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DETERMINING THE OPTICAL QUALITY OF FOCUSING COLLECTORS WITHOUT LASER RAY TRACING

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FOREWORD

A preliminary version of this report (How to Measure the Optical Quality of Focussing Solar Collectors Without Laser Ray Tracing; SERI/TP-34-251) was presented at the 1979 Silver Jubilee International Congress of the International Solar Energy Society in Joint Meeting with the American Section of the International Solar Energy Society, Inc., May 28 through June 1, 1979 in Atlanta, Georgia.

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ABSTRACT

This paper describes a novel alternative to the laser ray trace technique for evaluating the optical quality of focusing solar collectors. The new method does not require any equipment beyond that which is used for measuring collector efficiency; it could therefore become part of routine collector testing. The total optical errors resulting from imperfect specularity and from inaccuracies in reflector position or slope are characterized by an angular standard deviation $\sigma_{optical}$, the rms deviation of the reflected rays from the design direction. The method is based on the fact that the off-axis performance of a concentrator depends on $\sigma_{optical}$. An angular scan is performed; i.e., the collector output is measured as a function of misalignment angle over the entire range of angles for which there is measurable output (typically a few degrees). This test should be carried out on a very clear day, with the receiver close to ambient temperature (if the latter condition cannot be satisfied, appropriate corrections are necessary). The parameter $\sigma_{optical}$ is then determined by a least-squares fit between the measured and the calculated angular scan. We tested the method on a parabolic trough collector manufactured by Hexcel, but it is suitable for parabolic dishes as well.

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NOMENCLATURE

$B_{eff}(\theta)$	Effective source obtained as convolution of B_{sun} with error distribution
$B_{sun,\ radial}(\theta)$	Angular brightness distribution of the sun for point focus geometry (W/m^2 sterad)
$B_{sun,linear}(\theta_\perp)$	Angular brightness distribution of the sun for line focus geometry (W/m^2 rad)
C	Geometric concentration ratio (for example, a trough of aperture width D and receiver tube diameter d has $C = D/\pi d$)
$f(\theta)$	Angular acceptance function
I_b	Beam irradiance as measured by pyrheliometer (W/m^2), also called direct insolation
α	Absorptance of receiver
$\gamma(\theta_m)$	Intercept factor if collector is misaligned, that is, with its optical axis pointing an angle θ_m away from the sun
η	q_{net}/I_b = collector efficiency
η_o	Optical efficiency = $(\rho\tau\alpha)\gamma$
$\theta_\perp$	Projection of incidence angle on plane perpendicular to tracking axis
$\theta_\parallel$	Projection of incidence angle on plane of tracking axis and optical axis
θ_m	Misalignment angle = angle from center of sun to axis or plane of symmetry of collector
ρ	Reflectance of reflector
$(\rho\tau\alpha)$	Effective reflectance-transmittance-absorptance product of collector
$\sigma_{contour}$	rms angular deviation of contour from design direction
$\sigma_{displacement}$	Equivalent rms angular spread that accounts for imperfect placement of receiver relative to reflector
$\sigma_{specular}$	rms spread of reflected beam due to imperfect specularity of reflector material
$\sigma_{optical}$	rms angular spread caused by all optical errors
σ_{sun}	rms angular width of sun in line focus geometry
$\sigma_{tracking}$	rms angular tracking error
σ	Total rms beam spread
τ	Transmittance of collector glazing, if any
ϕ	Rim angle

SECTION 1.0

INTRODUCTION

Evaluation of the optical quality of a solar concentrator is important: to the designer, to tell him whether a collector needs improvement; and to the manufacturer, to ensure proper quality control. In addition to the optical efficiency η_o, it is important to have a measure of optical errors and of losses due to reflected radiation missing the receiver. The methods that are available or have been proposed for measuring the contour accuracy of solar concentrators require either laser ray tracing or flux mapping at the receiver surface. Both approaches can provide accurate results, but the equipment is specialized and expensive and demands a good deal of time and/or expertise [1,2].

The question arises, therefore, whether the instantaneous efficiency measurements that are performed as part of a standardized performance evaluation [3] could somehow be used to determine $\sigma_{optical}$ the rms angular beam spread caused by optical imperfections. This paper shows that this can indeed be accomplished by misaligning the collector slightly away from the sun and measuring the efficiency for several values of the misalignment angle. The optical error $\sigma_{optical}$ is then extracted by finding the theoretical curve that best fits these misalignment data. Thus, the determination of $\sigma_{optical}$, could become part of the standard test procedures for concentrating solar collectors. In a sense, this method employs the receiver itself as flux mapper. Compared to conventional flux mapping with point-like detectors, the present method is much simpler experimentally. The method is suitable for both photovoltaic and thermal collectors.*

The theory underlying this technique is described in Section 2.0. Section 3.0 presents the test results for a parabolic trough collector with cylindrical receiver, manufactured by Hexcel. The data obtained with this collector indicate that the reproducibility of this method is good (on the order of ±5%).

Unfortunately, a laser ray trace apparatus was not available for an independent determination of $\sigma_{optical}$.

*In some photovoltaics concentrators, the reflector is designed for uniformity of flux distribution and is not a parabola. The method is still applicable, but the angular acceptance function $f(\theta)$ in Eq. 2-9 would have to be recalculated for the data analysis.

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SECTION 2.0

THEORY

Since the theory of focusing solar collectors has been described elsewhere [4,5], a brief summary suffices at this point. The crucial concepts are the angular acceptance function and the intercept factor. The angular acceptance function $f(\theta)$ is defined as that fraction of a uniform beam of parallel rays incident on the aperture at an angle θ from the symmetry axis that reaches the receiver if the optics are perfect; $f(\theta)$ accounts for off-axis aberrations. Eqs. 2-1 and 2-2 list the angular acceptance function for parabolic trough and dish reflectors with round and with flat receivers. The rim angle is ϕ and the geometric concentration ratio C, defined as the ratio of the aperture area to the absorber surface area.

For a parabolic trough with cylindical receiver, the angular acceptance function is

$$f_{\text{trough, cyl.}}(\theta) = \begin{cases} 1 \text{ for } |\theta| < \theta_1 \\ \cot \frac{\phi}{2} \left(\frac{2 \tan (\phi/2)}{\pi C \theta} - 1 \right)^{1/2} \\ \quad \text{for } \theta_1 < |\theta| < \theta_2 \\ 0 \text{ for } |\theta| > \theta_2 \quad . \end{cases} \tag{2-1a}$$

where

$$\theta_1 = \frac{\sin \phi}{\pi C}$$

$$\theta_2 = \frac{2 \tan (\phi/2)}{\pi C} \quad .$$

For a parabolic dish with spherical receiver, the angular acceptance function is the square of Eq. 2-1a, with the replacement of πC by $2\sqrt{C}$:

$$f_{\text{dish, sphere}}(\theta) = \begin{cases} 1 \text{ for } \theta < \theta_1 \\ \cot^2 \frac{\phi}{2} \left(\frac{2 \tan (\phi/2)}{2\theta\sqrt{C}} - 1 \right) \\ \quad \text{for } \theta_1 < \theta < \theta_2 \\ 0 \text{ for } \theta_2 < \theta \quad , \end{cases} \tag{2-1b}$$

with

$$\theta_1 = \frac{\sin\phi}{2\sqrt{C}}$$

and

$$\theta_2 = \frac{2\tan(\phi/2)}{2\sqrt{C}} \quad .$$

For a parabolic trough with flat one-sided receiver, $f(\theta)$ is given by

$$f_{\text{trough, flat}}(\theta) = \begin{cases} 1 \text{ for } |\theta| < \theta_1 \quad , \\ \cot\frac{\phi}{2}\left\{\left[\left(4 + \frac{\tan\frac{\phi}{2}}{\theta C}\right)\frac{\tan\frac{\phi}{2}}{\theta C}\right]^{1/2} - 1 - \frac{\tan\frac{\phi}{2}}{\theta C}\right\}^{1/2} \\ \quad \text{for } \theta_1 < \theta < \theta_2 \\ 0 \text{ for } \theta_2 < |\theta| \quad , \end{cases} \tag{2-2a}$$

with

$$\theta_1 = \frac{\sin\phi\cos\phi}{C}$$

and

$$\theta_2 = \frac{2}{C}\tan\frac{\phi}{2} \quad .$$

For a parabolic dish with flat one-sided receiver, the exact expression for the angular acceptance function is more complicated. For practical applications, however, the following polynomial fit is acceptable:

$$f_{\text{dish, flat}}(\theta) = \begin{cases} 1 \text{ for } \theta\sqrt{C} < v_1 \\ a + bC\theta^2 + c(C\theta^2)^2 \\ \quad \text{for } v_1 < \theta\sqrt{C} < v_2 \\ 0 \text{ for } v_2 < \theta\sqrt{C} \quad . \end{cases} \tag{2-2b}$$

The coefficients a, b, c, v_1, and v_2 depend on rim angle and are tabulated in Table 2-1a; a more accurate four-term expansion with an additional term $d(C\theta^2)^3$ is given in Table 2-1b. Implicit in Eq. 2-1 and 2-2, and throughout this paper, is the assumption that the concentration is high enough ($C \gtrsim 10$ for line-focus and $C \gtrsim 100$ for point-focus concentrator) to permit the approximation of $\sin\theta$ by θ.

Table 2-1. COEFFICIENTS OF ANGULAR ACCEPTANCE FUNCTION FOR A PARABOLIC DISH WITH FLAT RECEIVER: THREE-PARAMETER FIT (a), FOUR-PARAMETER FIT (b)

(a) ϕ [degrees]	a	b	c	v_1	v_2
30	-1.8660	32.1042	-89.5992	0.4355	0.5342
35	0.2309	8.7987	-23.7599	0.4785	0.6284
40	0.8866	2.4950	-8.0311	0.5053	0.7226
45	1.1738	0.0861	-2.7177	0.5189	0.8205
50	1.2646	-0.7577	-0.8522	0.5179	0.9231
55	1.2466	-0.9444	-0.2199	0.4969	1.0290
60	1.2075	-0.9682	0.0309	0.4645	1.1407

(b) ϕ [degrees]	a	b	c	d	v_1	v_2
30	-4.4647	65.5256	-231.6741	199.6752	0.4365	0.5346
31	-4.5916	65.3298	-230.3732	215.6702	0.4806	0.5536
32	-3.2651	48.6801	-165.7419	145.2926	0.4536	0.5726
33	-2.9694	43.7084	-144.6810	125.8221	0.4517	0.5916
34	-2.6752	39.2132	-126.3405	108.4094	0.4598	0.6107
35	-1.8817	30.1432	-94.2664	76.2152	0.4682	0.6298
36	-0.9984	20.3357	-60.3045	41.6597	0.4708	0.6473
37	-0.8803	18.5920	-54.0918	37.6157	0.4498	0.6667
38	-0.5546	15.3131	-44.0733	29.8485	0.4757	0.6862
39	-0.2971	12.7096	-36.1594	23.7696	0.4879	0.7057
40	-0.1744	11.2891	-31.6287	20.5410	0.4758	0.7255
41	0.0281	9.3233	-25.9283	16.2998	0.4729	0.7454
42	0.2034	7.7235	-21.4737	13.1345	0.4948	0.7653
43	0.3484	6.4039	-17.8527	10.6252	0.4993	0.7853
44	0.4679	5.3146	-14.9032	8.6317	0.4999	0.8055
45	0.5406	4.5794	-12.8446	7.2859	0.4916	0.8260
46	0.6616	3.6087	-10.4495	5.7546	0.5010	0.8463
47	0.7394	2.9432	-8.7703	4.7180	0.5013	0.8670
48	0.7824	2.5347	-7.7098	4.1138	0.4972	0.8892
49	0.8420	2.0125	-6.4216	3.3377	0.4924	0.9101
50	0.8969	1.5651	-5.3625	2.7276	0.4924	0.9313
51	0.9437	1.1781	-4.4598	2.2215	0.4904	0.9527
52	0.9788	0.8666	-3.7263	1.8195	0.4852	0.9743
53	1.0122	0.5920	-3.1055	1.4926	0.4834	0.9962
54	1.0388	0.3587	-2.5779	1.2208	0.4793	1.0183
55	1.0557	0.1827	-2.1673	1.0151	0.4721	1.0411
56	1.0762	0.0037	-1.7782	0.8258	0.4686	1.0637
57	1.0897	-0.1388	-1.4587	0.6730	0.4622	1.0865
58	1.1025	-0.2654	-1.1845	0.5464	0.4575	1.1096
59	1.1123	-0.3772	-0.9430	0.4376	0.4514	1.1329
60	1.1166	-0.4623	-0.7488	0.3516	0.4425	1.1565

The intercept factor $\gamma(\theta_m)$ is that fraction of rays from the sun that reaches the receiver of a collector with real optical errors when the optical axis is misaligned by an angle θ_m from the center of the sun. The intercept factor is the convolution of the normalized angular brightness distribution of the sun, the distribution of optical errors, and the angular acceptance function for perfect optics.

The brightness distribution of the sun has been measured by the Lawrence Berkeley Laboratory circumsolar telescope as brightness $B_{sun,\ radial}(\theta)$ in W/m^2 steradians at an angle θ from the center of the solar disk. To yield the dimensionless intercept factor, B_{sun} must be normalized by the beam irradiance:

$$I_b = 2\pi \int_0^{2.8^o} d\theta \quad \theta\, B_{sun,\ radial}(\theta) \quad . \tag{2-3}$$

(The upper integration limit corresponds to the acceptance half-angle of the pyrheliometer, the instrument which is customarily used for measuring the so-called direct or beam insolation.) For line focus collectors, it is convenient to transform to the linear brightness distribution (in W/m^2):

$$B_{sun,\ linear}(\theta_\perp) = 2 \int_0^{2.8^o} d\theta_\parallel \; B_{sun,\ radial}\left[(\theta_\parallel{}^2 + \theta_\perp{}^2)^{1/2}\right] \quad , \tag{2-4}$$

where $\theta_\perp$ is the angular coordinate in the plane normal to the focal line and $\theta_\parallel$ the angular coordinate parallel to the focal line.

To standardize the tests described in this paper, it is advisable to take data only when the sky is very clear. The rms width of the sun under such conditions is

$$\sigma_{sun,\ linear} = 2.6 \pm 0.1 \text{ mrad} \tag{2-5a}$$

for line focus collectors, and

$$\sigma_{sun,\ radial} = 3.5 \pm 0.1 \text{ mrad} \tag{2-5b}$$

for point focus collectors. The variation of the brightness distribution between clear days (ratio of circumsolar over beam irradiance less than one percent) is sufficiently small that the analysis of the misalignment data can be based on the standard scan in Table 4-1 of Ref. [6] if a circumsolar telescope is not available.

In a solar concentrator, several statistically independent factors contribute to the optical error: contour errors, lack of perfect specularity [7], tracking errors (when averaged over time), and deformation and displacement of the receiver.

Each error type can be characterized by its rms angular width (one-sided deviation from the design direction). The dispersion $\sigma_{optical}$ for the total optical error is obtained by adding the squares of the individual dispersions:

$$\sigma^2_{optical} = 4\sigma^2_{contour} + \sigma^2_{specular} + \sigma^2_{displacement} + \sigma^2_{tracking} \quad . \tag{2-6}$$

($\sigma_{contour}$ is multiplied by two because of Snell's law; in Fresnel reflectors, $\sigma_{tracking}$ must also be multiplied by two.)

Note that this rule for combining standard deviations is valid regardless of the shape of the individual error distributions; they could be Gaussian, box-like, or anything else, since all distributions under discussion have zero mean. The total beam width σ is obtained by adding the rms width of the sun according to

$$\sigma^2 = \sigma^2_{optical} + \sigma^2_{sun} \quad . \tag{2-7}$$

Measurements of reflector surfaces [1] have shown that the distributions corresponding to $\sigma_{contour}$ and $\sigma_{specular}$ can be treated as Gaussian. The other terms may or may not be Gaussian.* However, when many statistically independent distributions are convoluted, the result is nearly Gaussian unless a single non-Gaussian contribution dominates [8]. In the case of focusing solar collectors, the Gaussian contour errors appear to be the largest, and a Gaussian approximation for the total optical error is reasonable; this is assumed for the rest of the paper.

The order of carrying out the convolution of angular acceptance function, solar brightness, and optical errors is immaterial. Let us first convolute the solar brightness distribution with a Gaussian distribution of optical errors to obtain the so-called effective source. For line focus geometry, the effective source depends only on $\theta_\perp$.

$$B_{eff,\ linear}(\theta_\perp) = \int_{-\infty}^{\infty} d\theta'_\perp\, B_{sun,\ linear}(\theta_\perp - \theta'_\perp) \times \exp\left(-\frac{\theta'^2_\perp}{2\sigma^2_{optical}}\right) / \left(\sqrt{2\pi}\ \sigma_{optical}\right) \quad . \tag{2-8a}$$

*Receiver displacements may be parallel or perpendicular to the aperture (or some combination), and the corresponding error distribution will in general not be Gaussian for a single collector module. Averaged over a large array of collectors, a Gaussian approximation for the displacement error distribution is likely, however, to be quite good.

The point focus case requires two-dimensional convolutions, and it is convenient to write the angles as two-dimensional vectors $\vec{\theta}$. Because of azimuthal symmetry, the effective source for point focus collectors depends only on $\theta = |\vec{\theta}|$.

$$B_{eff,\ radial}(\theta) = \iint_{-\infty}^{\infty} d\theta_x' \, d\theta_y' \; B_{sun,\ radial}\left(|\vec{\theta} - \vec{\theta}'|\right) \times \exp\left(-\frac{|\theta'|^2}{2\sigma_{optical}^2}\right) / \left(2\pi\sigma_{optical}^2\right) \quad . \tag{2-8b}$$

Finally, the intercept factor as a function of misalignment angle θ_m is obtained as a convolution of effective source and angular acceptance functions. For line focus collectors, θ_m is measured in the plane normal to the focal line, and the intercept factor is

$$\gamma_{linear}(\theta_m) = \int_{-\infty}^{\infty} d\theta_\perp \; f_{linear}(\theta_m - \theta_\perp) \; B_{eff,\ linear}(\theta_\perp)/I_b \quad . \tag{2-9a}$$

(If the incidence angle along the trough is nonzero, for example in a collector with an east-west tracking axis at times other than solar noon, θ_m is the projection of the incidence angle on the plane normal to the tracking axis.) For point focus collectors with azimuthal symmetry, the intercept factor depends only on $\theta_m = |\vec{\theta}_m|$, the angle between the center of the sun and the symmetry axis of the collector:

$$\gamma_{radial}(\theta_m) = \iint_{-\infty}^{\infty} d\theta_x' d\theta_y' \; f_{radial}\left(|\vec{\theta}_m - \vec{\theta}'|\right) \; B_{eff,\ radial}\left(|\vec{\theta}'|\right)/I_b \quad . \tag{2-9b}$$

In a real point focus collector, axial symmetry may be violated by gravity induced deformations and by manufacturing defects. To test for such a possibility, the angular scan should be performed in different azimuthal directions.

For parabolic reflectors, f_{linear} and f_{radial} are given in Eqs. 2-1 and 2-2; for other linear concentrator-types, they can be calculated by the method described in Refs. 4 and 5.

A convenient approximation is permitted if the optical errors are sufficiently large. If under clear sky conditions $\sigma_{optical}$ is larger than 5 mrad for line focus and 10 mrad for point focus collectors, the intercept factor is quite insensitive to details of the sun shape and the effective source can be replaced by a Gaussian distribution [2,4]. Since this is the case for the current generation of parabolic trough collectors [1], we have made this approximation for the data analysis in this paper; in other words, we have calculated the intercept factor according to

$$\gamma_{trough,\ Gauss}(\theta_m) = \int_{-\infty}^{\infty} d\theta_\perp \; f_{trough}(\theta_m - \theta_\perp) \; \frac{\exp\left(-\theta_\perp^2/2\sigma^2\right)}{\sigma\sqrt{2\pi}} \quad , \tag{2-10}$$

with the total width σ of Eq. 2-7.

Figure 2-1 shows schematically what the angular scan looks like for a parabolic trough with cylindrical receiver, rim angle $\phi = 90°$, and concentration ratio $C = 25$, for three values of the optical error: 0, 5, and 10 mrad. For this example, $(\rho\tau\alpha)$ was assumed to be one; hence, the intercept factor equals the optical efficiency. From these curves, one sees that this test is most sensitive to data taken around the curved portion of the graph; data corresponding to the halfway point, on the other hand, do not provide any information on $\sigma_{optical}$.

Due to reflection and absorption losses, the radiation incident on the collector is attenuated by a factor $(\rho\tau\alpha)$, where

ρ = solar reflectance of reflector;

τ = solar transmittance of receiver glazing, if any; and

α = solar absorptance of absorber.

(The parentheses indicate that the factor is an effective transmittance-reflectance-absorptance product, including secondary effects such as multiple reflections [9].) When the absorber surface is at ambient temperature, the heat loss is zero and the efficiency η equals the optical efficiency:

$$\eta(\theta_m) = \eta_o(\theta_m) = (\rho\tau\alpha)\ \gamma(\theta_m) \quad . \tag{2-11}$$

If the heat loss is not zero, an appropriate correction must be applied. Variation of $(\rho\tau\alpha)$ with θ_m is sufficiently small to be negligible for the present purpose.

Since $\gamma(\theta_m)$ depends on $\sigma_{optical}$, it is clear that an angular scan of $\eta(\theta_m)$ versus θ_m contains enough information to determine both $(\rho\tau\alpha)$ and $\sigma_{optical}$, at least in principle.

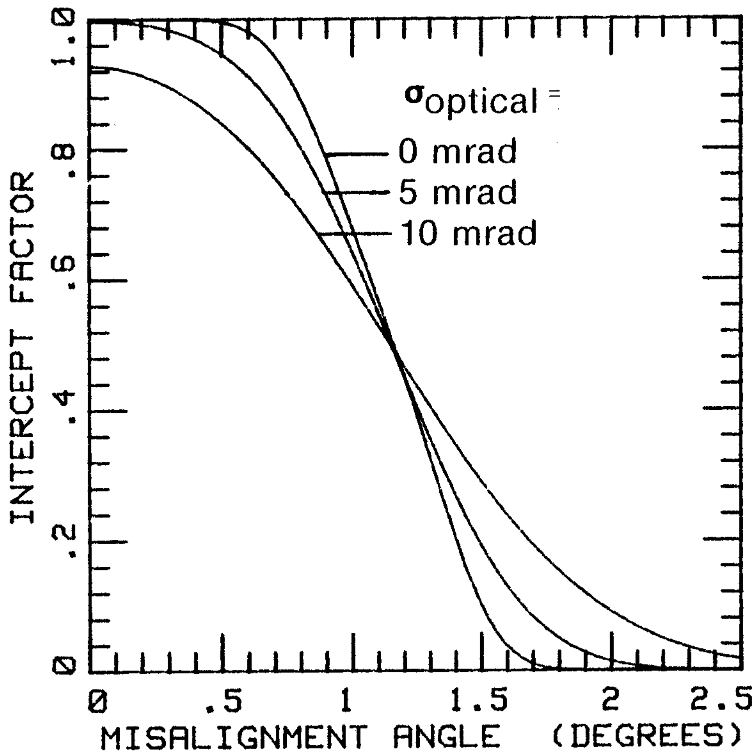

Figure 2-1. Intercept Factor vs. Misalignment Angle for $\sigma_{optical}$ = 0, 5, and 10 mrad

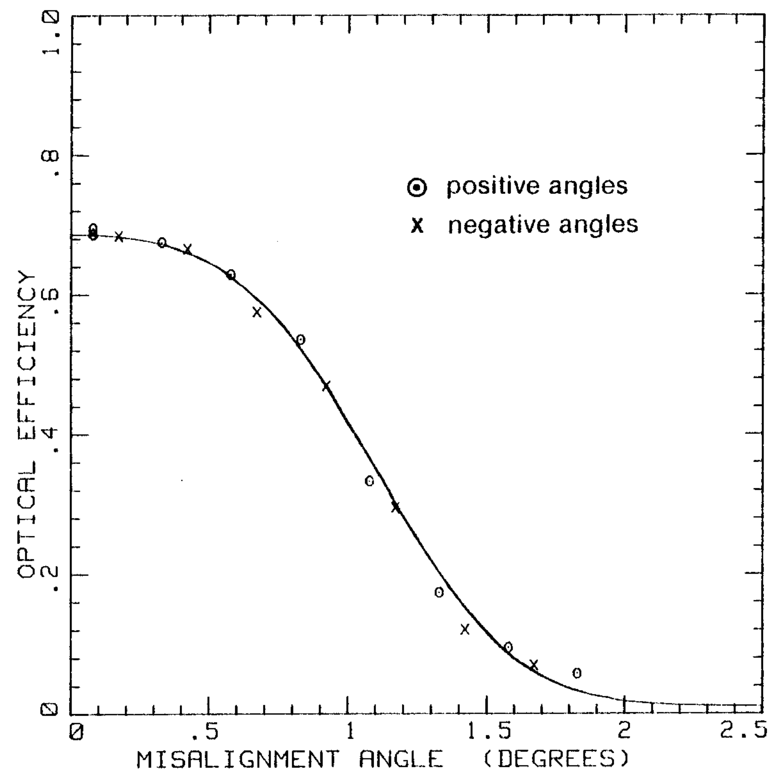

Figure 3-1. Test Data of Optical Efficiency vs. Misalignment Angle (Best Fit)

SECTION 3.0

EXPERIMENT

In order to determine whether this method is accurate enough to be useful in practice, we decided to test a parabolic trough collector manufactured by Hexcel [10]. The test setup is described in another publication [11]. The collector has a cylindrical receiver coated with black chrome. The heat shield and receiver glazing originally supplied by Hexcel were removed for this test, so $(\rho\tau\alpha)$ is simply $\rho\alpha$. The reflector is made of an aluminum honeycomb substrate, coated with FEK-163, an aluminized second-surface acrylic film manufactured by the 3M Company. The rim angle of the collector is $\phi = 72°$, and the geometric concentration ratio is $C = 20.9$. The tracking axis is horizontal in the east-west direction, and the tests were carried out at solar noon, so that the longitudinal incidence angle $\theta_{\parallel}$ vanishes. The collector time constant was less than one minute, sufficiently short to perform an entire angular scan in half an hour. (If the time constant is much longer, a rotating test stand may be desirable.)

Inspection of the Hexcel collector after reassembly at SERI revealed that a significant amount of radiation missed the receiver. This suggested the possibility that receiver placement away from the design focal length of 0.915 m (36 in.) might improve the performance. We therefore set the receiver at several different distances from the reflector apex and each time visually realigned the two reflector halves (which are hinged at the apex) to maximize the intercept of radiation. We facilitated this visual reflector alignment by covering one reflector half while working on the other. By this procedure, we found that the thermal collector efficiency was maximized for a receiver placement slightly (1.25 cm) further away from the apex than the design focal length. All subsequent tests were carried out with the receiver in this new position.

A typical scan of $\eta_o(\theta_m)$ versus (θ_m) is shown in Fig. 3-1. Positive and negative values of θ_m have been included on the same side because of symmetry. Plotting $+\theta_m$ and $-\theta_m$ together has the advantage of pointing out any systematic error in the zero alignment. A nonlinear least-squares fit to these data yields the values

$$F'\rho\alpha = 0.690 \tag{3-1}$$

and

$$\sigma = 6.5 \text{ mrad} \quad . \tag{3-2}$$

In the test procedure, inlet and outlet temperatures of the fluid were measured and only the product $F'\eta_o$ of heat extraction efficiency (also called collector efficiency factor [9]) and optical efficiency could be determined.

The theoretical scan corresponding to these parameters is shown by the solid line in Fig. 3-1. To evaluate the accuracy of this method, the scan was repeated several times, and $F'\rho\alpha$ and σ were calculated for each scan. The results are:

(3-3)

	$F'\rho\alpha$	σ (mrad)
	0.691	6.4
	0.658	6.1
	0.685	6.8
	0.690	6.5
	0.708	6.1
mean	0.686	6.4

The sample standard deviation for these five σ measurements is 0.3 mrad, and indicates that the reproducibility of this method is about 5%.

Lacking a reflectometer, we could not measure ρ and α seperately. Published values for clean materials suggest $\rho \approx 0.85$ and $\alpha \approx 0.95$. F' is calculated to be close to unity and certainly larger than 0.95 (in fact, it did not change noticeably when spirals were inserted within the receiver to increase the turbulence). Hence, we would have expected $F'\rho\alpha$ values greater than 0.77. The low measured values may be because of materials degradation (for example, the reflector was visibly scratched), but the issue remains unresolved without further data.

In these tests, the misalignment angle was monitored quite accurately, hence the tracking error does not contribute significantly to the beam spread and

$$\sigma^2_{\text{optical}} = 4\sigma^2_{\text{contour}} + \sigma^2_{\text{specular}} + \sigma^2_{\text{displacement}} \quad . \tag{3-4}$$

Assuming an rms width of 2.6 mrad for the sun, one therefore obtains from Eq. 2-3 the optical error

$$\sigma_{\text{optical}} = \left(6.5^2 - 2.6^2\right)^{1/2} \text{ mrad} \tag{3-5}$$

$$= 6.0 \pm 0.3 \text{ mrad}$$

for this experiment.

Unfortunately, we did not have a laser ray trace apparatus for an independent evaluation of the optical error. Measurements of σ_{specular} and σ_{contour} have been reported by Sandia Laboratories for reflectors also manufactured by Hexcel of a similar type but different focal length [1,12, and a communication with R. B. Pettit]. The contour error ranged from 1.8 mrad, before environmental exposure, to 2.2 mrad, after three months in an environmental test chamber, and σ_{specular} was on the order of 1 mrad. However, the values of σ_{specular} and σ_{contour} depend very much on how the FEK-163 film is bonded to the substrate.

If these values of $\sigma_{contour}$ and $\sigma_{specular}$ were applicable to the Hexcel collector tested at SERI, they would imply that the contribution $\sigma_{displacement}$, caused by displacement of the receiver and deformations of the parabola, is fairly large, on the order of 4 mrad. Visual inspection of the solar image at the receiver shows that the reflector is deformed; its curvature tends to be less than the design shape either because of the manufacturing process or because of weight-induced sag. A value of 4 mrad for the associated beam spread may be realistic. In view of the difficulty of measuring $\sigma_{displacement}$ directly, and in view of the lack of laser ray trace data for the collector tested at SERI, one can invoke the Sandia data only for a qualitative comparison. To this extent, our results are certainly consistent with the Sandia data, but further work is needed to evaluate the accuracy of the method described in this paper.

SERI

SECTION 4.0

CONCLUSIONS

We have shown that the optical quality of focusing solar collectors can be determined by measuring the performance over a range of misalignment angles, and then comparing the data with calculated results. The calculated results depend on the rms angular optical error $\sigma_{optical}$, and $\sigma_{optical}$ can be found by means of a nonlinear least-squares fit between data and calculation. The method has been tested on a parabolic trough collector and found to have acceptable reproducibility (better than 5%). For point focus collectors, the angular scan can be carried out in several different azimuthal directions in order to provide information on, for example, gravity induced deformations.

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15. Supplementary Notes

16. Abstract (Limit: 200 words)

This paper describes a novel alternative to the laser ray trace technique for evaluating the optical quality of focusing solar collectors. The new method does not require any equipment beyond what is used for measuring collector efficiency; it could therefore become part of routine collector testing. The total optical errors resulting from imperfect specularity and from inaccuracies in reflector position or slope are characterized by an angular standard deviation $\sigma_{optical}$, the rms deviation of the reflected rays from the design direction. The method is based on the fact that the off-axis performance of a concentrator depends on $\sigma_{optical}$. An angular scan is performed: i.e., the collector output is measured as a function of misalignment angle over the entire range of angles for which there is measurable output (typically a few degrees). This test should be carried out on a very clear day, with receiver close to ambient temperature (if the latter condition cannot be satisfied, appropriate corrections are necessary). The parameter $\sigma_{optical}$ is then determined by a least-squares fit between the measured and the calculated angular scan. We tested the method on a parabolic trough collector manufactured by Hexcel, but it is suitable for parabolic dishes as well. The method appears to be accurate enough to determine $\sigma_{optical}$ within about 10%.

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