for collectors in operation for 18 years [1]. Because of the limited long term performance data available for flat-plate collectors, there is a need for the development of accelerated life-cycle test procedures.

Development of an accelerated test procedure for collectors would have several favorable consequences in the advancement of the solar industry. Obviously, an accelerated test procedure would provide

additional long term performance information on which to base an assessment of economic feasibility. The results of an accelerated test procedure could be used as a basis for comparison of different collector models. Perhaps more importantly, the development of such a procedure would serve to enhance current collector theory by taking into account the long term reliability associated with various collector designs and component materials. Information acquired from research into the mechanisms of performance degradation may help to identify potential long term problems in collector design and construction.

Performance degradation can take place in any of the three major components of a flat-plate collector. Cover materials, absorber materials, and insulations each must maintain specific properties to assure reliable thermal and optical performance of the collector assembly. Cover materials should maintain a high transmittance for short wave (solar) radiation and a low transmittance for the infrared spectrum. Covers should not discolor or experience mechanical deformations which might cause seals to separate. The cover assembly should have the structural integrity to resist damage from impact (as with hail or vandalism), thermal cycling, and thermal shock (as when cold rain strikes a hot collector). Absorber materials and selective surfaces must sustain a high absorptivity for radiation in the solar spectrum, while maintaining a low emissivity value for longer wavelengths. Absorber coatings should remain integral to the base material to which they are applied. Surface treatments should maintain the properties for which they were designed. Additionally, absorber plates should resist

corrosion both in internal fluid passages and on the absorbing surface. Insulating material ought to retain a low thermal conductivity. Fibers or resins used as binders should not cause outgassing and should not adversely affect the optical properties of the collector assembly.

Each of these component properties are subject to degradation from several possible causes. Accumulative levels of solar irradiance have long been suspected as a major factor in collector performance degradation. Prolonged exposure to ultraviolet radiation is suspected to be a cause of degradation of optical properties such as transmittance and absorptivity for plastic-based materials. Atmospheric pollutants may also affect the cover transmittance and promote corrosion of metals. Further evidence indicates that elevated absorber plate temperatures, as occurs under stagnation conditions, may be a primary factor in overall performance decline.

Established methods have been commonly accepted to evaluate the performance of several of the component materials used in collector construction; however, these tests were not devised to evaluate material properties specifically for solar applications. Most test methods originate from specifications developed primarily for building and construction materials. While generally accurate methods exist for testing component material performance, few accelerated test methods for long term property evaluation have been established. It has not yet been demonstrated that the property changes in material samples may be correlated with long term performance changes in the overall collector

assembly. At the present time, there is no widely accepted accelerated test procedure for flat-plate collectors.

The currently accepted method of evaluating collector performance is the ASHRAE 93-77 standard, "Methods of Testing to Determine the Thermal Performance of Solar Collectors." This standard provides a detailed procedure for the determination of collector efficiency curves under specified test conditions. The approach used in this procedure is to measure the actual thermal output of the collector assembly in order to determine the fraction of incident solar energy that is collected. This test procedure only provides an evaluation of the collector performance at the time of the test. It does not provide information as to the long term performance of the collector. However, the procedure does provide a standard performance test method, the results of which may be used in comparing different collector models. At present, the only widely accepted method for determining performance degradation is to evaluate the thermal performance by successive applications of ASHRAE 93-77 at appropriate intervals of cumulative exposure. In addition to successive applications of the ASHRAE standard, there are test procedures under development which estimate collector performance degradation by monitoring the absorber plate temperature distribution under stagnation conditions at various intervals of cumulative exposure [2]. These latter methods are still under investigation and are not yet widely accepted.

Recognizing the need for development of an accelerated test procedure, the "Solar Collector Durability/Reliability Test Program" has

been sponsored by the National Bureau of Standards with funding from the United States Department of Energy [3]. In this program eight different commercial brands of flat-plate solar collectors were tested at outdoor test facilities and by use of indoor solar irradiance simulators. The program has been designed to facilitate investigation of performance degradation of collectors subjected to low flow rate and stagnation conditions over a period of approximately three years.

Several objectives were established for the Durability/Reliability Test Program. Unique design aspects of several of the commercial collectors are to be examined. A primary objective of the program is to identify the relevant degradation mechanisms which take place with prolonged exposure. If these mechanisms can be identified, attempts will be made to devise an accelerated test procedure for determining long term thermal performance. In the attempt to identify relevant degradation mechanisms, tests were performed on collector component material specimens as well as complete collector assemblies. Both entire collectors and the sample material specimens were exposed to indoor simulated solar exposure and actual outdoor exposure environments. Material samples were exposed under conditions similar to those experienced by entire collector assemblies in order to determine the correlation of the sample degradation with changes in performance of the complete collector assemblies. Tests were also performed to determine the effects of thermal shock and moisture penetration on collector performance. Solar simulators were employed (in addition to outdoor

exposure) to determine if the results from simulator testing can be correlated to actual exposure conditions.

The effects of differing climatic exposure environment has also been considered in the development of the Durability/Reliability Test Program. Test sites were chosen in four differing climatic regions of the United States to determine the influence of exposure environment on performance degradation. Particular characteristics of each of these regions as well as the rationale for their selection are presented in Chapter 2.

1.2 Scope of Investigation

The current investigation is concerned with an examination of the results reported in the NBS Durability/Reliability Test Program. This analysis emphasizes the results of outdoor tests performed on complete collector assemblies. Additional studies have been carried out to examine the results of material sample tests and to correlate material sample results to complete collector performance changes [4,10]. The present analysis is an examination of experimental results of tests performed under the direction of the National Bureau of Standards. Consequently, the procedures and methods followed in the testing phase were beyond the control of the present author.

In the analysis which follows, the results of the test program are examined to determine the extent of performance degradation experienced by collectors after prolonged exposure. An attempt is made to correlate the degradation of primary performance parameters with cumulative

exposure levels. The results of collector efficiency tests are examined for general trends as well as trends associated with particular exposure environments and test series.

Several facets of the test program and experimental facilities used are examined to determine effects of each on the reported results. Experimental instrumentation is examined to determine if variations in the reported results may be attributable to a particular apparatus. A weather compensation method is discussed and used to determine the effect of the test environment conditions on the reported results of each test. Finally, statistical approaches are used to determine if significant interlaboratory differences in the implementation of the test procedure have occurred.

Chapter 2

Background and Literature Review

This chapter is presented in order to review the basic principles of collector efficiency modeling and evaluation, and to provide a synopsis of current publications relating to this investigation. An overview of the "NBS Solar Collector Durability/Reliability Test Program" is presented in order to establish the context in which data was acquired. The literature review contains discussions of current publications on testing of component material performance degradation, collector performance degradation examinations which have been performed or are currently being planned, and methods of analysis of inter-laboratory test data.

2.1 Overview of the Solar Collector Durability/Reliability Test Program

The D/R Test Program is a result of Public Law 93-409, "Solar Heating and Cooling Demonstration Act of 1974." This act provides for the development of definitive performance criteria and standard testing methods for use by industry in evaluating materials, components, and systems. The program plan [3] was initiated in 1977 and actual outdoor testing began in 1978. The results of the outdoor testing aspect of this program, completed in 1982, are the object of the current investigation. As such, the subsequent sections outline the following aspects of the program relevant to outdoor testing performed.

2.1.1 Test Specimen Selection. Eight commercially available, liquid, flat-plate solar collectors have been selected for evaluation. These collectors have been chosen as being representative of commonly used materials and configurations. Figure 1 shows a typical cross section of a commercial collector. As shown in Fig. 1, the typical collector construction consists of a metal absorber plate with bonded or stitch welded fluid passages encased in insulation and covered with a transparent material. Table 1 provides a general description of the materials used in the eight collectors (collector designations A through H). Seven of the collectors (A through G) are configured in a parallel flow arrangement. Collector H has a serpentine flow pattern. Other unique design features include a convection suppression baffle in Collector C and a domed, fiber reinforced outer cover on Collector G. A complete specification of the construction materials used and the design configurations employed for each collector are provided in reference 3.

For purposes of identification, a collector code has been devised to specify the collector brand (letter designations A through H), the test site at which the collector was exposed (sites numbered 1 through 4), and the specific test series which the collector underwent (test series numbered 1 through 4). This identification code is specified as follows:

Collector brand - test site - test series

For example, collector A-3-1 is a model A collector, tested at site 3, and undergoing test series 1. This identification scheme has been used throughout the current investigation.

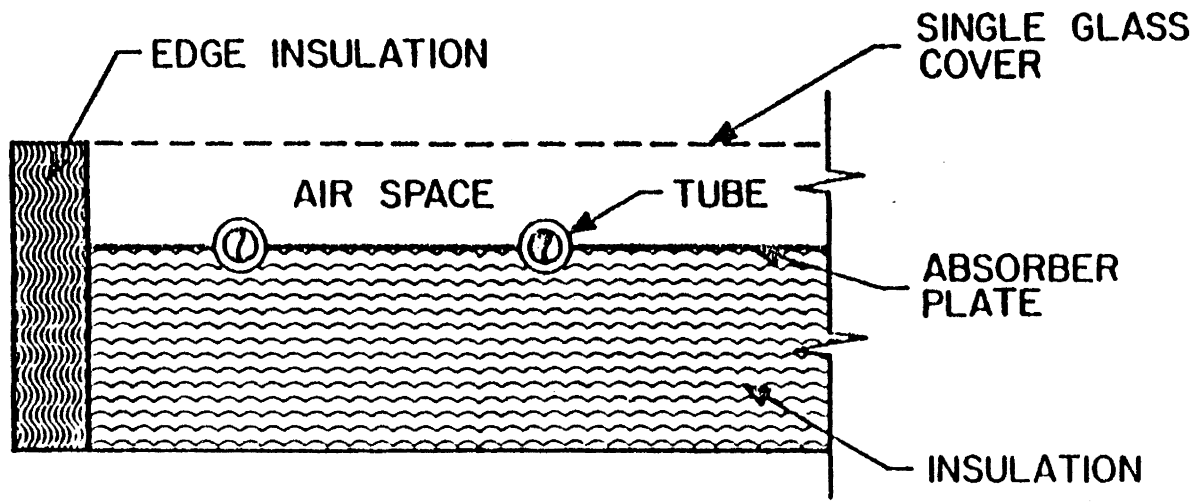

Figure 1. Cross Sectional View of Typical Liquid Type Flat-Plate Solar Collector.

†Table 1. Collector Test Specimen Description

Collector Code	Cover Material			Absorber Material			Average Area*	
	Outer	Inner	Solar Transmittance	Material	Solar Absorptance	Emittance	Gross (m^2)	Aperture (m^2)
A	Water White Glass	—	0.90	Black Nickel	0.87	0.13	2.150	1.831
B	Low Iron Glass	Low Iron Glass	0.88 (ea)	Black Velvet Paint	0.97	0.96	1.732	1.602
C	Plate Glass	Thin Film Heat Trap	0.86	Black Velvet Paint	0.98	0.92	2.589	1.924
D	Etched Glass	Etched Glass	0.96 (ea)	Black Chrome	0.97	0.07	1.655	1.402
E	FRP (Type I)	—	0.85	Lacquer Primer	0.95	0.87	1.892	1.720
F	Water White Glass	—	0.90	Copper Oxide	0.96	0.75	1.922	1.769
G	FRP (Type II)	FEP Film	0.84 0.96	Porcelain Enamel	0.93	0.86	2.563	2.188
H	Polyester Film	FEP Film	0.85 0.96	Siliconized Polyester Paint	0.95	0.89	2.916	2.641

†Reprinted from reference 3.

2.1.2 Test Site Selection. Four test sites have been selected for participation in the D/R Test Program. These sites were selected based upon the climatic conditions present at each, and based upon demographic data compiled for the United States. Sites were chosen in environments with substantial population density and a reasonable potential for solar applications. Sites were selected in each of four differing climatic divisions of the United States to examine differences in performance degradation resulting from exposure environment. The locations of these test sites with respect to U.S. geographic and climatic regions are shown in Fig. 2. The climatic regions depicted in this figure are based upon the major divisions of world climate as identified by Trewortha [5]. The characteristic climatic features of each test site are summarized as follows:

Test Site 1 is located in a desert environment. This site experiences high levels of ultraviolet radiation, hot and dry ambient conditions, and a high level of solar irradiation.

Test Site 2 is located in a coastal, salt air environment. This site is characterized by low to moderate levels of ultraviolet radiation, hot and humid ambient conditions, and a high level of solar irradiation.

Test Site 3 is located in an urban environment. This site experiences a moderate level of ultraviolet radiation, moderate and dry ambient conditions, and a high level of solar irradiation.

Test Site 4 is located in a suburban environment. This site is characterized by a moderate level of ultraviolet radiation,

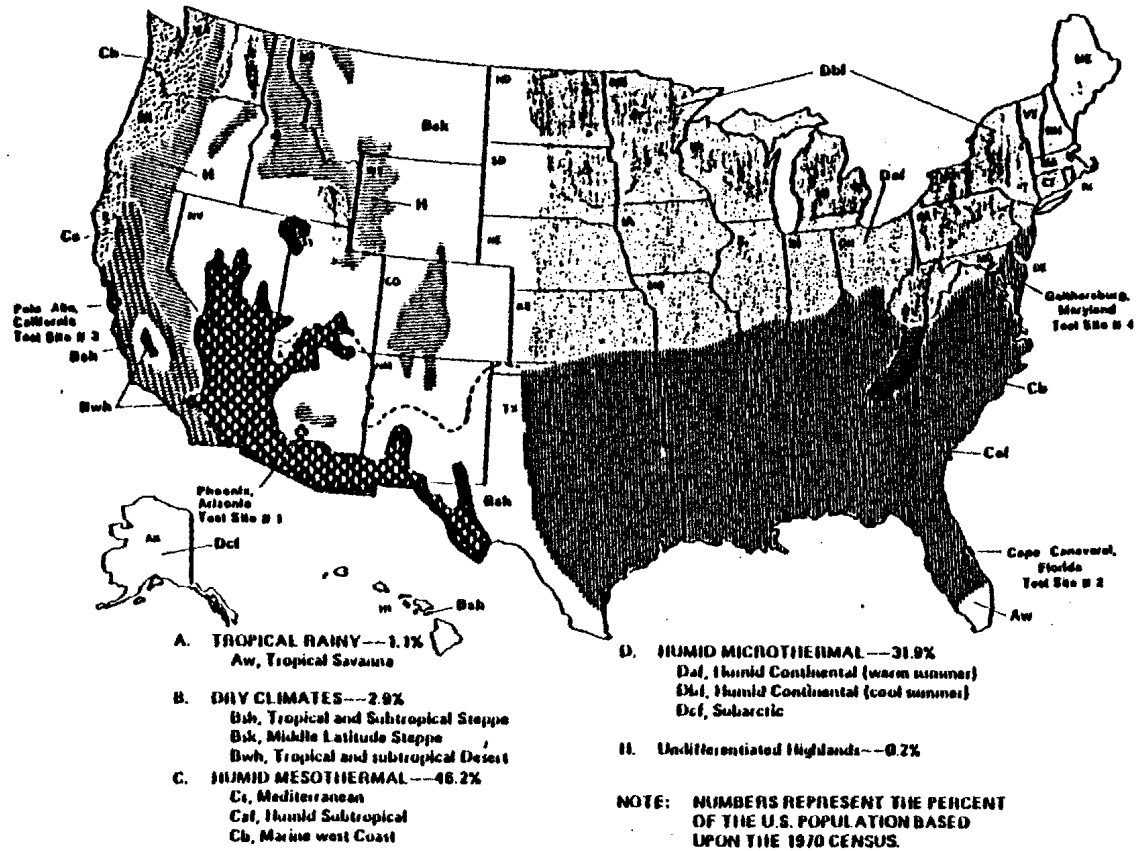

Figure 2. Location of Test Sites Participating in Durability/Reliability Test Program.

moderate and humid ambient conditions, and moderate levels of solar irradiation.

2.1.3 Test Series Design and Implementation. Four different test series have been devised to permit examination of collector degradation under severe operating conditions which may accelerate performance decrease. These operating conditions include dry stagnation, no flow stagnation, low flow rate operation, and augmented solar irradiation through use of reflectors. Thermal shock and moisture penetration tests have been incorporated into the design of test series 2. Performance retests after a 3-day preconditioning exposure have been conducted for all test series to determine the merit of preconditioning as specified in ASHRAE 93-77.

Table 2 shows a summary description of the field test series used in the program. This table contains the retest schedules followed, the specific conditions of exposure, and the purposes of each test series. The duration of total exposure of each of the test series are as follows:

Test series 1	0 through 480 exposure days
Test series 2	0 through 480 exposure days
Test series 3	0 through 240 exposure days
Test series 4	0 through 60 exposure days (series terminated)

where an exposure day is credited for each day of exposure with solar irradiation in the plane of the collector aperature in excess of 17,000 $kJ/m^2 \cdot day$. Following completion of exposure testing, all collectors

†Table 2. Field Test Series Description

TEST SERIES	COLLECTOR PERFORMANCE MEASUREMENT	CONDITIONS FOR WEATHERING EXPOSURE	PURPOSES OF TEST SERIES***
Series 1 "dry stagnation"	Initial measurement in accordance with ASHRAE 93-77 except delete 3-day pre-exposure and measurement of time constant. Performance re-test after 3, 15, 30, 60, 120 and 240 day exposures.*	Each collector pre-conditioned for each weathering exposure by purging with dry air to remove the remaining heat transfer fluid. Successive weathering exposures between performance re-tests provide cumulative exposures of 3, 15, 30, 60, 120, and 240 days.*	1. Observation of effects of dry stagnation on collector performance and other characteristics for various weathering times. 2. Provide data for comparison of solar simulator performance measurement with field data. 3. Provide data for comparing collector initial performance with and without 3-day pre-exposure per ASHRAE 93-77.
Series 2 "no-flow stagnation"	Initial measurement in accordance with ASHRAE 93-77 after 3-day pre-exposure. Delete measurement of time constant. Performance re-tests same as in Series 1.	Collectors pre-conditioned for weathering exposure by filling per NBSIR 78-1305A [9], capping and allowing to boil dry. Weathering exposures same as in Series 1 except that Thermal Shock Tests per NBSIR 78-1305A will be performed during first 30-day exposure on Series 2 test collectors only.	1. Observation of effects of no-flow stagnation on collector performance and other characteristics. 2. Observation of effects of Thermal Shock Tests representing (a) filling a hot collector with cool heat transfer medium and (b) summer rain on a hot collector. 3. Observation of static pressure leakage after 30 and 120 days of exposure.
Series 3 "controlled flow"	Performance of test collectors measured in accordance with ASHRAE 93-77, taking only 3 points. Delete 3-day pre-exposure and time constant measurement. Performance re-tests same as in Series 1.	During weathering exposure heat transfer flow rate maintained at 25% of operational flow rate for liquid.	1. Observation of effects of normal operation on collector performance and other characteristics.
Series 4 "dry stagnation with augmentation reflectors"	Initial measurement same as in Series 1. Performance re-tests same as in Series 1.	Pre-conditioning and weathering exposures same as in Series 1, except that a reflector** will be used on each collector during each day of weathering exposure*. Solar radiation measurements required both with and without reflector.	1. Observation of effects of dry stagnation on collector performance and other characteristics with solar radiation amplified by a reflector. 2. Obtaining temperature history within collectors for most severe exposure conditions.

* Individual days with solar radiation of 17,000 KJ/m^2·day or greater as measured in the plane of the collector aperture without the influence of a reflector.

** The reflector is described in Paragraph 2.2.1.3.

*** All series include provision of data for comparisons between test series, test sites (climatic regions), collector designs, etc.

† Reprinted from reference 3.

were returned to the National Bureau of Standards at Gaithersburg, MD for disassembly and evaluation of collector components' properties.

2.2 Flat-Plate Liquid Collector Efficiency Modeling and Evaluation

The only widely accepted measure of the performance of liquid flat-plate solar collectors is the efficiency curve for the collector. This section contains a review of the basic concepts associated with modeling the thermal performance of collectors by means of an efficiency curve. An overview of the ASHRAE 93-77 standard is provided as this method is the currently accepted standard for performance evaluation. The review which follows is not intended as a comprehensive examination of these subjects. Detailed description of collector performance modeling is provided in reference 6. Reference 7 details all specifications of the ASHRAE 93-77 standard.

2.2.1 Collector Performance Modeling. The primary performance index by which solar collectors are judged is the efficiency with which they capture impinging electromagnetic energy from the sun and convert it into thermal energy. The thermal efficiency of a collector at a given set of operating conditions is commonly defined as follows:

$$\eta = \frac{\text{energy gain by collector}}{\text{incident energy}} = \frac{\dot{m}C_p[t_e - t_i]}{A_g H_T} \qquad (1)$$

where t_e and t_i refer to the exiting and inlet fluid temperatures respectively.

The useful energy gain of the collector may be determined from the Hottel-Whillier-Bliss performance model for collectors of this type.

This model results in the following expression [6] for useful energy gain per unit aperture area:

$$\dot{q}''_u = H_T(\tau\alpha) - U_L(t_{pm} - t_a) \tag{2}$$

where H_T represents the energy incident on the tilted collector aperture. In the first term on the right of Eq. 2 the transmittance-absorptance produce, $(\tau\alpha)$, indicates the fraction of impinging energy which is transmitted through the cover(s) and is absorbed by the absorber plate. The second term represents the overall energy loss of the collector assembly. The heat loss coefficient, U_L, accounts for convection and radiation losses. Notice that Eq. 2 requires the mean plate temperature to determine the useful gain. Because of the large temperature distribution of the absorber surface, this temperature is not easily determined. Since the mean plate temperature cannot be measured directly, it is convenient to define a heat removal factor, F_R, which is the ratio of the actual useful energy gain to the energy gain that would be realized if the entire collector surface was at the inlet fluid temperature. In terms of the collector operating parameters, the heat removal factor may be expressed as:

$$F_R = \frac{\dot{m}C_p[t_e - t_i]}{A_a\{H_T(\tau\alpha) - U_L(t_i - t_a)\}} \tag{3}$$

Using this expression, Eq. 2 may be rewritten as:

$$\dot{q}''_u = F_R\{H_T(\tau\alpha) - U_L(t_i - t_a)\} \tag{4}$$

Utilizing this expression for useful energy gain, the thermal efficiency may be expressed as:

$$\eta = \frac{A_a}{A_g} \{F_R(\tau\alpha) - F_R U_L \frac{(t_i - t_a)}{H_T}\} \quad (5)$$

Equation 5 represents the currently accepted defining relation for thermal efficiency modeling of flat-plate liquid collectors. The parameters $F_R(\tau\alpha)$ and $F_R U_L$ are assumed constant. Consequently, efficiency is modeled as a first-order linear function of the parameter $(t_i - t_a)/H_T$. Figure 3 shows the resulting model of collector efficiency. As indicated by the form of Eq. 5, $F_R(\tau\alpha)$ is the efficiency intercept and $F_R U_L$ is the slope of the efficiency curve.

The assumptions of constant $F_R(\tau\alpha)$ and $F_R U_L$ are reasonable for efficiency tests. The transmittance absorptance product, $(\tau\alpha)$, is determined by collector optical properties and is relatively insensitive to test environment. The overall loss coefficient, U_L, is strongly dependent upon environmental factors. The parameter U_L depends on factors such as wind speed, ambient temperature and mean plate temperatures. The heat removal factor, F_R, is a weak function of U_L, and consequently exhibits some temperature dependence. It has been shown in previous examinations that the errors inherent in assuming $F_R(\tau\alpha)$ and $F_R U_L$ to be constants are overshadowed by experimental errors and variations caused by differing test environments [8,9,10]. In a later section, the validity of the first-order linear model of efficiency will be examined.

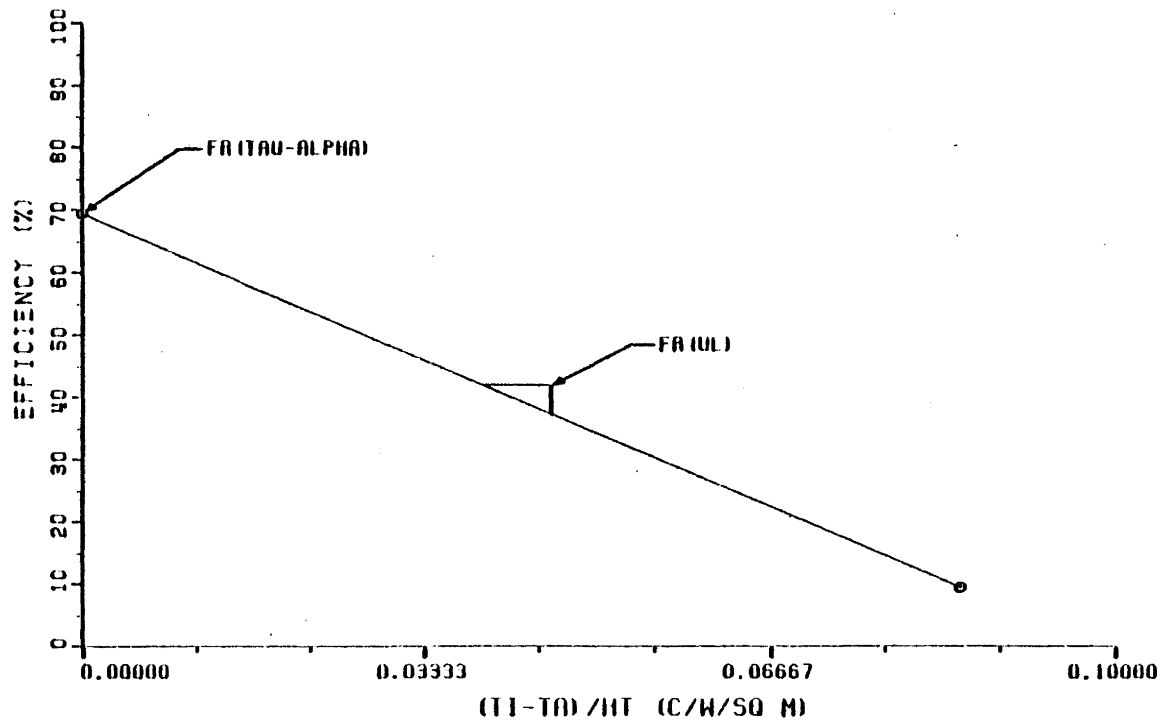

Figure 3. Typical Collector Efficiency Curve.

2.2.2 Efficiency Curve Determination by Use of the ASHRAE 93-77 Standard.

The ASHRAE 93-77 standard establishes permissible operating conditions necessary for determination of efficiencies. Table 3 shows the allowable environmental conditions for testing. As shown in this table, the allowable weather conditions represent minimum or maximum values of weather parameters acceptable for testing. These conditions allow for significant variation of test environments for outdoor testing. A later section of this investigation will examine the affects of test environment on the reported values of $F_R(\tau\alpha)$ and $F_R U_L$.

In addition to allowable test weather conditions, the ASHRAE 93-77 standard establishes several instrumentation accuracy and precision specifications. Acceptable experimental facilities and overall test procedures are detailed in reference 7. The experimental procedure requires that tests be performed under quasi-steady conditions. This requirement should be assured by circulating the heat transfer fluid through the collector at the appropriate temperature until the inlet temperature remains constant for a minimum of 15 minutes. This procedure should be repeated for tests at each particular inlet temperature. Reference 7 recommends that tests be performed at at least four different inlet fluid temperatures in order to properly establish an efficiency curve.

Once the experimental apparatus is established to be within the specifications, the actual procedure for determining the collector efficiency curve is a straightforward method. Efficiency measurements

Table 3. Allowable Weather Conditions

Condition	Value
Solar radiation	> 630 W/m^2
Wind speed	< 4.5 m/s
Ambient	< 30 C

are performed at four values of t_i with at least four data points taken at each value of t_i. Data points consist of the ordered pairs of measured efficiencies and $(t_i-t_a)/H_T$'s. The measured efficiency is determined by integrating Eq. 1 over a five minute interval or a period of time equivalent to the collector time constant, whichever is larger (Reference 7 also establishes test procedures for determination of the collector time constant.) When a normal-incidence altazimuth mount is used (such as those employed at test sites 1 and 2 of this investigation), this time period may be reduced to 1/2 of the collector time constant or five minutes, whichever is larger.

Once at least four data groupings are obtained, a first or second-order least-squares curve fit may be established as the collector efficiency curve. Using a first-order fit, the ordinate intercept is recognized as the parameter $F_R(\tau\alpha)$, and the slope of this curve establishes the parameter F_RU_L.

2.3 Literature Review

A review of current publications pertaining to flat-plate solar collectors has revealed that while considerable research has been performed in the areas of collector performance theory and design, few examinations into long term performance degradation have been made. The review which follows is concerned with the available literature in three areas: testing of collector component material performance degradation, collector performance degradation examinations, and methods of analysis of interlaboratory test data.

Several accelerated test methods have been established for testing materials used in building and construction. References 11 and 12 detail many of these methods. The accelerated tests described in these references are devised for materials that are used in solar collectors. However, these test procedures were not designed to evaluate material properties specifically for solar applications.

Some collector component materials testing has been conducted in an attempt to establish long term degradation trends of these materials when used in solar applications. Exposure testing has been performed on cover and absorber materials by Gilligan [13,14]. Reference 13 provides a description of the test methods employed to measure collector properties. Collectors in this examination were subjected to augmented solar irradiation through use of mirrors. Degradation correlations were attempted with limited success. Suggestions are offered for future attempts at devising degradation models. Reference 14 documents the data accumulated through Gilligan's study. Evaluation of polymer cover materials has also been conducted by Cheng and Bannerot [15]. This study showed that significant degradation in the transmittance of polymer covers was experienced after only 10 months of exposure in specially constructed test boxes. Reference 15 presents a discussion of the construction of the apparatus employed and the procedures followed in testing. Both of the aforementioned examinations of component materials degradation were conducted on samples which were exposed in outdoor environments and degradation was determined from actual changes in material properties.

As previously discussed, the National Bureau of Standards' Durability/Reliability Test Program is also concerned with the determination of component material deterioration. In references 4 and 10, attempts are made to correlate degradation of material samples to overall collector performance degradation. Development of such a correlation would be highly desirable in that it is possible that long term performance predictions could be made without the need of testing entire collector assemblies. A correlation of this type would also yield valuable information as to the specific causes of collector performance degradation.

Of the information available on the few collector performance degradation studies which have been performed, there is evidence that significant performance degradation is to be expected over the collector life-cycle. In reference 1, Löf reports that efficiency decreases of up to 30 percent have been observed in collectors exposed for a period of 18 years. Another study, conducted by investigators at Wyle Laboratories, showed degradations of 0 to approximately 10 percent in thermal efficiency for collectors exposed under dry stagnation for a period of 1 year [16]. The conclusions of this study were that (1) stagnation conditions have the most severe effect on double-glazed, selective coated collectors because of the higher temperature achieved, and (2) some flat black paints and selective coatings may oxidize at stagnation temperatures, degrading performance significantly. While each of the aforementioned studies of collector performance degradation has contributed significant data as to long term performance, neither study

has resulted in development of an accelerated test procedure for flat-plate collectors.

Development of such an accelerated test is one of the primary objectives of the NBS Durability/Reliability Test Program. To this end, the D/R test program is engaged in collector testing in various climatic regions to examine the effects of environment on degradation. As a consequence, collectors are being tested at several laboratories. The results of such a test program are subject to variability among laboratories in implementation of test procedures and in the various experimental test facilities. As a result, methods of interpreting interlaboratory test data must be utilized.

Several methods of analysis of interlaboratory tests are presented in the literature. However, most of these methods are designed to evaluate the test procedure, rather than test results from multiple laboratories. Of the methods of analysis found to be applicable to test results, two methods of particular interest were found. The first method involves a study of the standard deviation within sites and between sites for such a test. The method as developed by J. Mandel is detailed in reference [17]. This method of analysis permits the quantization of a measure of precision (the standard deviation) of interlaboratory test results. This method is based upon a test with an equal number of replicates at each laboratory. Mandel and Paule have also extended this method to account for tests with unequal numbers of replicates [18]. The other method found to be applicable to data from several laboratories is a graphical approach developed by W. J. Youden

[19]. Through application of this graphical approach, diagnostics of interlaboratory test differences may be performed. This graphical approach may also be used to determine a measure of precision of the reported results.

Chapter 3

Analysis and Discussion

This chapter presents an analysis of the results of the National Bureau of Standards' Solar Collector Reliability/Durability Test Program. The analysis provides an examination of the experimental data to determine whether the thermal performance of collectors tested has significantly degraded as a result of prolonged exposure under stagnation and low flow conditions.

To determine the extent of degradation which has taken place, some characteristic measure of thermal performance must be selected. The most commonly used thermal performance parameter is the measured thermal efficiency curve for a collector. In particular, the ordinate intercept, $F_R(\tau\alpha)$, and the slope, $F_R U_L$, of the linearized collector efficiency curve are commonly used to characterize thermal performance. Changes in these two parameters reflect changes in overall collector performance. The reported values of the these two parameters for all tests conducted in the program are presented in Appendix A. This tabulation of reported results serves as the data base from which all analysis has been conducted.

The analysis which follows examines the test program and the experimental procedures followed in addition to the reported results of the collector efficiency tests performed. Examination of differences between collectors undergoing different test series at the same test site, as well as collectors undergoing the same test series at different

test sites will be made. The experimental procedures employed and the apparatus used will be examined to determine their effect on the reported results.

3.1 Examination of Results as Reported

The reported values of the parameters $F_R(\tau\alpha)$ and F_RU_L have been plotted as functions of exposure time to examine the changes of each. Multiple plots have been prepared to examine site to site differences and differences among test series.

Figures 4 and 5 show plots of the performance parameters as functions of exposure days for collector A, test series 1 through 4, performed at laboratory 1. The mean values and the standard deviations of data about the mean values are shown in each figure. The standard deviation, σ, about the mean value has been calculated as follows:

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N - 1}}$$

where

x_i = (i)th individual data value

$\bar{x}$ = mean value of data

N = number of data points

Since the scatter in the data fluctuates both above and below the mean value in a somewhat random fashion, the calculated standard deviation represents a quantitative measure of the scatter.

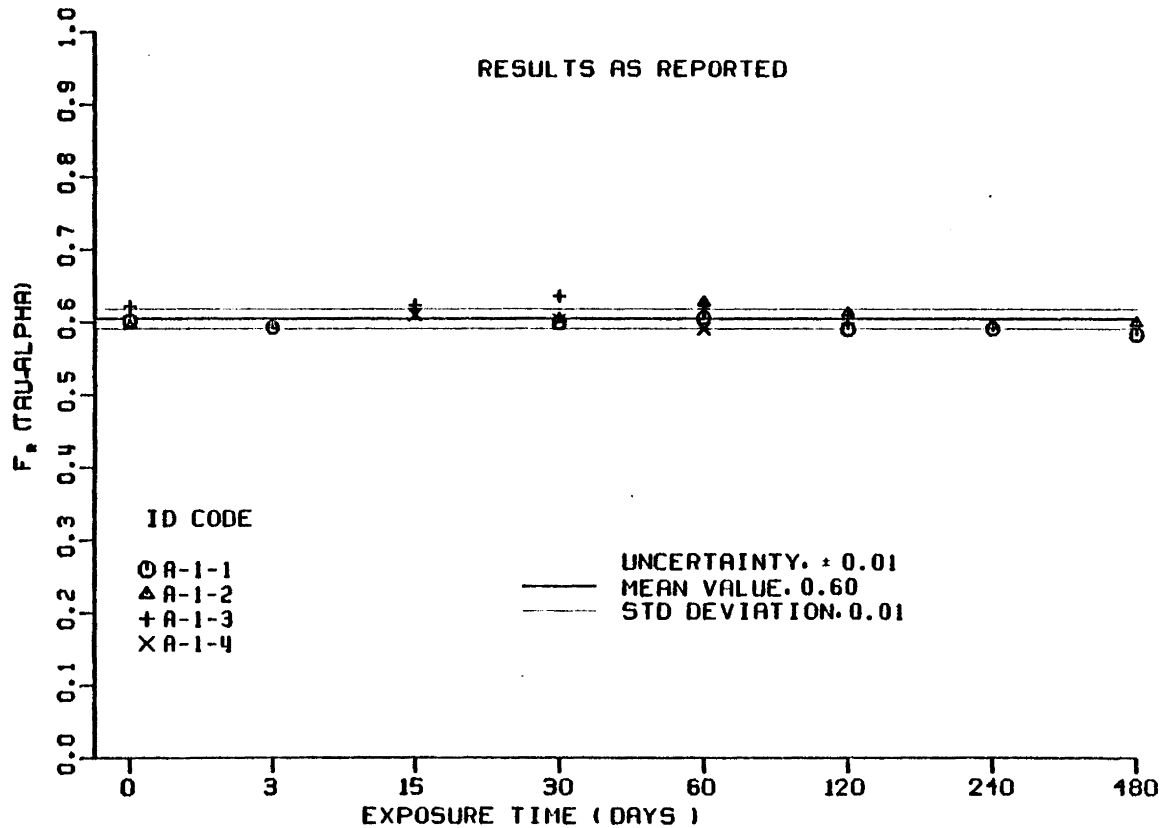

Figure 4. Reported Values of $F_R(\tau\alpha)$ for Collector A, Test Site 1, All Test Series vs Exposure Time.

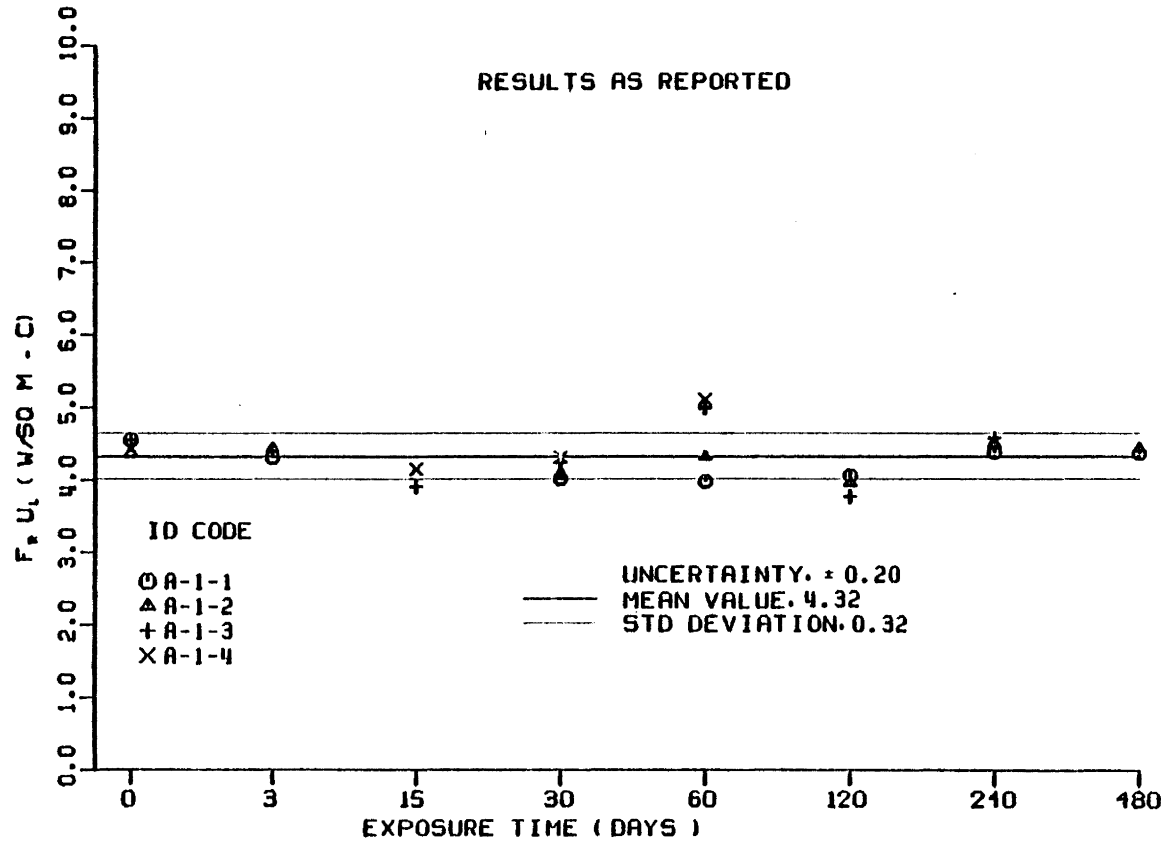

Figure 5. Reported Values of $F_R U_L$ for Collector A, Test Site 1, All Test Series vs Exposure Time.

Figures 4 and 5 reveal two characteristics which have been found to be typical for all collectors in the test program. First, the plots of $F_R U_L$ vs exposure days exhibit far more scatter in the data than do the corresponding plots of $F_R(\tau\alpha)$. More importantly, these figures show that the random scatter in the data is of the same order of magnitude as any general changes in performance.

The greater scatter in the $F_R U_L$ plots is expected because this parameter is affected more strongly by environmental and test conditions than the ordinate intercept, $F_R(\tau\alpha)$. The parameter $F_R U_L$ is characteristic of the overall energy loss from the collector. This loss is influenced by such factors as wind speed and ambient temperature during testing. Additionally, visual inspection reports from the participating laboratories suggest that the insulation of some collectors may undergo some type of curing process which would affect $F_R U_L$.

The parameter $F_R(\tau\alpha)$ does not exhibit such a strong environmental dependence. It is more of an optical efficiency measure. Consequently, it should be a somewhat more repeatable performance measure. Herein, more emphasis has been devoted to examining the changes of $F_R(\tau\alpha)$ with exposure as a characteristic index of collector performance since it is less dependent on environmental conditions during testing. Later, attempts will be made to analyze the environmental dependence of both $F_R(\tau\alpha)$ and $F_R U_L$.

As shown in Fig. 4, the random scatter in the reported values of $F_R(\tau\alpha)$ is of the same order of magnitude as any general degradation of performance. This observation held for nearly all collectors in this

test program. The standard deviation of $F_R(\tau\alpha)$ about the mean is 0.01. Previously, an experimental uncertainty of ± 0.01 has been calculated for determination of $F_R(\tau\alpha)$ using the Kline-McClintok method of uncertainty analysis [10]. This value represents the experimental uncertainty associated with the prescribed apparatus and testing procedures for determining $F_R(\tau\alpha)$ as set forth in ASHRAE 93-77. Thus, for this particular collector-site combination, as with the majority of collector-site combinations, the changes in $F_R(\tau\alpha)$ are essentially within the experimental uncertainty of the test method and specified testing apparatus. As a result, it is difficult if not impossible to draw any general conclusions as to degradation which may have taken place.

Figure 5 shows that the standard deviation about the mean value of F_RU_L is 0.32. The uncertainty limits calculated for determination of F_RU_L are ±0.20 [10]. Clearly, the random spread in the data exceeds this calculated uncertainty. It has been noted that the parameter F_RU_L is strongly dependent on environmental factors at the time of testing. In addition, it is possible that the experimental techniques used did not fully meet the testing specifications set forth in ASHRAE 93-77. Whatever the cause, the excessive scatter in the reported values of F_RU_L precludes drawing any general conclusions as to collector degradation based on changes in this parameter.

The same general characteristics observed in plots of collector-site combinations were found in plots of collector-series combinations. That is, the scatter in reported values of F_RU_L far exceeds the scatter

in $F_R(\tau\alpha)$ values; and performance changes with exposure time are relatively random. However, as indicated in Fig. 6 and Fig. 7, the standard deviation about the mean values of $F_R(\tau\alpha)$ and F_RU_L are significantly higher for collector-series combinations than for the corresponding collector-site combinations. This increase in standard deviation when collectors tested at different sites are plotted vs exposure is typical. This fact suggests that some interlaboratory differences are present. These differences may be attributable to procedural differences among participating laboratories, environmental dependence of test results not accounted for by the test procedure, or product variability among collectors. These possibilities will be examined in subsequent sections.

Because of the relatively small changes seen in the parameter $F_R(\tau\alpha)$, few conclusive statements can be made with regard to long term degradation trends. However, one general trend which has been observed is an initial period of increase in $F_R(\tau\alpha)$ to some exposure level, usually between 30 and 60 days of 1500 BTU/day exposure. Beyond this exposure level, $F_R(\tau\alpha)$ appears to decrease monotonically with exposure time.

Figure 8 shows values of $F_R(\tau\alpha)$ normalized to the initial test value for Collector A, test series 1 and 2, as functions of exposure. Since each value has been normalized to the initial test value, this figure depicts the fraction of the baseline value by which the parameter has changed. The graphs for laboratories 1 and 2 are of particular interest. These plots show the "peak" behavior between 30 and 60

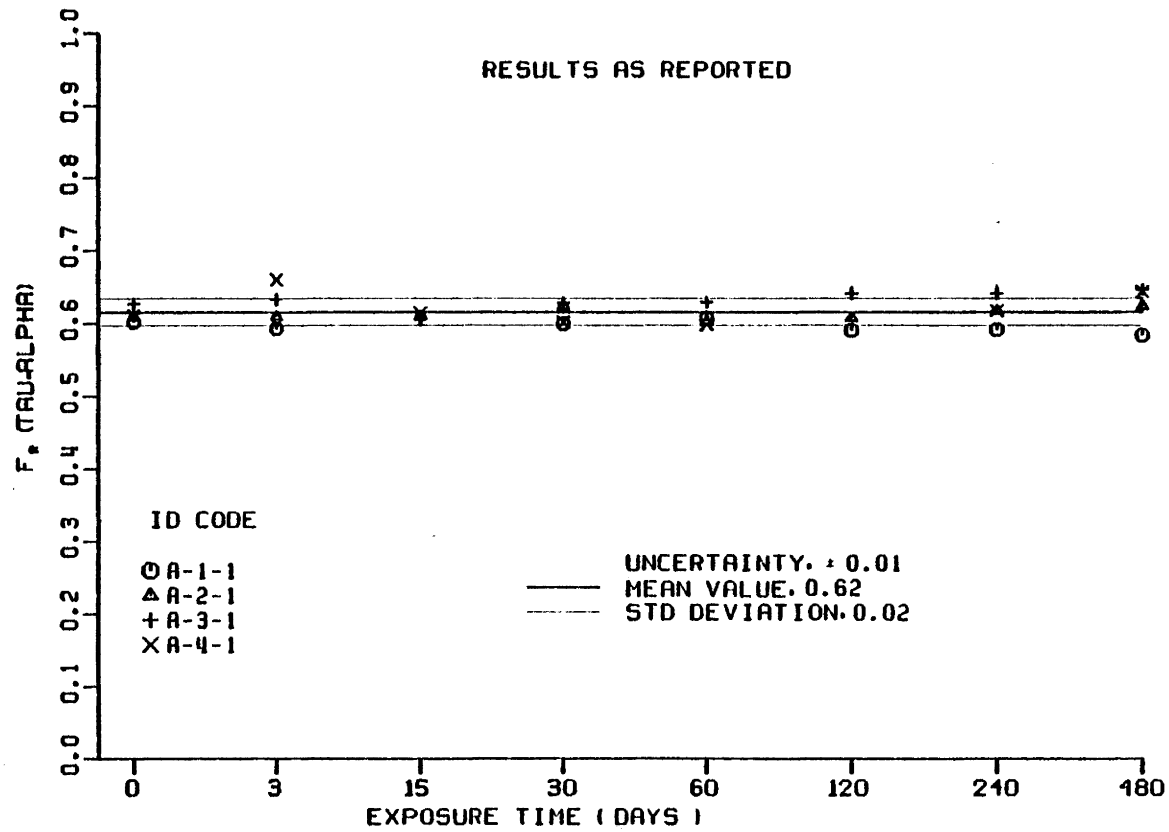

Figure 6. Reported Values of $F_R(\tau\alpha)$ for Collector A, All Test Sites, Test Series 1 vs Exposure Time.

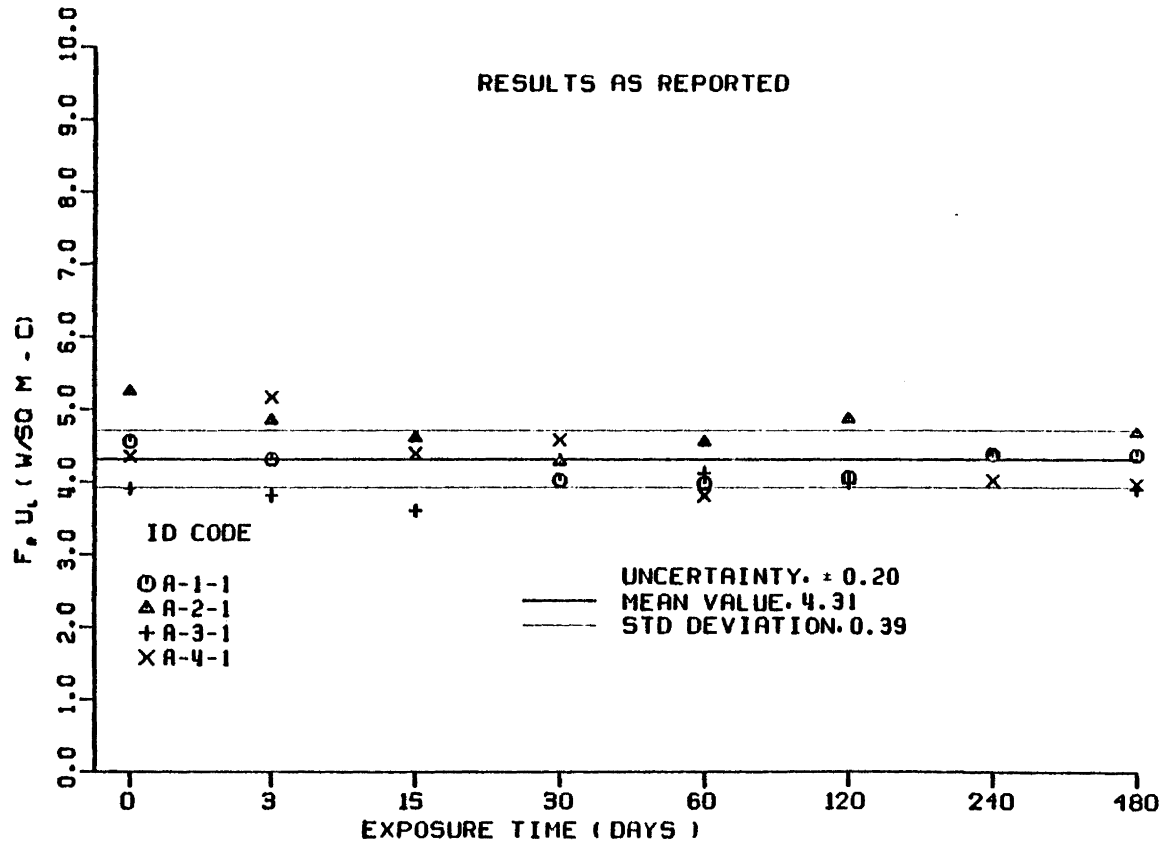

Figure 7. Reported Values of $F_R U_L$ for Collector A, All Test Sites, Test Series 1 vs Exposure Time.

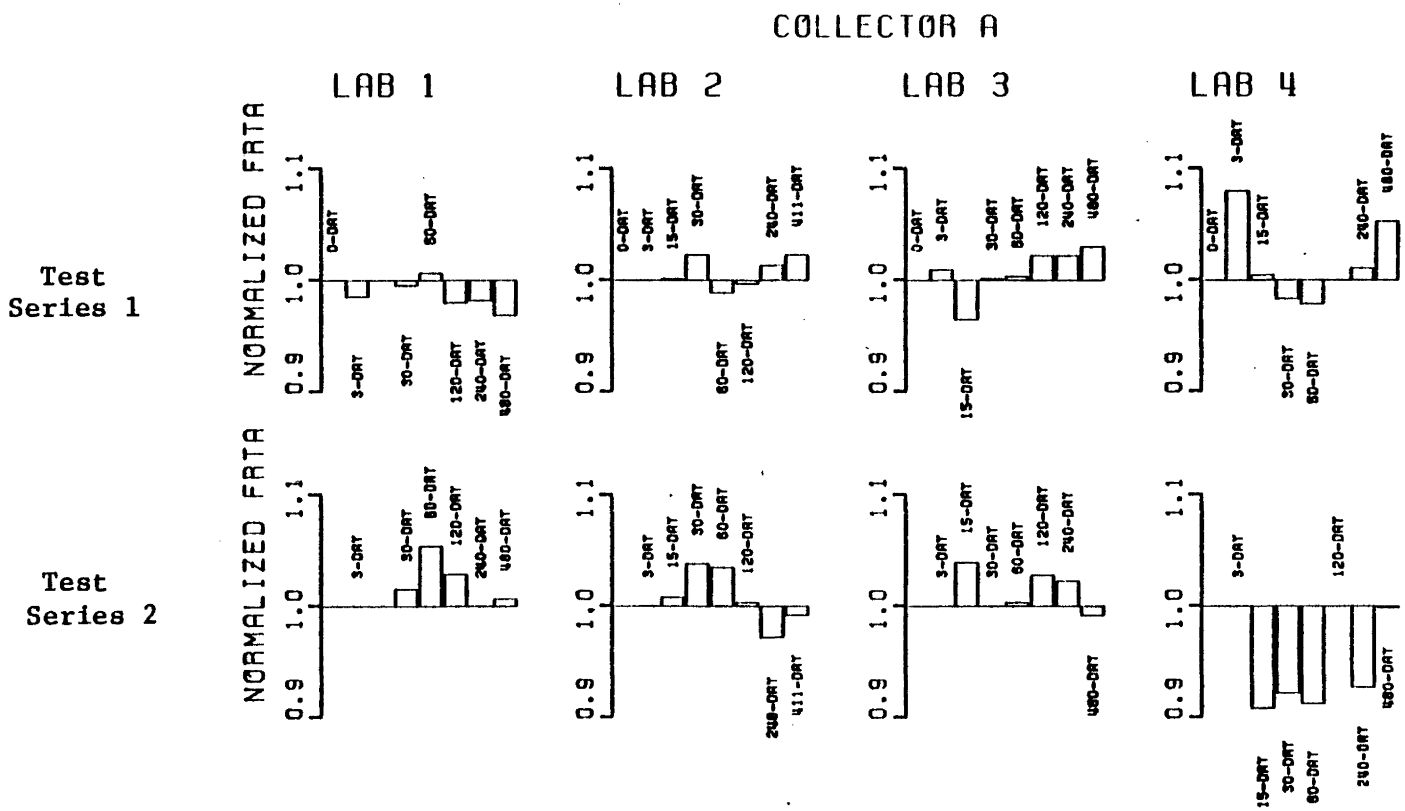

Figure 8. Reported Values of $F_R(\tau\alpha)$ Normalized to Initial Test Values for Collector A, Test Series 1 and 2 vs Exposure Time.

exposure days. This general trend in reported values of $F_R(\tau\alpha)$ was observed in approximately one-half of the collectors analyzed. Further evidence has been found in recent literature that transmittance (τ) values of polymer covers exhibit a similar initial increase followed by a monotonic decrease with exposure [15].

An analysis of visual inspection reports made during the program was carried out in an attempt to find a plausible explanation of this unexpected behavior. In this examination a consistent pattern of condensate cycling was observed for all collectors. Also, nearly all collectors were reported to have a milky-white or gray film present on the inner surface of the innermost cover for an extended period of time. The inspection reports suggested that this film may have been left as a residue of the condensate cycling or possibly insulation outgassing. However, no pattern emerged from the analysis of visual inspection reports which appeared consistently with the peak behavior of $F_R(\tau\alpha)$.

Attempts to correlate the 30-60 exposure day peak with particular collector materials were also made without success. The $F_R(\tau\alpha)$ peak occurred for collectors with glass as well as polymer covers. Correlations of this behavior with absorber plate materials and types of insulation were attempted with equally inconclusive results. Apparently, a simple straightforward explanation of the peak behavior is not possible.

It is possible that the 30-60 exposure day peak behavior could occur as a result of two or more compensating mechanisms. It is conceivable that following initial exposure some aspects of collector

performance may improve. Wrinkling of the absorber surface may occur, resulting in an increase in absorptivity. Initial stagnation exposure may drive trapped moisture from the collector's insulation, thus reducing its conductivity. At the same time, optical degradation mechanisms may begin. These compensating mechanisms may exist simultaneously during initial exposure. At intermediate levels of exposure (30-60 exposure days) it is possible that the degradation mechanisms could become dominant causing a decrease in $F_R(\tau\alpha)$ with subsequent exposure.

While such an explanation may seem plausible, it has yet to be demonstrated with conclusive evidence. In fact, the mechanisms by which long term optical degradation take place are not yet known. Further examination of the 30-60 exposure day peak behavior is warranted since the mechanism or mechanisms responsible for this pattern may well be significantly related to the long term mechanism(s) by which collector performance degradation takes place.

While examination of normalized (to initial test values) values of $F_R(\tau\alpha)$ vs exposure has not produced any conclusive findings as to long term degradation, some observations can be made which suggest areas of further study which might prove beneficial. Of the four laboratories participating in the program, the collectors tested at laboratory 1 show some apparent degradation most frequently. As previously discussed, this laboratory is located in a desert environment. It is to be expected that this type of environment with its high ambient temperatures and commonly clear sky conditions will result in higher collector

stagnation temperatures than collectors tested in other environments. Also, this laboratory receives amounts of solar irradiation in excess of the qualifying 17000 kJ/m^2 · day (minimum specified level for an "exposure day") nearly every day. As a result, the cumulative solar irradiation received by collectors at this site is less than the cumulative total received at other sites. These facts suggests that stagnation temperature may be the key operating parameter in inducing accelerated degradation.

Further evidence that elevated stagnation temperatures may cause accelerated degradation can be found in the results of series 4 testing. This test series, augmented exposure through the use of mirrors, showed the most consistent pattern of performance degradation through the first 60 exposure days. The use of augmentation reflectors resulted in levels of solar irradiation higher than would otherwise be experienced. As a consequence, higher stagnation temperatures were associated with collectors undergoing this test series. Unfortunately, difficulties arose from the use of reflectors. Uniformity of the levels of irradiation across the collector aperture area could not be maintained. Measurements of the total irradiation reaching the collector were difficult to obtain. These problems along with other experimental difficulties forced the cancellation of this test series after 60 exposure days.

Because the most consistent patterns of degradation observed in this program have occurred in instances where the stagnation temperatures were the highest, elevated stagnation temperature may eventually

prove to be an important ingredient in the development of an accelerated test procedure for flat plate collectors.

3.2 Examination of the Effect on $F_R(\tau\alpha)$ of Modeling Efficiency as a 1st Order Linear Function of $\Delta t/H_T$

The analysis of reported values of $F_R(\tau\alpha)$ and F_RU_L entails the assumption that efficiency curves obtained by testing are 1st order linear functions of $\Delta t/H_T$. Efficiency curves typically exhibit some downward concavity. As a result, the validity of comparing values of $F_R(\tau\alpha)$ as characteristic parameters of collector performance needs to be established.

To observe the effects of the linearized model, a comparison has been made of the values of $F_R(\tau\alpha)$ obtained by instantaneous efficiency measurements with the inlet temperature equal to the ambient temperature to the reported values as extrapolated from the linearized model. The "measured" values of $F_R(\tau\alpha)$ were taken to be the instantaneous efficiencies measured with $\Delta t/H_T$ less than or equal to 0.001 $°C/W \cdot m^{-2}$. Figure 9 shows the results of this comparison. The measured values are shown as the abscissa with the extrapolated values shown as the ordinate. A line of slope 1 has been shown to represent the ideal agreement of measured and extrapolated values. Figure 9 shows that the extrapolated values are consistently higher than those measured. However, each extrapolated value is within 1.0 efficiency per cent of the measured value.

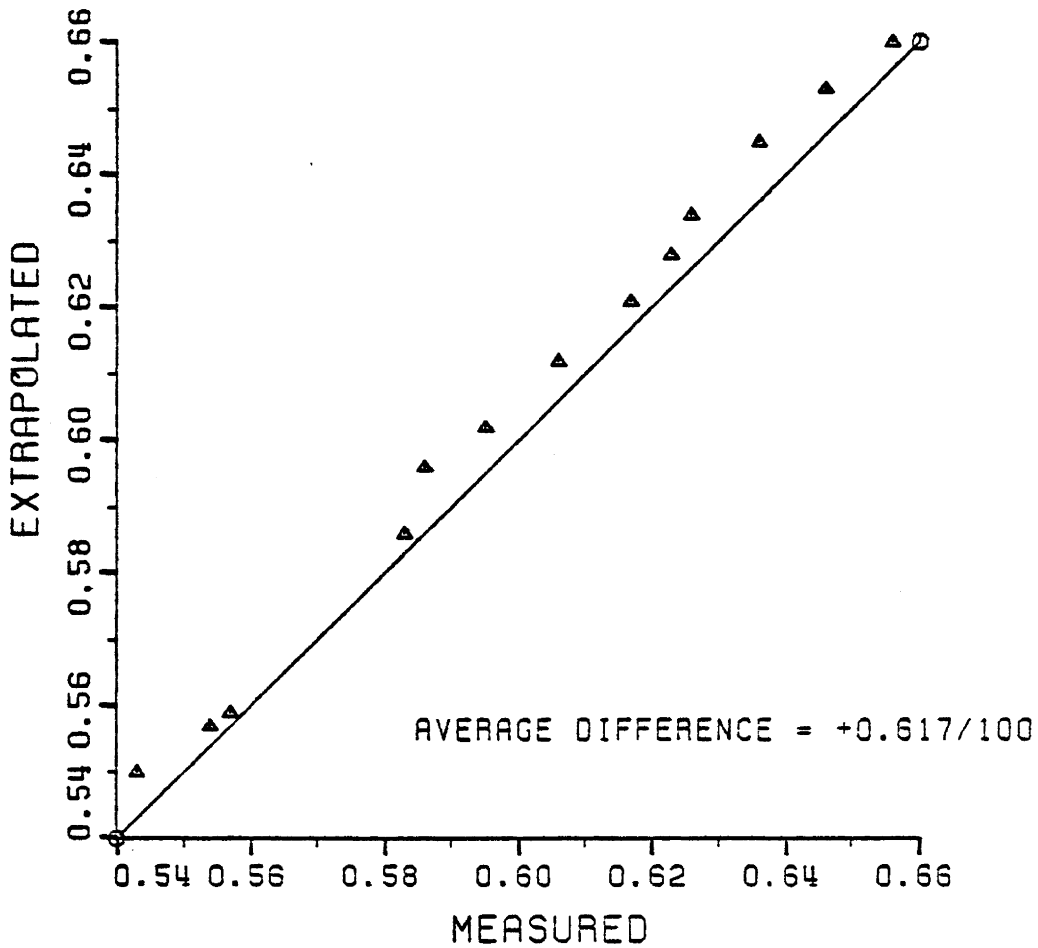

Figure 9. Comparison of $F_R(\tau\alpha)$ as Extrapolated from the Linearized Efficiency Curve to Efficiencies Actually Measured with the Inlet Fluid Temperature Equal to Ambient.

Modeling collector efficiency as a 1st order linear function introduces a small but consistent error in the value of $F_R(\tau\alpha)$. However, since this error is small and consistent, all collector efficiency curves may be assumed to be affected by about the same amount. The linearized model does not contribute to the scatter in reported values of this parameter. Hence, comparisons of values of $F_R(\tau\alpha)$ obtained throughout the program are valid.

3.3 Examination of Experimental Apparatus as a Possible Cause of Anomalous Results

A previous section showed that general changes in the two primary performance parameters were of about the same order of magnitude as the random scatter in the measured results. Consequently, it is in order to further investigate the accuracy associated with the experimental facilities and instrumentation used throughout the program.

There were no universal degradation trends with exposure time observed in the reported values of $F_R(\tau\alpha)$ or F_RU_L. Increases in both parameters were frequently observed. In fact, several collectors, especially those tested at laboratory 3, experienced a consistent increase in both parameters throughout the entire 480 days of exposure. In other words, after nearly three years of exposure the performance of several collectors was better than their original performance based on the reported results. Physical reasoning dictates that these results be considered suspect.

Because of these anomalous results, an investigation was carried out concerning the experimental apparatus and procedures. An analysis was performed to examine the effect of changes in pyranometer sensitivity with time. Temperature dependence of pyranometers used was examined as well. Finally, an attempt was made to correlate excessive data scatter with a particular pyranometer or test stand.

The literature suggests that claims of pyranometer accuracy and precision may be quite optimistic. As discussed by Zerlaut [20], the results of a round robin pyranometer calibration test indicate that several factors significantly affect pyranometer performance. Problems with linearization, stability, cosine response, tilt effects and data recording may combine to produce errors in the determination of $F_R(\tau\alpha)$ of from 3 1/2 to 4 per cent.

An analysis has been performed to examine the net effect of pyranometer sensitivity changes on the reported results. From calibration histories provided by the participating laboratories, it has been observed that generally pyranometer sensitivity decreases with time. The net effect of a pyranometer sensitivity decrease is to credit the collector with less solar irradiance than it actually receives. Consequently, measured values of $F_R(\tau\alpha)$ are greater than actual.

$$F_R(\tau\alpha) = \eta \Big|_{t_i = t_a} = \frac{\dot{m}C_p(t_e - t_i)}{A_g H_T} \tag{6}$$

Pyranometer sensitivity changes with time have no effect on reported values of $F_R U_L$.

To compensate for changes in pyranometer sensitivity, the reported values of solar irradiation in the plane of the collector, H_T, must be corrected. Since this term appears in the denominator of the defining equation for efficiency, the proper compensation is as follows:

$$F_R(\tau\alpha) = \frac{\dot{m}C_p(t_e - t_i)}{A_g H_T} \times \frac{\text{Sensitivity at time of test}}{\text{Sensitivity at calibration}} \qquad (7)$$

As indicated, values of pyranometer sensitivity at the time of each test are needed to properly execute the compensation. However, pyranometer calibrations were performed on an average of twice per year, rather than at the time of each test. Therefore, some means of interpolation is necessary to obtain an approximation of the sensitivity at the time of the test.

Two methods of interpolation were examined. These methods were linear interpolation between bracketing calibrations and an exponential scheme recommended by laboratory 1. This exponential scheme was based on the premise that changes in sensitivity with time were proportional to the magnitude of the sensitivity. It was found that the two methods of interpolation yielded essentially identical results since the period between bracketing calibrations was relatively small. For simplicity only the results of analysis using the linear interpolation are presented herein.

The reported values of $F_R(\tau\alpha)$ from laboratory 2 are of particular interest for examining the effects of pyranometer sensitivity changes with time. This laboratory used the pyranometer calibration constants from calibrations performed at the beginning of the test program for

data reduction throughout. The other participating laboratories employed updated calibration constants from periodic calibrations. Consequently, the values of $F_R(\tau\alpha)$ reported by laboratory 2 represent a "worst case" with regard to errors introduced by pyranometer sensitivity changes with time.

A computer algorithm was developed to correct the reported ordinate intercepts for laboratory 2. Figure 10 shows a typical correction curve. (Correction curves for the other pyranometers used are presented in Appendix B.)

Typically, changes of 2 to 3 per cent in the reported values of $F_R(\tau\alpha)$ resulted from this correction. Figures 11 through 14 show that typically this correction had no significant effects on the reported values. While sensitivity changes introduce a minor error in the reported results, this source of error is not sufficiently large to mask any degradation trends. After correction, the values of $F_R(\tau\alpha)$ still exhibited random fluctuations at least of the same magnitude as any general degradation trend.

In addition to pyranometer sensitivity changes with time, a correction methodology was developed to account for instrument sensitivity to temperature. Temperature sensitivity may be an important factor in pyranometer performance because of the construction of the instrument. A pyranometer is basically a thermopile. The output of any thermopile decreases as its operating temperature is increased for a given Δt. Because of this nonlinearity with respect to operating temperature, temperature compensation of reported results was performed. Because of

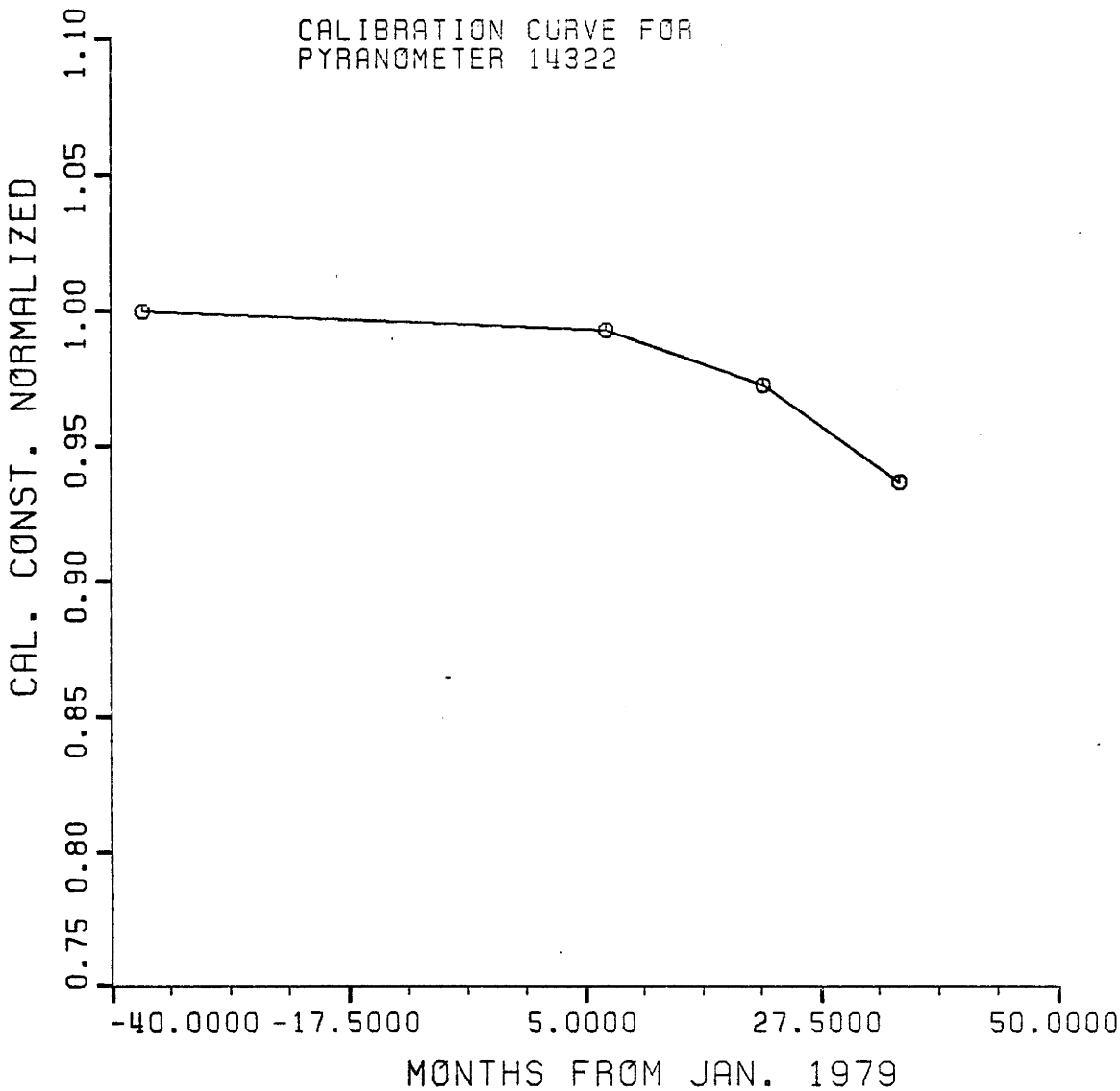

Figure 10. Typical Pyranometer Sensitivity Compensation Curve.

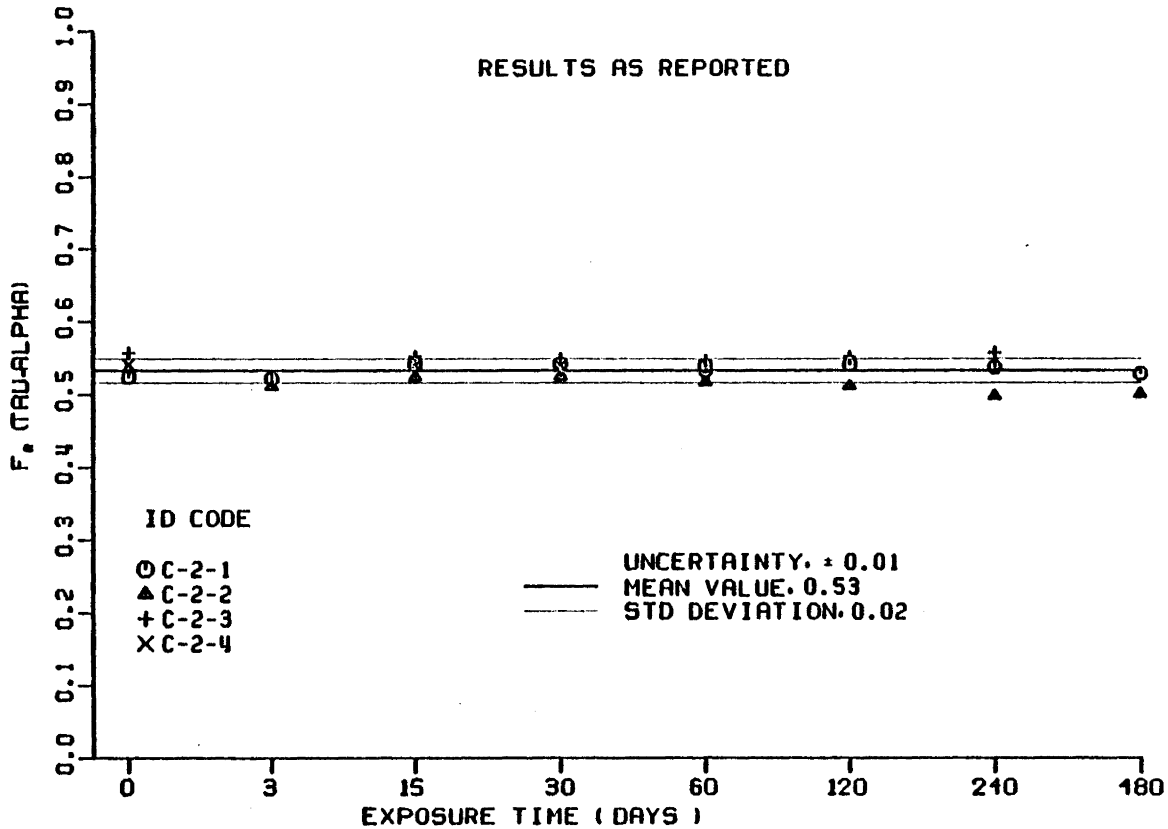

Figure 11. Values of $F_R(\tau\alpha)$ vs Exposure as Reported for Collector C, Test Site 2, All Test Series.

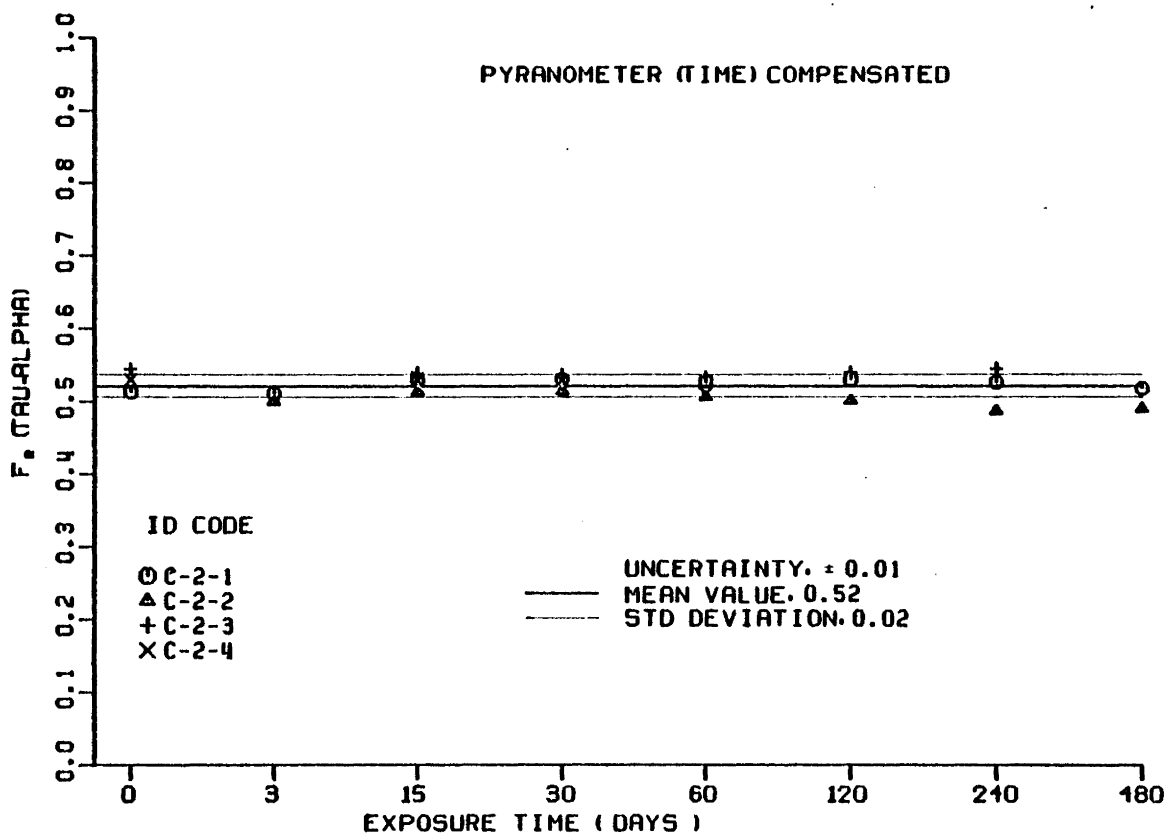

Figure 12. Values of $F_R(\tau\alpha)$ vs Exposure for Collector C, Test Site 2, All Test Series; Compensated for Time Varying Pyranometer Sensitivity.

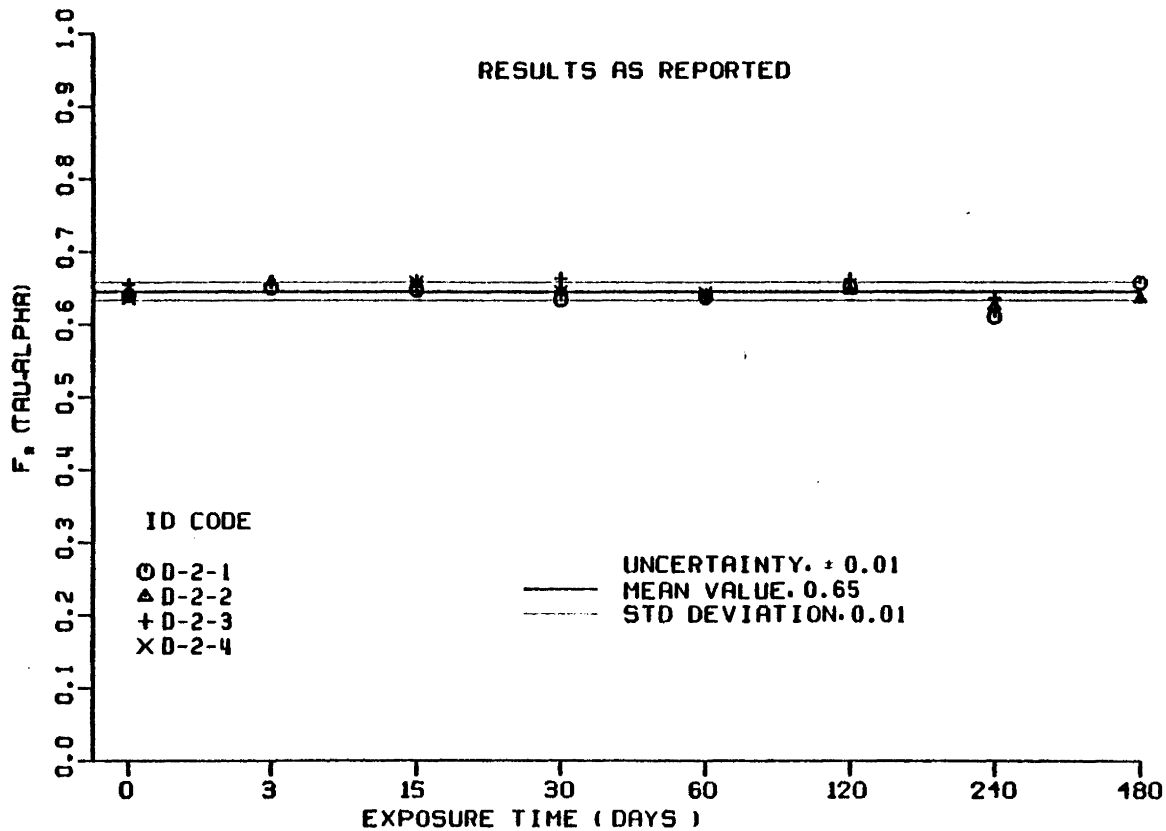

Figure 13. Values of $F_R(\tau\alpha)$ vs Exposure as Reported for Collector D, Test Site 2, All Test Series.

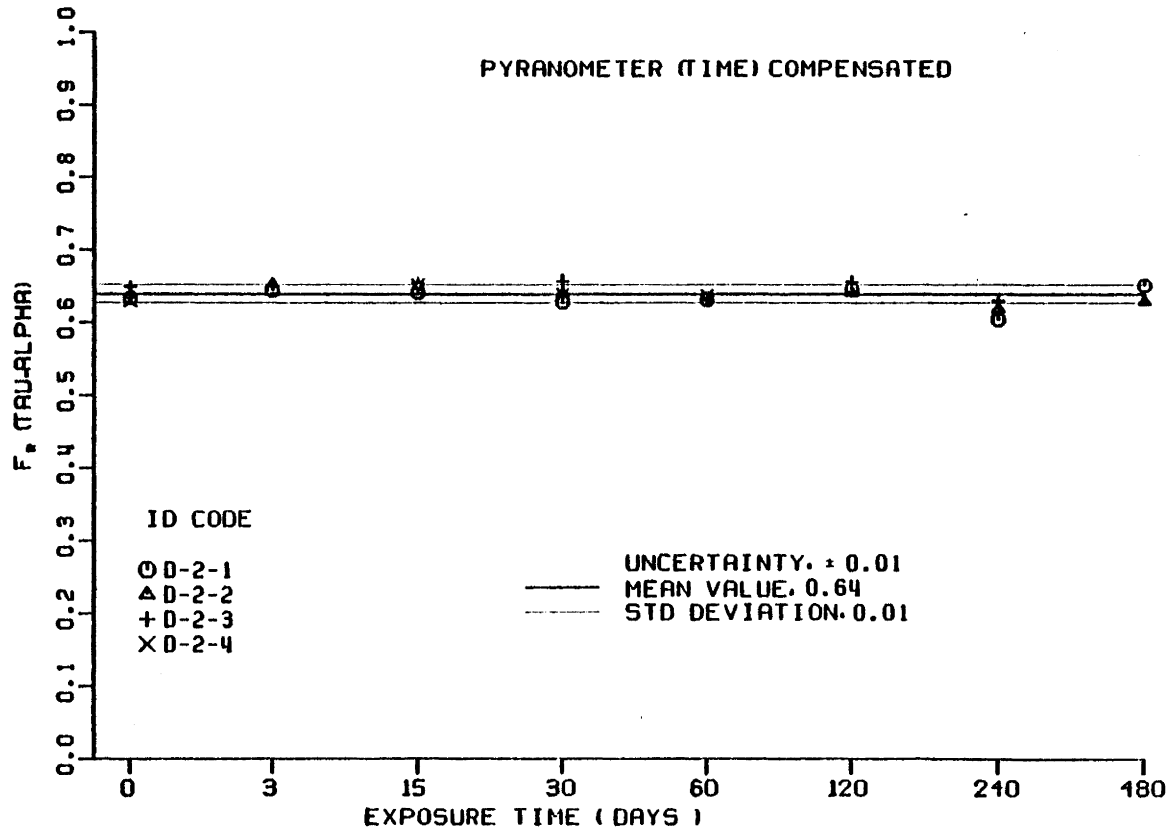

Figure 14. Values of $F_R(\tau\alpha)$ vs Exposure for Collector D, Test Site 2, All Test Series; Compensated for Time Varying Pyranometer Sensitivity.

limited calibration data as to the temperature dependence of pyranometers used, the instrument sensitivity to operating temperature was assumed to be invariant with time and was taken from the latest calibration information available. Computer algorithms were again prepared to compensate reported results based on the average ambient temperature during each test. It was found that temperature compensation did not result in any significant changes in the reported results. Figures 15 and 16 show the results of temperature correction on the results for collectors C and D. These figures show that the compensation for temperature dependence of the pyranometers used was insignificant.

In summary, changes in pyranometer sensitivity with respect to time introduced errors in the reported values of $F_R(\tau\alpha)$ of 2.0 to 3.0 per cent. Errors introduced as a result of sensitivity dependence on temperature were of the order of 0.2 to 0.6 per cent and are relatively insignificant.

In addition to examining the effects of pyranometer calibration constants used, an analysis has been made to determine if a particular pyranometer or test stand could be identified as a major source of the scatter in the data. This was evaluation accomplished by identifying values of $F_R(\tau\alpha)$ which fell outside of the calculated experimental uncertainty limits as measured from linear curve fits of $F_R(\tau\alpha)$ as a function of exposure. Figure 17 presents a graphical illustration of this procedure. The experimental uncertainty in determining $F_R(\tau\alpha)$ was taken to be $\pm$ 0.01 as calculated by Culkin [10]. Any values of $F_R(\tau\alpha)$

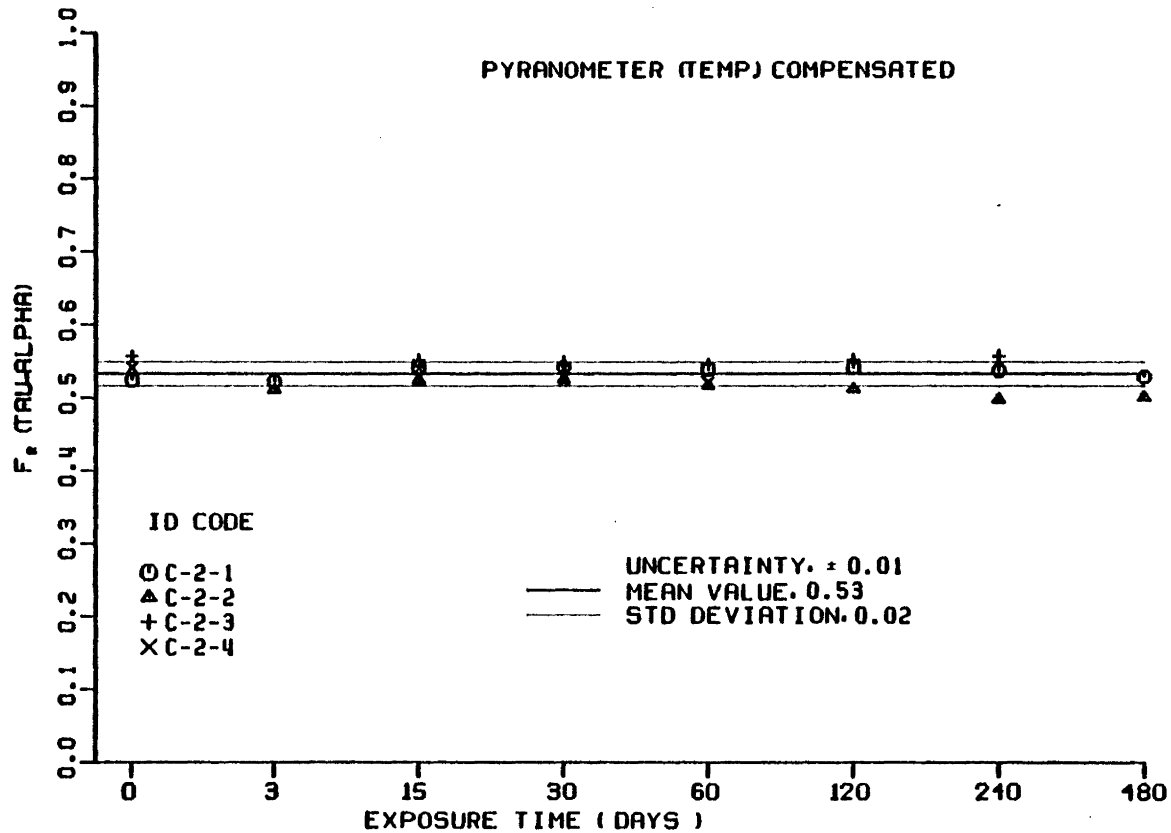

Figure 15. Values of $F_R(\tau\alpha)$ vs Exposure for Collector C, Test Site 2, All Test Series; Compensated for Pyranometer Temperature Dependence.

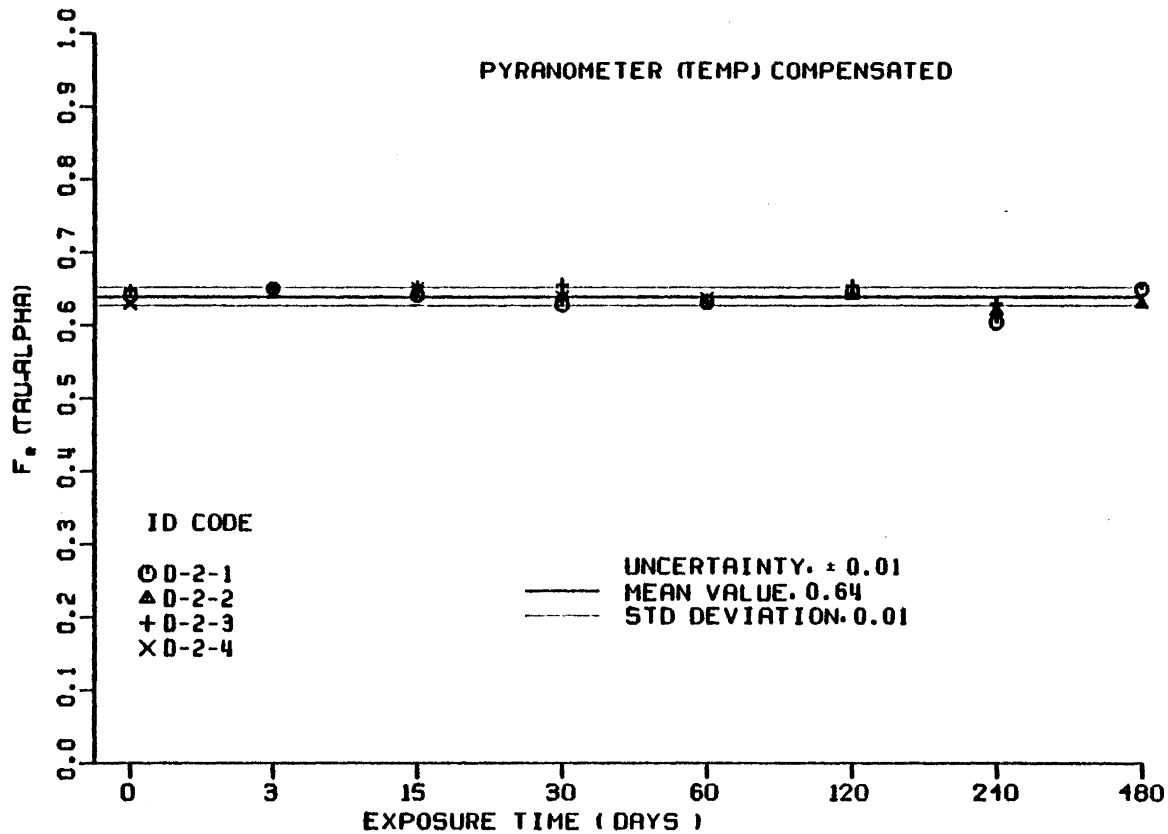

Figure 16. Values of $F_R(\tau\alpha)$ vs Exposure for Collector D, Test Site 2, All Test Series; Compensated for Pyranometer Temperature Dependence.

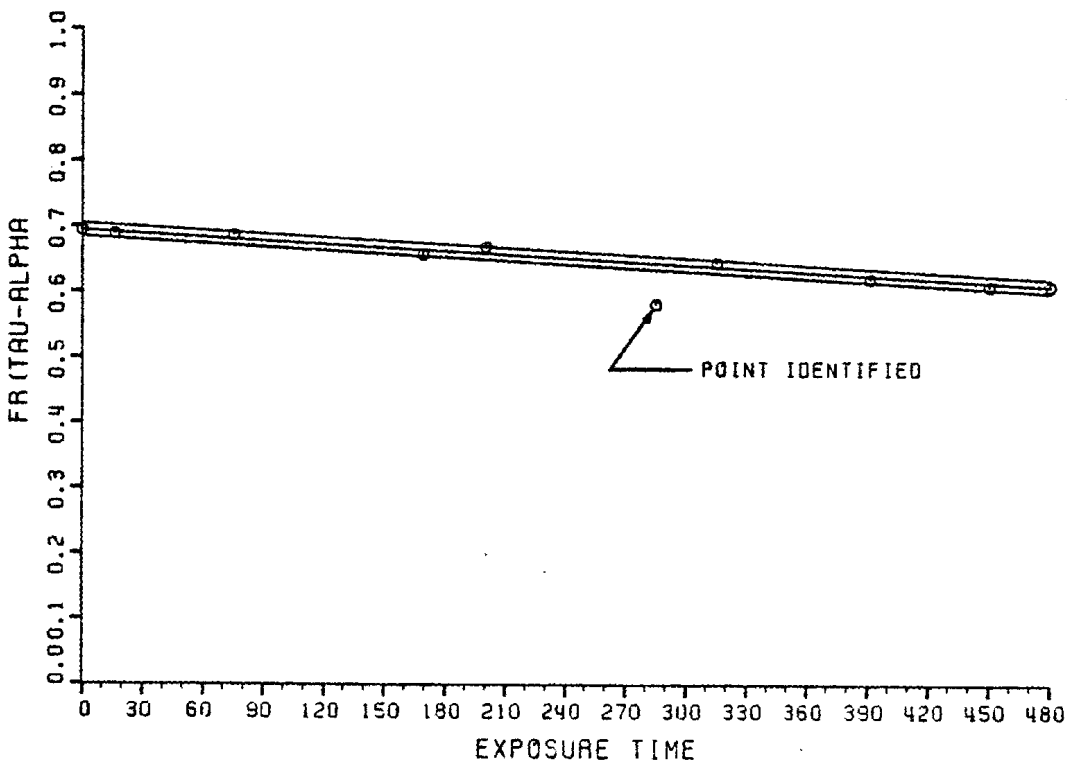

Figure 17. Graphical Illustration of Identification Procedure.

beyond this uncertainty from the linear fit were recorded along with the particular pyranometer and test stand used for that test.

To prevent an unjust bias of such an analysis, the number of times each pyranometer and test stand were used was tabulated as well. Percentages of the number of times used a particular pyranometer or test stand yielded results outside of the permissible uncertanity band were then computed. Table 4 shows the results of this analysis through the first 120 exposure days.

These tabulated results show that no one pyranometer or test stand can be identified as a primary source of data spread. It should be noted that of the points identified as outside the permissible uncertainty band, as many were found to be high as were found to be low. This result also held true for individual pyranometers. In other words, the points identified as suspect were randomly distributed. The pyranometers and test stands yielding such points were random as well.

3.4 Adjustment of Reported Values of $F_R(\tau\alpha)$ and F_RU_L to a Reference Set of Environmental Conditions

The results of efficiency testing may be affected by the test environment. Environmental factors such as wind speed, ambient temperature, total solar irradiation, and the fraction of scattered irradiance at the time of test may substantially affect both the heat transfer and optical characteristics of the collector assembly.

Table. 4. Tabulations of the Percentage of Times Used that a Particular Pyranometer or Test Stand Yielded Results Beyond the Experimental Uncertainty Limits from the 1st Order Curve Fit of $F_R(\tau\alpha)$ vs Exposure Time.

Pyranometer Serial Number or Test Stand	Number of Times Used	Percentage of Times Used When Values are Beyond Experimental Uncertainty
14317	16	18.75%
14318	25	12.00%
14319	13	38.46%
14320	5	40.00%
14321	21	9.52%
14322	10	30.00%
17349	25	20.00%
18273	14	42.86%
Stand 1	12	25.00%
Stand 2	15	26.67%
Stand 3	25	16.00%
Stand 4	23	13.04%
Stand 5	24	25.00%
Stand 6	32	31.25%

Error of estimate associated with 1st order fits

0-day	3-day	15-day	30-day	60-day	120-day
0.11	0.11	0.19	0.23	0.15	0.07

Note: Analysis through 120 exposure days.

The parameter $F_R U_L$ is particularly sensitive to the test environment. The overall loss coefficient, U_L, represents the algebraic sum of the top, edge, and back loss coefficients. The heat loss from the collector occurs primarily through the top (cover) of the assembly. The top loss coefficient is a function of the convective heat transfer coefficient, ambient temperature, and the mean absorber plate temperature. An empirical formula for calculation of U_{Top} develop by Klein (1979) shows this dependence for glass covered collectors.

$$U_{top} = \left\{ \frac{N}{\frac{C}{t_{pm}}\left[\frac{(t_{pm} - t_a)}{(N + f)}\right]^e} + \frac{1}{h_w} \right\}^{-1} + \frac{\sigma(t_{pm} + t_a)(t_{pm}^2 + t_a^2)}{(\epsilon_p + .00591\, Nh_w)^{-1} + \frac{2N + f - 1 + 0.133\epsilon_p}{\epsilon_g} - N} \qquad (8)$$

where

N = number of glass covers

$f = (1 + 0.089\, h_w - 0.1166\, h_w \epsilon_p)(1 + 0.07866N)$

$C = 520(1-0.000051\, \beta^2)$ for $0° < \beta < 70°$. For $70° < 90°$; use $\beta = 70°$

$e = 0.43\ (1-100/t_{pm})$

β = collector tilt (degrees)

ϵ_g = emittance of glass (0.88)

ϵ_p = emittance of plate

t_a = ambient temperature (K)

t_{pm} = mean plate temperature (K)

h_w = convective (wind) heat transfer coefficient (W/sq m · C).

Several terms in this equation are strongly dependent upon the test environment. Ambient temperature appears directly in the calculation.

The convective heat transfer coefficient is a strong function of wind speed. Also, total solar irradiation indirectly enters into the determination of U_{top}. The mean plate temperature, t_{pm}, is proportional to the level of incident radiation. As result, U_L and consequently $F_R U_L$ are dependent upon environmental conditions at the time of each efficiency test.

Because of the possible effects of the test environment on the measured values of $F_R(\tau\alpha)$ and $F_R U_L$, a correlation of results from efficiency tests performed under any particular set of weather conditions to a reference set of "standard" conditions is in order. The goal of such a correlation is to remove the dependence of the test results on environmental factors.

The motivation for correlating test results to a reference set of conditions is twofold. A correction to one set of standard conditions should result in a reduction in the spread of values of $F_R(\tau\alpha)$ and $F_R U_L$ which may be attributed to differing environmental conditions for tests performed at different times. Rarely, if ever, will the weather be constant for any two test dates. Secondly, correction to a unique set of environmental conditions provides a common basis from which test results from different test sites may be compared. A correction of this type is necessary to remove the environmental dependence of the test results so that an analysis may be made to determine if interlaboratory differences in testing exist. Such an analysis will be presented in a subsequent section.

An analytical procedure has been developed at VPI & SU to perform this correction to standard weather conditions [8,21,22]. The standard test environment used in the correction is presented in Table 5. The values shown in this table represent approximately median weather conditions for the continental United States. These values also represent approximately the median values of the test conditions experienced throughout the test program.

A detailed description of the correction procedure developed at VPI & SU is presented by W. C. Thomas in reference 8. The correction employed consists of using an analytical model of the collector under consideration to calculate efficiencies at standard and at test conditions for a particular $\Delta t/H_T$. The difference between these calculated efficiencies is then added to the measured efficiency. This correction may be written as

$$\eta(X, \text{Std. Conditions})_{\text{corrected}} = \eta(X, \text{Test Conditions})_{\text{measured}} + [\eta(X, \text{Std. Conditions})_{\text{calculated}} - \eta(X, \text{Test Conditions})_{\text{calculated}}] \quad (9)$$

where

$X = (t_i - t_a)/H_T$ is held constant. Experimental verification of the validity of this procedure has been demonstrated with reasonable success [8,21,22].

The information required for this correction includes pertinent weather parameters and collector operating conditions during testing. Physical characteristics of the collector construction are also required. In addition, heat transfer characteristics of the absorber plate, cover assembly, and insulation are necessary. These

†Table 5. Standard Test Environment Used in Compensation for Environmental Dependence of Reported Results

Condition	Value
Ambient Temperature	20°C
Solar Irradiance	1000 W/sq m
Incident Beam Angle	15 deg.
Diffuse Fraction of Irradiance	0.15
Wind Speed	3 m/s
Test Fluid	Water
Flow Rate	0.02 kg/s-sq m
Collector Slope	45 deg.

† Reprinted from reference 8.

characteristics are then used to create an analytical model of the collector under consideration.

The correction procedure as outlined has been used to reference the test results of collectors B and E to standard weather conditions for all tests performed. Collectors B and E have been selected for analysis because these collectors are typical of the most prevalent designs and construction materials commerically available. Both collectors are arranged in a parallel flow configuration. Collector B has a double, low-iron glass cover with a copper absorber plate. Collector E has a single polymer (Kalwal Sun-lite Premium II) cover and a copper absorber plate. The physical characteristics and heat transfer properties used in the correction were obtained from baseline measurements conducted at the time of initial exposure. These values are shown in Table 6.

Figure 18 shows an aggregate plot of all instantaneous efficiency measurements made for collector B-1-1. This figure represents a typical aggregate plot for the two collectors under consideration. The efficiency curve predicted by the model has been superimposed as a solid line. This figure shows that the agreement between the model and the data is quite good, as was the agreement for all collector-site-series combinations examined. Appendix C contains plots similar to Fig. 18 for the other series-site combinations for collectors B and E.

Having established valid models for the two collectors under consideration, the correction procedure was implemented to determine if the scatter in the reported values of $F_R(\tau\alpha)$ and F_RU_L could be attributed to environmental factors. Plots of the corrected values as

Table 6. Baseline Values of Optical and Heat Transfer Properties of Collectors Band E

Property	Collector B	Collector E
α	0.98	0.95
ε_p	0.92	0.87
k_e	0.0095 mm^{-1}	0.074 mm^{-1}
τ	0.89	0.85

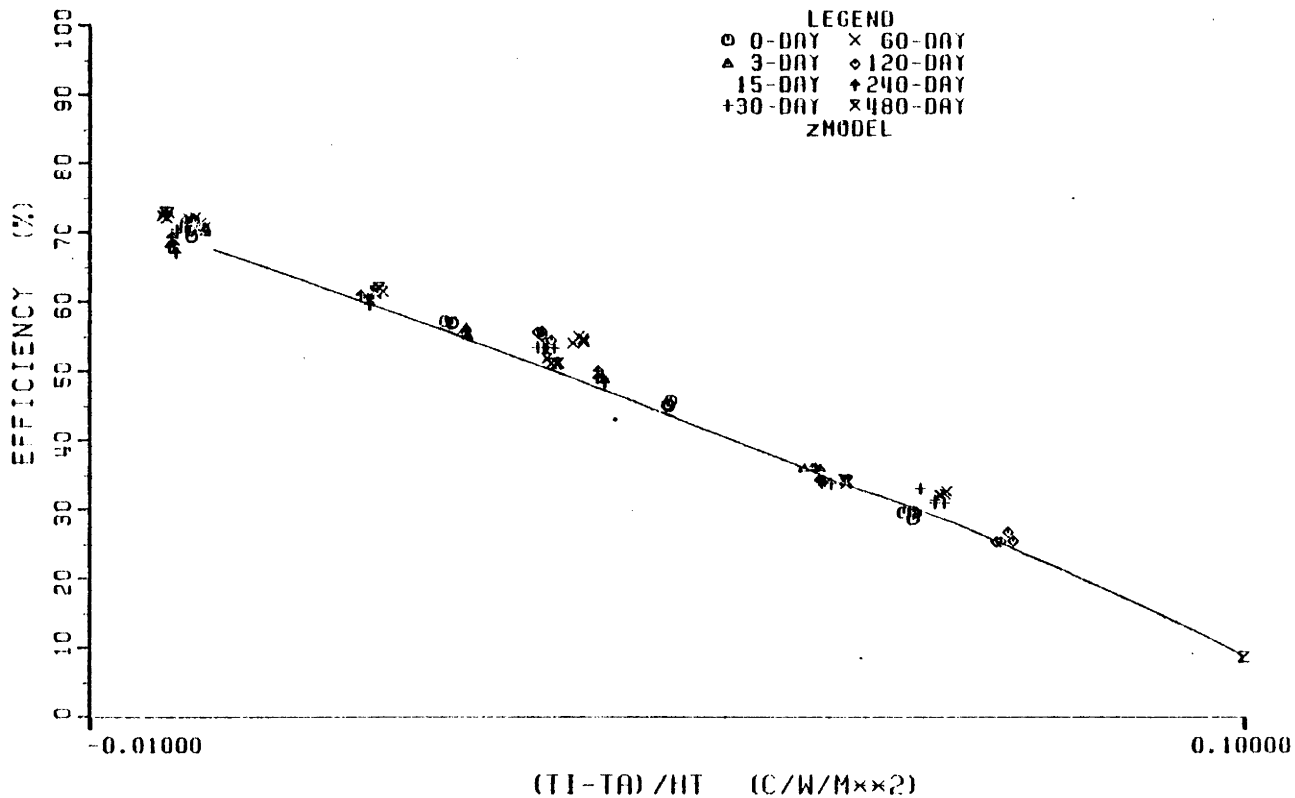

Figure 18. Aggregate Plot of All Instantaneous Efficiency Measurements Made for Collector B-1-1 with Analytical Model Prediction.

functions of exposure time were prepared and comparisons of these were made to the plots of the "results as reported". Figures 19 through 26 show typical plots of these types. As these plots show, compensation for environmental differences at the time of testing does not significantly alter the reported results.

An analysis of the graphical results show that no significant changes in the trends, or lack of trends, in the values of $F_R(\tau\alpha)$ and F_RU_L resulted from taking into account different environmental best conditions. The mean values of $F_R(\tau\alpha)$ remained with ±0.01 efficiency per cent of the mean values of the reported results by site or by series. The mean values of F_RU_L increased by an average of 0.22 W/m^2C. This slight increase was probably a result of the "standard" value of wind speed being slightly higher than the average wind speed experienced during the testing. More importantly, the standard deviations about the mean values did not change significantly for either $F_R(\tau\alpha)$ or F_RU_L. The weather correction employed did not reduce the scatter in the data, nor did it change the magnitude of the mean values of either parameter. As a result, it may be concluded that environmental factors during testing are not a major cause of scatter in the reported values of $F_R(\tau\alpha)$ or F_RU_L. Further, the levels of the performance parameter values as reported did not change markedly for any of the individual test sites, indicating that weather conditions during testing did not differ greatly from the median values used as a reference.

Additionally, the plots of the corrected values of $F_R(\tau\alpha)$ and F_RU_L showed no new trends or recognizable general degradation trends. The

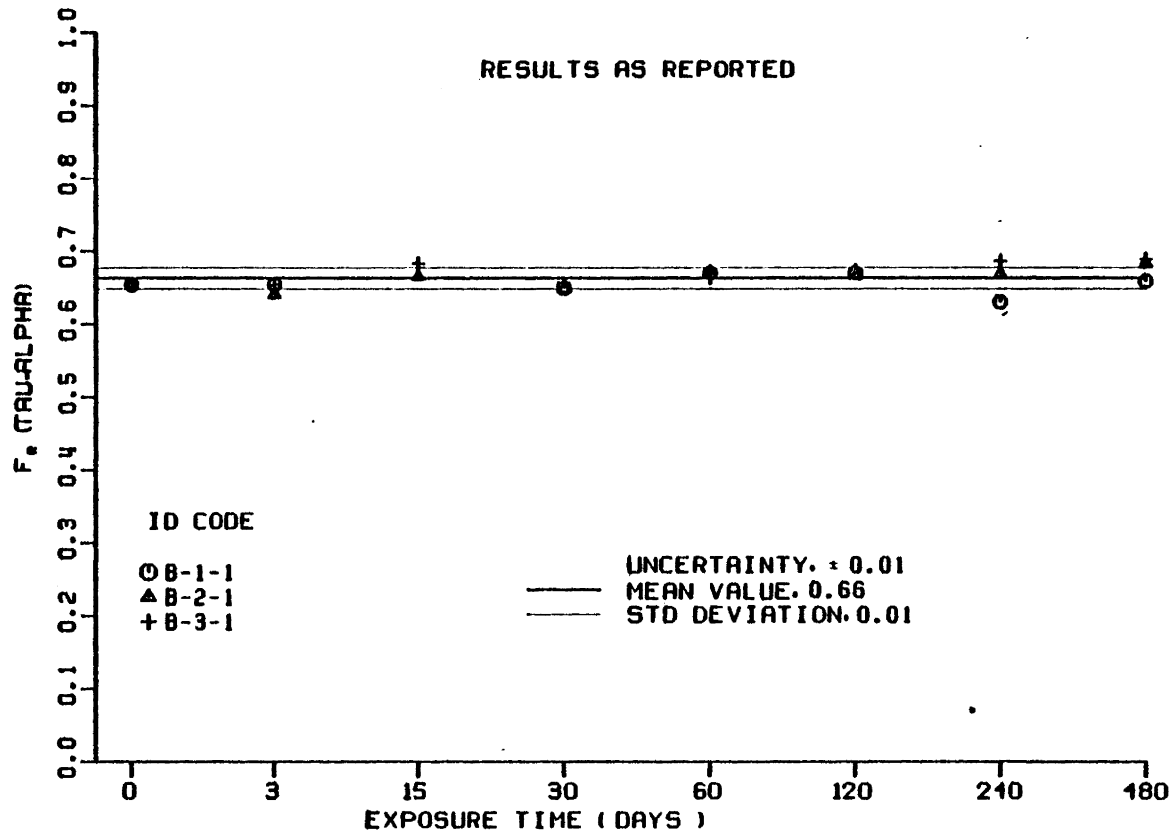

Figure 19. Reported Values of $F_R(\tau\alpha)$ for Collector B, Test Sites 1, 2, and 3, Test Series 1 vs Exposure Time.

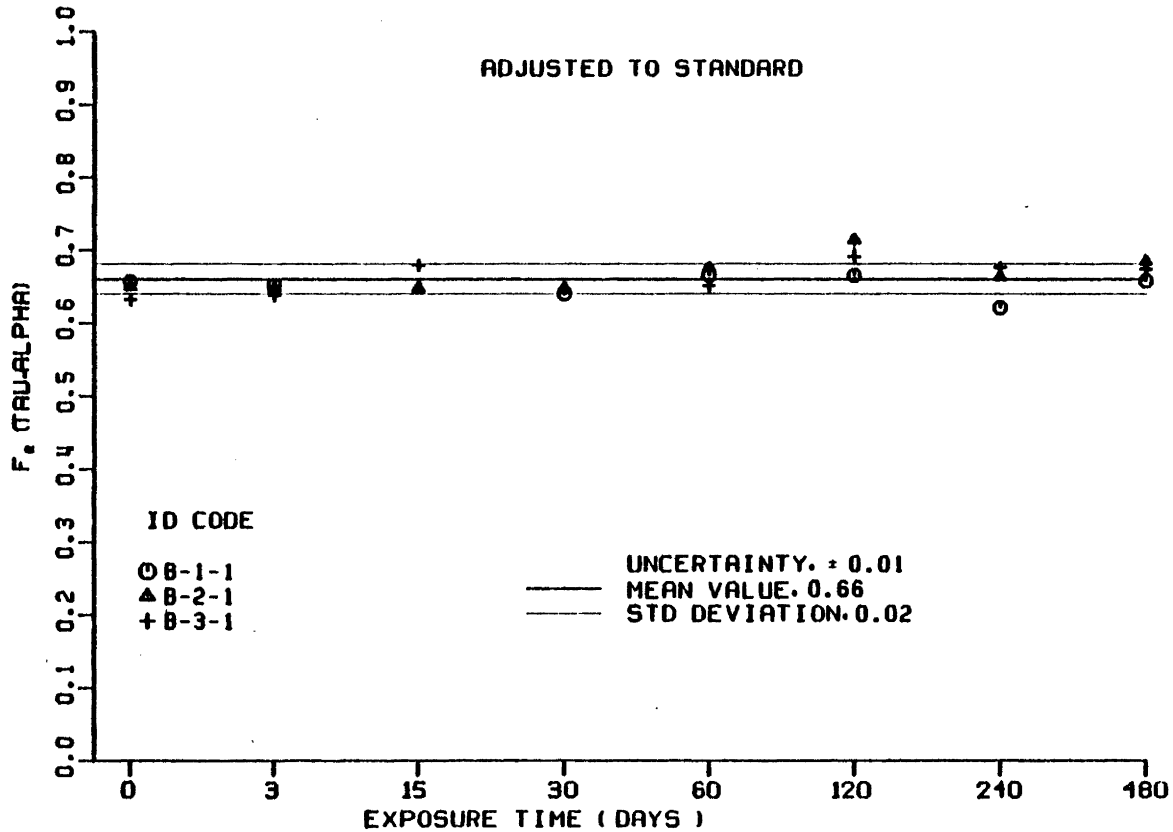

Figure 20. Values of $F_R(\tau\alpha)$ for Collector B, Test Sites 1, 2, and 3, Test Series 1; Adjusted to Standard Weather Conditions.

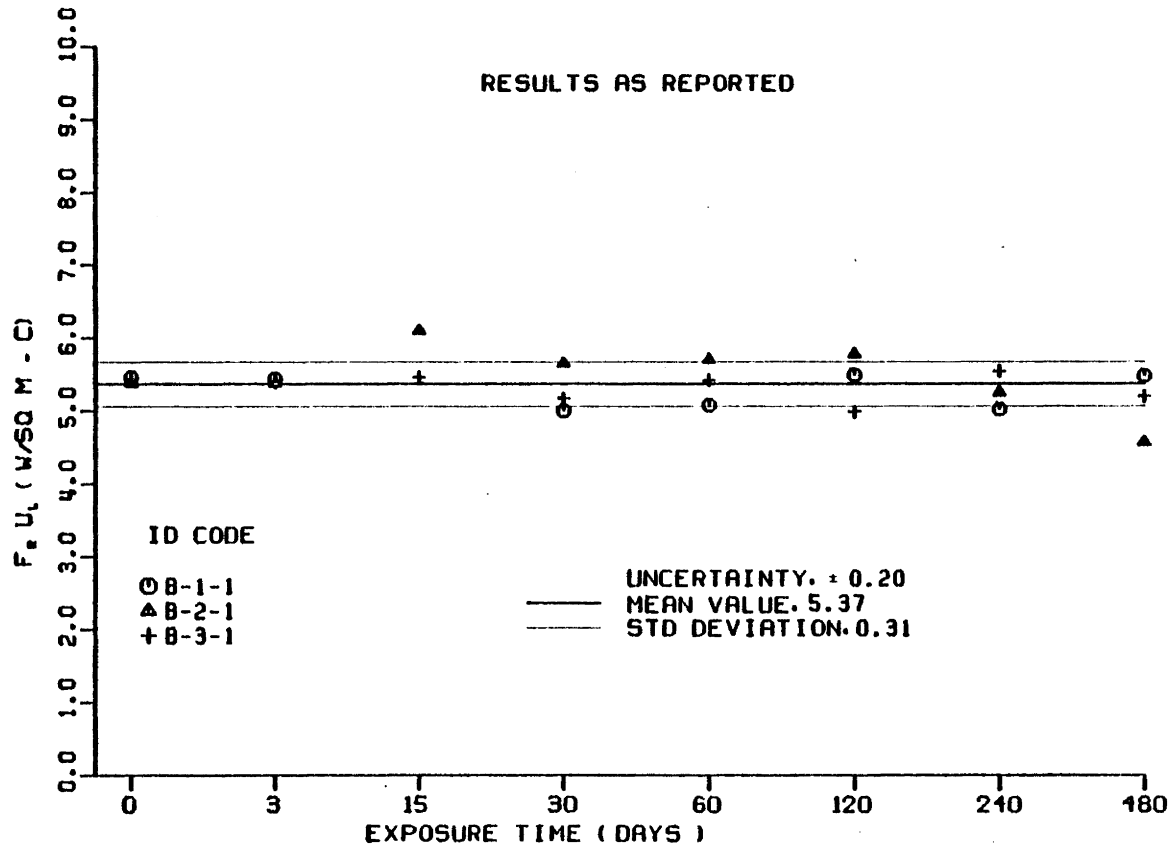

Figure 21. Reported Values of $F_R U_L$ for Collector B, Test Sites 1, 2, and 3, Test Series 1 vs Exposure Time.

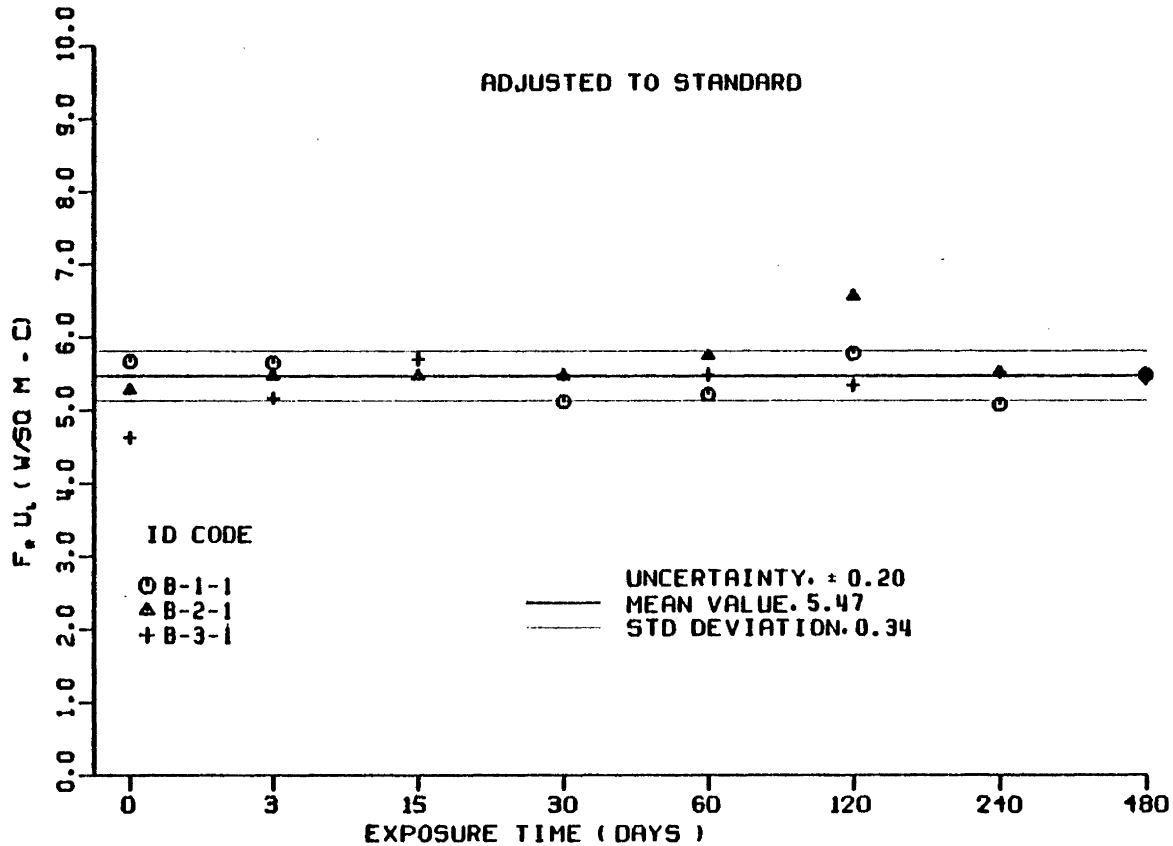

Figure 22. Values of $F_R U_L$ for Collector B, Test Sites 1, 2, and 3, Test Series 1; Adjusted to Standard Weather Conditions.

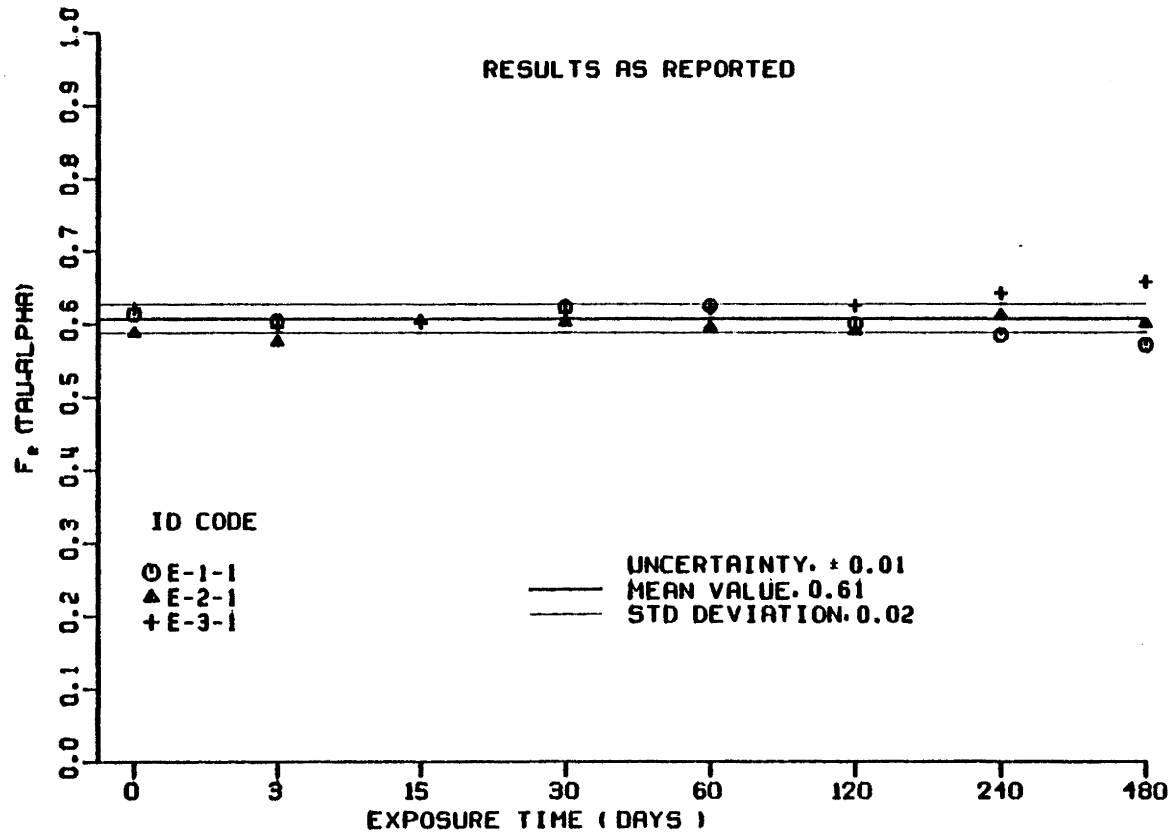

Figure 23. Reported Values of $F_R(\tau\alpha)$ for Collector E, Test Sites 1, 2, and 3, Test Series 1 vs Exposure Time.

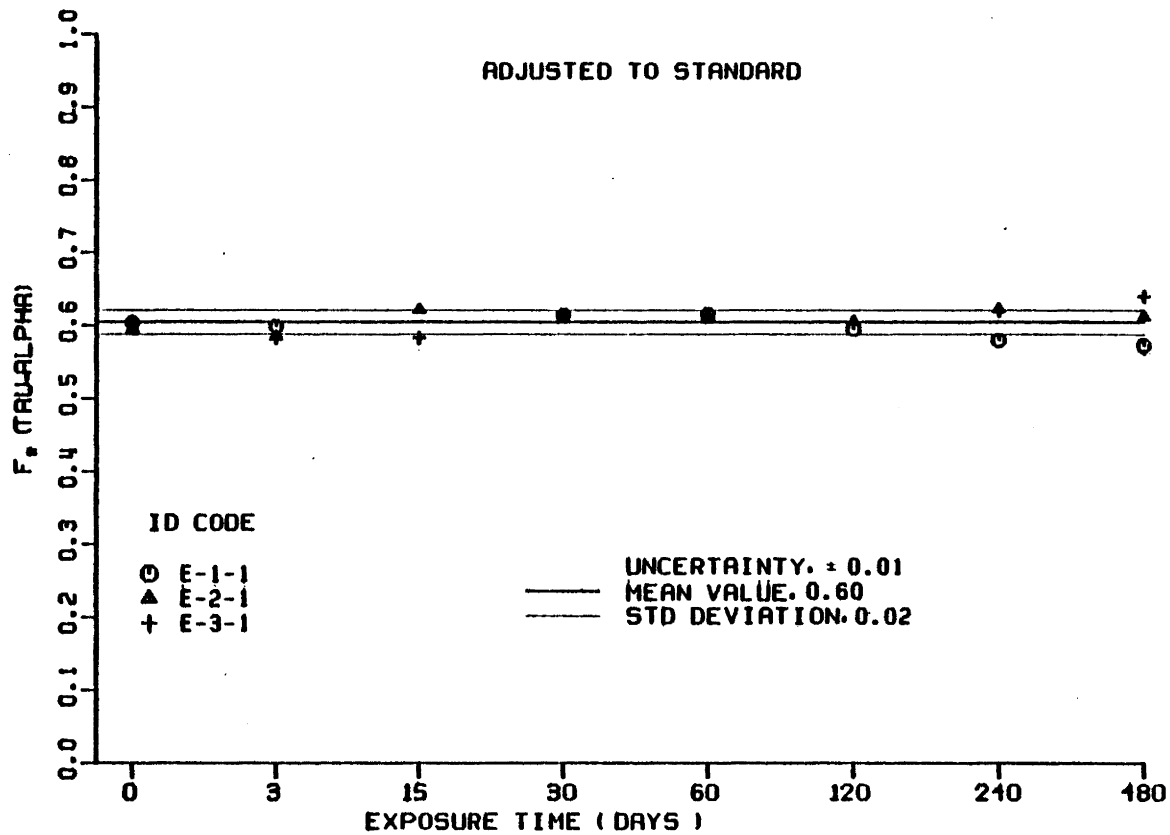

Figure 24. Values of $F_R(\tau\alpha)$ vs Exposure for Collector E, Test Sites 1, 2, and 3, Test Series 1; Adjusted to Standard Weather Conditions.

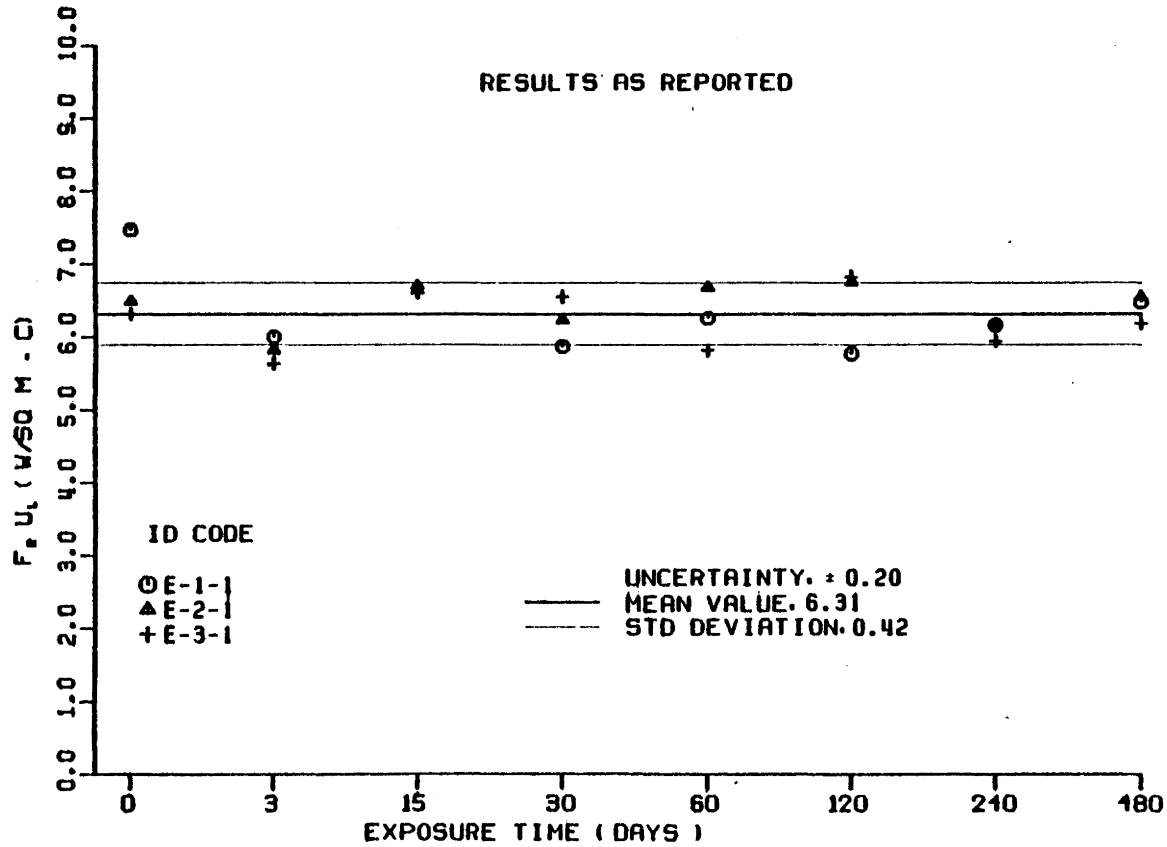

Figure 25. Reported Values of $F_R U_L$ for Collector E, Test Sites 1, 2, and 3, Test Series 1 vs Exposure Time.

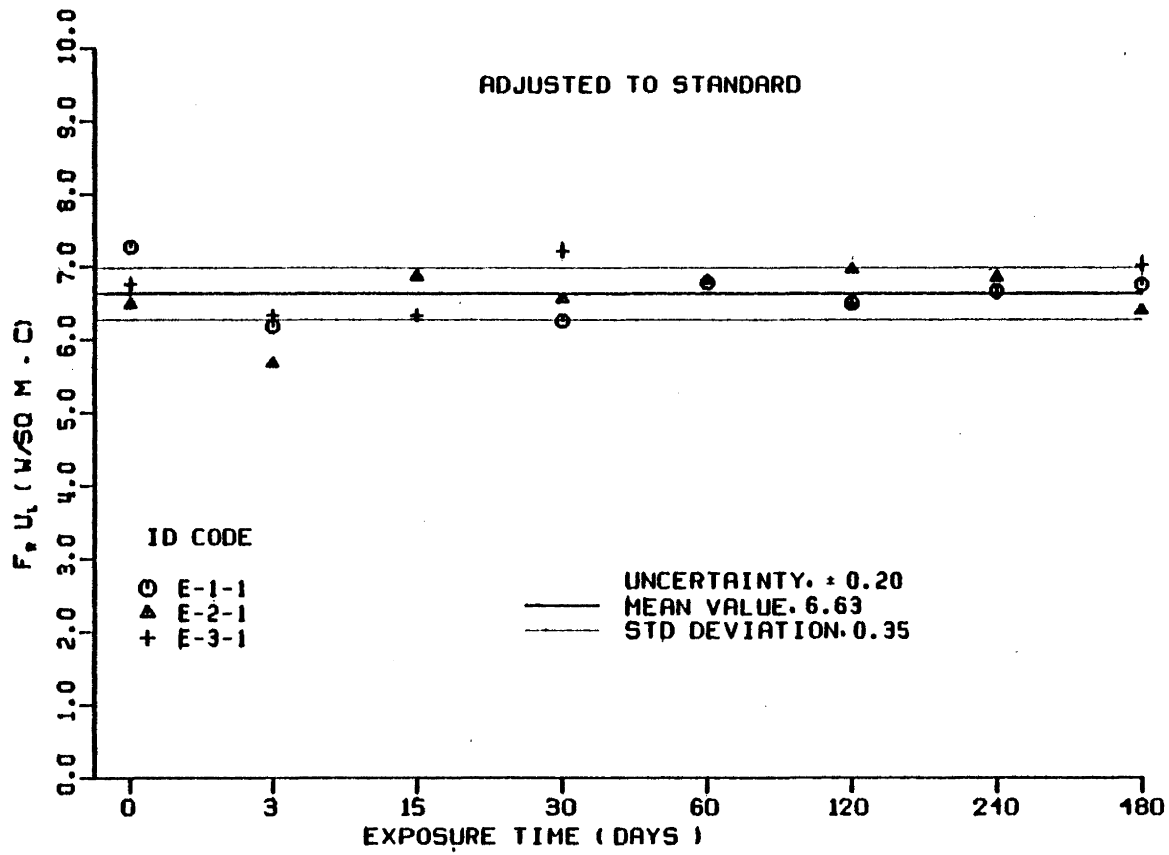

Figure 26. Values of $F_R U_L$ vs Exposure for Collector E, Test Sites 1, 2, and 3, Test Series 1; Adjusted to Standard Weather Conditions.

weather compensation did not affect the 30-60 exposure day peak behavior of $F_R(\tau\alpha)$. Thus, this anomalous behavior does not appear to be caused by environmental conditions during testing.

3.5 Analysis of Interlaboratory Differences by Statistical Methods

An analysis has been conducted to determine if significant interlaboratory differences could be detected in the test program data and results. Previously, it was shown that the primary performance parameters were not significantly affected by the test environments. However, other factors such as instrument calibration and test implementation may cause systematic differences in the results reported from the test laboratories. The analysis of this section has been conducted to determine if such differences are present, and if so, what effect these differences have on the reported results.

Two methods of analysis are used to investigate possible interlaboratory differences. One method is a modification of a graphical approach recommended by W. J. Youden [19]. The other approach is a comparison of standard deviations and variances of test results within and between test sites at the beginning of the test program to these same quantities at the completion of the program. The calculation of within and between site standard deviations is based on a well established method of statistical analysis developed by J. Mandel [17]. For the current analysis, "weather corrected" values of $F_R(\tau\alpha)$ and F_RU_L for collectors B and E have been used in order to minimize the influence of weather induced variability.

3.5.1 Description of Graphical Approach.

The graphical approach to analysis of interlaboratory tests as developed by Youden is a simple, straightforward method based upon some elementary statistical principles. The strategy is to plot ordered pairs of measured values for two different samples on a pair of normal axes. In the present analysis, the two samples considered are collectors B and E. The "data points" consist of ordered pairs of the measured values of a performance parameter obtained at an equivalent level of exposure at a specific laboratory. These ordered pairs are plotted with the values of the performance parameter for one collector as the ordinate and the value for the other collector as the abscissa for each laboratory. A horizontal median line is then drawn, separating the data into two equally probable regions of finding a value of the ordinate collector parameter. Similarly, a vertical median line is drawn to create two regions in which the probability is 1/2 of finding a abscissa collector value in either section. As a consequence, the plot will effectively be separated into four regions. If the test program experiences only random measurement errors, the probability of a given ordered pair falling into any one of the four regions is 1/4. The points obtained from a program influenced only by random measurement errors will lie in a circular pattern centered at the intersection of the median lines. As reported by Youden, this configuration is rarely encountered. Rather, the points tend to congregate in the upper right and lower left quadrants. Points in these quadrants represent cases when a particular laboratory measures the parameter high for both

samples (upper right quadrant) or low for both samples (lower left quadrant). Congregations of points for a particular laboratory in one or the other of these quadrants indicates that the laboratory has experienced a modification in the test procedure in such a way as to introduce a constant error causing the measured values to be consistently high or consistently low. If the points for a particular laboratory tend to congregate along the median lines, a sensitivity of the test procedure to the magnitude of values measured is indicated. Interpretation of other data patterns are possible and will be presented as necessary.

3.5.2 Application of Graphical Analysis to the Durability/ Reliability Test Program.

In order to implement this graphical approach, a "null hypothesis" is assumed, i.e., no degradation or improvement in the performance parameters occurred with time. This assumption is necessary for interpretation of data point configurations. By this assumption, it is assumed that configurations which arise are caused by interlaboratory differences rather than changes in the parameters with time. Since the changes with time of each performance have been shown to be relatively small and usually random, the null hypothesis assumption as outlined is reasonable enough to provide a general estimation of interlaboratory differences. Later this assumption will be relaxed (and the method modified) to make some estimation of the precision associated with the test program.

Figures 27 through 30 show the results of the graphical approach for ordered pairs of $F_R(\tau\alpha)$ and $F_R U_L$ for collectors B and E, test series 1 and 2.

The ordered pairs of $F_R(\tau\alpha)$ values for test series 1 and 2 are shown in Figs. 27 and 28. These two figures show the tendency for data pairs to congregate in quadrants II and III as expected from the previous discussion. As can be seen in both figures, the data pairs for laboratory 2 show a particular tendency to congregate in quadrant II. It appears that test results from this laboratory may be influenced by some factor or some aspect of the test procedure not evident in the results from other laboratories. Previous analysis has shown that time varying sensitivity changes in the calibration constants of pyranometers used at laboratory 2 resulted in reported values of $F_R(\tau\alpha)$ which were determined to be 2-3 per cent higher than actual. This fact provides partial explanation of the anomaly seen in Figs. 27 and 28. Figure 28 also shows a congregation of data pairs from laboratory 3 in quadrant III. Since this pattern for laboratory 3 is not evident in Fig. 27, it appears that test series 2 may be affected by some factor not prevalent in test series 1.

While the tendencies outlined above suggest possible areas of concern, they do not represent conclusive evidence of interlaboratory differences in the determination of $F_R(\tau\alpha)$. The tendencies outlined represent cases when approximately one half of the ordered pairs from a particular laboratory fell in a particular quadrant. Further, the clustering of these points near the intersection of the median lines

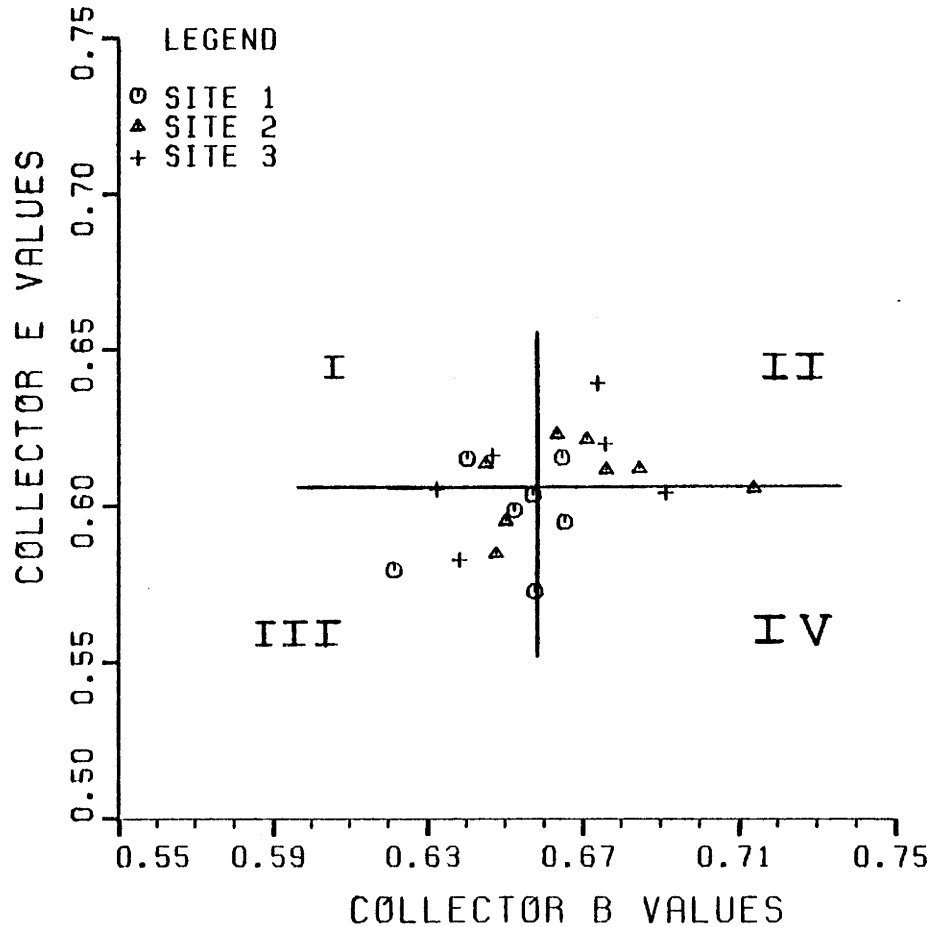

Figure 27. Graphical Analysis of $F_R(\tau\alpha)$ Values for Collectors B and E, Test Series 1.

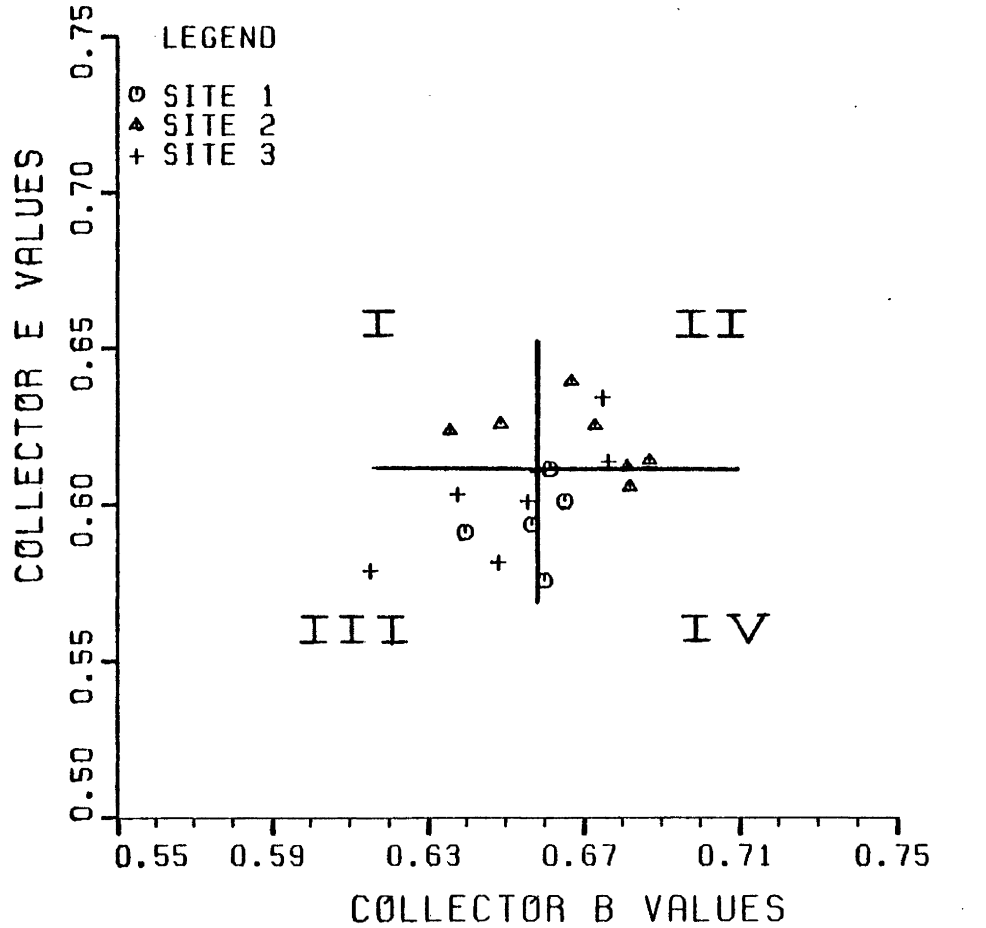

Figure 28. Graphical Analysis of $F_R(\tau\alpha)$ Values for Collectors B and E, Test Series 2.

rather than far out in the respective quadrants indicates that the tendencies are not highly significant.

Figures 29 and 30 show that the overall configurations of data pairs for F_RU_L are distributed in circular patterns about the intersections of the median lines. This general pattern suggests that the determination of F_RU_L experienced random errors in measurement. This result is expected as a consequence of the uncertainties associated with determining F_RU_L. On a laboratory by laboratory basis, there is no significant evidence of substantial interlaboratory differences. The F_RU_L data pairs from laboratory 2, however, show some tendency to congregate in quadrant II. This fact indicates that there may be concern that some minor systematic error could be present in determination of F_RU_L at laboratory 2.

It should be noted that the observations made from analysis of Figs. 27 through 30 rest on the assumption of a null hypothesis as to changes of the performance parameters with time. Congregations of data pairs from a particular laboratory in any one quadrant may be a result of the performance durability of collectors in the exposure climate of that laboratory. However, examination of the primary performance parameters as functions of exposure time revealed that changes in each parameter were small. Consequently, the assumption of no changes in the performance parameters should suffice to indicate significant interlaboratory differences in the reported results.

The graphical approach as presented provides a qualitative examination of the reported results. The null hypothesis assumption has been

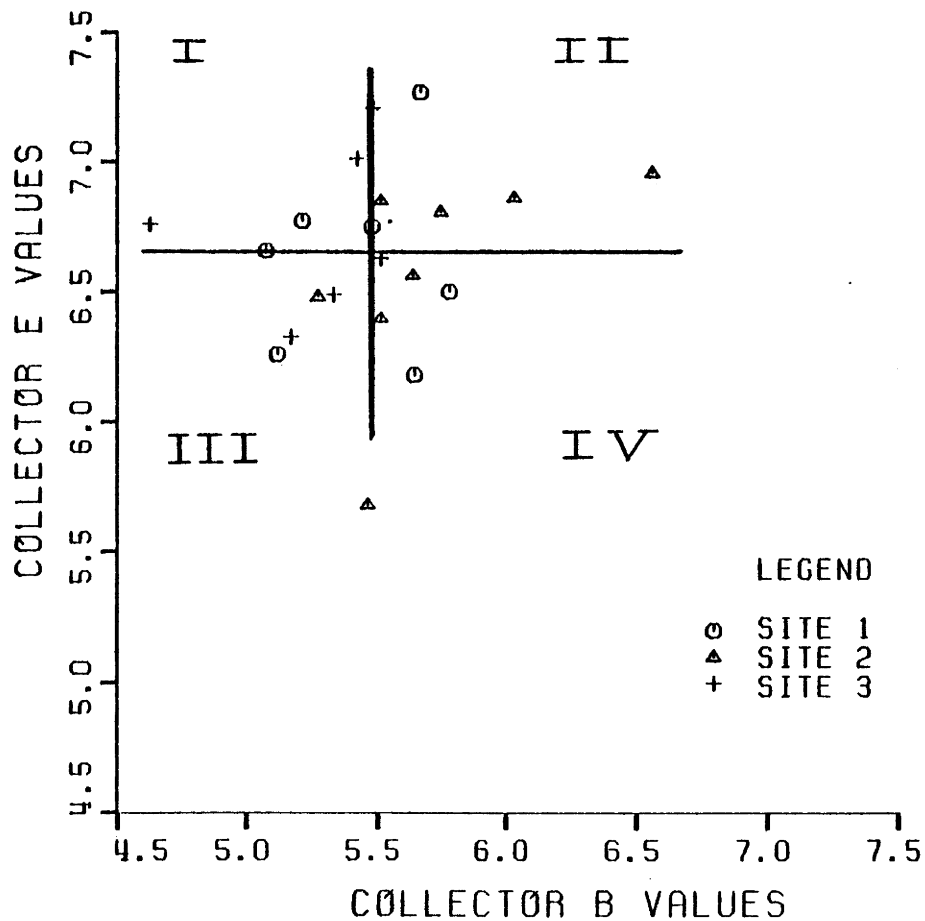

Figure 29. Graphical Analysis of $F_R U_L$ Values for Collectors B and E, Test Series 1.

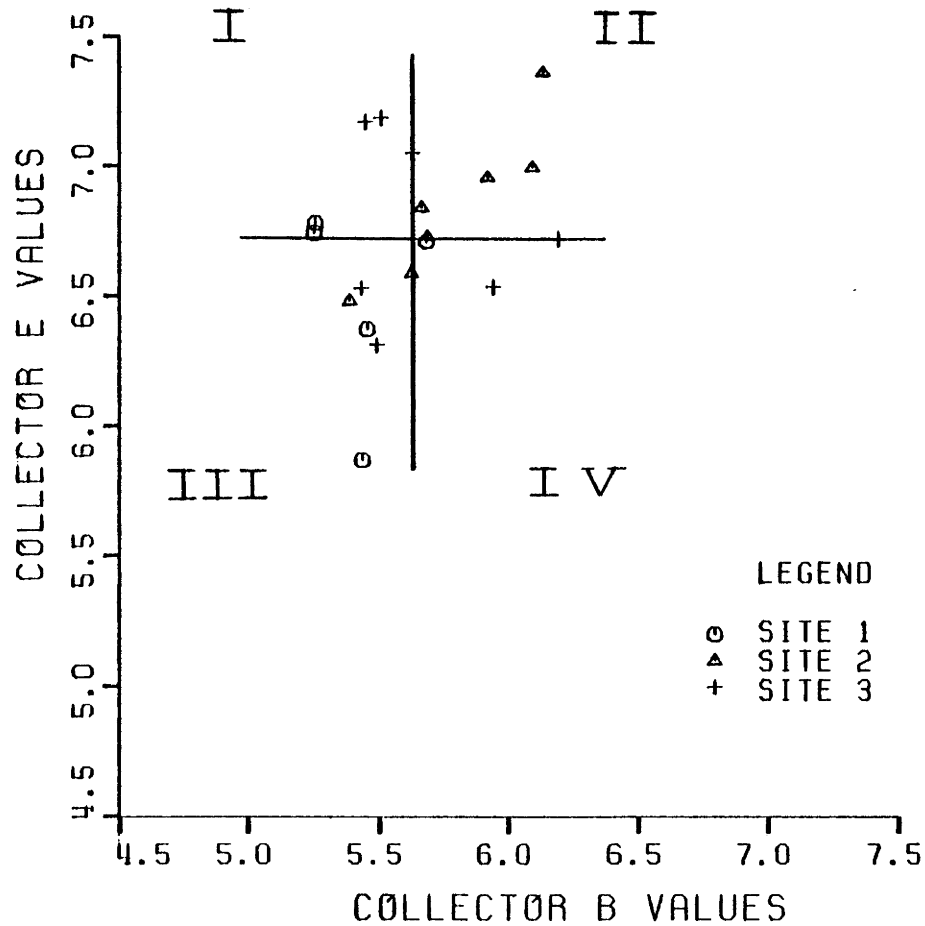

Figure 30. Graphical Analysis of $F_R U_L$ Values for Collectors B and E, Test Series 2.

invoked to facilitate the analysis. The next section presents a modification of Youden's basic approach developed by the present author to account for the possible changes in the measured values (performance parameters) with time and to ascribe some estimate of precision to the test method.

3.5.3 Description of Modifications of Youden's Graphical Analysis Necessary to Account for Time Rates of Change in Measured Values.

Youden's method also yields information concerning the precision of the test method for single- or double-sample round robin tests [19]. This analysis is based on the following procedure. Ordered pairs of measured values for two samples are plotted and median lines are drawn in as before. A 45 degree line is then constructed through the intersection of the median lines and extending into quadrants II and III. This line represents a relation between values measured for the two samples as shown in Fig. 31. As discussed in reference 19, the perpendicular distance of each ordered pair to this 45 degree line can be used to make an estimation of the standard deviation of the single result by multiplying this distance by $\sqrt{\pi/2}$. The standard deviation of sample population is computed as the product of the average distance of data points to the 45 degree line times $\sqrt{\pi}/2$. By assuming that a normal circular distribution results, circles are then constructed with radii of various multiples of this overall standard deviation (centered at the intersection of the median lines) which correspond to a percentage of

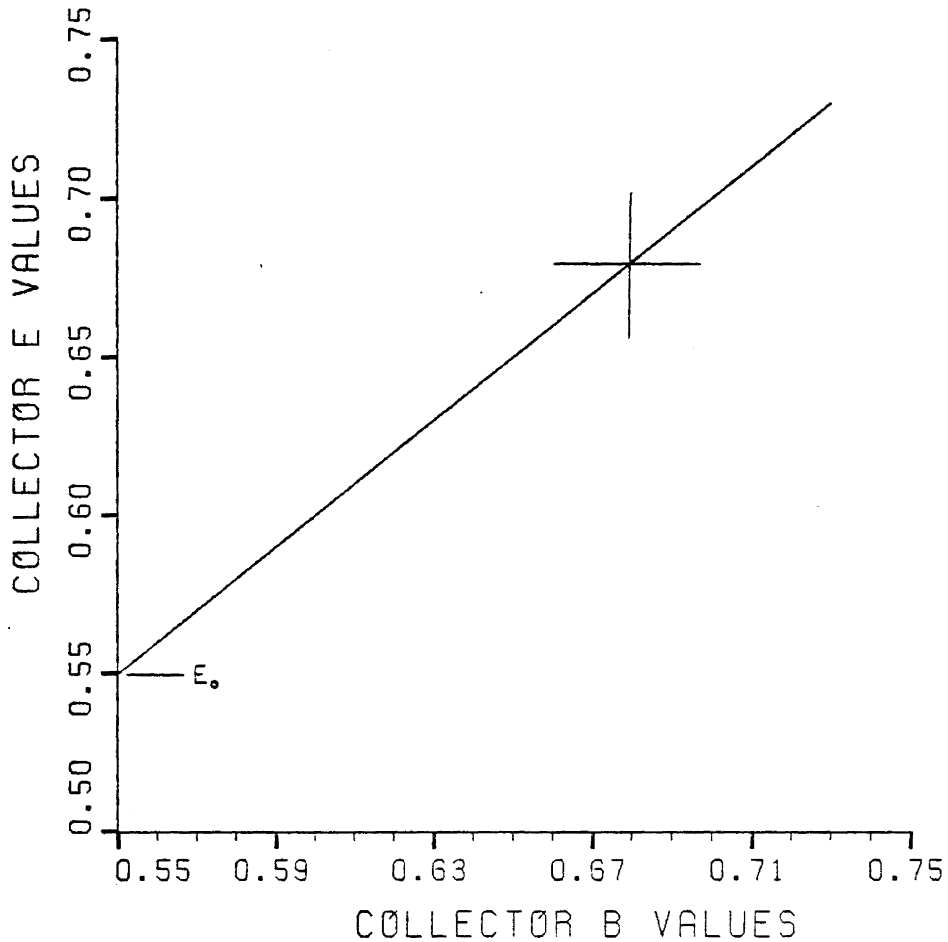

Figure 31. Graphical Development of Youden's Method.

points which should fall within. The percentage of points expected to fall within the circle is calculated as

$$\% = 100\ [k - \exp(\frac{-b^2}{2})]$$

where b is the multiple of the standard deviation used in determining the radius of the circle. Thus a circle of radius 2 1/2 times the overall standard deviation should contain approximately 95 percent of all plotted points. An excessive number of data points outside such a circle suggests test procedural or measurement problems.

Youden's precision analysis cannot be directly employed on the results of the Durability/Reliability Test Program without making some necessary assumptions. Youden's method is valid for testing a procedure by using results of a round robin test which does not consider changes in the measured property with time; that is, the measurable property is assumed to have some specific fixed value. In order to use Youden's method for the present data, the approach is to assume that the time rate of change of each sample is the same. This assumption seems valid since both of the collectors under consideration are similar in construction and are made of similar materials. Both collectors have a parallel flow configuration and both have copper absorber plates. As a consequence, it seems reasonable to expect that the degradation rates of each are similar. Letting $E(\theta)$ and $B(\theta)$ represent the measured values of one performance parameter for each collector at some exposure level or time, θ. The assumption then becomes

$$\frac{\partial E(\theta)}{\partial \theta} = \frac{\partial B(\theta)}{\partial \theta} \qquad (10)$$

At the original time of exposure, the relation between $E(\theta)$ and $B(\theta)$ is defined by the 45 degree line for the initial exposure test to be

$$E(0) = B(0) + E_o \tag{11}$$

As a result, Eq. 10 can be integrated with respect to time to yield

$$\int_0^{\theta} \frac{\partial E(\theta)}{\partial(\theta)} d = \int_0^{} \frac{\partial B(\theta)}{\partial \theta} d\theta$$

$$E(\theta) = B(\theta) + C \tag{12}$$

Applying the initial condition (Eq. 11) the result becomes

$$E(\theta) = B(\theta) + E_o \tag{13}$$

which is the equation of the 45 degree line for any fixed θ. Therefore, the intersections of the median lines generated for each level of exposure would all lie along the initial 45 degree line as shown in Fig. 32. As a consequence, the distance of each point from the 45 degree line will still give an estimation of the standard deviation of that result in the context of the particular time that the test was performed. This analysis is based upon the proposition that these distances may still be averaged to obtain an estimate of the overall standard deviation of the measurements. Circles may still be drawn on a single set of median lines to indicate a percentage of data pairs expected to be contained within. This single set of median lines should be constructed as an aggregate of the superimposition of each individual set of median lines. In the present case, the single set of median lines or "median axes" will be taken to be the initial test value

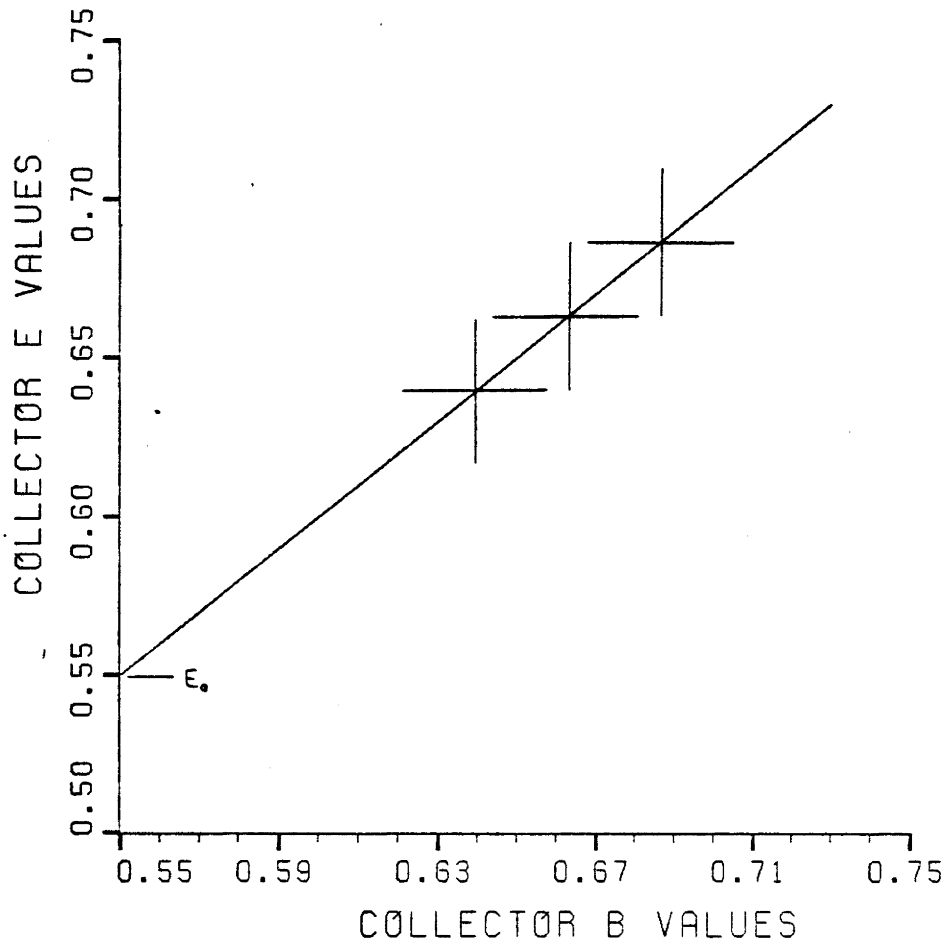

Figure 32. Locus of Intersections of Median Lines.

medians for simplicity. The data pairs for each subsequent retest are superimposed upon the initial test graph such that the median lines coincide. These median axes will not have significance with respect to the values of the ordered pairs. Rather, the significance of such a plot is in the relative distances of the data pairs from the origin of the "median axes". Having constructed such a plot, circles with diameters in specific multiples of the overall standard deviation may be drawn. An excessive number of points for a particular laboratory outside a specific circle indicates that laboratory can be considered as reporting values which are suspect.

3.5.4 Application of Modified Youden's Method to Reliability/ Durability Test Program.

The modified version of Youden's method described in the preceding section has been applied to collectors B and E for test series 1 and 2 with the necessary assumptions as previously outlined. Calculations of the average distances from the 45 degree line and of the overall standard deviations are presented in Appendix D. The resulting aggregate plots are shown in Figs. 33 through 36. On each plot, the 45 degree line, the 2 1/2 standard deviations circle, and the overall standard deviation are shown.

Figures 33 through 36 show that the overall precision of the test program is good. There are few data pairs which lie outside the prescribed standard deviation circle. Further, no one laboratory yielded data pairs outside the circle on a frequent basis. Consequently, no

particular laboratory can be identified as having unique problems with systematic errors or test procedures. Also, substantial differences in the precision between laboratories is not apparent as a result of the graphical analysis.

3.5.5 Discussion of Within and Between Site Standard Deviations as Measures of Interlaboratory Differences.

In addition to a graphical analysis of the data, a more quantitative approach has been made to examine interlaboratory differences. This approach is to compute the within site standard deviation, σ_w, and the between site standard deviation, σ_b, for collectors B and E at the beginning of the test program and again at the end of the test program. The standard deviations, σ_w and σ_b, obtained for results at the end of the program are then compared with these same quantities as determined for the initial tests. Significant variations in either σ_w or σ_b indicate some change in the overall precision of the test program. In particular, an increase in the between site standard deviation would indicate that significant interlaboratory differences in implementing the test method have developed during the course of the program. As with the graphical analysis, "weather corrected" values of the primary performance parameters have been used to minimize the influence of test environment.

The within site and between site standard deviations have been computed by applying a well-established analysis of variance as described by J. Mandel [17]. The within site standard deviation, σ_w,

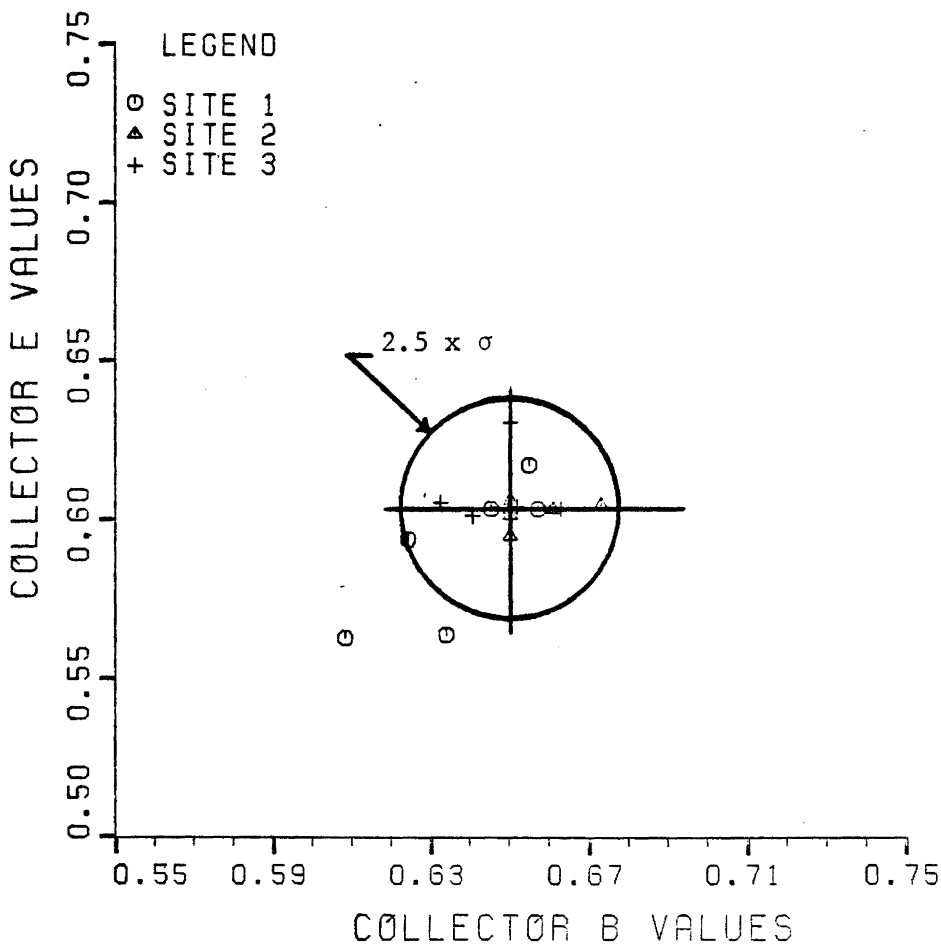

Figure 33. Graphical Measure of the Precision Associated with Determination of $F_R(\tau\alpha)$ for Test Series 1.

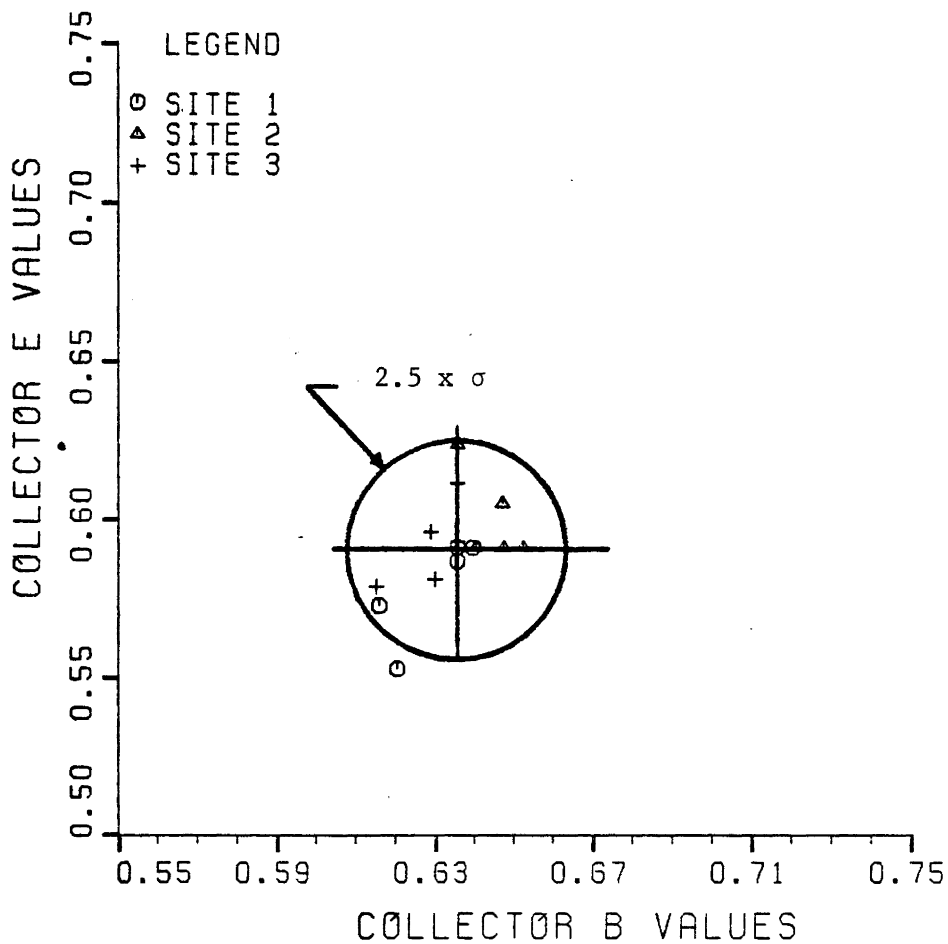

Figure 34. Graphical Measure of Precision Associated with Determination of $F_R(\tau\alpha)$ for Test Series 2.

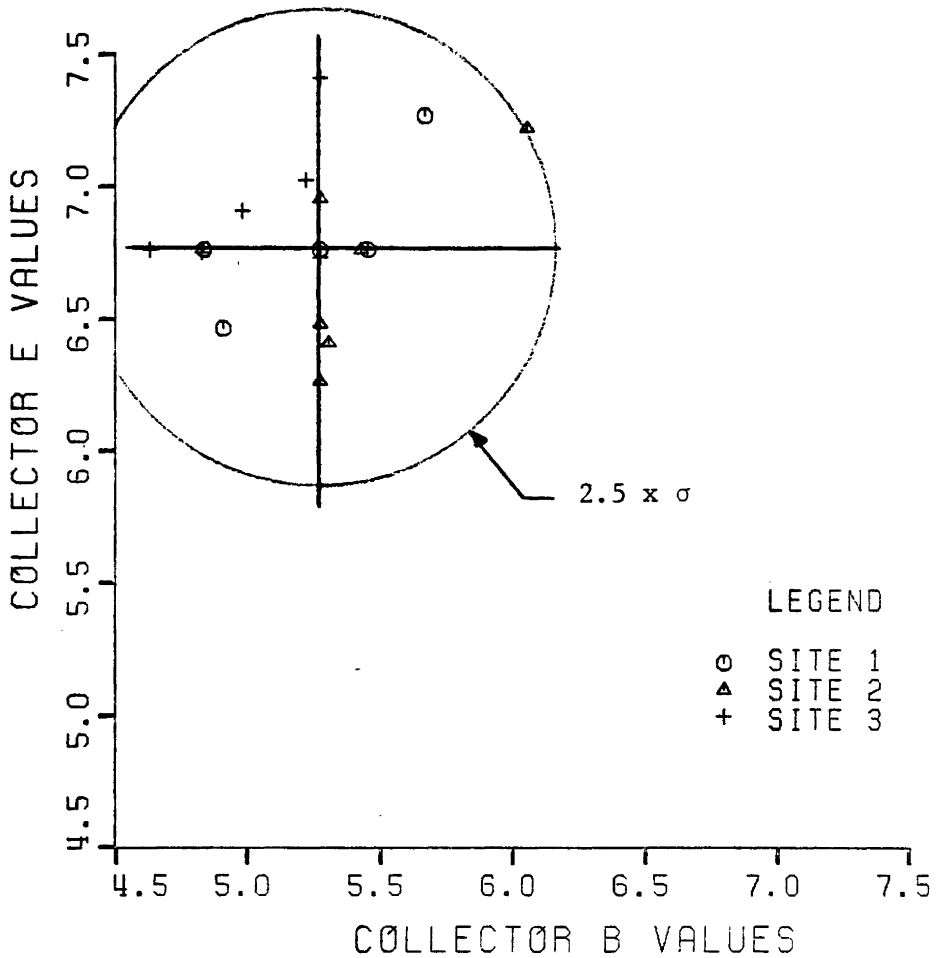

Figure 35. Graphical Measure of Precision Associated with Determination of $F_R U_L$ for Test Series 1.

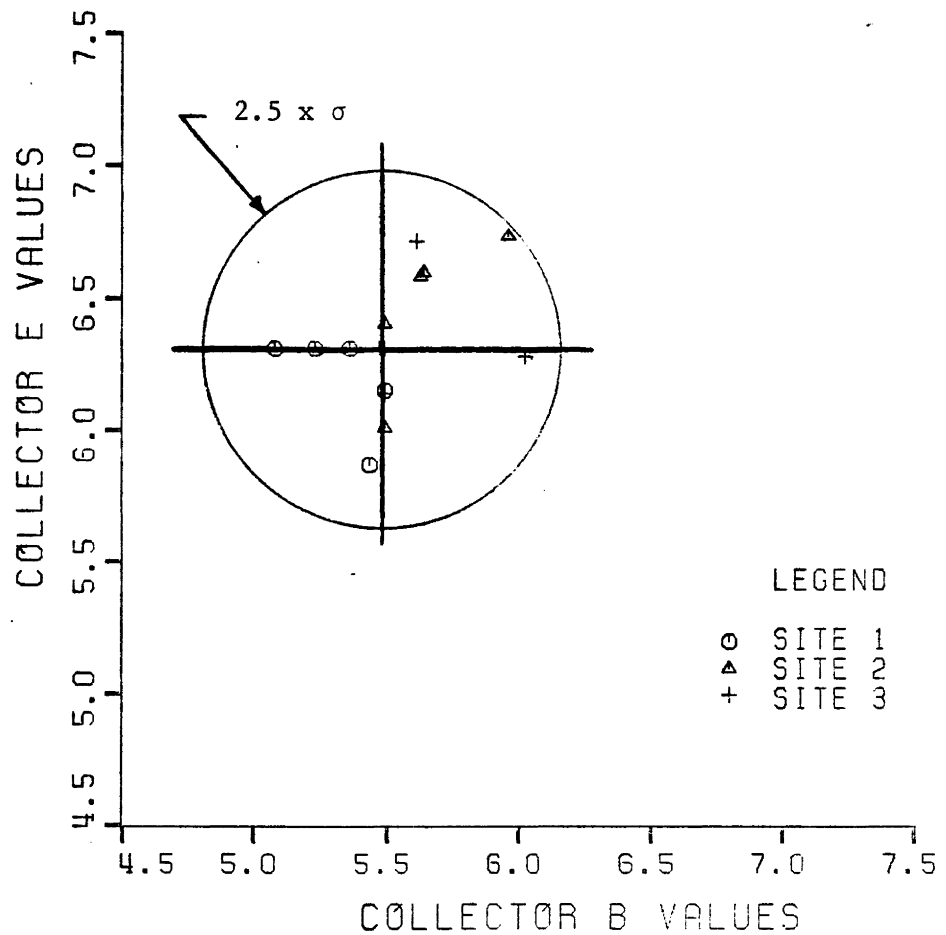

Figure 36. Graphical Measure of Precision Associated with Determination of $F_R U_L$ for Test Series 2.

provides a measure of the precision of individual laboratories in instituting the test procedure. The between site standard deviation, σ_b, indicates the precision of the test program. The σ_b measures the precision of the overall method in light of possible measurement difficulties and systematic errors. As such, σ_b is the primary indicator of interlaboratory differences.

3.5.6 Examination of Within and Between Site Standard Deviations in the Durability/Reliability Test Program.

To institute this type of analysis, some assumptions must be made because of the complications of degradation being dependent on climatic exposure environment as well as possible differences in instrumentation or test procedures. For the purpose of the following analysis, the following assumptions have been made. First, it is assumed that the differences in test series 1 and 2 are negligible. As such, the values obtained for the primary performance parameters from the two tests may be considered to be two sample measurements of the same quantity. Based on examination of the two test series' performance parameters with time, this assumption is reasonable. It is also assumed that the effect of exposure climate on degradation is negligible in comparison to the test method variations experienced in the program. In other words, the standard deviations obtained through this analysis are assumed to be caused by measurement difficulties and variation of the test procedure rather than by differing degradations of the performance parameters at different sites. The validity of this assumption may be questioned; but

because the effects of differing degradation among sites cannot be eliminated from the reported results, this assumption is necessary. The implications of the assumptions made in order to facilitate this analysis will be discussed as they pertain to the outcome of this analysis.

Tables 7 through 10 show the calculations of σ_w and σ_b for the collectors under examination. These calculations show that for both performance parameters for each collector, the within site standard deviation was lower at the end of the program than it was initially. This fact indicates that the precision of the individual laboratories improved with time. Of the between site standard deviations obtained, the values at the final retest are approximately the same as at the initial test. Notice in Tables 7 through 10 one half of the values of σ_b are equal to σ_w. This occurs when the standard deviation of the replicates, σ_{rep}, exceeds the standard deviation of the means, $\sigma_{\bar{x}}$. This occurrence indicates that the variability in the measured values far outweighs the variability of the mean values averaged for all laboratories. Since the standard deviation between sites, σ_b, cannot logically assume a smaller value than the standard deviation within sites, σ_b is equal to the within site standard deviation. This result is particularly prevalent in the analysis of F_RU_L values. Once again, this analysis indicates that a wide variety of factors must affect the determination of F_RU_L.

The results of this analysis indicate that there were no significant changes in the implementation of the test procedure during the life of the program. The reduction in the within site standard

Table 7. Analysis of Within and Between Site Standard Deviations for Determination of $F_R(\tau\alpha)$ for Collector B, Series 1 and 2.

0-Day Calculations

Test Site	Data		Average ($\bar{x}$)	Standard Deviation (σ)	Variance(σ^2)
1	0.657	0.640	0.6485	0.01202	0.000145
2	0.650	0.636	0.6430	0.00990	0.000098
3	0.632	0.615	0.6235	0.01202	0.000145

$\text{Avg } (\bar{\bar{x}}) = 0.6383$

$\sigma(\bar{x}) = 0.0131$

$\sigma^2_{rep} = 0.000129$

$\sigma_w = \sqrt{0.000129} = 0.0114$

$\sigma_b = \sqrt{(0.0131)^2 - \frac{1}{2}(0.000129)} = 0.0103$

480-Day Calculations

Test Site	Data		Average ($\bar{x}$)	Standard Deviation (σ)	Variance(σ^2)
1	0.658	0.660	0.6590	0.00140	0.000002
2	0.685	0.687	0.6860	0.00140	0.000002
3	0.674	0.675	0.6745	0.00071	0.0000005

$\text{Avg } (\bar{\bar{x}}) = 0.6732$

$\sigma(\bar{x}) = 0.0135$

$\sigma^2_{rep} = 0.0000015$

$\sigma_w = \sqrt{0.0000015} = 0.0012$

$\sigma_b = \sqrt{(0.0135)^2 - \frac{1}{2}(0.0000015)} = 0.0134$

Table 8. Analysis of Within and Between Site Standard Deviations for Determination of $F_R U_L$ for Collector B, Series 1 and 2

0-Day Calculations

Test Site	Data		Average ($\bar{x}$)	Standard Deviation (σ)	Variance(σ^2)
1	5.670	5.437	5.5535	0.16476	0.02714
2	5.276	5.628	5.4520	0.24890	0.06195
3	4.631	5.494	5.0625	0.61023	0.37238

$\text{Avg}(\bar{\bar{x}}) = 5.3560$

$\sigma(\bar{x}) = 0.2592$

$\sigma^2_{rep} = 0.15382$

$\sigma_w = \sqrt{0.15382}$

$= 0.3922$

$\sigma_b = \sqrt{(0.2592)^2 - \frac{1}{2}(0.15382)}$

$= \text{N/A}$

$\therefore \sigma_b = \sigma_w = 0.3922$

480-Day Calculations

Test Site	Data		Average ($\bar{x}$)	Standard Deviation (σ)	Variance(σ^2)
1	5.482	5.258	5.370	0.15839	0.02509
2	5.515	5.389	5.452	0.08910	0.00794
3	5.428	5.508	5.468	0.05657	0.00320

$\text{Avg}(\bar{\bar{x}}) = 5.430$

$\sigma(\bar{x}) = 0.0526$

$\sigma^2_{rep} = 0.01208$

$\sigma_w = \sqrt{0.01208}$

$= 0.1099$

$\sigma_b = \sqrt{(0.0526)^2 - \frac{1}{2}(0.01208)}$

$= \text{N/A}$

$\therefore \sigma_b = \sigma_w = 0.1099$

Table 9. Analysis of Within and Between Site Standard Deviations for Determination of $F_R(\tau\alpha)$ for Collector E, Series 1 and 2

0-Day Calculations

Test Site	Data	Average($\bar{x}$)	Standard Deviation (σ)	Variance(σ^2)
1	0.6036 0.5913	0.59745	0.00870	0.00008
2	0.5953 0.6239	0.60960	0.02022	0.00041
3	0.6056 0.5791	0.59235	0.01874	0.00035

$\text{Avg}(\bar{\bar{x}}) = 0.5998$

$\sigma(\bar{x}) = 0.0089$

$\sigma^2_{rep} = 0.00028$

$\sigma_w = \sqrt{0.00028}$

$= 0.0167$

$\sigma_b = \sqrt{(0.0089)^2 - \frac{1}{2}(0.00028)}$

$= \text{N/A}$

$\therefore \sigma_b = \sigma_w = 0.0167$

480-Day Calculations

Test Site	Data	Average($\bar{x}$)	Standard Deviation (σ)	Variance(σ^2)
1	0.5727 0.5758	0.57425	0.00219	0.000005
2	0.6121 0.6141	0.61310	0.00141	0.000002
3	0.6395 0.6345	0.63700	0.00354	0.000013

$\text{Avg}(\bar{\bar{x}}) = 0.6081$

$\sigma(\bar{x}) = 0.0317$

$\sigma^2_{rep} = 0.000007$

$\sigma_w = \sqrt{0.000007}$

$= 0.0026$

$\sigma_b = \sqrt{(0.0317)^2 - \frac{1}{2}(0.000007)}$

$= 0.0316$

Table 10. Analysis of Within and Between Site Standard Deviations for Determination of $F_R U_L$ for Collector E, Series 1 and 2

0-Day Calculations

Test Site	Data		Average ($\bar{x}$)	Standard Deviation (σ)	Variance(σ^2)
1	7.270	5.872	6.5710	0.98853	0.97720
2	6.482	6.587	6.5345	0.07425	0.00551
3	6.765	6.315	6.5400	0.31820	0.10125

$\text{Avg}(\bar{\bar{x}}) = 6.5485$

$\sigma(\bar{x}) = 0.0197$

$\sigma^2_{rep} = 0.36132$

$\sigma_w = \sqrt{0.36132}$

$= 0.6011$

$\sigma_b = \sqrt{(0.0197)^2 - \frac{1}{2}(0.36132)}$

$= \text{N/A}$

$\therefore \sigma_b = \sigma_w = 0.6011$

480-Day Calculations

Test Site	Data		Average ($\bar{x}$)	Standard Deviation (σ)	Variance(σ^2)
1	6.754	6.783	6.7685	0.02051	0.00042
2	6.398	6.483	6.4405	0.06010	0.00361
3	7.016	7.188	7.1020	0.12162	0.014792

$\text{Avg.}(\bar{\bar{x}}) = 6.7703$

$\sigma(\bar{x}) = 0.3308$

$\sigma^2_{rep} = 0.00627$

$\sigma_w = \sqrt{0.00627}$

$= 0.0792$

$\sigma_b = \sqrt{0.3308 - \frac{1}{2}(0.00627)}$

$= 0.3260$

deviation from the beginning of the program to the end suggests that within laboratories, the precision of implementing the test procedure actually improved. Further, because the between site standard deviations for each parameter remained essentially unchanged, apparently no systematic errors or variations of the test procedure have developed.

Chapter 4

Results and Conclusions

The analysis of the data and results from the "NBS Solar Collector Durability/Reliability Test Program" has revealed that the collectors tested generally showed excellent durability through 480 days of severe exposure conditions. In fact, investigation of degradation mechanisms was hampered by a lack of significant consistent patterns of measured collector performance degradation.

Analysis of the distribution of reported values of the primary performance parameters $F_R(\tau\alpha)$ and F_RU_L about mean values of these parameters (plotted with exposure) showed that performance changes were random. Further, the standard deviation of reported values of $F_R(\tau\alpha)$ about such mean values was generally within the experimental uncertainty as calculated by Culkin [10] for determination of this parameter. The standard deviation of reported values of F_RU_L about mean values, however, exceeded the experimental uncertainty in several cases. The excessive scatter in F_RU_L values may be caused by a general difficulty of the test procedure to adequately account for all factors which influence its determination. Since the scatter in the values of the primary performance parameters is random, it is concluded that 480 days of stagnation exposure is not a sufficient exposure period to induce patterns of consistent performance degradation for the collectors tested.

While consistent degradation trends were not apparent, some consistent unexpected results were encountered. The parameter $F_R(\tau\alpha)$

was observed to increase during the initial exposure period for nearly one-half of the collectors. This increase peaked between 30 and 60 days of exposure. The reason for this pattern has not yet been established.

Although measured degradation was not severe, analysis of the results showed that degradation of material properties is more likely to correlate with stagnation temperature than with solar irradiance. This conclusion is supported by the observation that degradation was most severe at laboratories and for test series which experienced the highest stagnation temperatures. Consequently, elevated stagnation temperature, rather than total solar irradiation, may be the key parameter in devising an accelerated test procedure for flat-plate collectors.

The assumption of $F_R(\tau\alpha)$ being a constant when modeling collector efficiency has been shown to be valid for purposes of comparison. It has been shown that $F_R(\tau\alpha)$ values extrapolated from linearized efficiency curves are from 0 to 1.0 efficiency percentage point higher than those measured with the collector inlet temperature approximately equal to ambient temperature. Thus, it may be concluded that errors associated with modeling collector efficiency as a 1st order linear function of the parameter $(t_i - t_a)/H_T$ are negligible.

A detailed investigation of the experimental uncertainties associated with particular instruments used in the D/R Test Program showed that no one specific instrument was responsible for excessive experimental error. Analysis of the pyranometers used showed that changes in

instrument sensitivity with time resulted in discrepancies of 2 to 3 per cent of the reported values of $F_R(\tau\alpha)$ for one laboratory. However, compensation of $F_R(\tau\alpha)$ to account for pyranometer sensitivity changes did not alter the generally random changes in this parameter with exposure time. It has been shown that a particular test stand or pyranometer could not be identified as a source of scatter in reported values of the primary performance parameters.

An analysis of the effects of differing weather conditions resulting from testing at multiple sites and from seasonal weather variability within sites has shown that the generally random scatter in the parameters $F_R(\tau\alpha)$ and F_RU_L was not induced by environmental factors during testing. Compensation of the reported values of $F_R(\tau\alpha)$ and F_RU_L by correction to a reference set of weather test conditions did not reduce the scatter of either of these parameters. Consequently, weather conditions at the time of testing are not responsible for the generally random scatter in the test results.

Two statistical approaches were used to analyze the results from the four laboratories. These statistical studies showed that all laboratories had approximately equal precision in applying the test procedures. None of the laboratories showed evidence of significant systematic errors in applying the test method. Generally, the distribution of reported values of the primary performance parameters, after compensation for test weather environment, showed a normal distribution of the data. Thus, it is concluded that significant

interlaboratory differences in attaining values of $F_R(\tau\alpha)$ and F_RU_L in this program were not present.

In summary, the most important conclusion to be drawn from this investigation is that collectors in this program tested by successive applications of the ASHRAE 93-77 standard did not show any significant patterns of consistent performance degradation. Within the limited range of change that was observed, no patterns could be detected which could be attributed to differing test environments, effects of efficiency modeling, particular experimental apparatus, or a particular test facility.

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APPENDICES

APPENDIX A

Reported Values of $F_R(\tau\alpha)$ and $F_R U_L$

COLLECTOR	RETEST DAYS															
	0		3		15		30		60		120		240		480	
	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL
A-1-1	0.602	4.562	0.593	4.308	N/A	N/A	0.599	4.023	0.606	3.978	0.590	4.060	0.591	4.381	0.583	4.366
A-1-2	N/A	N/A	0.596	4.440	N/A	N/A	0.605	4.092	0.628	4.318	0.613	3.960	0.596	4.505	0.600	4.440
A-1-3	0.622	4.549	N/A	N/A	0.623	3.910	0.636	4.244	0.623	4.987	0.598	3.766	0.596	4.585	N/A	N/A
A-1-4	0.601	4.429	N/A	N/A	0.610	4.148	0.603	4.307	0.591	5.107	N/A	N/A	N/A	N/A	N/A	N/A
A-2-1	0.609	5.250	0.609	4.850	0.610	4.610	0.623	4.280	0.602	4.550	0.607	4.870	0.617	4.392	0.623*	4.679
A-2-2	N/A	N/A	0.605	4.980	0.610	5.100	0.628	4.110	0.626	5.630	0.607	5.190	0.588	4.184	0.600*	4.394
A-2-3	0.612	4.490	N/A	N/A	0.637	5.120	0.622	4.560	0.610	5.150	0.610	5.020	0.604	4.305	N/A	N/A
A-2-4	0.581	4.427	N/A	N/A	0.629	4.967	0.617	4.893	0.608	5.113	N/A	N/A	N/A	N/A	N/A	N/A
A-3-1	0.627	3.910	0.633	3.810	0.605	3.600	0.628	4.310	0.629	4.120	0.641	3.980	0.641	4.360	0.646	3.901
A-3-2	N/A	N/A	0.612	3.660	0.636	4.450	0.612	4.390	0.614	4.250	0.629	4.030	0.626	4.420	0.607	3.544
A-4-1	0.611	4.349	0.660	5.167	0.614	4.389	0.601	4.583	0.598	3.805	N/A	N/A	0.617	4.024	0.643	3.974
A-4-2	N/A	N/A	0.655	5.445	0.595	4.571	0.604	4.702	0.598	4.350	N/A	N/A	0.607	4.430	0.654	4.505
B-1-1	0.654	5.460	0.654	5.437	N/A	N/A	0.649	5.001	0.670	5.078	0.670	5.490	0.630	5.022	0.659	5.479
B-1-2	N/A	N/A	0.640	5.428	N/A	N/A	0.661	5.306	0.668	5.074	0.669	5.170	0.656	5.594	0.651	5.440
B-1-3	0.652	5.476	N/A	N/A	0.652	5.350	0.688	5.420	0.656	5.624	0.647	5.173	0.648	5.610	N/A	N/A
B-1-4	0.666	5.459	N/A	N/A	0.669	5.536	0.681	5.539	0.636	5.038	N/A	N/A	N/A	N/A	N/A	N/A
B-2-1	0.654	5.380	0.640	5.384	0.665	6.105	0.648	5.648	0.673	5.705	0.666	5.780	0.668	5.254	0.683*	4.572
B-2-2	N/A	N/A	0.646	5.696	0.659	6.209	0.651	5.693	0.669	5.636	0.669	5.770	0.688	5.891	0.685*	5.349
B-2-3	0.648	5.588	N/A	N/A	0.666	5.852	0.668	6.011	0.662	5.364	0.668	5.320	0.671	5.608	N/A	N/A
B-2-4	0.648	5.730	N/A	N/A	0.651	5.737	0.655	5.869	0.653	5.824	N/A	N/A	N/A	N/A	N/A	N/A
B-3-1	0.652	5.433	0.653	5.390	0.683	5.460	0.656	5.174	0.663	5.417	0.674	4.990	0.686	5.540	0.689	5.200
B-3-2	N/A	N/A	0.636	5.180	0.654	5.150	0.653	5.159	0.668	5.520	0.675	5.060	0.694	5.750	0.690	5.349
B-4-1	0.672	5.212	0.696	5.865	0.709	5.746	0.719	5.723	0.622	4.616	0.651	4.719	0.688*	5.440	0.673	5.007
B-4-2	N/A	N/A	0.680	6.200	N/A	N/A	0.687	5.383	0.654	4.452	0.647	4.753	0.705*	5.881	0.665	4.984
C-1-1	0.545	4.377	0.528	4.076	N/A	N/A	0.528	3.889	0.534	3.627	0.531	4.059	0.511	3.834	0.492	3.838
C-1-2	N/A	N/A	0.520	3.969	N/A	N/A	0.538	3.915	0.529	3.717	0.527	4.172	0.512	3.591	0.493	3.929
C-1-3	0.538	3.908	N/A	N/A	0.524	4.105	0.522	3.566	0.530	4.283	0.524	3.714	0.510	4.457	N/A	N/A
C-1-4	0.540	4.465	N/A	N/A	0.496	3.765	0.485	3.345	0.465	3.828	N/A	N/A	N/A	N/A	N/A	N/A
C-2-1	0.524	4.531	0.522	4.324	0.541	4.578	0.542	4.488	0.539	4.098	0.541	4.294	0.537	3.942	0.529*	3.813
C-2-2	N/A	N/A	0.511	4.268	0.524	4.513	0.525	3.929	0.517	3.968	0.512	4.173	0.498	3.840	0.501*	3.983
C-2-3	0.557	4.739	N/A	N/A	0.552	4.105	0.549	4.586	0.546	4.456	0.552	4.131	0.557	4.420	N/A	N/A
C-2-4	0.541	4.802	N/A	N/A	0.540	4.604	0.540	4.549	0.521	4.022	N/A	N/A	N/A	N/A	N/A	N/A
C-3-1	0.549	4.228	0.530	3.919	0.540	3.889	0.531	3.867	0.528	3.799	0.541	3.747	0.536	3.776	0.556	3.907
C-3-2	N/A	N/A	0.517	4.044	0.531	3.782	0.530	4.026	0.523	3.725	0.543	3.600	0.538	3.839	N/A	N/A
C-4-1	0.552	4.151	0.573	4.849	0.540	3.975	0.546	4.713	0.532	3.833	0.524	3.311	0.507*	3.832	0.483	2.880
C-4-2	N/A	N/A	0.549	4.060	0.552	3.992	0.532	4.537	0.525	4.491	0.548	3.958	0.518*	3.811	0.540	3.389
D-1-1	0.648	3.468	0.629	3.152	N/A	N/A	0.632	2.654	0.642	2.648	0.644	3.180	0.620	2.969	0.617	3.060
D-1-2	N/A	N/A	0.633	3.179	N/A	N/A	0.639	3.059	0.649	2.790	0.666	3.220	0.635	2.781	0.622	3.015
D-1-3	0.626	2.833	N/A	N/A	0.613	2.982	0.637	3.174	0.618	3.090	0.634	2.902	0.619	3.229	N/A	N/A
D-1-4	0.640	3.200	N/A	N/A	0.623	2.968	0.632	2.790	0.605	3.013	N/A	N/A	N/A	N/A	N/A	N/A

* INDICATES RETEST WAS PERFORMED AT EXPOSURE OTHER THAN INDICATED IN HEADING.

COLLECTOR	RETEST DAYS															
	0		3		15		30		60		120		240		480	
	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL
D-2-1	0.640	3.410	0.650	3.200	0.647	3.490	0.634	3.250	0.637	3.300	0.651	3.820	0.610	3.789	0.657*	3.498
D-2-2	N/A	N/A	0.659	3.010	0.656	3.290	0.646	3.470	0.641	3.400	0.647	3.720	0.625	3.164	0.635*	3.578
D-2-3	0.655	3.450	N/A	N/A	0.660	3.400	0.663	3.280	0.640	2.950	0.662	3.280	0.636	3.564	N/A	N/A
D-2-4	0.636	3.385	N/A	N/A	0.658	3.434	0.645	3.364	0.643	3.485	N/A	N/A	N/A	N/A	N/A	N/A
D-3-1	0.647	2.555	0.641	2.410	0.619	2.610	0.639	2.940	0.648	3.040	0.632	2.425	0.634	2.740	0.650	3.140
D-3-2	N/A	N/A	0.635	3.640	0.629	2.620	0.652	3.100	0.657	3.110	0.646	2.487	0.645	2.870	0.661	3.134
D-4-1	0.636	3.055	0.657	3.276	0.688	3.946	0.691	3.583	0.642	2.953	0.616	3.021	0.656*	3.353	0.633	2.950
D-4-2	N/A	N/A	0.670	3.384	0.678	3.390	0.664	3.100	0.645	2.646	0.625	2.396	0.647*	3.281	0.634	2.822
E-1-1	0.613	7.465	0.605	5.997	N/A	N/A	0.624	5.866	0.625	6.260	0.600	5.770	0.585	6.158	0.571	6.479
E-1-2	N/A	N/A	0.598	6.443	N/A	N/A	0.624	6.269	0.619	6.129	0.605	5.480	0.596	6.645	0.569	6.359
E-1-3	0.599	6.801	N/A	N/A	0.595	6.063	0.609	6.222	0.616	6.470	0.604	6.680	0.578	6.032	N/A	N/A
E-1-4	0.590	6.149	N/A	N/A	0.619	5.805	0.618	5.574	0.595	7.101	N/A	N/A	N/A	N/A	N/A	N/A
E-2-1	0.588	6.488	0.576	5.816	0.605	6.700	0.602	6.233	0.595	6.679	0.590	6.750	0.612	6.185	0.600*	6.546
E-2-2	N/A	N/A	0.619	6.580	0.630	7.639	0.616	6.515	0.613	6.769	0.612	6.450	0.611	6.737	0.601*	6.633
E-2-3	0.602	7.027	N/A	N/A	0.614	6.963	0.610	5.970	0.609	6.780	0.605	6.810	0.620	6.330	N/A	N/A
E-2-4	0.603	6.045	N/A	N/A	0.595	6.448	0.588	6.234	0.569	6.653	N/A	N/A	N/A	N/A	N/A	N/A
E-3-1	0.621	6.306	0.596	5.630	0.602	6.600	0.616	6.547	0.621	5.820	0.625	6.820	0.642	5.945	0.657*	6.179
E-3-2	N/A	N/A	0.595	5.584	0.598	6.560	0.626	6.696	0.617	5.830	0.633	6.880	0.637	5.871	0.651*	6.332
E-4-1	0.619	6.257	0.598	5.990	0.597	6.331	0.594	6.172	0.618	6.451	N/A	N/A	0.611	5.837	0.619	6.050
E-4-2	N/A	N/A	0.602	6.217	0.583	5.996	0.585	5.792	0.614	6.451	N/A	N/A	0.610	6.016	0.618	4.937
F-1-1	0.665	6.504	0.648	5.152	N/A	N/A	0.668	5.152	0.664	5.859	0.633	5.590	0.616	5.655	0.631	6.433
F-1-2	N/A	N/A	0.638	6.728	N/A	N/A	0.659	5.798	0.644	5.528	0.642	5.627	0.615	5.291	0.621	6.200
F-1-3	0.646	5.802	N/A	N/A	0.632	5.927	0.672	5.680	0.653	6.473	0.651	5.837	0.620	6.289	N/A	N/A
F-1-4	0.644	6.093	N/A	N/A	0.639	5.682	0.631	5.401	0.617	6.312	N/A	N/A	N/A	N/A	N/A	N/A
F-2-1	0.652	6.799	0.666	6.280	0.678	5.895	0.675	6.101	0.661	6.167	0.651	5.921	0.624	6.068	0.648*	6.270
F-2-2	N/A	N/A	0.661	6.256	0.646	6.676	0.684	6.084	0.653	6.566	0.664	6.528	0.650	6.820	0.662*	6.496
F-2-3	0.668	6.068	N/A	N/A	0.656	6.081	0.687	6.100	0.665	6.143	0.664	6.376	0.650	6.319	N/A	N/A
F-2-4	0.653	6.141	N/A	N/A	0.652	6.171	0.658	6.047	0.626	5.746	N/A	N/A	N/A	N/A	N/A	N/A
F-3-1	0.679	5.350	0.674	4.936	0.651	5.916	0.663	6.058	0.657	5.479	0.653	5.394	0.668	5.570	0.666	5.405
F-3-2	N/A	N/A	0.660	4.967	0.627	5.922	0.642	6.172	0.655	5.826	0.646	5.388	0.652	5.684	0.653	5.530
F-4-1	0.657	5.860	0.631	5.337	0.651	5.769	0.637	5.383	0.655	5.798	N/A	N/A	0.651	5.370	0.648	5.354
F-4-2	N/A	N/A	0.623	5.655	0.627	5.740	0.616	5.451	0.634	6.651	N/A	N/A	0.622	5.136	0.690	7.331
G-1-1	0.572	5.905	0.548	5.322	N/A	N/A	0.563	5.438	0.584	5.025	0.567	5.672	0.548	5.276	0.528	5.877
G-1-2	N/A	N/A	0.567	5.429	N/A	N/A	0.568	5.431	0.566	5.010	0.565	5.066	0.514	5.305	0.537	5.899
G-1-3	0.553	5.480	N/A	N/A	0.539	5.347	0.581	5.039	0.552	5.538	0.546	4.550	N/A	N/A	N/A	N/A
G-1-4	0.563	5.463	N/A	N/A	0.549	4.948	0.503	4.933	0.538	5.884	N/A	N/A	N/A	N/A	N/A	N/A
G-2-1	0.550	5.540	0.556	5.253	0.553	5.238	0.559	5.168	0.560	5.455	0.560	5.928	0.516	5.325	N/A	N/A
G-2-2	N/A	N/A	0.534	5.201	0.541	5.110	0.514	4.590	0.541	5.543	0.547	5.638	N/A	N/A	N/A	N/A
G-2-3	0.546	5.397	N/A	N/A	0.566	5.052	0.587	4.968	0.563	5.539	0.564	5.458	0.521	5.578	N/A	N/A
G-2-4	0.529	5.367	N/A	N/A	0.569	5.528	0.563	4.824	0.555	5.645	N/A	N/A	N/A	N/A	N/A	N/A

* INDICATES RETEST WAS PERFORMED AT EXPOSURE OTHER THAN INDICATED IN HEADING.

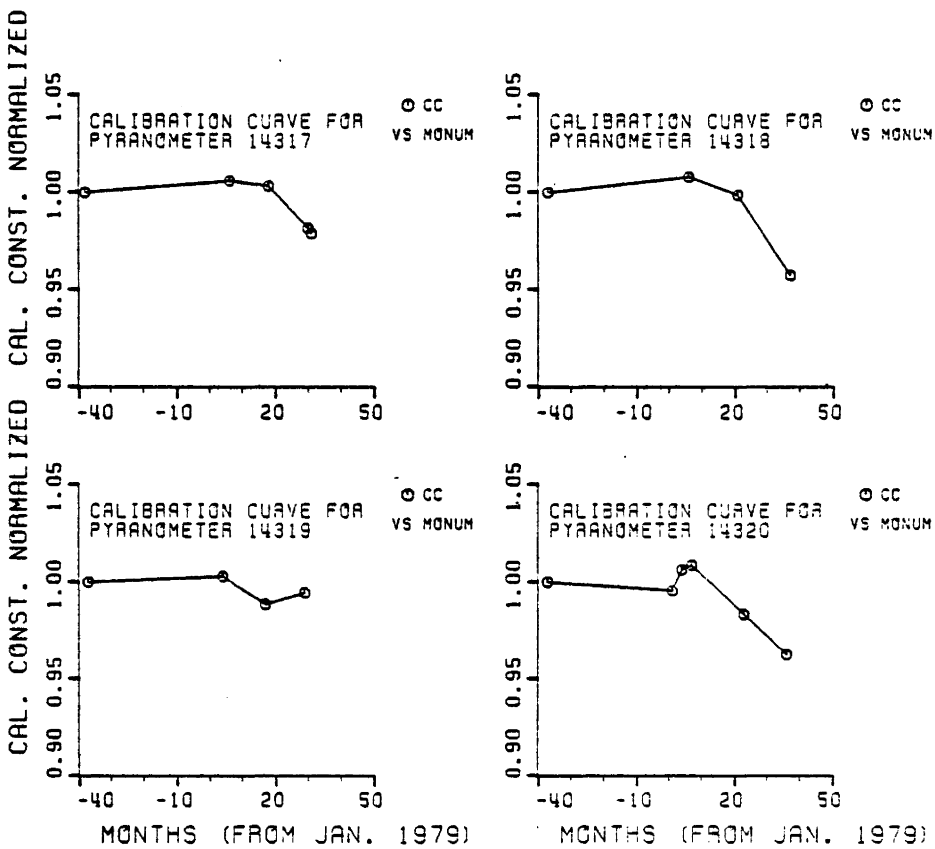
COLLECTOR	RETEST DAYS															
	0		3		15		30		60		120		240		480	
	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL	FRTA	FRUL
G-3-1	0.586	5.329	0.548	4.614	0.557	5.281	0.573	5.241	0.572	4.906	0.569	5.599	0.572	4.974		
G-3-2	N/A	N/A	0.549	4.550	0.559	5.604	0.576	5.587	0.570	4.997	0.572	5.723	0.582	5.139		
G-4-1	0.588	5.587	0.601	5.865	0.572	5.258	0.569	5.429	0.571	4.952	N/A	N/A	0.550	4.438	N/A	N/A
G-4-2	N/A	N/A	0.595	5.894	0.557	5.002	0.553	5.281	0.559	4.975	N/A	N/A	0.539	4.824	N/A	N/A
H-1-1	0.636	5.776	0.615	5.672	0.627	5.380	0.613	4.907	0.656	5.230	0.633	4.790	0.608	5.522	0.594	5.286
H-1-2	N/A	N/A	0.641	5.483	0.618	5.338	0.638	5.177	0.648	5.068	0.638	4.590	0.594	5.423	0.581	5.229
H-1-3	0.632	5.770	N/A	N/A	0.624	5.180	0.654	5.455	0.643	5.990	0.627	5.821	0.628	5.575	N/A	N/A
H-1-4	0.643	5.505	N/A	N/A	0.617	4.405	0.628	4.901	0.584	5.444	N/A	N/A	N/A	N/A	N/A	N/A
H-2-1	0.625	6.014	0.618	5.654	0.630	5.902	0.638	5.575	0.618	5.540	0.615	5.350	0.618	5.851	0.575*	5.096
H-2-2	N/A	N/A	0.629	5.710	0.626	5.887	0.632	5.295	0.624	5.620	0.629	5.490	0.620	5.680	0.534*	4.356
H-2-3	0.623	6.108	N/A	N/A	0.659	6.344	0.663	5.904	0.624	5.790	0.643	5.670	0.628	5.208	N/A	N/A
H-2-4	0.607	5.930	N/A	N/A	0.637	6.049	0.622	5.258	0.597	5.677	N/A	N/A	N/A	N/A	N/A	N/A
H-3-1	0.638	5.620	0.647	5.590	0.665	5.630	0.634	5.293	0.629	5.440	0.638	5.040	0.628	5.510	0.616	4.941
H-3-2	N/A	N/A	0.627	5.571	0.653	5.450	0.639	5.599	0.630	5.650	0.639	5.010	0.645	5.740	0.636	5.117
H-4-1	0.640	5.144	0.648	5.218	0.635	5.190	0.652	6.212	0.585	5.655	0.605	4.072	0.593*	4.769	0.583	4.467
H-4-2	N/A	N/A	0.653	5.320	0.658	5.116	0.643	5.678	0.628	5.809	0.633	4.464	0.603*	4.993	0.620	5.072

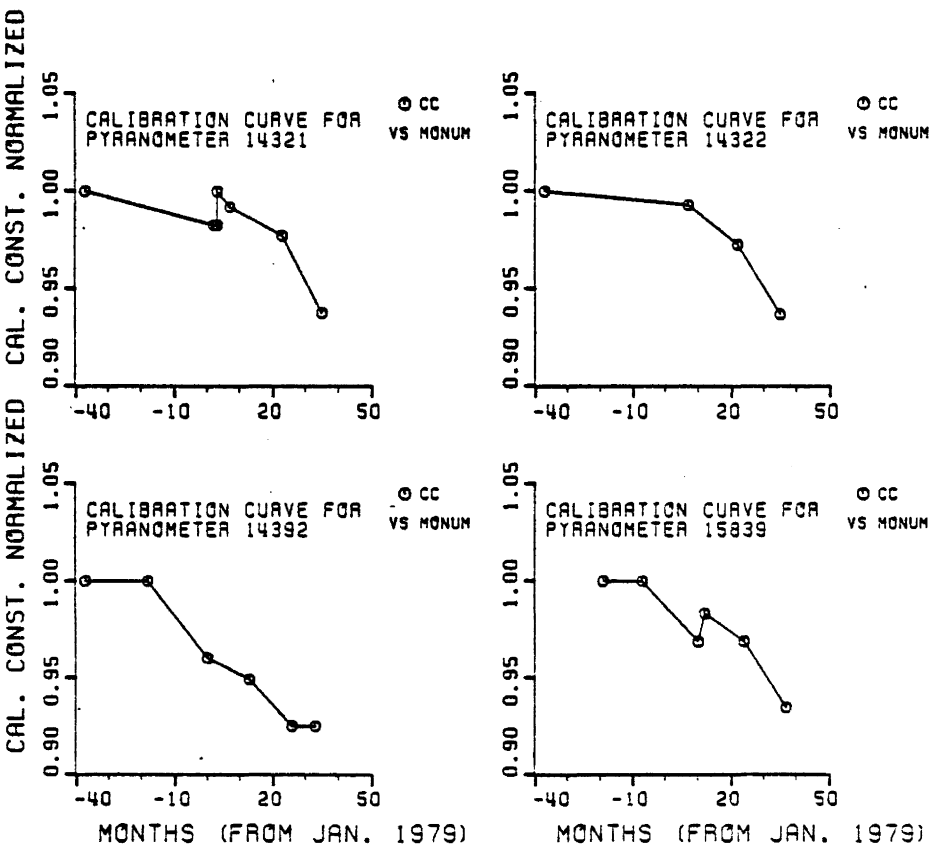
* INDICATES RETEST WAS PERFORMED AT EXPOSURE OTHER THAN INDICATED IN HEADING.

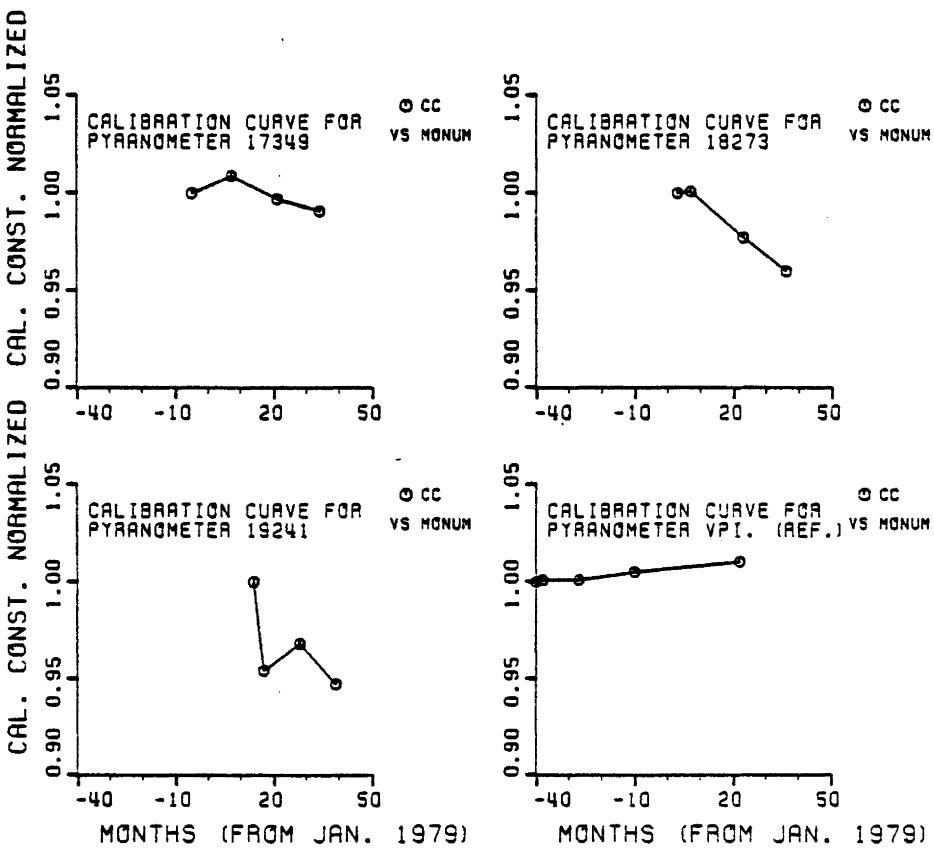
NOTES: 1) ALL COEFFICIENTS BASED ON COLLECTOR GROSS AREA.
2) UNITS OF FRUL ARE AS FOLLOWS: DEGREES(C)/W/SQ M .

APPENDIX B

Pyranometer Sensitivity Correction

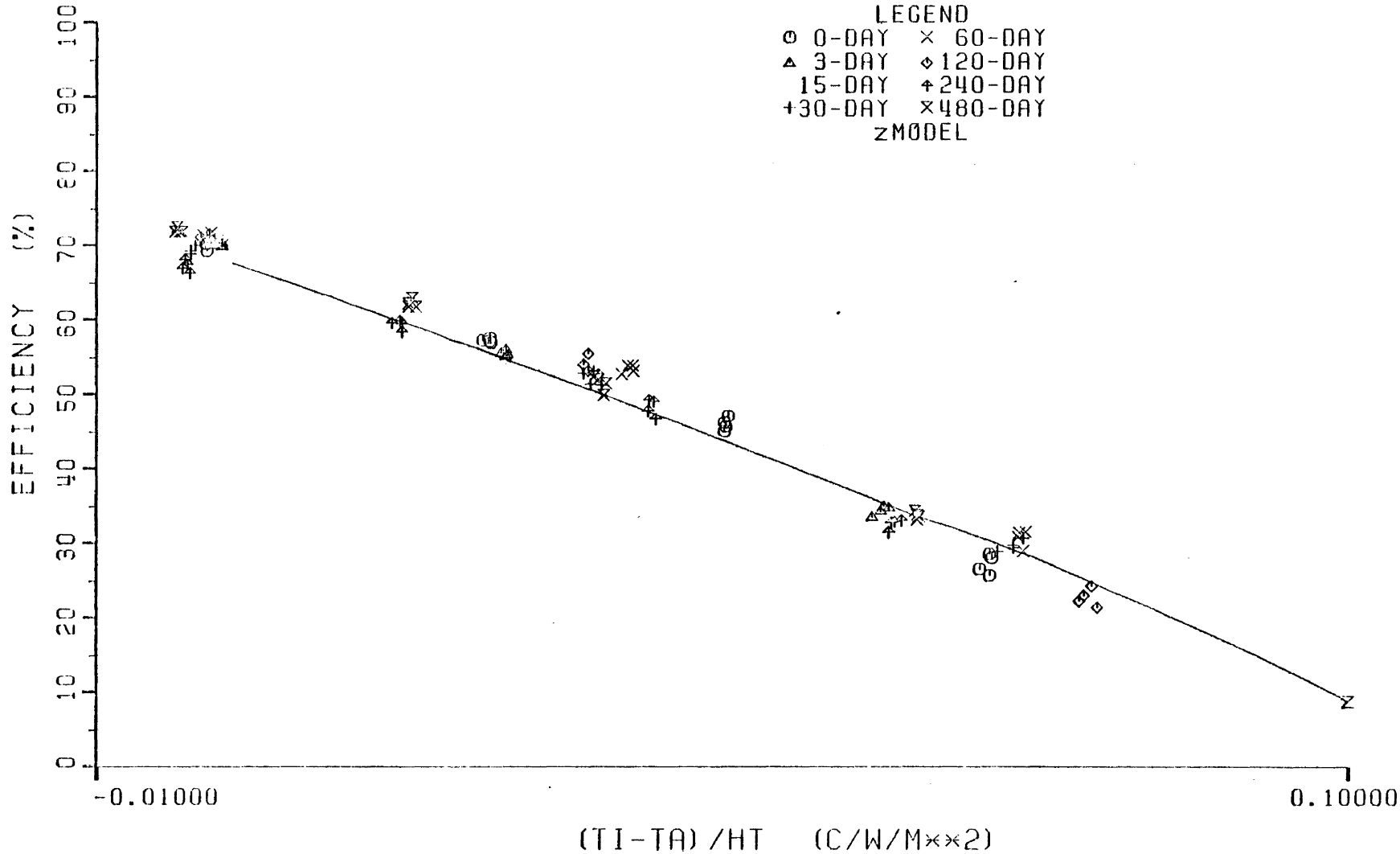

CAL. CONST. NORMALIZED
CALIBRATION CURVE FOR PYRANOMETER 14317
CALIBRATION CURVE FOR PYRANOMETER 14318
CALIBRATION CURVE FOR PYRANOMETER 14319
CALIBRATION CURVE FOR PYRANOMETER 14320
⊙ CC VS MONUM
0.90 0.95 1.00 1.05
-40 -10 20 50
MONTHS (FROM JAN. 1979)


CAL. CONST. NORMALIZED
CALIBRATION CURVE FOR PYRANOMETER 14321
CALIBRATION CURVE FOR PYRANOMETER 14322
CALIBRATION CURVE FOR PYRANOMETER 14392
CALIBRATION CURVE FOR PYRANOMETER 15839
CC VS MONUM
0.90
0.95
1.00
1.05
-40
-10
20
50
MONTHS (FROM JAN. 1979)

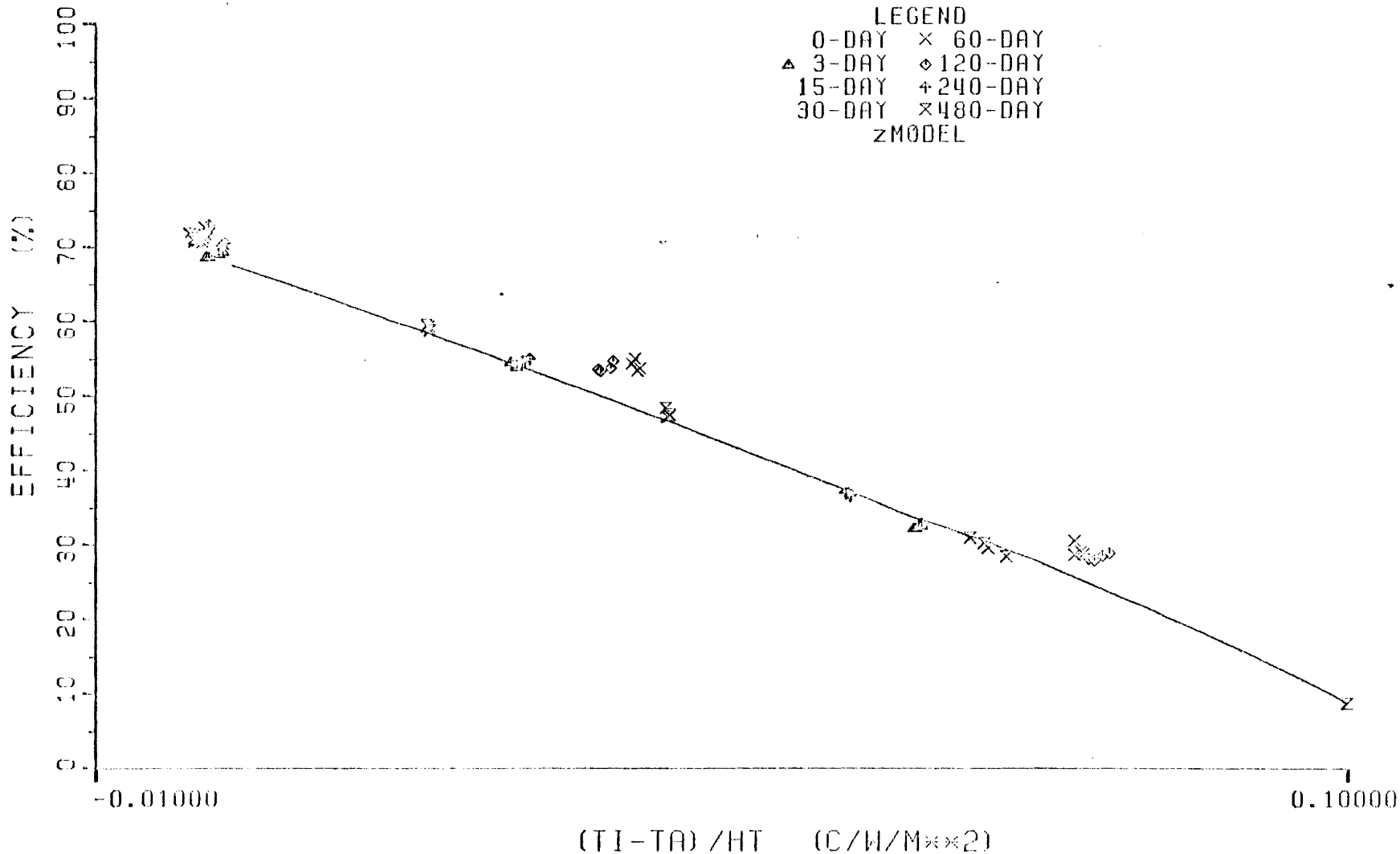

CAL. CONST. NORMALIZED
CALIBRATION CURVE FOR PYRANOMETER 17349
CALIBRATION CURVE FOR PYRANOMETER 18273
CALIBRATION CURVE FOR PYRANOMETER 19241
CALIBRATION CURVE FOR PYRANOMETER VPI. (REF.)
Θ CC VS MONUM
0.90
0.95
1.00
1.05
-40
-10
20
50
MONTHS (FROM JAN. 1979)

APPENDIX C

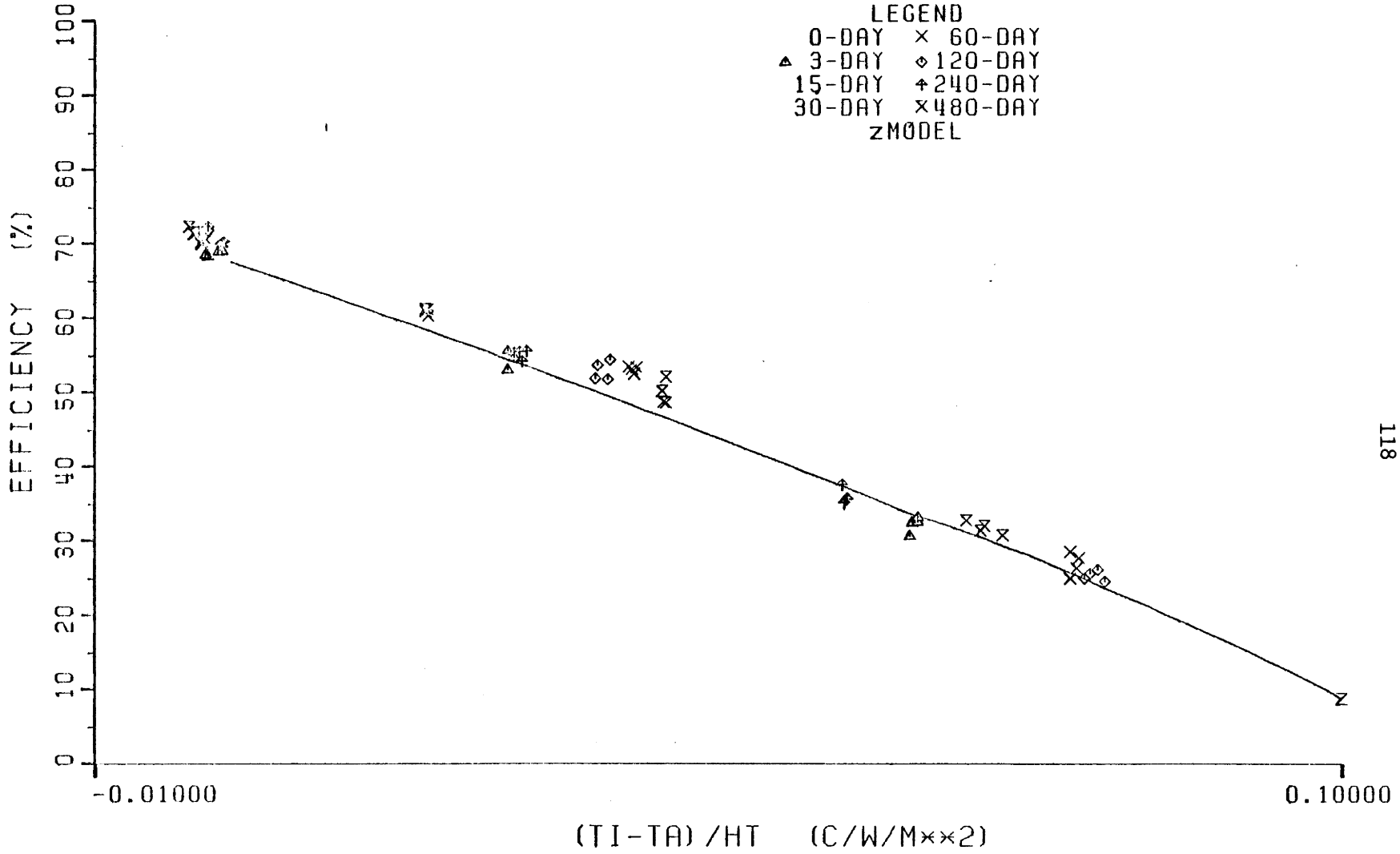
Aggregate Plots of Series-Site Combinations of Efficiency through 480 Exposure Days Showing Measured and Predicted Values



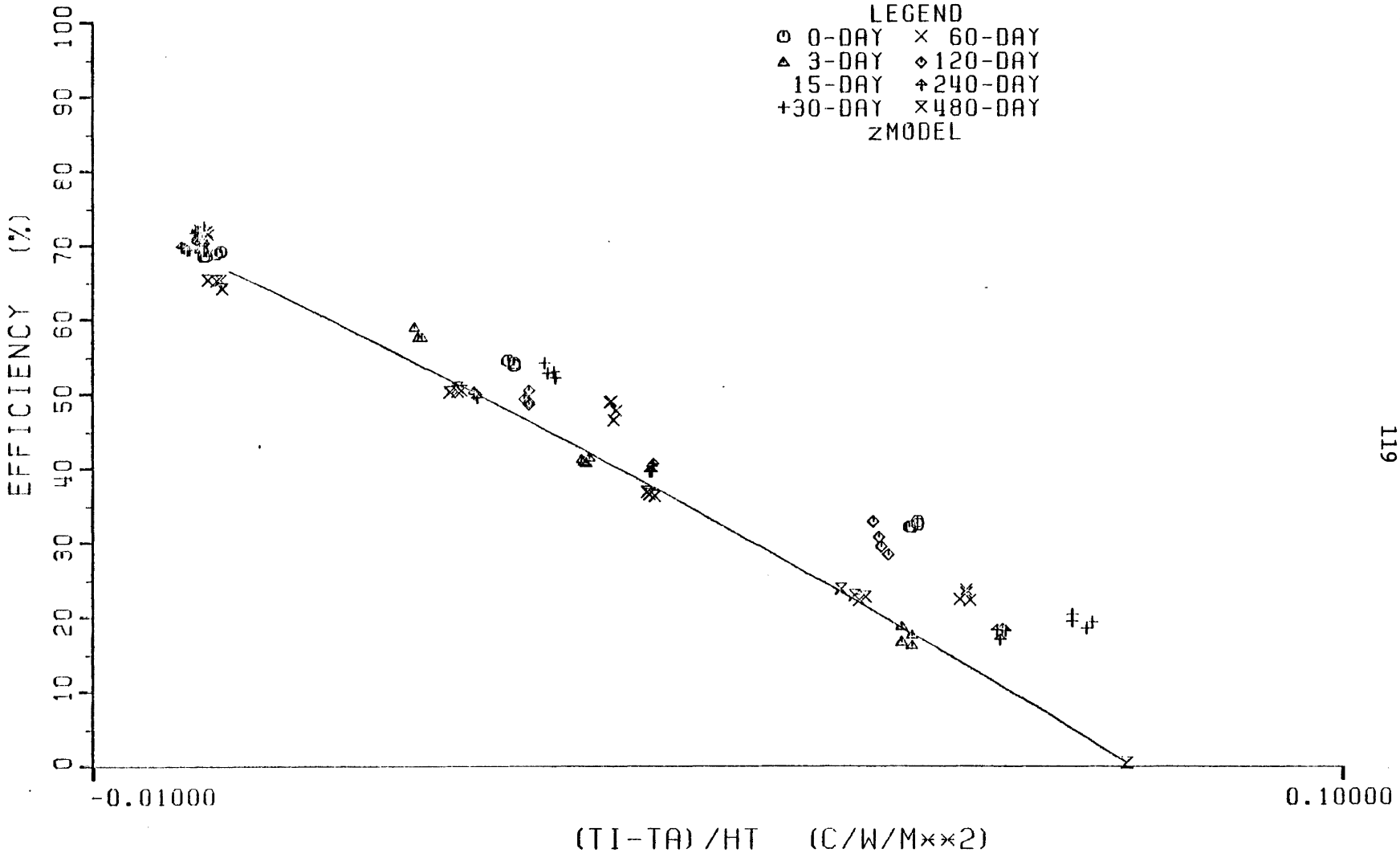
Aggregate plot for collector B-1-1, corrected to standard weather conditions.



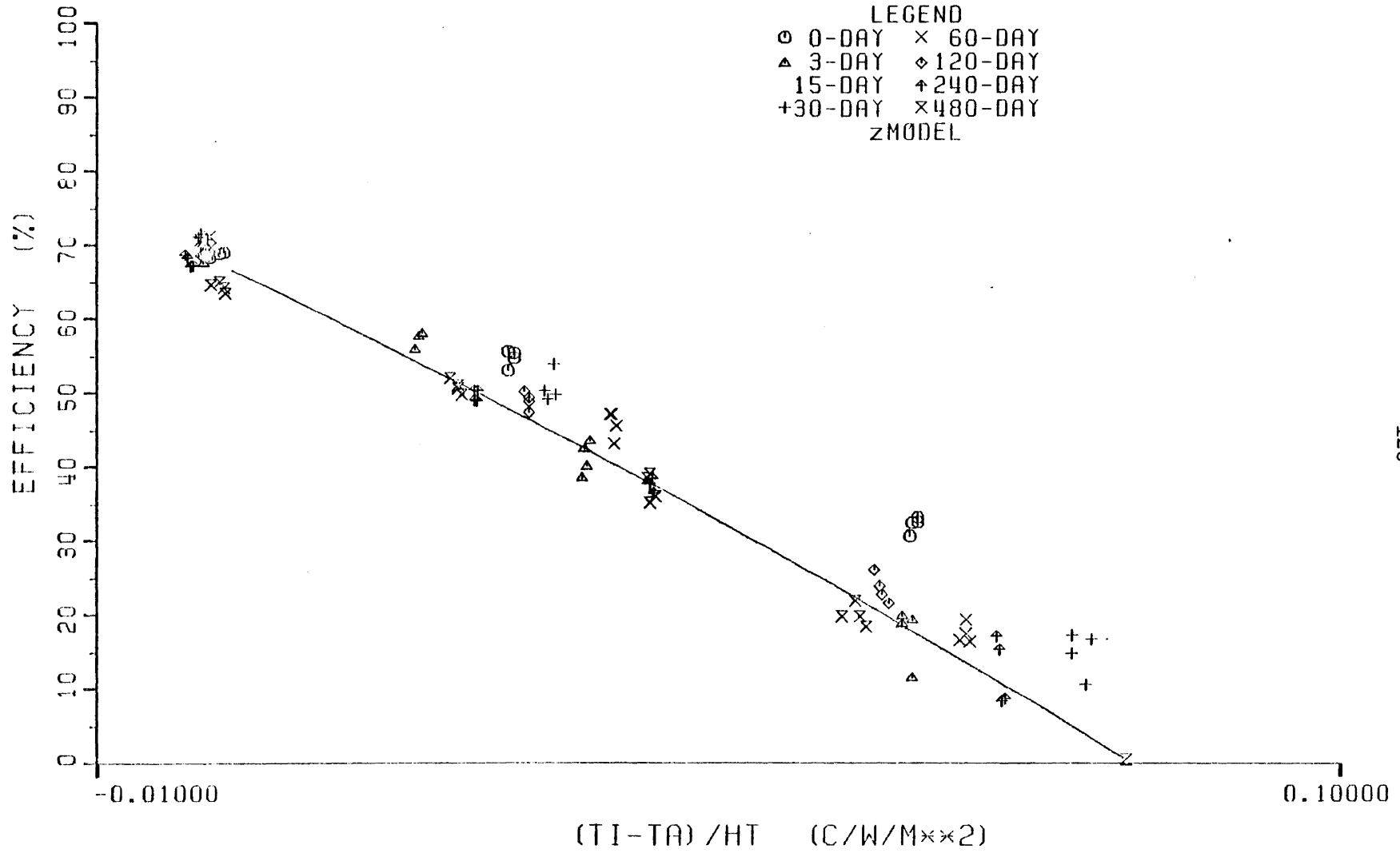
Aggregate plot for collector B-1-2, results as reported.



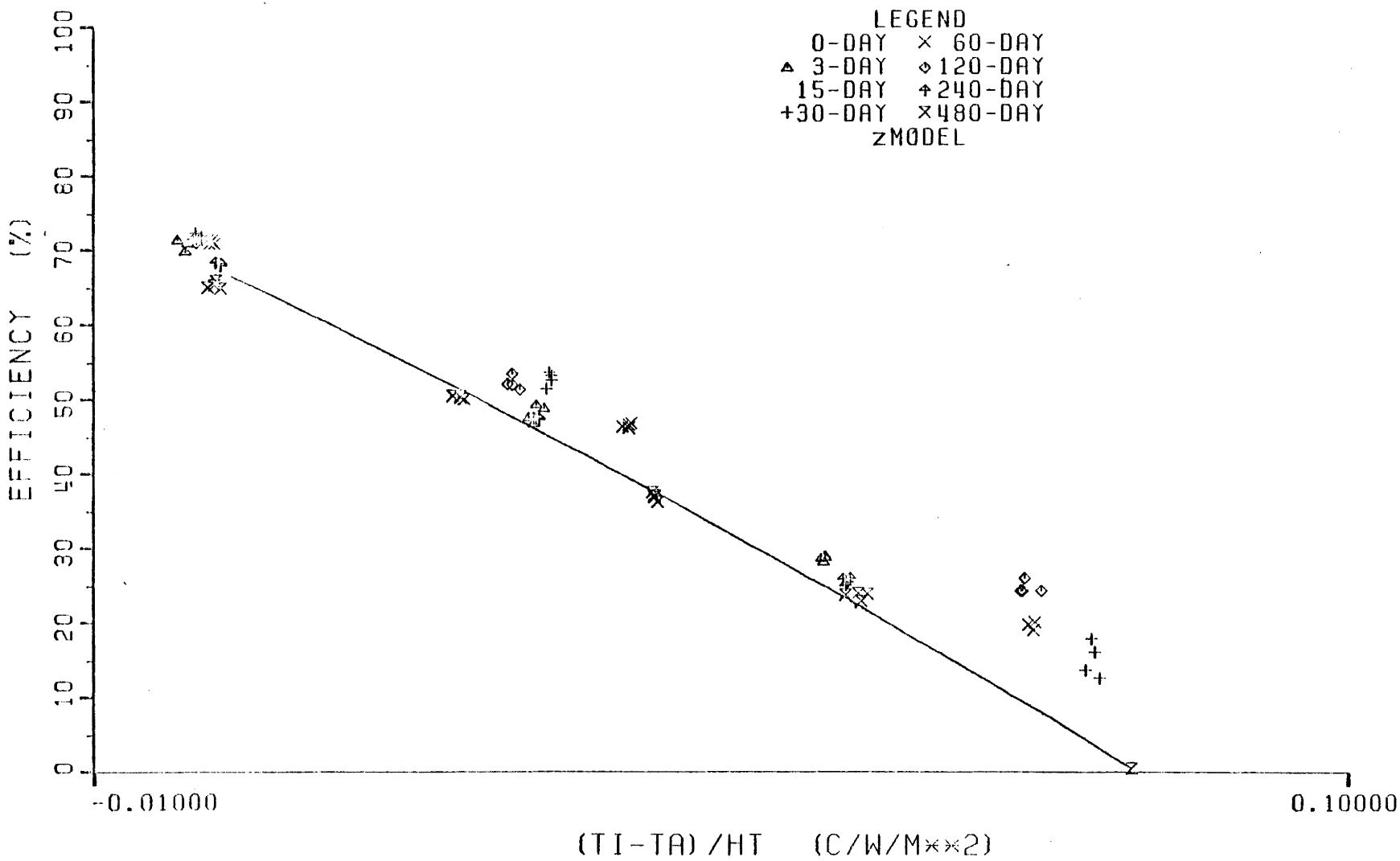
Aggregate plot for collector B-1-2, corrected to standard weather conditions.



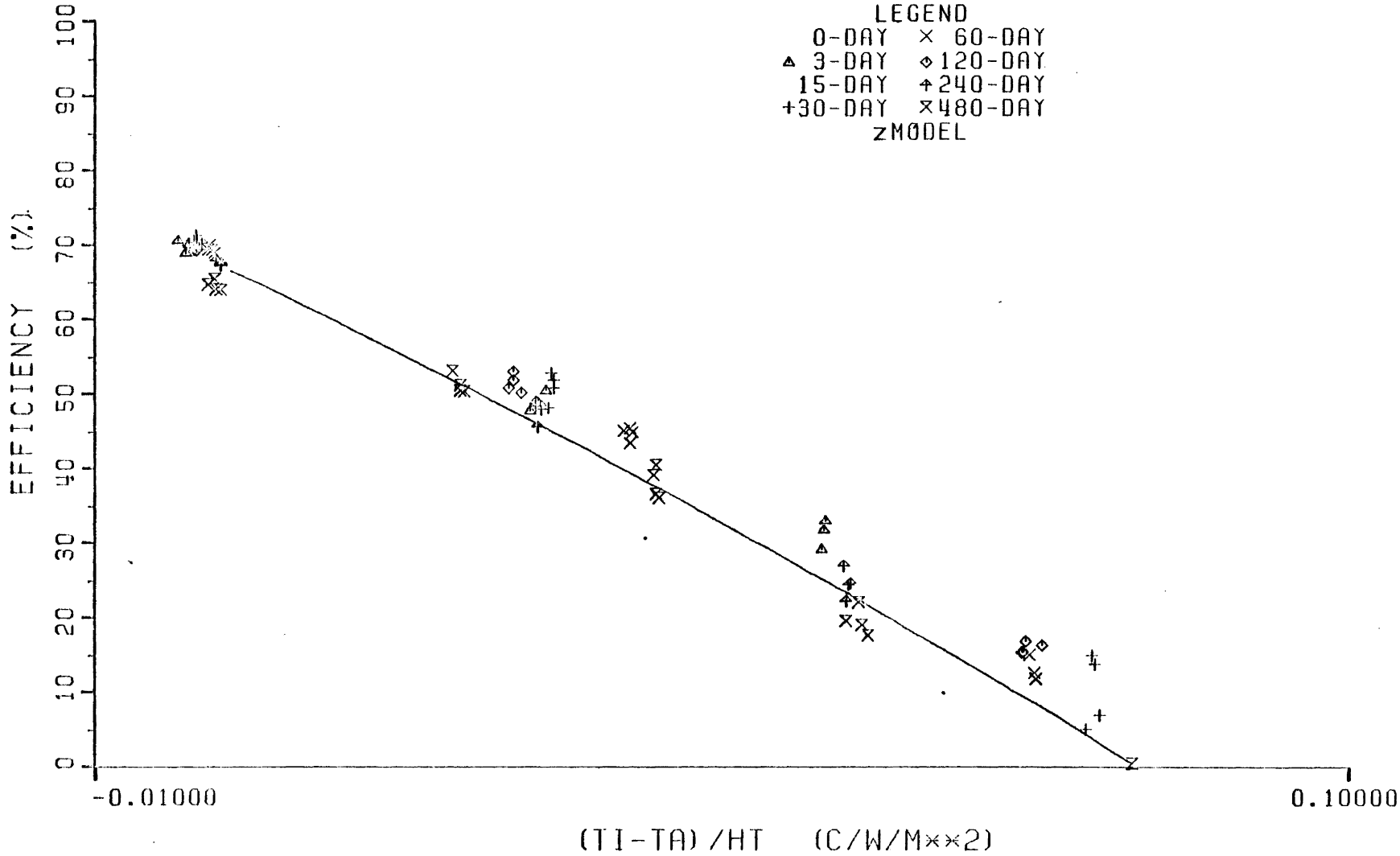
Aggregate plot for collector E-1-1, results as reported.



Aggregate plot for collector E-1-1, corrected to standard weather conditions.



Aggregate plot for collector E-1-2, results as reported.



Aggregate plot for collector E-1-2, corrected to standard weather conditions.

APPENDIX D

Calculation of Standard Deviations

Through Application of Modified Graphical Approach

FR(TA) PAIRINGS SERIES 1

B	E	E-B	E-B-(EAVG-BAVG)
0.6572000E+00	0.6036000E+00	-0.5359995E-01	-0.1131829E-02
0.6524000E+00	0.5988000E+00	-0.5360001E-01	-0.1131888E-02
0.6403000E+00	0.6154000E+00	-0.2489996E-01	0.2756817E-01
0.6648000E+00	0.6156000E+00	-0.4920000E-01	0.3268126E-02
0.6654000E+00	0.5949000E+00	-0.7050002E-01	-0.1803189E-01
0.6214000E+00	0.5796000E+00	-0.4180002E-01	0.1066810E-01
0.6578000E+00	0.5727000E+00	-0.8510000E-01	-0.3263187E-01
0.6503000E+00	0.5953000E+00	-0.5500001E-01	-0.2531882E-02
0.6478000E+00	0.5848000E+00	-0.6300002E-01	-0.1053190E-01
0.6713000E+00	0.6215000E+00	-0.4979998E-01	0.2668146E-02
0.6451000E+00	0.6136000E+00	-0.3149998E-01	0.2096814E-01
0.6762000E+00	0.6118000E+00	-0.6439996E-01	-0.1193183E-01
0.7140000E+00	0.6058000E+00	-0.1082000E+00	-0.5573189E-01
0.6634000E+00	0.6230000E+00	-0.4039997E-01	0.1206816E-01
0.6847000E+00	0.6121000E+00	-0.7260001E-01	-0.2013188E-01
0.6325000E+00	0.6056000E+00	-0.2689999E-01	0.2556813E-01
0.6383000E+00	0.5827000E+00	-0.5559999E-01	-0.3131863E-02
0.6467000E+00	0.6161000E+00	-0.3060001E-01	0.2186811E-01
0.6914000E+00	0.6044000E+00	-0.8700001E-01	-0.3453189E-01
0.6761000E+00	0.6201000E+00	-0.5599999E-01	-0.3531870E-02
0.6741000E+00	0.6395000E+00	-0.3459996E-01	0.1786816E-01

AVERAGES

0.6305089E+00	0.5780405E+00	-0.5246812E-01	0.1607120E-01

FR(TA) PAIRINGS SERIES 2

B	E	E-B	E-B-(EAVG-BAVG)
0.6397000E+00	0.5913000E+00	-0.4839998E-01	0.5850047E-03
0.6614000E+00	0.6115000E+00	-0.4990000E-01	-0.9150058E-03
0.6653000E+00	0.6014000E+00	-0.6389999E-01	-0.1491500E-01
0.6568000E+00	0.5939000E+00	-0.6289995E-01	-0.1391496E-01
0.6600000E+00	0.5758000E+00	-0.8420002E-01	-0.3521504E-01
0.6357000E+00	0.6239000E+00	-0.1179999E-01	0.3718500E-01
0.6670000E+00	0.6395000E+00	-0.2749997E-01	0.2148502E-01
0.6488000E+00	0.6258000E+00	-0.2300000E-01	0.2598499E-01
0.6729000E+00	0.6254000E+00	-0.4750001E-01	0.1484975E-02
0.6820000E+00	0.6058000E+00	-0.7620001E-01	-0.2721502E-01
0.6813000E+00	0.6122000E+00	-0.6909996E-01	-0.2011497E-01
0.6869000E+00	0.6141000E+00	-0.7280004E-01	-0.2381505E-01
0.6152000E+00	0.5791000E+00	-0.3609997E-01	0.1288502E-01
0.6482000E+00	0.5817000E+00	-0.6649995E-01	-0.1751496E-01
0.6378000E+00	0.6035000E+00	-0.3429997E-01	0.1468502E-01
0.6557000E+00	0.6013000E+00	-0.5440003E-01	-0.5415037E-02
0.6586000E+00	0.6107000E+00	-0.4789996E-01	0.1085028E-02
0.6766000E+00	0.6139000E+00	-0.6269997E-01	-0.1371498E-01
0.6751000E+00	0.6345000E+00	-0.4060000E-01	0.8284988E-02

AVERAGES

0.6262495E+00	0.5772645E+00	-0.4898499E-01	0.1560603E-01

WHERE: B=VALUE OF PARAMETER FOR COLLECTOR B
E=VALUE OF PARAMETER FOR COLLECTOR E
AVG...DENOTES AVERAGE QUANTITY

FRUL PAIRINGS SERIES 1

B	E	E-B	E-B-(EAVG-BAVG)
0.5670000E+01	0.7270000E+01	0.1600000E+01	0.5029573E+00
0.5647000E+01	0.6183000E+01	0.5359993E+00	-0.5610437E+00
0.5121000E+01	0.6264000E+01	0.1143000E+01	0.4595661E-01
0.5218000E+01	0.6778000E+01	0.1559999E+01	0.4629564E+00
0.5783000E+01	0.6501000E+01	0.7180004E+00	-0.3790426E+00
0.5078000E+01	0.6659000E+01	0.1581000E+01	0.4839573E+00
0.5482000E+01	0.6754000E+01	0.1271999E+01	0.1749563E+00
0.5276000E+01	0.6482000E+01	0.1206000E+01	0.1089573E+00
0.5467000E+01	0.5682000E+01	0.2150002E+00	-0.8820429E+00
0.6032000E+01	0.6864000E+01	0.8320007E+00	-0.2650423E+00
0.5639000E+01	0.6564000E+01	0.9250002E+00	-0.1720428E+00
0.5750000E+01	0.6810000E+01	0.1060000E+01	-0.3704262E-01
0.6562000E+01	0.6959000E+01	0.3969994E+00	-0.7000437E+00
0.5517000E+01	0.6853000E+01	0.1335999E+01	0.2389565E+00
0.5515000E+01	0.6398000E+01	0.8829994E+00	-0.2140436E+00
0.4631000E+01	0.6765000E+01	0.2134001E+01	0.1036958E+01
0.5174000E+01	0.6330000E+01	0.1156000E+01	0.5895710E-01
0.5486000E+01	0.7213000E+01	0.1727000E+01	0.6299572E+00
0.5338000E+01	0.6491000E+01	0.1153000E+01	0.5595684E-01
0.5516000E+01	0.6629000E+01	0.1113000E+01	0.1595688E-01
0.5428000E+01	0.7016000E+01	0.1587999E+01	0.4909563E+00

AVERAGES

0.5242267E+01	0.6339314E+01	0.1097043E+01	0.3579897E+00

FRUL PAIRINGS SERIES 2

B	E	E-B	E-B-(EAVG-BAVG)
0.5437000E+01	0.5871000E+01	0.4340000E+00	-0.6011972E+00
0.5254000E+01	0.6748000E+01	0.1494000E+01	0.4588032E+00
0.5455000E+01	0.6375000E+01	0.9200001E+00	-0.1151972E+00
0.5686000E+01	0.6711000E+01	0.1025001E+01	-0.1019669E-01
0.5258000E+01	0.6782000E+01	0.1523999E+01	0.4888020E+00
0.5627000E+01	0.6587000E+01	0.9600000E+00	-0.7519722E-01
0.6134000E+01	0.7362000E+01	0.1228001E+01	0.1928034E+00
0.5687000E+01	0.6732000E+01	0.1045000E+01	0.9802818E-02
0.5665000E+01	0.6842000E+01	0.1177000E+01	0.1418028E+00
0.5922000E+01	0.6958000E+01	0.1036000E+01	0.8029938E-03
0.6092000E+01	0.6997000E+01	0.9049997E+00	-0.1301975E+00
0.5388000E+01	0.6482000E+01	0.1094001E+01	0.5880356E-01
0.5493000E+01	0.6315000E+01	0.8219995E+00	-0.2131977E+00
0.5634000E+01	0.7053000E+01	0.1419000E+01	0.3838034E+00
0.5450000E+01	0.7174000E+01	0.1724000E+01	0.6888027E+00
0.6195000E+01	0.6719000E+01	0.5240002E+00	-0.5111971E+00
0.5434000E+01	0.6534000E+01	0.1100000E+01	0.6480312E-01
0.5944000E+01	0.6538000E+01	0.5939999E+00	-0.4411974E+00
0.5508000E+01	0.7187000E+01	0.1679000E+01	0.6438026E+00

AVERAGES

0.5363144E+01	0.6398345E+01	0.1035197E+01	0.2752848E+00

WHERE B=VALUE OF PARAMETER FOR COLLECTOR B
E=VALUE OF PARAMETER FOR COLLECTOR E
AVG...DENOTES AVERAGE QUANTITY

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INVESTIGATION OF PERFORMANCE DEGRADATION AND TEST METHODS FOR FLAT-PLATE SOLAR COLLECTORS

by

Daniel Edward Douro

(ABSTRACT)

An analysis of outdoor collector performance data collected as part of the NBS Durability/Reliability Test Program is presented. The data is analyzed for consistent patterns of performance degradation resulting from prolonged outdoor exposure at low flow rate and stagnation conditions. The analysis includes examination of the effects of pyranometer sensitivity changes with time and sensitivity dependence on temperature. Performance results are compensated for differences in test environments by use of an analytic correction routine. A statistical examination of the implementation of the testing procedure is made to identify interlaboratory differences.