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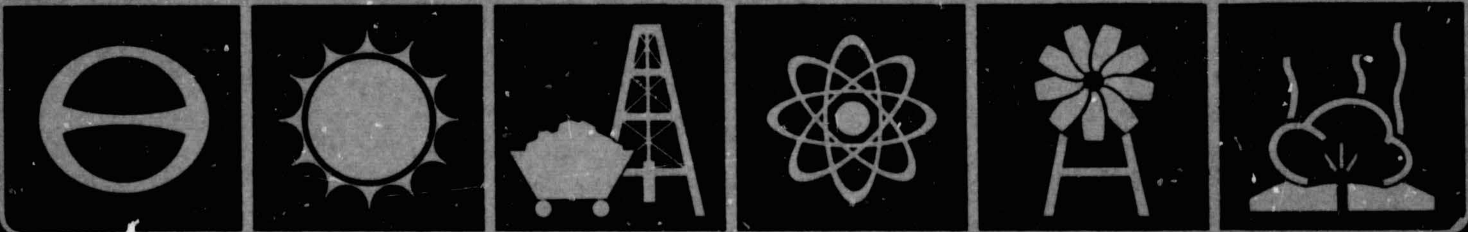
Systematic Rotation and Receiver Location Error Effects on Parabolic Trough Annual Performance

George W. Treadwell, Norman R. Grandjean

Sandia National Laboratories
energy report



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SYSTEMATIC ROTATION AND RECEIVER LOCATION ERROR EFFECTS ON PARABOLIC TROUGH ANNUAL PERFORMANCE

George W. Treadwell, Norman R. Grandjean
Component and Subsystem Development
Division 4716

Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

This report deals with the effects of certain systematic errors on performance and, therefore, their influence on the design of troughs. Systematic rotation error is the angle between the reflector vertex-focus axis and the vertex-sun axis; systematic receiver location error is the vectorial deviation of a receiver from focus.

The existence of systematic rotation errors and systematic receiver location errors can have a significant effect on the annual performance of parabolic trough collectors. These systematic errors can exist in addition to errors which are random in nature and which, therefore, can be treated statistically. Systematic rotation errors of 0.016 radians result in annual performance degradation of greater then 30%. Systematic receiver location errors can have a similar effect depending upon magnitude.

This report is an extension of previous efforts in developing the analytical tools for optimizing parabolic trough designs for consideration by industry. The current work outlines the technique for calculating the influence of systematic errors on performance and suggests methods for identifying and minimizing these errors.

SYSTEMATIC ROTATION AND RECEIVER LOCATION ERROR EFFECTS ON PARABOLIC TROUGH ANNUAL PERFORMANCE

Introduction

This report describes the influence that systematic rotation error* and systematic receiver location error** have on the annual performance predicted for parabolic troughs.

In 1976, the first effort to establish the influence of receiver location errors was documented.[1] It was determined that a receiver with an outside diameter (OD) of 25.4 mm (1 in.) mounted on a trough with a 2-m (6.56 ft) aperture, could be moved ± 3 mm (1/8 in.) from focus on the vertex-to-focus axis without significantly degrading performance. This determination was expanded by A. C. Ratzel and C. E. Sisson[2,3] to include the influence that aiming and receiver-misalignment errors had on performance during selected clear days. They reached similar conclusions.

The previous analytical capabilities were improved by using typical meteorological year (TMY) weather data as an input[4] and by revisions to create a three-dimensional code that permitted the analysis of the sag of a receiver due to gravity.[5] This code has been further revised to permit determination of the simultaneous influence that systematic rotation error and systematic receiver location error have on the annual performance of the trough.

The following data, obtained from the latest analysis, will enable a designer to determine cost-to-performance trade-offs. These trade-offs would be based on various design requirements and methods of dimensioning, as well as their relationships to costs of various materials and structural methods, using the tools, dies, and fixtures necessary to produce a trough that functions.

This report illustrates the potential degradation of performance due to systematic geometric effects in addition to the effect that random optical errors† of the system have on performance.

A designer who recognizes the influence that both types of errors (systematic and random) have on performance, can associate the cost of fabricating and installing the system with a given level of performance. He can then determine whether

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* The angle between a vertex-to-sun axis and a vertex-to-focus axis; aiming error is one example.

** The vectorial position of a receiver geometric center with respect to focus.

† Those that can be treated statistically, such as reflector slope errors and tracking errors.

performance enhancement justifies the cost of incorporating more restrictive tolerances into the design, or of introducing different materials and methods of construction. He can also reexamine those methods of dimensioning, fabricating, and assembling that were acceptable in the past and, by using this new analytical capability, determine if they are still acceptable.

Model Description

The model (Figure 1) for this analysis has been used for previous studies.[4,5] It uses appropriate portions of the SOLTES library[6] and was used on the CDC 7600 computer.

The collector subroutine, previously used for thermo-optical analysis, is a three-dimensional representation of a parabolic trough that considers a number of parameters: e.g. reflector length and width, receiver and glass cover diameter, receiver angular position and rim angle. The subroutine has been modified from its previous versions to include systematic receiver location errors and systematic rotation errors with reference axes, as illustrated in Figure 2.

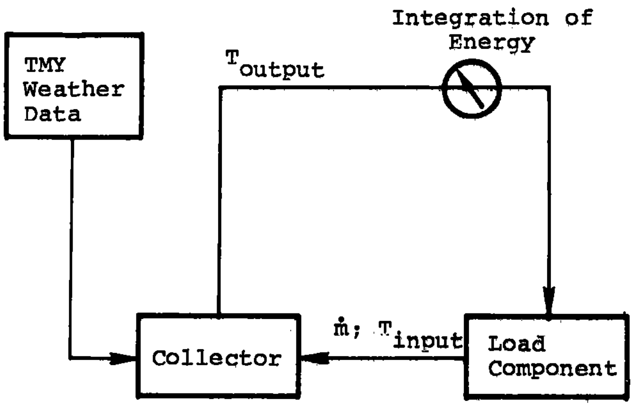

Figure 1. Schematic of analytical model

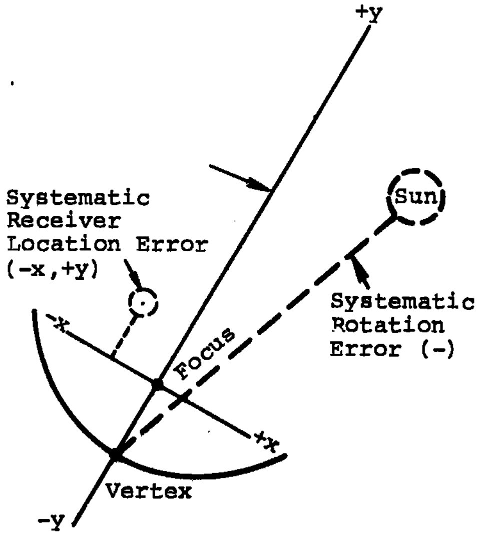

Figure 2. Systematic receiver location and rotation errors

As was done in a previous study,[5] the mechanical deformation of the receiver due to operating temperature and to gravity, as a function of the tracking angle, has been included. The weather input is the typical meterological year (TMY) for Albuquerque; results were integrated over the course of the TMY to predict annual performance.

The definition (Table 1) of the geometric and optical model that was used is compatible with those characteristics that are expected to emerge from the collector development program currently in progress at Sandia National Laboratories.[7]

The code has been arranged to analyze one-axis tracking troughs, oriented on either a north-south or east-west axis at all latitudes below 49° North. To reduce running time, advantage was taken of the earth-to-sun angular relationships and their symmetry during the year. The maximum running time, regardless of symmetry, is less than 1200 seconds.

Table 1.
Parabolic Trough Collector Specifications

<u>Mechanical</u>	
Length	= 31.25 m (102.5 ft.)
Width	= 2 m (6.56 ft.)
No. of Support Posts for Receiver	= 11
Annulus Gap	= 7.3 mm (0.287 in.)
Rim Angle	= 1.57 radians (90°)
Orientation	= N/S horizontal or E/W
<u>Thermo-optical</u>	
Reflectance	= 0.9
Selective Coating	= Black Chrome
Glass Emittance	= 0.9
Reynolds No. Input	= 120,000
Liquid Input	= 260°C (500°F)
Flux Integration Angle	= 0.143 radians (8.2°)
Number of Interpost Segments Analyzed	= 2

The model does not include blocking or shadowing of the receiver due to mechanical supports or adjacent rows of collectors; it assumes a continuous glass-jacketed receiver with uniform gains and losses. The collector length selected for analysis is that capable of being driven by one motor without significant torsion wind-up. Although end effects are precisely calculated, the optical energy that is intercepted is integrated, then averaged over the length and circumference of the receiver. It has been assumed that errors examined in this analysis are constant throughout the TMY; the rationale will be discussed later.

Analysis Results

Most of the analysis was conducted with a receiver having an OD of 31.8mm (1-1/4 in.), although the optimum previously calculated was 25.4 mm (1 in.) for a high quality design.[5] The high quality design is reflected in the figures, which illustrate results of the analysis and could represent a design in which systematic errors would be negligible. However, since it is likely that systematic errors can and do exist in current designs, a 31.8-mm receiver seems to be a more reasonable diameter for a trough with a 2-m aperture.

The analysis was conducted with standard deviations of system optical errors, σ system,* of 0.007 and 0.010 rad. It must be emphasized that the system error is random and is usually treated statistically as a normal distribution, using the theoretical focus of the trough as a reference line. Experimental trough assemblies with a system error of 0.007 rad or less have been installed at Sandia National Laboratories. The choice of an error of 0.010 rad shows trends that are relative to the arbitrary minimum of 0.007 rad.

Systematic Rotation Errors

Results from analyzing the influence that systematic rotation errors have on performance (Figure 3) indicate that the degradation in annual performance is greater than 20% for all cases when the rotation error is 0.016 rad (~1°). At that level, the so-called "optimum design" is the most sensitive to degradation because of rotation error; a degradation of such magnitude that it would be unacceptable to many designers. That is why all remaining analyses were conducted with a rotational error limit of ± 0.008 rad (Figure 4) by changing the scale of Figure 3.

Intuition would lead one to expect that the optimum diameter of 25.4 mm would be more sensitive to rotation errors than that of a larger receiver because of the optical view angle. This expectation is reconfirmed when one reviews Figure 4 portraying the relationships between receiver size, systematic rotation errors, system error, and predicted annual performance. The performance of a 25.4-mm receiver degrades more rapidly than that of a 31.8-mm receiver as the magnitude of rotation errors increases. The 1% higher level of performance of the so-called "optimum design" is erased when a rotation error of ± 0.004 rad is reached. The slight asymmetry of the results is due to the effect of gravity on the receiver as a function of the tracking angle. A rotation error of ± 0.004 rad results in only a nominal reduction (~1%) in annual performance by a 31.8-mm receiver for system errors of 0.007 and 0.010 rad. A 31.8-mm receiver has about the optimum diameter for a system error of 0.010 rad[5] and is only minimally affected by modest rotation errors of less than ± 0.004 rad.

Systematic Receiver Location Errors

The other error investigated was the systematic receiver location error. The analysis was based on the assumption that it is possible to mislocate the receiver's geometric center at its support points up to 5 mm (~0.2 in.) in the x and y directions (Figure 2). Because of sensitivity to rotation errors displayed by the 25.4-mm receiver, this analysis was limited to a 31.8-mm receiver.

The influence that both system errors have on annual performance is shown in Figure 5 (error of 0.007 rad) and Figure 6 (error of 0.010 rad). The six sets of x and y data portray the performance envelope for any x and y deviation of up to

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* $\sigma_{system} = \sigma_{sys} = \sqrt{4\sigma^2_{slope} + \sigma^2_{tracking} + \sigma^2_{sun} + \sigma^2_{reflector}}$

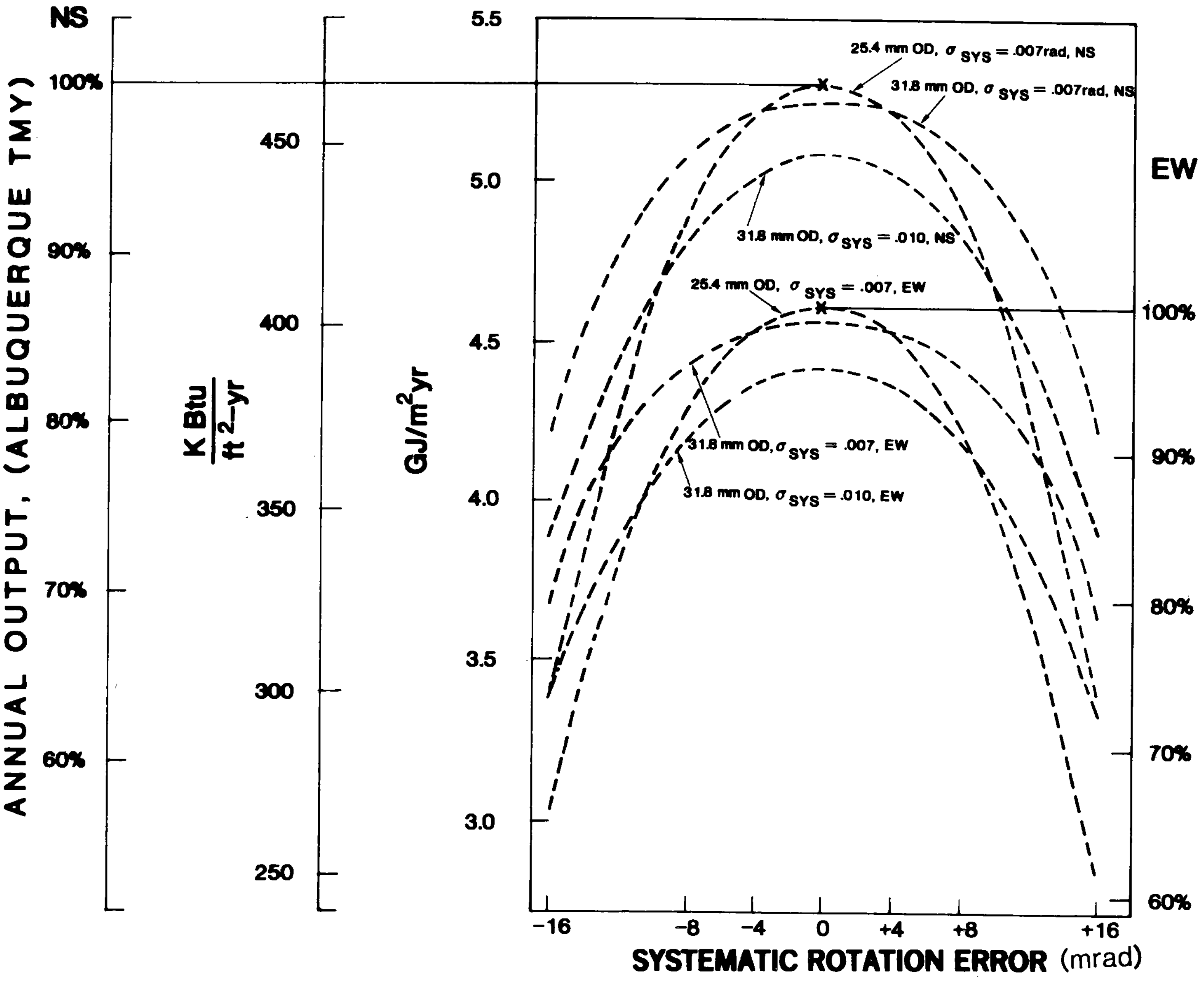

Figure 3. Influence of receiver size, system error, and systematic rotation error on parabolic trough collector performance (Albuquerque TMY). (See elsewhere for collector configuration.)

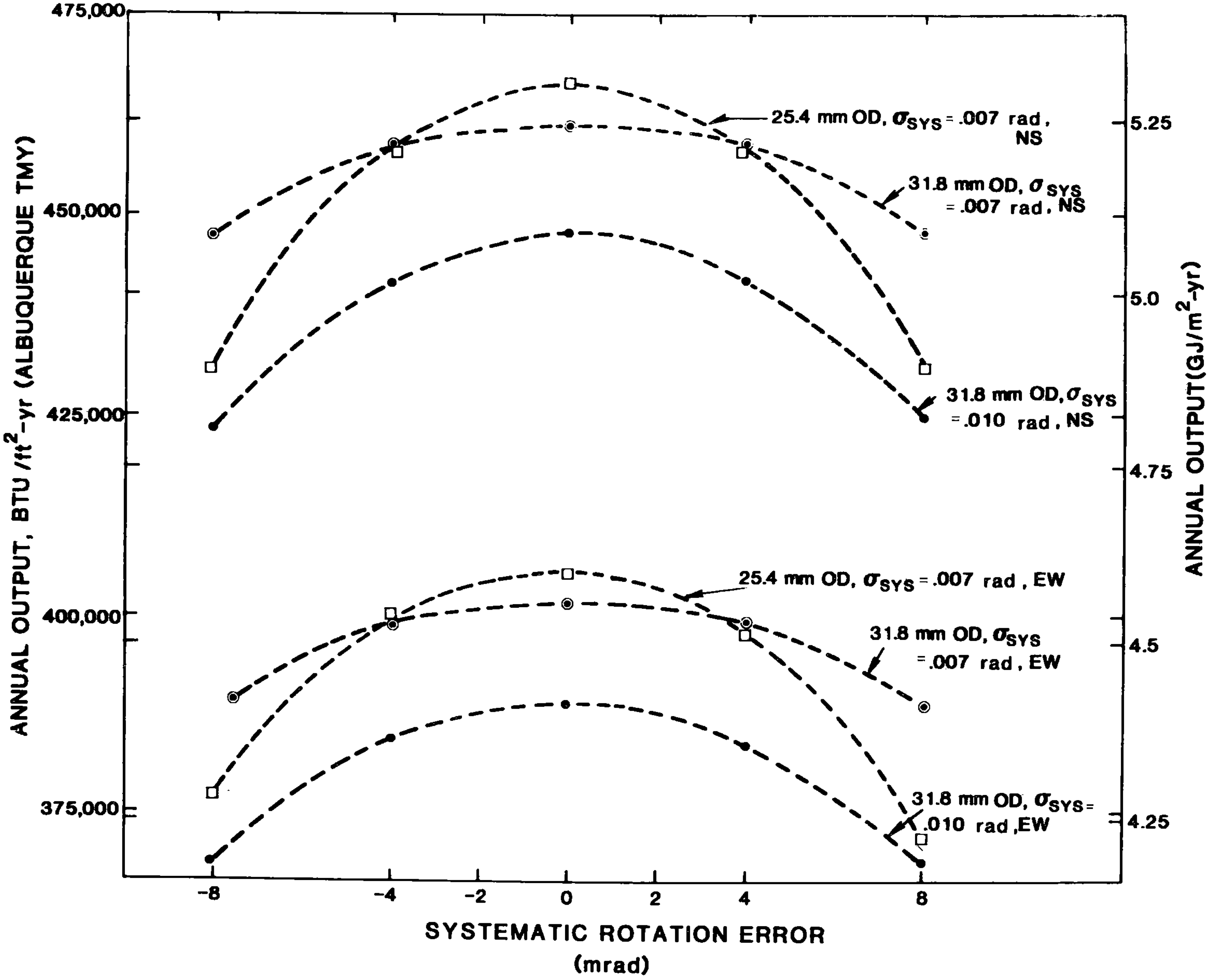

Figure 4. Influence of receiver size, system error, and systematic rotation error on performance.

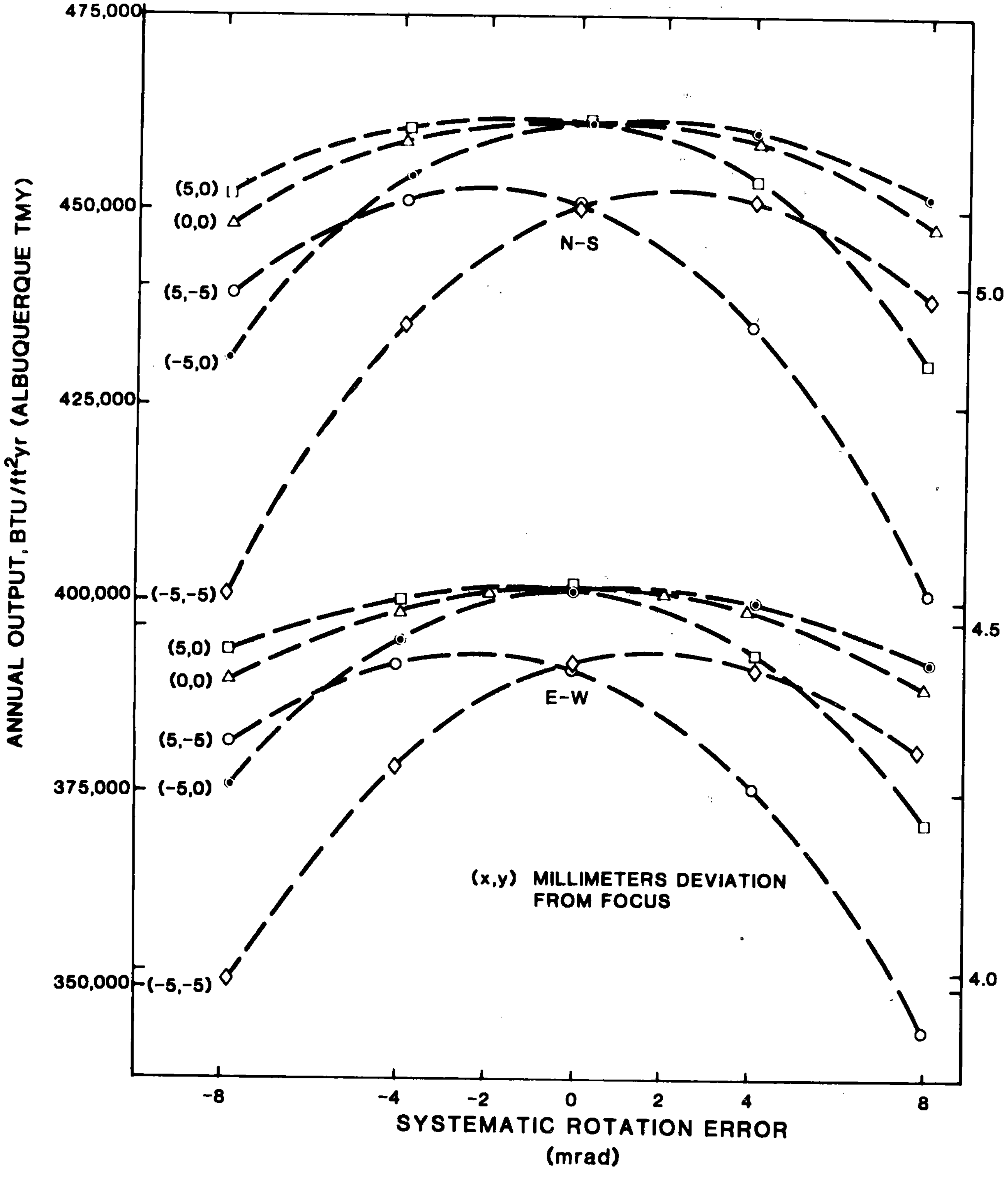

Figure 5. Influence of systematic rotation and systematic receiver location error on performance of 31.8 mm diameter receiver with 0.007 radian system error.

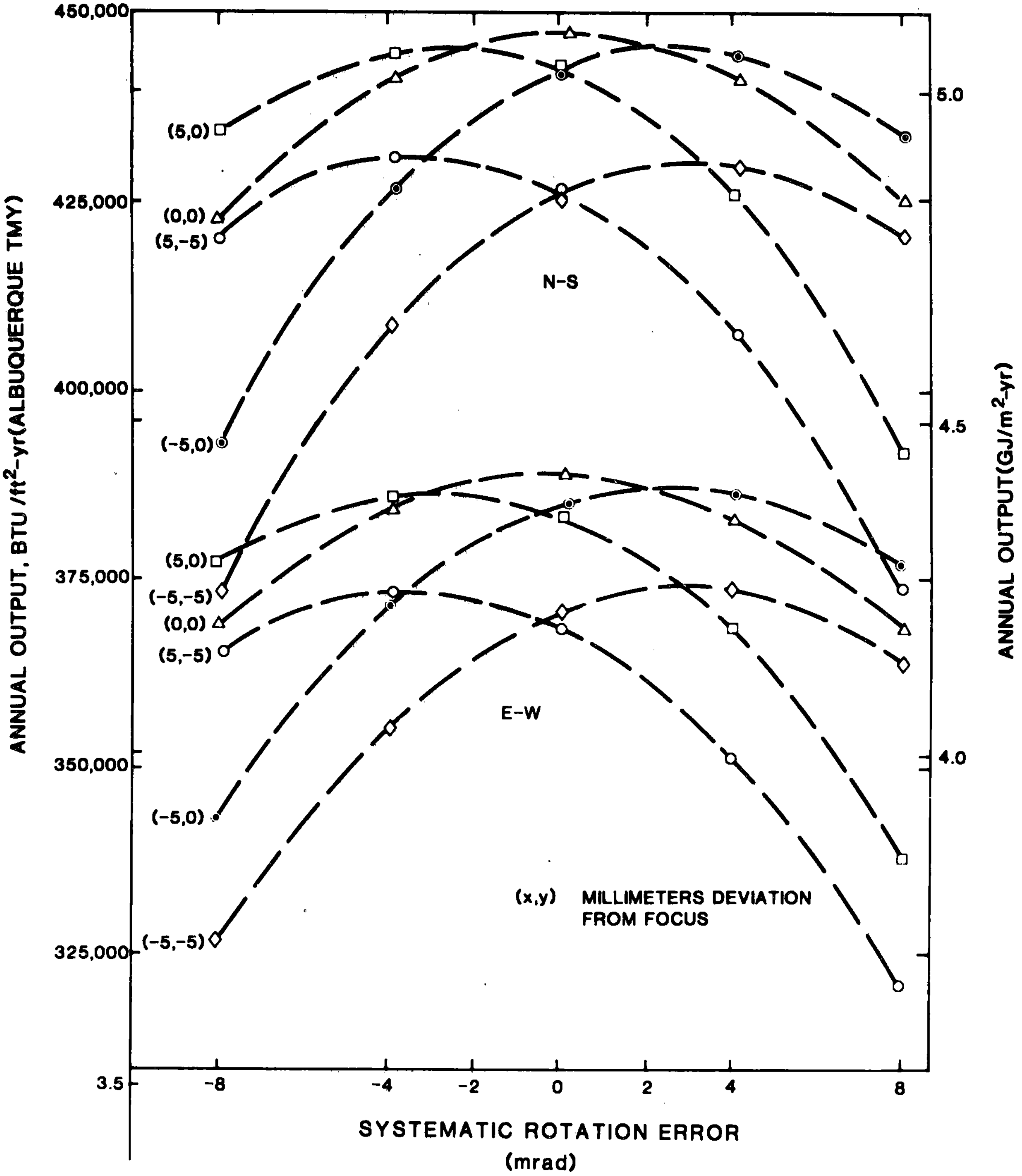

Figure 6. Influence of systematic rotation and systematic receiver location error on performance of 31.8 mm diameter receiver with 0.010 radian system error.

5 mm;* other x and y combinations fall within the envelope shown. Both figures show that systematic receiver location errors, together with systematic rotation errors, have a significantly deleterious effect on performance. In fact, as would be expected, degradation occurs even with some combinations of location errors without rotation errors. Also, the position for optimum performance of any given receiver location error is at any systematic rotation error value other than zero. For example, a collector with a rotation error of -0.004 rad and receiver location errors of (-5, -5) could be re-oriented to a +0.002 rad rotation error and achieve significantly better performance.

In analyzing systematic receiver location errors, it was assumed that each receiver support point was uniformly mislocated. It could also have been assumed that the receiver support points formed a straight line that was not parallel to the theoretical focal line, and the degradation could be calculated by interpolation using either Figures 5 or 6.

Regardless of the technique (dimensioning or assembly), the contiguous assemblies on the receiver will form a straight line so that thermal expansion can be accommodated without buckling the receiver or bending the support posts.

The results obtained in this analysis hold for the Albuquerque TMY location; however, the insights developed on previous studies[4,5] lead us to estimate that similar degradations due to these errors are factors that must be considered when designing parabolic troughs for any site.

Comparisons

By knowing the results of this analysis and comparing them with what might result from design alternatives, a designer can choose the best way to dimension, fabricate, and assemble collector troughs and choose which are the best components for a particular cost and performance.

The systematic rotation error is perhaps easier to confront because it deals only with direction. One example of such an error is a mis-orientation between an orientation indicator and the vertex-to-focus axis. Another is the reflector being rotated about the vertex-to-focus axis during assembly. Yet another is some combination of these two, in which the optical axis is not parallel to the geometric axis.

A computer-driven tracking system relies on an orientation indicator that is supposed to identify the direction of the vertex-to-focus axis. To the extent that orientation is incorrect, a constant error exists. An active sun-seeker for

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*Note the sign convention for (x, y) deviation from focus in Figure 2.

tracking relies on the orientation of its mounting. This orientation causes the seeker-optical and the vertex-focus to be axes in parallel. As before, misorientation causes a constant error. The seeker also relies on the sensors and circuitry to determine and maintain this parallelism. Electronic "drift" due to selective aging of balancing circuits can also cause a constant error. Thus, systematic rotation errors can and do occur and result in constant misalignment over the course of the collector's life. The questions the designer must answer are: How much error is too much?; and, How much will it cost to reduce the error to a tolerable level?

In the collector that has been analyzed, a designer may be willing to accept the ~1.0% performance penalty and then design and fabricate a collector that allows a rotation error of 0.004 rad. This implies that acceptance equipment demonstrating such a tolerance level actually exists. Unfortunately, the designer has to know which particular factor or feature in a collector is causing the error. The way of dimensioning or the assembly technique, itself, may be causing a pseudoerror that the acceptance equipment does not detect. This could occur if the receiver positioning assembly is mounted without reference to the axis of the reflector.

Suppose a collector has a rotation error range of ± 0.004 rad and that this error is acceptable. The designer must still consider the additional influence that systematic receiver location errors have on performance because they will compound the degradation. It is extremely difficult to identify and locate the theoretical focal line of the trough and then emplace a receiver exactly at this line, at least at the receiver support points. Usually, in fact, the receiver is placed on an "eye-pleasing" line. If the receiver cannot be located correctly at the support points, even more degradation can be expected.

Because of the potential degradation due to the combination of both errors (Figures 5 and 6), a designer may be forced to attempt tightening tolerances, if it can be done at reasonable cost, because total installed field cost is the basis for cost-to-performance trade-offs. For example, a 5% improvement in annual performance means a potential reduction of about 5% in numbers of collectors, plumbing and insulation, land area, and controls, yet provides nominally the same output as before the improvement. Because of the importance of the added efficiency, a designer may be willing to install additional tooling and fixtures to obtain more accurate assemblies and still have a better performance-to-cost relationship.

In many instances, errors are not known. In such a situation, a flux integrator mounted along a receiver line could be used to aim a collector string to the intercept position of maximum flux. This position would not only compensate for systematic rotational and location errors but also for receiver sag caused by gravity and tracking angle. Figures 5 and 6 indicate that such a device and strategy can never completely compensate for the errors unless they are negligible to begin with. If planes are not previously defined, we cannot know simply by using a flux-line sensor when the collector departs from optimum performance because "hunting" time and driving gear backlash are involved. In other words, the flux sensor could be used only to compensate partially for inaccuracies in mechanical design, making the best out of a bad situation in which errors were intolerable to begin with.

An alternative to a flux sensor is to introduce datum features into the designs in such a manner that they minimize mechanical errors, and by using predictive (computer) tracking based on inclinometers or shaft encoders. With such an alternative, the designer can obtain the maximum level of performance by reducing the errors in the system. For maximum effect, such datum features must be integrated with fixtures, tooling, and acceptance equipment.

The designer must weigh the performance-to-cost benefits of developing: a fluxline sensor and associated electronics (for recognizing clouds, sunrises, and sunsets); datum features for predictive tracking such as microprocessors and attitude indicators; or, perhaps, a hybrid design that includes both predictive tracking and flux-line sensing.

It is the opinion of the authors that systematic rotation and receiver location errors must be identified and controlled in order for collectors to be acceptable to a wide variety of users.

Future Use

The data generated in this analysis can form the basis for part of a performance data handbook. Completing a similar analysis for all TMY sites could be instructive, but extending this work will be left to the reader. The code can be obtained through Argonne National Laboratory.

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