SERI/TP-253-3324
UC Category: 234
DE88001152

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Allan Lewandowski
Solar Energy Research Institute

Joseph O'Gallagher
Enrico Fermi Institute

April 1988

Prepared for the
Annual Meeting of ASES
Cambridge, Massachusetts
20-24 June 1988

Prepared under Task No. ST812231

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401-3393

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy **A02**

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications, which are generally available in most libraries: *Energy Research Abstracts, (ERA); Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR);* and publication, NTIS-PR-360 available from NTIS at the above address.

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Allan Lewandowski
Thermal Systems Research Branch
Solar Energy Research Institute
1617 Cole Blvd.
Golden, Colorado 80401

Joseph O'Gallagher, Ph.D.
Enrico Fermi Institute
University of Chicago
5640 S. Ellis Ave.
Chicago, Illinois 60637

ABSTRACT

This paper describes an analytical study of several performance-related benefits of using a secondary concentrator in point-focus dish designs. Previous research efforts have shown that design-point performance of dishes can be improved with secondary concentrators, especially for dishes with higher optical errors or at higher receiver operating temperatures. This work addresses the sensitivity to changes in design-point parameter values corresponding to both tracking and optical errors. An analytical model and a ray-trace model were used in analyzing these sensitivities. Results indicate that properly designed secondaries can significantly increase the tolerance to tracking errors and decrease the sensitivity to changes in optical errors from design-point values. Two approaches are recommended on which to base the design of the secondary.

1. INTRODUCTION

Secondary concentrators can significantly improve the performance of many point-focus dish systems (1,2). This is particularly true for those systems with either large optical errors or high receiver operating temperatures. However, there can also be significant benefits for those systems having low optical errors or low receiver temperatures. These benefits are not in design-point performance, but occur in those cases where design-point parameters may no longer apply.

A difference between the design-point parameters and actual parameters can significantly affect dish performance. This is particularly true for tracking errors and optical errors. It is possible, however, to mitigate these effects by using a secondary concentrator. A trumpet-type secondary placed at the focal point of the dish significantly reduces the sensitivity to changes in both tracking and optical errors. For a dish design with typical focal-length-to-diameter ratios, f/D, a trumpet-type secondary is the most effective. A schematic of this secondary on a parabolic dish concentrator is shown in Fig 1.

Changes from design-point tracking and optical errors could occur for several reasons. Structural deflections may take place with gusty winds and can result in significant tracking errors. It may be possible to design a structure for larger deflections with a secondary and consequently reduce cost. It is also likely that the structural and optical performance of any dish system will degrade over time. This could be caused by creep of membrane materials, weakening of the structure due to wind-induced oscillations, the effects of daily and seasonal temperature variations, and other environmental effects. Although it is not possible to fully quantify the magnitude of these effects, it is possible to assess how changes in optical errors affect performance.

In this paper, models of a point-focus dish system were used to study the sensitivities to tracking errors and to changes in optical errors on the overall efficiency of the system. A description of the models used to

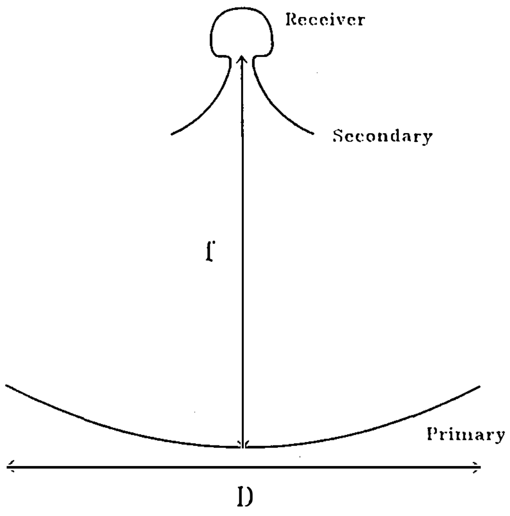

Fig. 1. Schematic representing a trumpet-type secondary on a parabolic dish concentrator.

calculate overall efficiency is given in Section 2. Section 3 discusses the analytical results for sensitivity to tracking errors and optical errors. Finally, several significant conclusions concerning dish design emerge from these results.

2. METHODOLOGY

Calculating the overall efficiency for a dish system requires a knowledge of the optical performance of the concentrator and the heat-loss characteristics of the receiver. The following equations describe the overall thermal efficiency of a dish:

$$\eta = Q_{NET}/IA \tag{1}$$

$$\eta = [Q_{OPT} - (Q_{RAD} + Q_{CONV} + Q_{COND})]/IA \tag{2}$$

$$\eta = \rho \eta_s G \gamma \alpha_e - [\epsilon_e \sigma (T^4 - T_a^4) + h_c(T - T_a) + (A_w/A_r) h_k (T - T_a)]/(IC_{geom}) \tag{3}$$

Two methods for predicting the overall thermal efficiency were used in this paper. Both use the same heat-loss model; however, they represent different approaches for calculating the intercept factor, γ. The first is an analytical approach that assumes all errors are normally distributed and relates errors at the concentrator surface to errors in the target plane by a particular approximation. This approach was first developed at the Jet Propulsion Laboratory (JPL) for parabolic dishes (3). In this method, tracking errors are treated as normally distributed. Thus, this method is not suitable for predicting the effect of constant tracking errors.

The second approach uses a ray-trace procedure that is not limited to parabolic shapes and normally distributed errors and thus is much more versatile. This approach was developed at the University of Chicago (2). This method was used to predict the effects of constant tracking error. The effect of a secondary on the dish's performance was approximated by a relationship generated as part of the University of Chicago's research and is used in both methods.

The heat-loss model described in Eq. (3) is relatively straightforward, except for the convective heat-loss coefficient, h_c. This coefficient is a function of receiver tilt and temperature. The convective loss parameters are based on French cavity heat-loss experiments (4). Other parameters for optical and thermal loss calculations are listed in the nomenclature (Section 6).

Two approaches to using a secondary were proposed in this analysis. The first is to design the system for maximum performance with the secondary. Optimizing performance this way results in a smaller receiver aperture and a larger intercept factor. The second is to design the system so that adding a secondary maintains the same efficiency as for the primary-only system. This second approach results in a somewhat larger secondary and a lower overall concentration than for the first approach. In addition, the receiver aperture is larger than for the primary-only design and consequently will have a larger intercept factor.

These approaches can be visualized in Fig. 2 for a dish with a focal-length-to-diameter ratio, f/D, of 0.6. This figure shows the overall collector efficiency as a function of receiver aperture radius. As the aperture radius increases, the intercept factor and the heat losses increase, resulting in a trade-off between them. An optimum is reached where incremental increases in intercept (and optical performance) are balanced by the incremental increases in heat loss. The trade-off is shown in the figure at an operating temperature of 800° and for a dish both with and without secondary.

Designing for maximum efficiency with a secondary results in both greater efficiency and a smaller receiver aperture as indicated by the peak in the curve in Fig. 2. When designing a secondary for equivalent efficiency, an aperture radius slightly larger than the optimum for the primary-only concentrator will result. This is indicated by projecting a horizontal line from the peak of the primary-only curve to the right until it intersects the secondary curve. The larger aperture allows for greater variation in position and distribution of the concentrated solar radiation without great changes in the intercept.

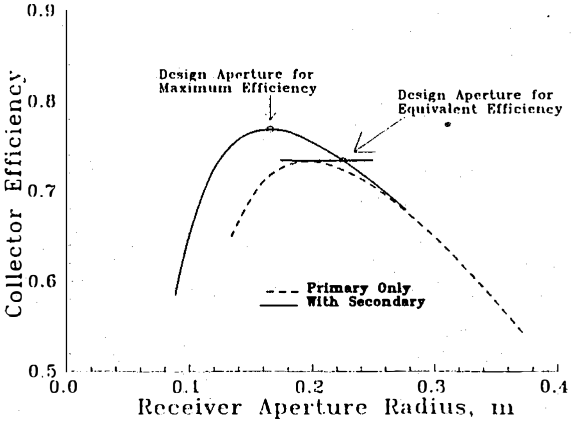

Fig. 2. Trade-off between optical intercept and heat loss to maximize efficiency for a dish with f/D = 0.6, operating at 800°C, and baseline optical parameters indicated in the nomenclature.

3. RESULTS

Since a secondary essentially increases the acceptance of a dish system, one of its advantages is that the secondary increases the tolerance to errors, like tracking or sun size. In the case of tracking errors, the ray-trace model developed at the University of Chicago was used to assess the effects small errors in dish pointing had on performance. The resulting flux profiles on the target are asymmetric and tend to increase the thermal load on the secondary. The predictions of the performance under these off-track conditions assume that the errors are not time varying; i.e., the dish is operated at steady state with a fixed tracking error. This means that these results are an upper bound to performance penalties associated with tracking errors that will likely exist under dynamic conditions induced by fluctuating wind loads.

For a dish system operating at 500°C and σ_{slope} = 1 mrad, the effect of a secondary designed for equivalent efficiency (e.g., equivalent for no tracking error) is shown in Fig. 3. The system with a secondary is nearly insensitive to off-track angle up to about 10 mrad. To achieve 90% of the on-track efficiency (η = ~0.80), the primary-only system could off-track up to about 7 mrad, whereas the system with a secondary could off-track up to 13 mrad, nearly a 90% improvement. For a dish with low optical errors, there is relatively little gain in on-track performance from a secondary. However, substantial gains can be achieved in tracking error tolerance, especially if the system is designed for this purpose. Although not described in this paper, results for a dish designed with a secondary to maximize performance show greater tolerance than for the primary-only design but less than that achieved with a secondary designed to increase tracking tolerance.

The choice of design approach for a dish system with σ_{slope} = 5 mrad and operating at 500°C is not as straightforward as for the previous case. At larger optical errors, the benefit of a secondary is increased for on-track performance. However, the sensitivity to tracking error is still greater for the secondary system designed for equivalent efficiency. Figure 4 illustrates the results for this type of secondary system when larger optical errors in the primary are assumed. Here, 90% of the on-track efficiency occurs at an off-track angle of about 13 mrad, whereas the system with a secondary could off-track up to 28 mrad, over a 115% improvement. Note also that the system with a secondary is nearly insensitive to off-track angles up to about 20 mrad.

Choosing between higher on-track performance and greater tracking tolerance will be decided by how cost affects the two approaches. Allowing more dynamic response in the structure (i.e., greater tracking errors) could be achieved by reducing the weight and strength of structural members, which could also reduce cost. The viability of this approach was not explored but would require detailed structural analysis of specific concentrator designs.

The design of any dish assumes some knowledge of the optical errors in the system. Several reasons could account for the differences between the actual optical errors in a dish and those used in design. Fabrication uncertainties, especially of membrane-dish concepts, may cause unexpected errors. Transportation and field installation, including alignment procedures, may be difficult to

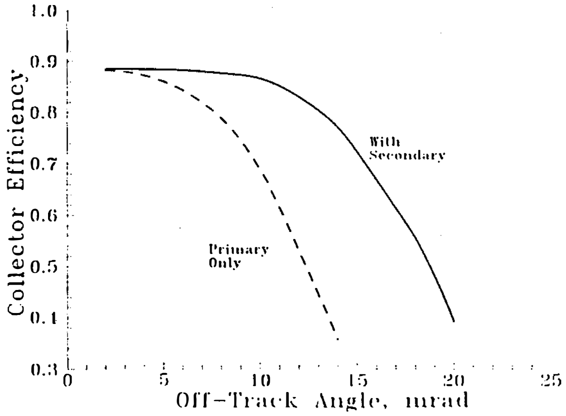

Fig. 3. Effect of a secondary designed for equivalent efficiency on a dish system with f/D = 0.6, operating at 500°C, and σ_{slope} = 1 mrad.

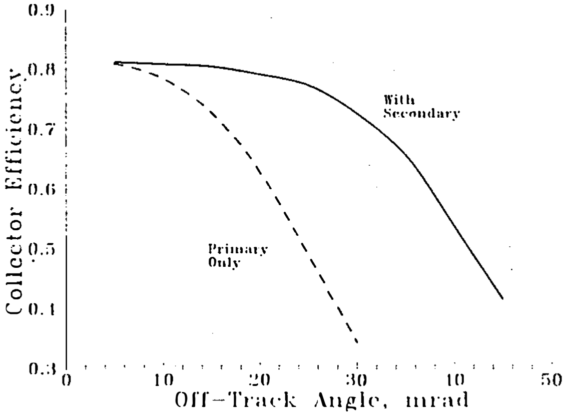

Fig. 4. Effect of a secondary designed for equivalent efficiency on a dish system with f/D = 0.6, operating at 500°C, and σ_{slope} = 5 mrad.

control. For a given system to become operational as an accurate reproduction of its design may require stringent quality control, which could be expensive. In addition, changes over the life of the system (e.g., creep or thermal expansion) could result in increased errors. It is impossible to predict the magnitude of potential changes in actual versus design conditions, but it is possible to analytically show the effect of those differences. The analytical model was used to assess the effects on performance for dish systems where the design optical errors are not achieved in operation.

At an operating temperature of 500°C, primary-only and secondary systems (designed for maximum performance) are extremely sensitive to deviations of actual slope errors if a low design value of slope error was assumed. This case is shown in Fig. 5. If a primary-only system is designed with σ_{slope} = 2 mrad and actually achieves a 5 mrad value, the performance decreases nearly 27%. A system with a secondary suffers a 24% decrease under the same conditions. However, if these same systems are designed for 5 mrad and actually achieve 2 mrad, there is only an 8% penalty for a primary-only system and a 5% penalty for a secondary system. This comparison is with the case where the design and achieved slope errors are 2 mrad. Compared with the maximum efficiency for a system designed with a 5 mrad slope error, the penalty is almost 3% for a primary-only system and 2% for a secondary system. This is equivalent to a 100% increase in the optical error budget for only a 5% reduction in efficiency. At the same time, the sensitivity to differences between actual slope error and design value is vastly reduced.

At 800°C these trends are qualitatively the same but have greater magnitudes. As shown in Fig. 6, a primary-only system designed at 2 mrad that actually achieves a 5 mrad value decreases performance by 36%. A system with a secondary suffers a 32% decrease under the same conditions. However, if these same systems are designed for 5 mrad and actually achieve 2 mrad, there is only an 18% penalty for a primary-only system and a 9% penalty for a secondary system compared with the case where the design and achieved slope errors are 2 mrad. Compared with the maximum efficiency for a system designed with a 5 mrad slope error, the penalty is almost 9% for a primary-only system and 6% for a secondary system. This is equivalent to a 100% increase in the optical error budget for only a 6% reduction in efficiency.

Based on these results, the design-point optical errors should approach the largest expected errors over the lifetime of the system. This design approach will yield the maximum performance over the lifetime of a design where the optical errors are likely to increase with time. When a system is designed for a larger optical error, a secondary is needed to maximize performance. These results argue for an approach that sees the possibility of optical performance degrading with time and that designs the entire system to maximize long-term performance, recognizing that initial performance may be less than potentially achievable.

Designing a dish with a secondary to achieve an efficiency equivalent to the primary-only dish system also results in a decrease in sensitivity. When this approach is taken at a design σ_{slope} = 2 mrad, the dish with a secondary exhibits far less sensitivity to larger optical errors than the primary-only dish. As shown in Fig. 7, at an actual slope error of 5 mrad, the efficiency of the dish with a secondary is 25% greater than the efficiency of the primary-only dish. This approach is a compromise between designing for low optical errors and designing for high optical errors. It results in a negligible drop in maximum performance but maintains the low sensitivity to changes in optical errors.

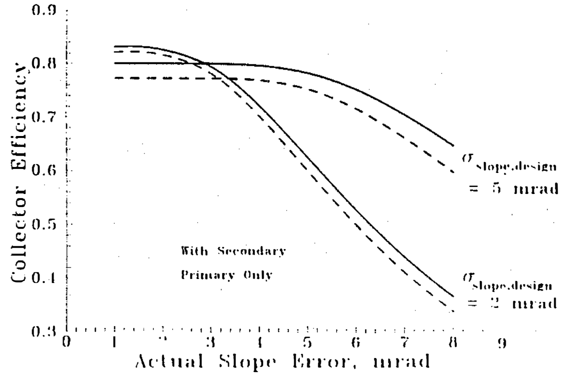

Fig. 5. Effect of deviations of actual vs. design slope errors for a dish with f/D = 0.6, operating at 500°C.

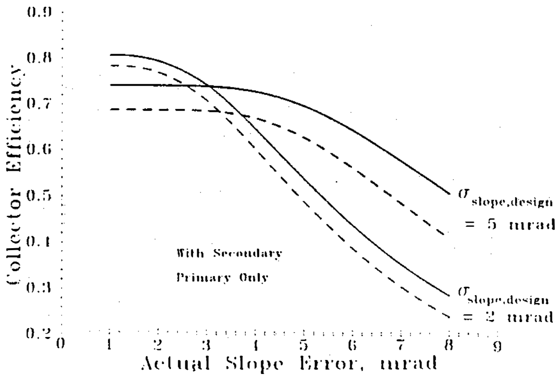

Fig. 6. Effect of deviations of actual vs. design slope errors for a dish with f/D = 0.6, operating at 800°C.

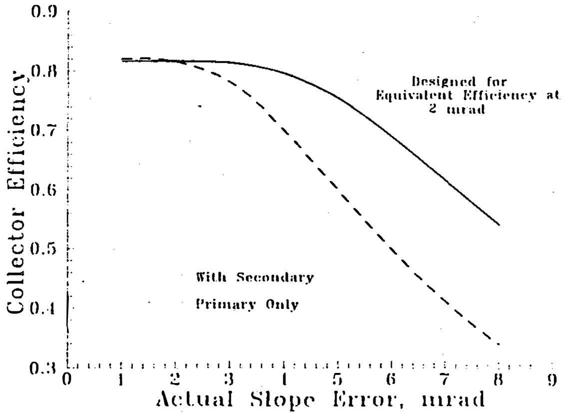

Fig. 7. Effect of a secondary designed for equivalent efficiency at σ_{slope} = 2 mrad on a a dish system with f/D = 0.6 and operating at 500°C.

4. CONCLUSIONS

From the major results of this study, several design approaches evolve that could affect the typical design process for point-focus dish systems. These approaches apply to structural and control system design to accommodate increased tracking errors and apply to the selection of design-point optical errors to minimize sensitivity to changes in optical errors over the life of the system.

For a dish with low optical errors, a secondary should be designed so the dish has the same efficiency as the primary only with no tracking errors. Even though there is relatively little gain in on-track performance from a secondary, there will be substantial gains in tracking error tolerance. For a dish with higher optical errors, the benefit of a secondary is increased for on-track performance. However, the tolerance to tracking error is still great. The choice of how to design the secondary will be based on other considerations, in particular, costs.

Assuming optical errors will degrade over time, designing for a low optical error can result in great sensitivity. Designing at higher optical errors reduces the sensitivity with a small penalty in maximum obtainable performance. This penalty can be reduced dramatically with a secondary designed for optimum performance. These results argue for designing at larger values of optical errors and incorporating a secondary concentrator in the design.

Instead of optimizing performance with a secondary, a slightly different approach is to design the secondary so equivalent performance is achieved at some design optical error. The sensitivity to changes in optical errors then decreases significantly. Here, the secondary plays a much more significant role in the reduced sensitivity. With this approach, design-point optical errors can remain low, but the secondary is an essential part of the design process.

Using a secondary concentrator in point-focus concentrator design can significantly benefit performance. There are two approaches to secondary design that will affect the performance similarly. A secondary can be designed that assumes higher optical errors, in which case maximum performance should be considered. Alternatively, a secondary can be designed that assumes low optical errors where equivalent performance should guide the design. Either of these approaches will reap benefits both in increased tolerance to tracking errors and reduced sensitivity to changes in optical errors over the life of the dish.

5. ACKNOWLEDGMENT

The SERI research was supported by the U.S. Department of Energy's Solar Thermal Technology Program. Research at the University of Chicago was supported through SERI subcontract no. XK-4-04070-03.

6. NOMENCLATURE

A = concentrator aperture area, m^2

A_r = receiver aperture area, m^2

A_w = receiver external wall area, m^2

A_w/A_r = 5

C_{geom} = geometric concentration ratio, A/A_r

D = concentrator aperture diameter, m

f = concentrator focal length, m

G = blockage factor, 0.967

h_c = convective heat-loss coefficient, W/m^2 C

h_k = conductive heat-loss coefficient, 0.737 W/m^2

I = direct normal irradiance, 800 W/m^2

Q_{CONV} = $A_r h_c (T - T_a)$

Q_{COND} = $A_w h_k (T - T_a)$

Q_{NET} = $Q_{OPT} - [Q_{RAD} + Q_{CONV} + Q_{COND}]$

Q_{OPT} = $IA\rho\eta_s G\gamma\alpha_e$

Q_{RAD} = $A_r \epsilon_e \sigma (T^4 - T_a^4)$

T = receiver temperature, °C

T_a = ambient temperature, 20°C

Greek

α_e = receiver effective absorptance, 0.998

ε_e = effective receiver emittance, 0.982

η_s = secondary throughput (if used)

ρ = concentrator reflectance, 0.90

ρ_s = secondary reflectivity, 0.90

γ = intercept factor = $\gamma(\delta,\phi)$

ϕ = rim angle

σ = Stefan-Boltzman constant, 5.667×10^{-8} W/m^2 K^4

δ = $(4\sigma^2_{slope} + \sigma^2_{spec} + \sigma^2_{track} + \sigma^2_{sun})^{1/2}$

σ_{slope} = surface normal error, 3 mrad

σ_{spec} = specularity error, 2 mrad

σ_{track} = random tracking error, 1.7 mrad

σ_{sun} = sun size, 2.73 mrad

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