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PERFORMANCE CHARACTERISTICS OF A 1.8 BY 3.7 METER FRESNEL LENS SOLAR CONCENTRATOR

Leon J. Hastings and Steve L. Allums

February 12, 1979

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PERFORMANCE CHARACTERISTICS OF A 1.8 BY 3.7 METER FRESNEL LENS SOLAR CONCENTRATOR

Leon J. Hastings and Steve L. Allums
NASA/George C. Marshall Space Flight Center, Alabama

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PERFORMANCE CHARACTERISTICS OF A 1.8 BY 3.7 METER FRESNEL LENS SOLAR CONCENTRATOR

Leon J. Hastings and Steve L. Allums[1]
NASA/George C. Marshall Space Flight Center

ABSTRACT

Line-focusing acrylic Fresnel lenses with application potential in the 200° to 370°C range have been analytically and experimentally investigated. The measured solar concentration characteristics of a 1.8 by 3.7 m (6 by 12 ft) lens and its utilization in a solar collection mode are summarized in this paper. A measured peak concentration ratio of 62 with 90 percent of the transmitted energy focused into a 5.0 cm width was achieved. A peak concentration of 59 and a 90 percent target width of 4.3 cm were analytically computed. The experimental and analytical lens transmittance was 78 percent and 86 percent, respectively. The lens was also interfaced with a nonevacuated receiver assembly and operated in the collection mode. With a natural oxide absorber tube coating ($\alpha/\epsilon = 0.79/0.10$), the measured collection efficiency ranged from 43 percent at 200°C to 34 percent at 260°C. Efficiency improvements to the 40 to 50 percent range can be achieved with second generation lenses and higher performance absorptive coatings.

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[1] Aerospace Engineers.

INTRODUCTION

Activities at and sponsored by the Marshall Space Flight Center (MSFC) have been in progress to establish a technical data base on line-focusing acrylic Fresnel lenses that can generate temperatures in the 200° to 370°C range. Compared to other concentration concepts, the technique is relatively unexplored; however, the acrylic lens is adaptable to mass production techniques by casting and/or calendaring-extrusion processes which permit relatively low manufacturing costs. The durability and weatherability of acrylic and the ease of cleaning are other desirable qualities.

Initial phases of the Fresnel lens concept development were devoted to definition of lens optical performance. A simplified analytical model was developed by Ball State University and utilized in performance sensitivity studies [1]. A "grooves-down" lens configuration, as opposed to grooves toward the Sun, with an f-number of one was indicated to be optimum from a transmittance and concentration profile standpoint. Subsequently, the analytical model for the grooves-down geometry was refined and used in conjunction with experimentation to further define optical performance characteristics [2]. The experimentation was performed with a 56 cm wide, f-1, acrylic lens. The effort reported herein and in Reference 3 extends these earlier investigations to the testing and analysis of a full-scale lens, 1.83 by 3.66 m. The two principal objectives of the present phase were to (1) define the solar transmission and focusing characteristics of the lens, i.e., its optical performance, and (2) utilize the lens in the solar collection mode by interfacing it with a receiver assembly.

EXPERIMENTAL METHOD

Hardware

The test article is depicted in Figure 1. The Fresnel lens is 1.83 by 3.66 m and consists of an array of 45.7 cm square panels[2] which were manufactured by Optical Sciences Group, Inc. Two panel configurations were utilized and are identified as inside panels (those adjoining the lens axial centerline) and outside panels. The lens tracks the Sun (two axis tracking) and focuses along the receiver assembly approximately 1.68 m beneath the lens. The collector longitudinal axis is aligned N-S. Polyvinyl material forms an enclosure that protects the lens grooved surface and receiver assembly from direct atmospheric exposure, minimizing contamination/degradation and thermal convection losses due to wind.

The receiver tube assembly is not evacuated and consists of an absorber tube mounted in a reflecting cavity. The absorber tube is 1.9 cm diameter

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[2] The utilization of an array of panels was necessitated by the manufacturing size limitations that existed within the U.S. when the lens was ordered. Future mass-produced lenses would not be limited to the 45.7 cm panel size.

stainless steel which has been corrugated to promote wall-fluid heat transfer and heat treated to produce a natural oxide absorptive coating, $\alpha/\epsilon = 0.79/0.10$. Two reflective cavity design approaches utilizing ALZAK, Type I, material have been pursued (Figure 2). The initial receiver design tested (Configuration I) was based on the focusing of energy into the reflective cavity aperture rather than directly on the tube, thereby minimizing absorber tube temperature gradients. Additionally, by focusing on the cavity aperture (6.6 cm) rather than the tube, E-W Sun-tracking error effects are minimized. The second receiver approach tested (Configuration II) basically involves tube placement directly at the focus, thereby decreasing reliance on reflective surfaces. The cavity apertures are normally covered with a Teflon FEP transparent film. The heat transport medium is Therminol 66, a single phase commercial thermal fluid.

Approach

The investigation had two principal objectives: definition of the lens optical performance and utilization of the lens for solar collection. First, the lens transmission and focusing characteristics were analytically modeled and bench tested at the component level using the test setup depicted in Figure 3. The lens was then assembled in the full scale configuration and its optical performance again checked to assess the impact of the assembly process. Finally, when the lens was interfaced with the receiver tube assembly and operated in the solar collection mode, the lens and receiver tube influences on the total collection efficiency could be distinguished. The collector performance data were acquired during steady-state conditions with the primary test variables being absorber tube fluid inlet temperature and flow rate. The inlet to outlet temperature difference, mass flow rate, and direct solar flux incident on the lens were the recorded parameters used to determine collection efficiency.

LENS CONCENTRATION CHARACTERISTICS

Baseline Performance

The focal plane concentration profiles measured in the bench tests and on the full scale test article are compared with that computed in Figure 4. The component tests indicated a peak concentration ratio of 67 with a 90 percent target width of 4.2 cm, i.e., the width required to intercept 90 percent of the transmitted energy. The full scale correlation with the bench test data was reasonable. However, the profiles did vary with position along the collection tube assembly, primarily due to slight structural misalignments inherent in the support of the multiple lens panels. The nominal peak concentration was 62 with a variation of ±3 percent; the 90 percent target width variation was ±8 percent from a nominal width of 5.0 cm. Approximately 95 percent of the energy transmitted by the lens was intercepted by the 6.6 cm trough aperture. The analytical model resulted in a peak concentration of 59 and a 90 percent target width of 4.3 cm. Thus, the analytical and experimental profile correlation is considered good, although the analytical profile indicated a slightly higher energy transmittance.

The computed and bench test measured lens transmittances (Figure 4) averaged 86 percent and 81 percent, respectively. The analytical/experimental data correlated well on the inside panels; however, the outside panels indicated an abrupt decrease in measured transmission efficiency. The transmission should not have varied significantly across the inside/outside panel interface. Based on the inside panel and previously measured transmittance data [1,2], modified manufacturing techniques should increase the overall lens transmittance to the 85 to 86 percent level. When assembled in the full scale configuration (Figure 1), the effective lens transmittance was approximately 78 percent. Structural shadowing and misalignment contributed to this transmittance degradation relative to the bench test results.

Sun-Tracking Deviations

Measured concentration profiles corresponding to E-W Sun-lens orientation deviations from 0 to 0.75 deg were measured (Figure 5). The general trends with misalignment are much like those previously observed [2] with a 56 cm lens, i.e., profile shifting, symmetry alteration, and peak concentration reduction at angles above 0.5 deg. The lateral profile shift directly influences the receiver target width requirements. To accommodate orientation deviations of ±0.25 deg and ±0.75 deg, e.g., 90 percent target width increases of 1.1 cm and 4.7 cm, respectively, are required. For the range of angular errors tested, the target width increase can be predicted reasonably well by adding the peak position shift, for a particular orientation, to the 0 deg target width.

Sun alignment deviations up to 6 deg in the longitudinal direction (N-S plane) were tested. Angles up to 5 deg had no significant effects on peak concentration or target width. Thus, the primary design consideration is that a collector receiver length must accommodate the N-S profile shifting produced by longitudinal orientation deviations.

COLLECTOR TESTING

Performance Overview

The collector performance overview illustrated by Figure 6 presents current and projected collection efficiency versus average absorber tube fluid temperature. The Configuration I receiver assembly was initially placed with the reflective cavity aperture at the focal plane, and the average collection efficiency ranged from 40 percent at 90°C to 25 percent at 260°C. Based on the lens performance data and visual observation, the energy was properly focused into the trough aperture by the lens. It was concluded that the reflective trough was not performing as expected. This conclusion was tentatively confirmed by moving the trough assembly 3.2 cm toward the lens such that the aperture was defocused approximately -2 percent. This adjustment increased the energy directly impinging on the tube and decreased the energy concentrated on the reflective surface. The "spillover" (energy focused outside the aperture) was increased from 4 percent to 11 percent, approximately the maximum that could be tolerated. As indicated by Figure 6, the defocused condition resulted in a modest but definite performance improvement, e.g., increased from 25 to 29 percent at 260°C.

Based on the preceding results, subsequent receiver assemblies have involved tube placement at the focal plane to further increase energy directly focused on the tube surface. Configuration II resulted in an efficiency improvement to 34 percent at 260°C. Contrary to expectations, the optical efficiency with Configuration II was unchanged relative to that with Configuration I. Apparently, the efficiency improvement was due to decreased thermal losses associated with the smaller reflective surface. Additionally, a detailed computer model of the Configuration II receiver was developed and certified by correlation with the test data. This model was then used to project collection efficiencies with a black chrome coating ($\alpha/\epsilon = 0.95/0.30$). At 260°C, the efficiency improved to 43 and 48 percent with the present and projected lens transmittance, respectively. The efficiency increase with an evacuated environment surrounding the tube would range from 4 percent at 150°C to 10 percent at 260°C.

Sun-Tracking Deviations

The influences on collection efficiency of Sun-tracking deviations in the transverse (E-W) and longitudinal (N-S) directions were measured with receiver Configuration I only and are illustrated in Figure 7. Transverse deviations of 0.5 deg or less had no measurable effect on the collector performance because approximately 85 percent of the energy was still focused into the trough aperture. The energy spillover increased rapidly above 0.5 deg, and the collection efficiency decreased accordingly. Longitudinal alignment deviations up to 2.0 deg did not affect the efficiency. The receiver tube assembly length was sized to tolerate a 5.0 deg longitudinal deviation, but support structure shadowing prevented testing at higher angles. Based on present and previous bench testing, 5.0 deg deviations should have no significant effects.

Other Design Considerations

The primary thermal variable affecting collector efficiency was fluid/tube temperature. Other parameters or effects considered included the incident solar flux, fluid flow rate, and the FEP window on the trough aperture. The direct solar flux variations were small during a given day, but conditions for specific days have ranged from 470 to 900 W/m^2. Solar flux magnitude did not significantly affect performance with receiver Configuration I. Performance with Configuration II did not indicate a sensitivity to solar flux except at levels below 470 W/m^2. Therefore, it was interesting to note that when the standard data presentation format of "collector efficiency versus $\Delta T/I$"[3] was utilized, significant data scatter occurred, especially when data collected at various solar flux levels were compared. Figure 8 illustrates this effect using the Configuration I data. Generally, the slope of efficiency versus $\Delta T/I$ became steeper with increasing solar flux[4] and indicates that the utilization of $\Delta T/I$ as a scaling parameter was not valid for this particular concentrator/receiver configuration. When the same data were plotted in terms of efficiency versus average fluid temperature, the data scatter was reduced to a reasonable level (Figure 9). Similar trends were noted with the Configuration II receiver.

The removal of the FEP cover did not significantly affect performance with receiver Configuration I, probably because other losses overshadowed the FEP thermal benefits. Configuration II performance definitely decreased with FEP removal, e.g., decreased 16 percent at 260°C. Collection efficiencies with two FEP layers spaced 0.635 cm apart were unchanged relative to the single layer configuration.

The influence of flow rate on efficiency was generally not discernible over the range of 100 to 540 kg/hr. Some data scatter did occur at flow rates

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[3] ΔT is average fluid to ambient temperature difference and I is incident direct solar flux.

[4] NBS Recommended Test Standards [4] indicate that this same performance trend can be expected with flat plate collectors although the effect is less pronounced.

less than 70 kg/hr where the flow rate/temperature combination resulted in near laminar flow. Flow rate effects were more apparent in the absorber tube wall/fluid temperature data. The tube wall-to-fluid and circumferential temperature differentials increased with solar flux and decreased with increasing fluid flow and temperature. Basically, however, the measured temperature differentials were controlled by the flow rate/temperature combination. For example, at 4.5 liters/min the tube wall-to-fluid and circumferential gradients were less than 20° and 10°C, respectively, for the entire range of other test conditions.

COST PROJECTIONS

The acrylic Fresnel lens is adaptable to mass production techniques by casting and/or calendaring extrusion processes which permit relatively low manufacturing costs, e.g., $\$21.5 - 24.75/\mathrm{m}^2$ ($\$2 - 2.30/\mathrm{ft}^2$) [5,6]. McDonnell Douglas Astronautics, Western Division, has recently performed detailed Fresnel lens collector design optimization/cost studies and testing [7]. Costs of approximately $\$183/\mathrm{m}^2$ ($\$17/\mathrm{ft}^2$) and $\$108/\mathrm{m}^2$ ($\$10/\mathrm{ft}^2$) with and without installation, respectively, have been projected, based on a mass production status. Additionally, the durability and weatherability of acrylic [8] and the ease of cleaning are qualities which enable reasonable maintenance costs [7]. Thus, the Fresnel lens is cost competitive with other concentrator approaches.

CONCLUSIONS

Relative to the profiles produced by an earlier 56 cm lens, the focusing properties of the present 1.8 m lens were much improved. A baseline peak concentration of 59 and a 90 percent target width of 4.3 cm were computed for the 1.8 m lens. Bench testing indicated a peak concentration of 67 with a 90 percent target width of 4.2 cm. When assembled in the full scale configuration of 1.8 by 3.6 m, the nominal peak concentration and target width were 62 and 5 cm, respectively. Furthermore, future mass-produced lens assemblies will not have to contend with the support/alignment of multiple small panels, thereby enabling full scale lens performance improvements.

The measured and computed lens transmittance was 78 and 86 percent, respectively. Minor transmittance difficulties experienced with one of the two lens panel configurations should be correctable and enable a transmittance improvement in future lenses.

Solar collection tests have been conducted with nonevacuated receiver assemblies with a natural oxide absorber tube coating. The initial receiver concept tested involved focusing the concentrated energy into a reflective cavity aperture rather than directly on the 1.9 cm absorber tube. Collection efficiencies ranged from 40 percent at an average fluid temperature of 125°C to 29 percent at 260°C. Subsequent testing with the 1.9 cm tube placed at the focal plane and a smaller reflective cavity resulted in a collection efficiency of 34 percent at 260°C. With the more efficient black chrome absorptive coating and a projected lens transmittance of 85 percent, collection efficiencies of 48 percent at 260°C are achievable.

The Fresnel lens concept has been demonstrated to be a viable approach for solar concentration, especially considering that the experimentation described herein was performed with a "first generation" lens. Improved lenses can be mass produced at relatively low costs.

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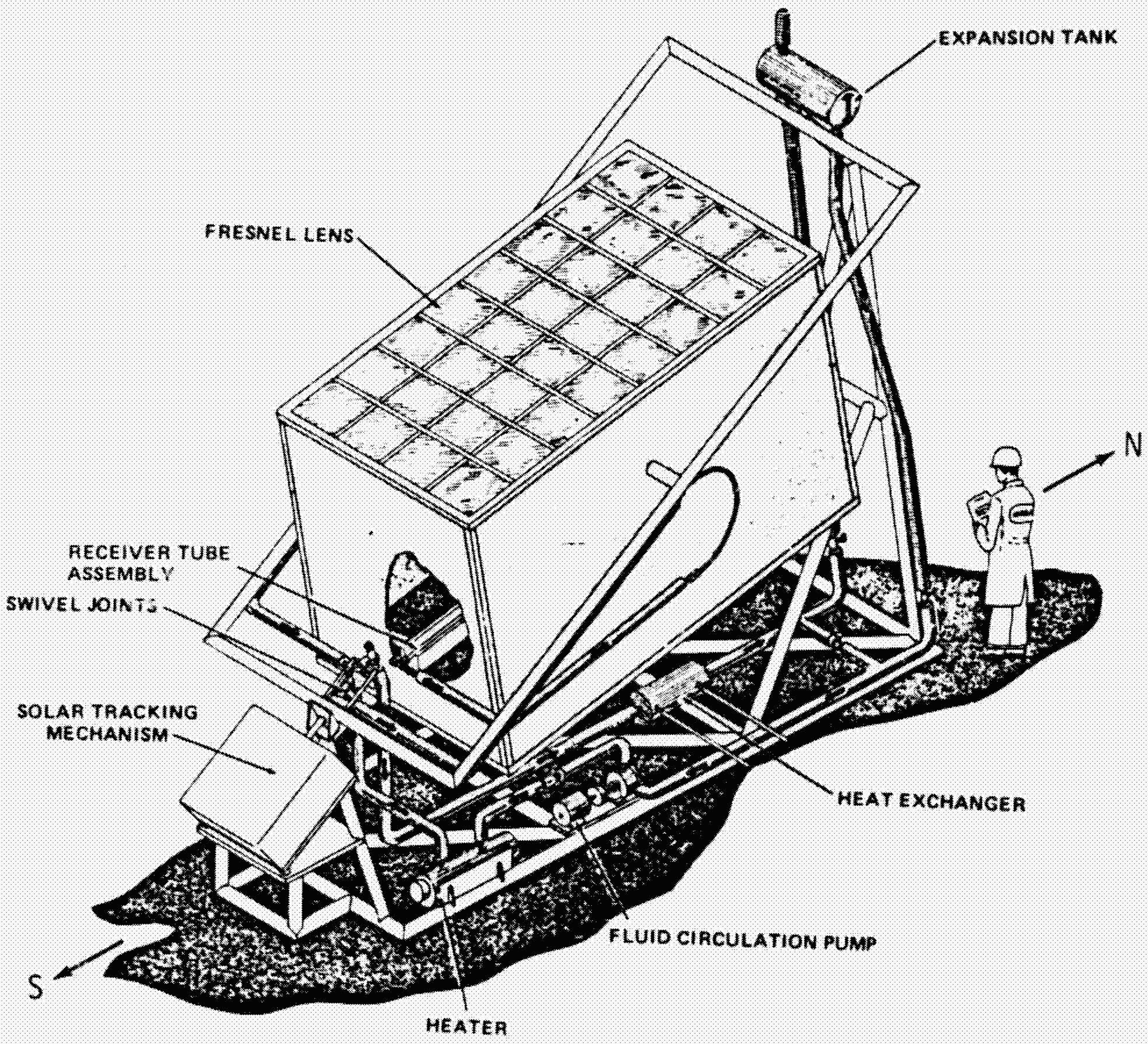

Figure 1. Fresnel lens test article.

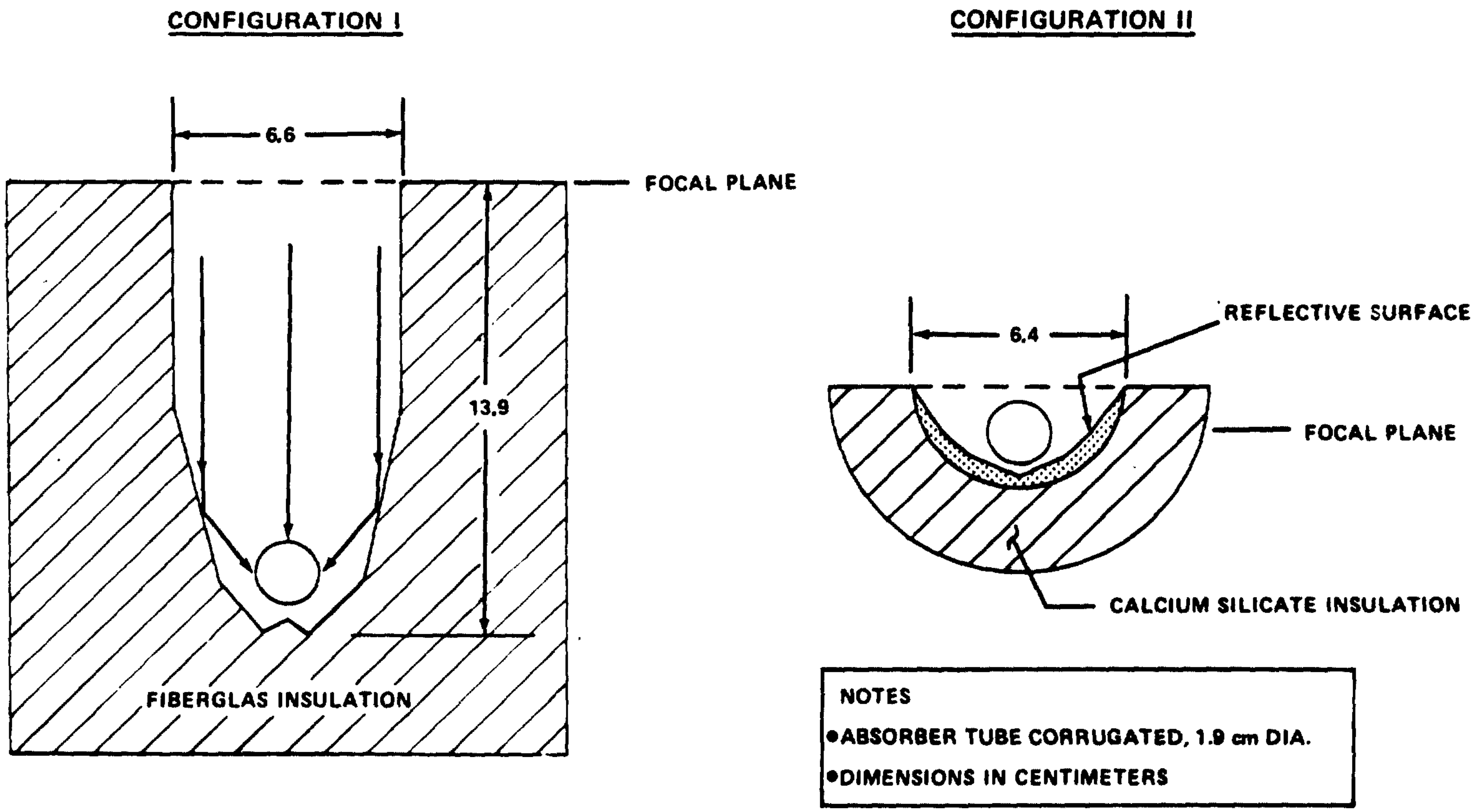

Figure 2. Receiver assembly configurations tested.

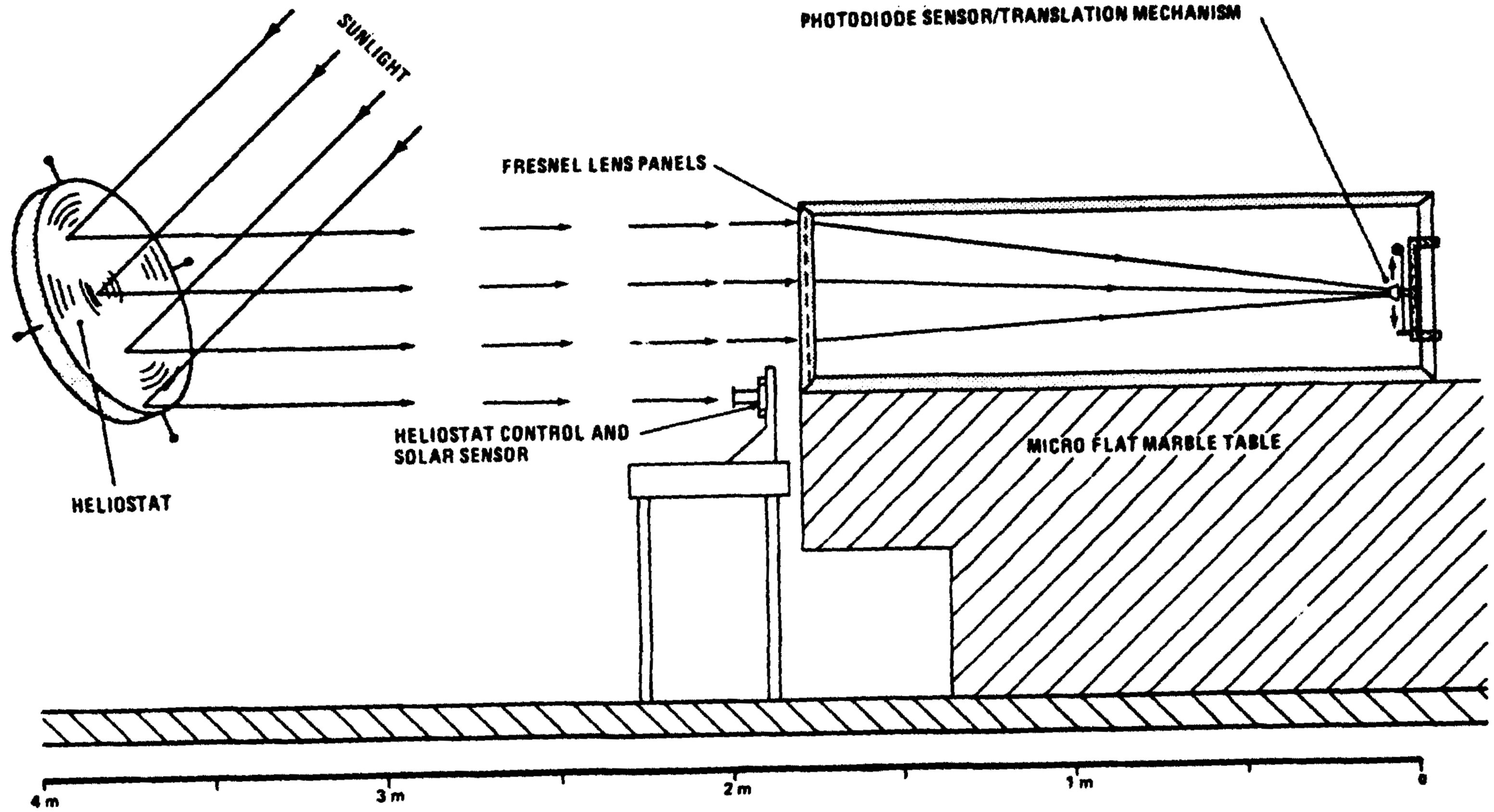

Figure 3. Bench test setup.

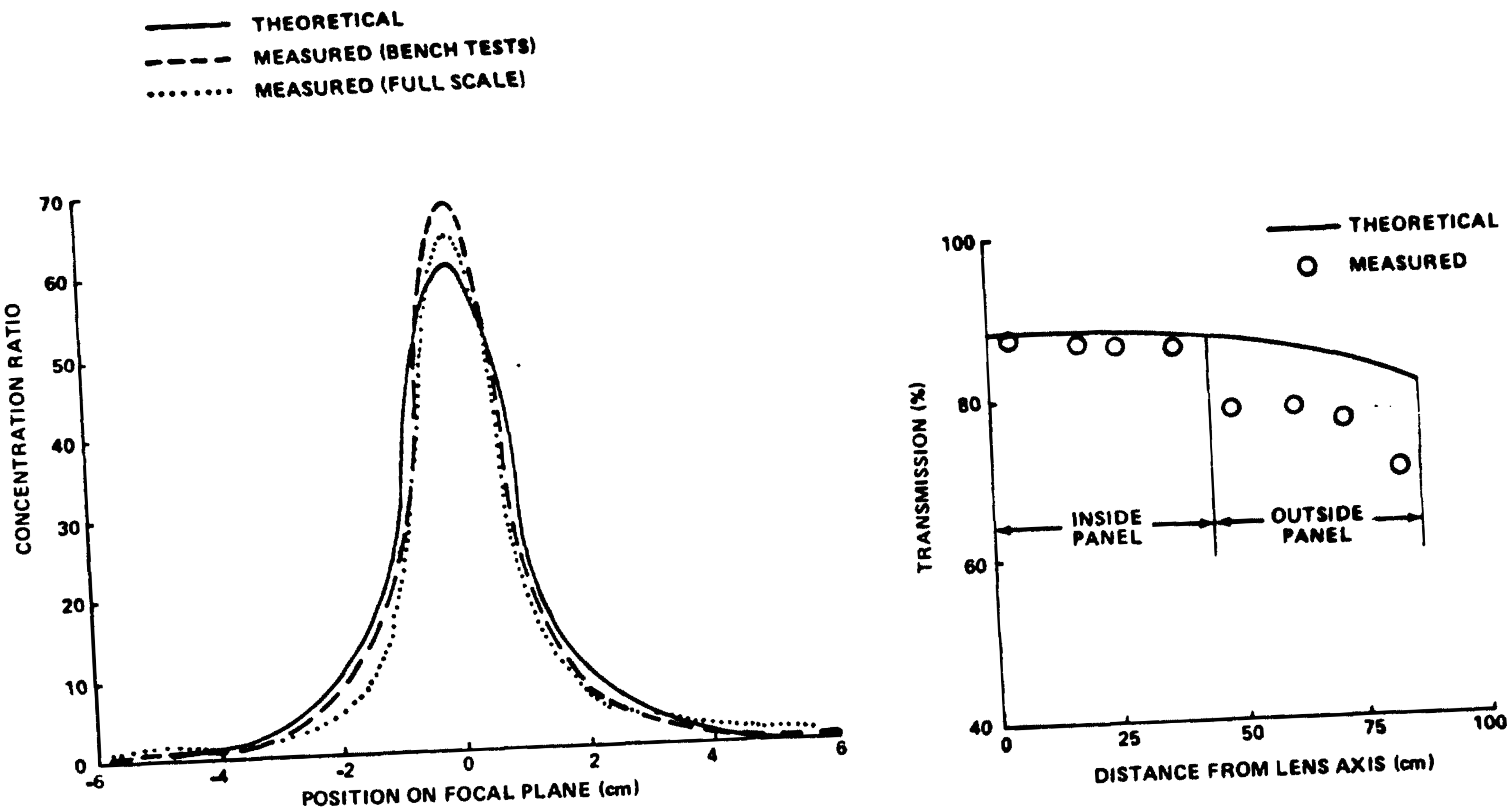

Figure 4. Focal plane concentration profile and lens solar transmission.

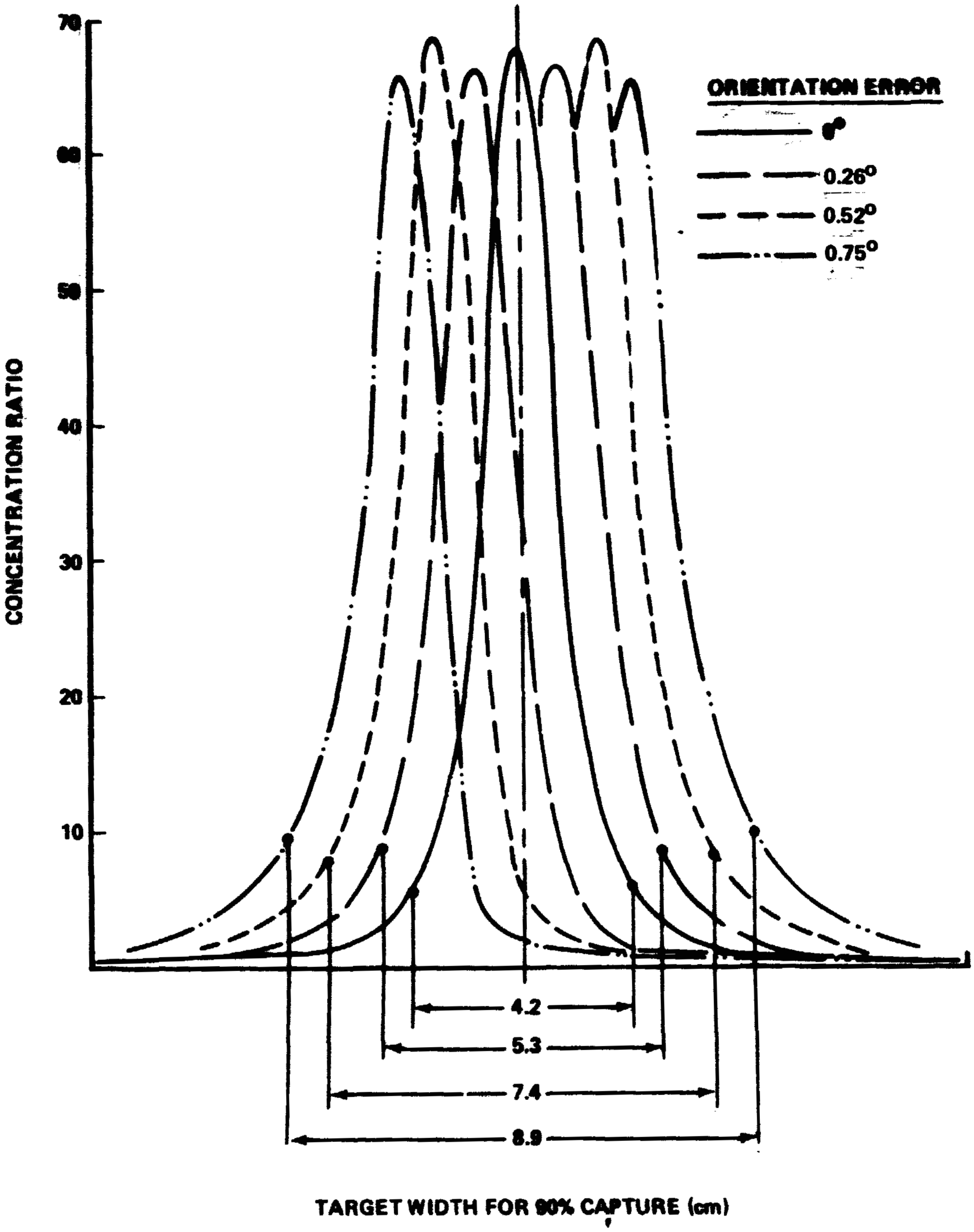

Figure 5. Measured intensity profile variations with transverse misalignment.

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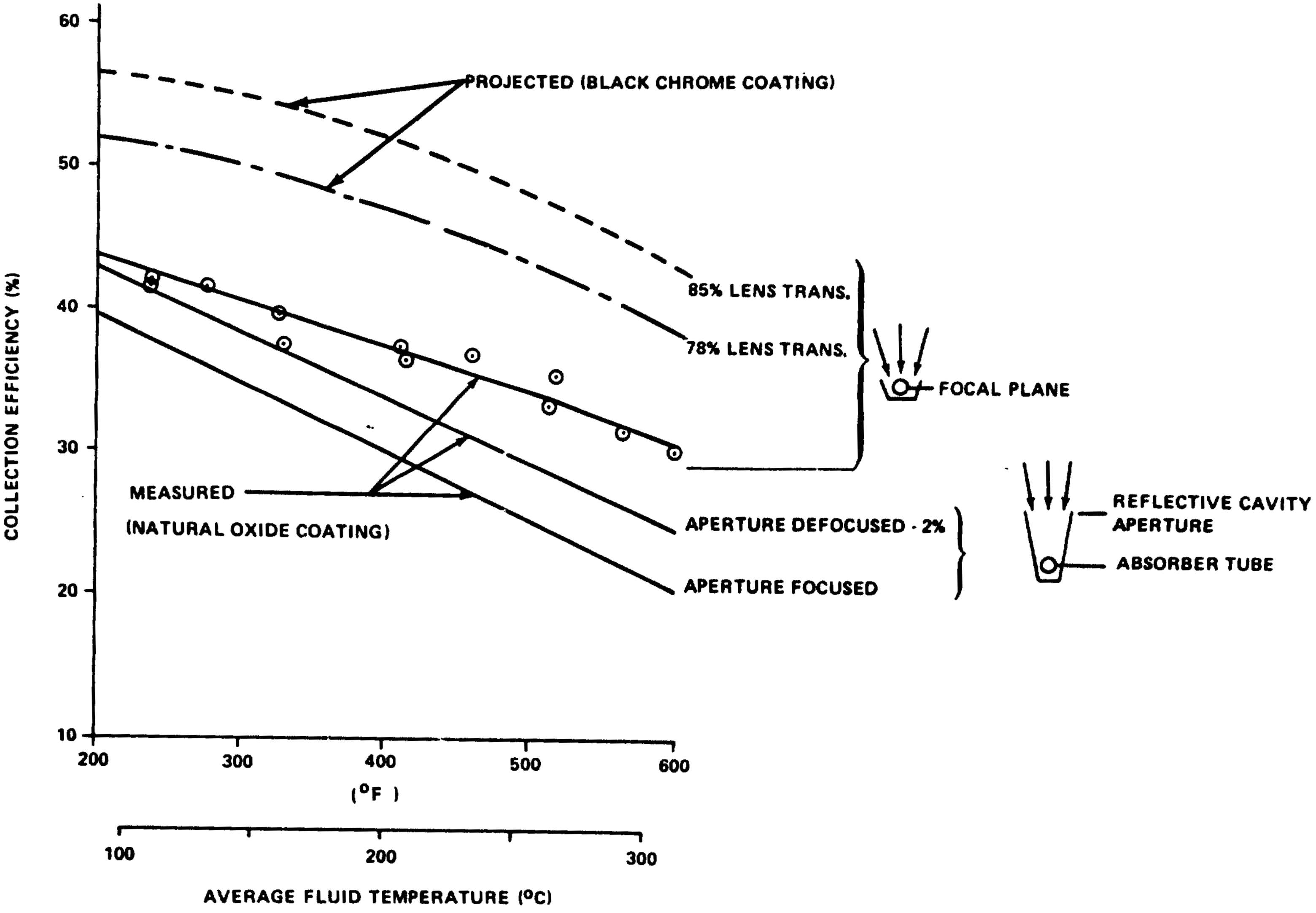

Figure 6. Collector performance overview.

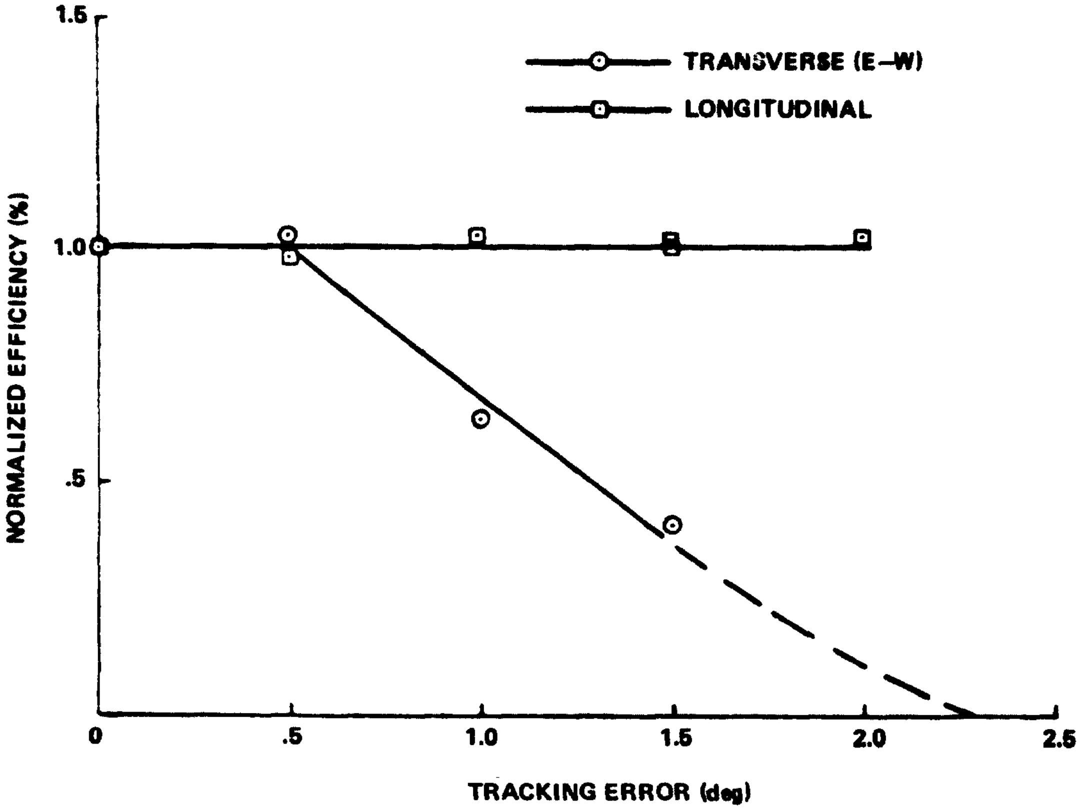

Figure 7. Measured Sun alignment effects on collector performance.

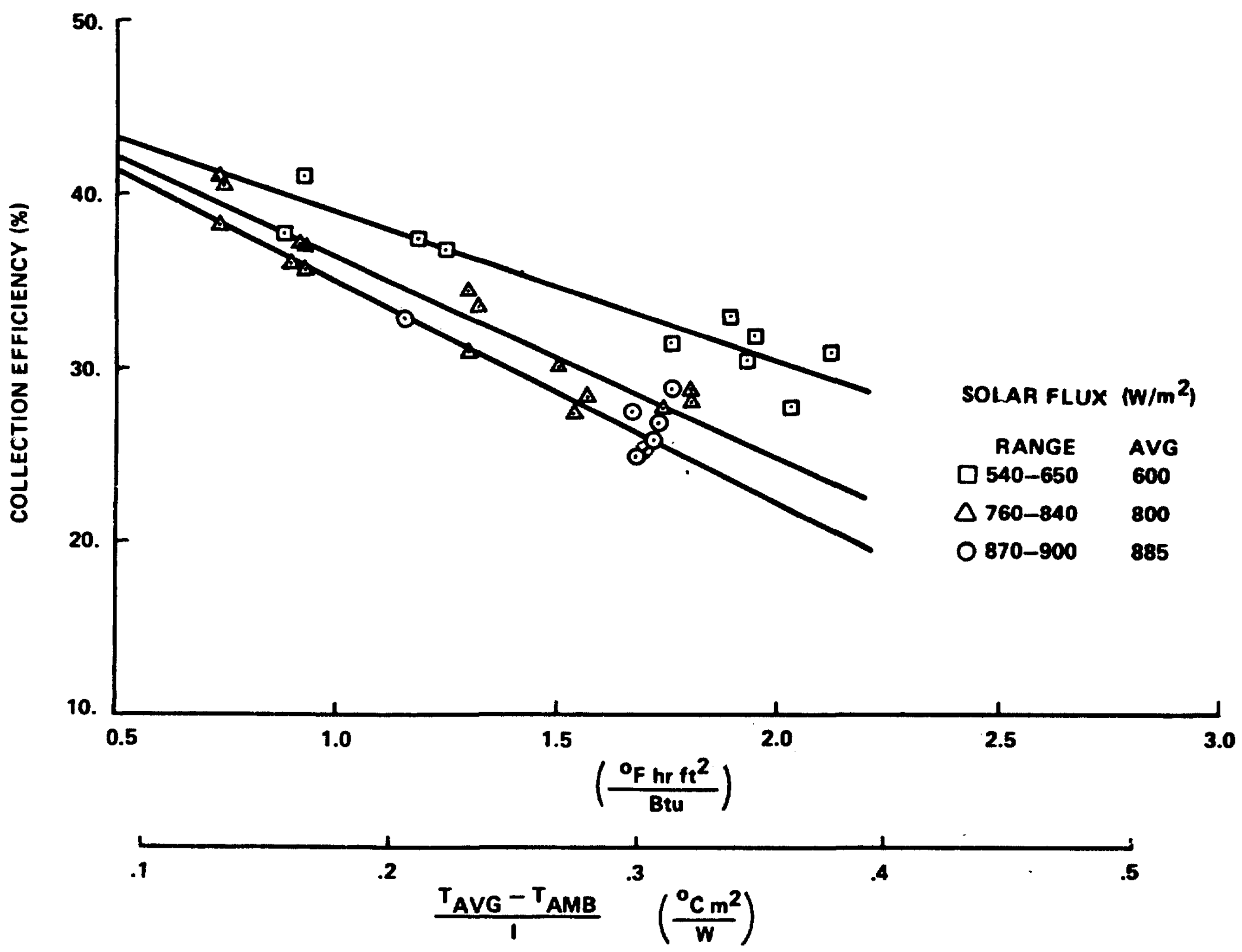

Figure 8. Solar flux level effects on measured collection efficiency versus ΔT/I, receiver Configuration I.

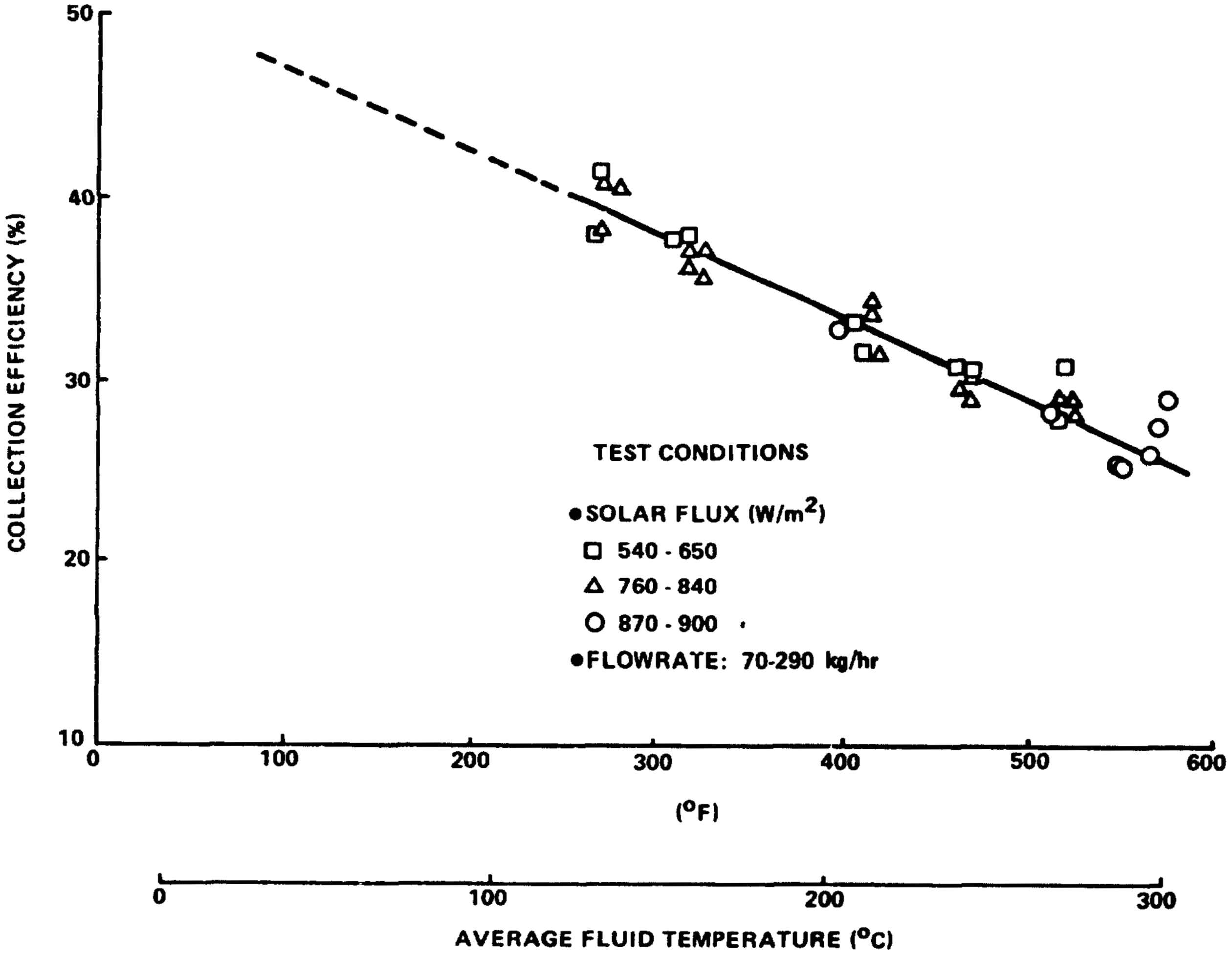

Figure 9. Collection efficiency versus fluid temperature at various flux levels, receiver Configuration I.