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A Subcontract Report

J. O'Gallagher
R. Winston
The University of Chicago

Prepared under Subcontract No. XK-4-04070-03

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A Division of Midwest Research Institute
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PREFACE

The research and development described in this document was conducted within the U.S. Department of Energy's Solar Thermal Technology Program. The goal of this program is to advance the engineering and scientific understanding of solar thermal technology and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates the solar flux using tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single, tower-mounted receiver. Point focus concentrators up to 17 meters in diameter track the sun in two axes and use parabolic dish mirrors or Fresnel lenses to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multimodule system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100°C in low-temperature troughs to over 1500°C in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve each system concept through solar thermal materials, components, and subsystems research and development and by testing and evaluation. These efforts are carried out with the technical direction of DOE and its network of field laboratories that works with private industry. Together they have established a comprehensive, goal-directed program to improve performance and provide technically proven options for eventual incorporation into the Nation's energy supply.

To successfully contribute to an adequate energy supply at reasonable cost, solar thermal energy must be economically competitive with a variety of other energy sources. The Solar Thermal Technology Program has developed components and system-level performance targets as quantitative program goals. These targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and developing optimal components. These targets will be pursued vigorously to ensure a successful program.

In this report, prepared by the University of Chicago as part of a subcontracted effort, the potential performance and cost benefits of nonimaging secondary concentrators are explored for dish applications. The use of secondaries clearly has the potential to either improve performance (by increasing concentration) or decrease cost (by relaxing optical tolerances). To further quantify these effects, the University of Chicago has undertaken an analytical effort aimed at improving our understanding of the implications of secondaries and the role they can play in developing more cost-effective and competitive systems.

We at SERI would like to acknowledge the diligent efforts of Joseph O'Gallagher, University of Chicago, in leading the effort that resulted in this report. We would also like to acknowledge the many reviewers who provided valuable comments and suggestions concerning the work reported herein. These individuals include Barry Butler, Science Applications, Inc.; Richard Diver, Sandia National Laboratories—Albuquerque; Jose Martin, Lowell University; Ari Rabl, Princeton University; Walter Short, SERI; and David White, Solar Kinetics, Inc. Finally, this document was prepared under the guidance of the Office of Solar Heat Technologies, U.S. Department of Energy.

Allan Lewandowski, Technical Monitor

Approved for

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SUMMARY

Objective

The use of nonimaging, secondary concentrators in point-focus applications may allow the development of more cost effective primary concentrators by a combination of either improved performance or cost reductions. Secondaries, although offering the potential for reduced design requirements, may also offer an increased design flexibility. Up to the present, a general assessment of secondaries had not been conducted. Thus, the objective of this study is to develop as complete an understanding as possible of the quantitative performance and cost benefits associated with deploying nonimaging secondary or terminal concentrators at the focal zone of point-focus solar thermal concentrators (dishes). Subsidiary objectives related to fulfilling this main objective are to

- Develop generalized performance models for dish concentrator systems, with and without secondaries, as functions of design and operating parameters
- Apply these models to analyze quantitatively the performance trade-offs associated with concentrator systems using secondaries relative to those employing conventional single-stage concentrators
- Identify the potential of dish concentrator systems that employ secondaries for reducing the cost of delivered thermal energy relative to other current or projected designs
- Explore preliminary questions relevant to the application of secondaries to advanced conceptual designs, including innovative configurations and possibly central receivers.

Discussion

A variety of nonimaging optical devices, similar in principle to the well-known compound parabolic concentrator (CPC), can be deployed in the focal zone of image-forming primary concentrators. Such two-stage configurations have the capability of approaching the thermodynamic limit on geometrical concentration for a given angular field of view. This is the maximum possible concentration allowed by physical conservation laws and is impossible to achieve with a focusing primary by itself. In a point-focus reflecting geometry, this typically means that the nonimaging secondary can deliver an additional factor of two to four in concentration above that possible with the primary alone. This unique capability can be used to increase either the total concentration or the effective angular field of view of the concentrating optics (or perhaps some of each). For solar thermal applications these parameters are related respectively to increased performance (thermal efficiency) or relaxed optical tolerances (mirror slope error, angular tracking, etc.).

A performance model has been developed that uses a Monte Carlo ray-trace procedure to determine the focal plane distribution of a paraboloidal primary as a function of optical parameters and then calculates the corresponding optimized concentration and thermal efficiency as a function of temperature, both with and without the secondary.

The model was used to explore the performance trade-offs associated with a number of design variables and conditions. These trade-offs were conducted for systems both with and without secondary concentrators in order to assess the relative impact of the secondary. Trade-offs conducted included the effect of slope errors, temperature, focal ratio (focal length/diameter), and the shape of the error distribution. The tolerance to off-track errors (systematic tracking error) was also explored. Since approximations to the ideal parabolic primary concentrator shape may be more cost-effective, the performance of spherically shaped primaries was analyzed as a preliminary study of alternate primary concentrator contours.

To examine the potential cost benefits associated with secondaries, a model for the rational optimization of performance versus cost trade-offs has been developed in preliminary form. This model requires a knowledge of the dependence of both performance and costs on the design parameter of interest and shows that the optimum occurs when the logarithmic derivatives of the two functions are equal. In the absence of real analytic information for the costs as a function of slope error, the cost model is illustrated in terms of some assumed relationships. These suggest potential reductions in the cost of delivered energy of at least 10% to 20%, which are likely to far outweigh the cost of the secondary.

Conclusions

The major findings of the performance and cost trade-off studies carried out in this study are as follows:

- In general, the optimized thermal efficiency for a two-stage concentrator system lies significantly above that for a single-stage system if all other characteristic parameters are the same for both systems. For a baseline reference case for which a secondary is expected to be useful, namely, a primary dish with a focal length to diameter ratio of 0.6, and a characteristic Gaussian slope error of 5 mr operated at a receiver temperature of 1000°C, the optimized efficiency with a secondary is found to be 0.70 compared with 0.59 for the primary alone. For most of the parameter range considered, that is, for slope errors greater than about 2 mr or operating temperatures greater than about 600°C, the model predicts that the relative efficiency gain of a system using a secondary concentrator is always ≥5%. Even in the limit of very high optical quality ($\sigma_{slp} \leq 1$ mr) or very low operating temperatures ($T \leq 400$°C), there is a small residual efficiency improvement of 1% to 2%.

  For example, curves showing the thermally optimized instantaneous performance, with and without a secondary, are compared in Figure S-1 as a function of receiver operating temperature. These curves are for the same baseline case as described above. The efficiency gain with a secondary varies from 2.5% (a relative gain of 3% in energy delivered) at 500°C to 13.5% (a relative gain of 30%) at 1200°C. Curves such as this are shown to be a general feature of comparisons between one and two-stage systems.

- At fixed focal ratio, the relative performance advantage of a concentrator system using a secondary increases if either the temperature or the primary slope error or both are increased. It remains significant at temperatures above 400°C, even in the "high performance limit" of slope errors <2 mr.

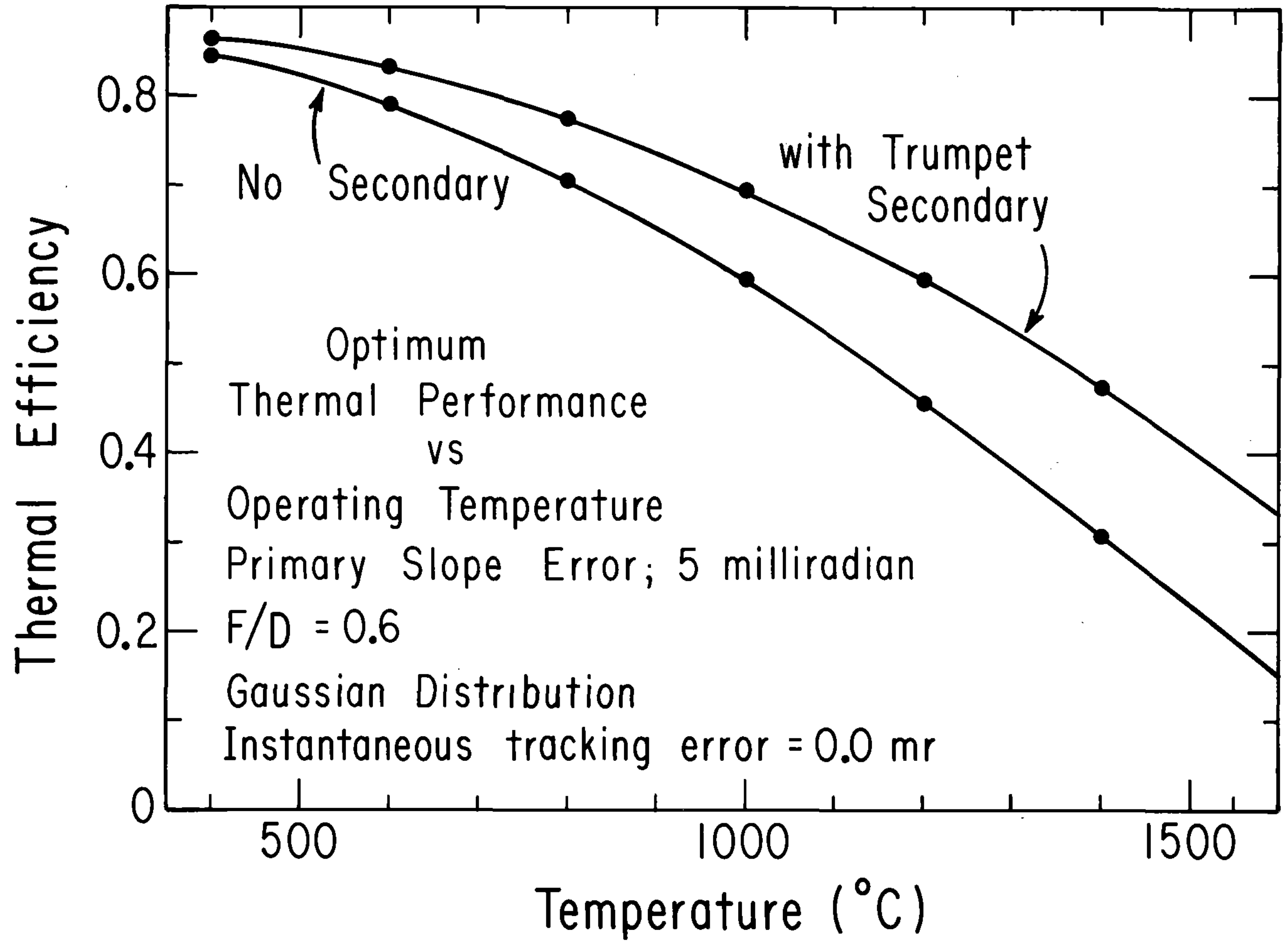

Figure S-1. Illustration of the Performance Improvement Provided by a Nonimaging Trumpet Secondary as a Function of Design Temperature. The primary is a reference baseline paraboloid with relaxed optical errors. The solid points are optimized efficiencies calculated by balancing thermal losses against intercept gains using a focal plane distribution determined by Monte Carlo ray-tracing.

- At fixed moderate-to-high temperature and constant slope error, the optimum efficiency, as a function of increasing focal ratio, is roughly constant or slowly increasing with a secondary but strongly decreasing without it. The shape of these relationships is shown to depend somewhat on the form of the optical error distribution.
- A simple model for the secondary effective optical efficiency (net throughput) as a function of the focal plane energy distribution and the primary and secondary geometric concentration ratios shows that to a very good approximation, the optical efficiency of a trumpet secondary approaches unity for energy that would have been intercepted by a given receiver aperture in its absence. This means that one can never lose performance by adding such a secondary (even in the limit of high primary optical quality); one can only gain, or at worst, break even.
- An investigation of the relative performance of one- and two-stage systems in the limit where there may be only a small relative efficiency gain (e.g.,

low operating temperatures or small slope error) shows that in such cases one can design for a large gain in off-track tolerances, typically about a factor of two relative to the value corresponding to a single-stage system.

- The relative performance of one- and two-stage systems when the primary is spheroidal rather than paraboloidal shows that the performance advantage with a secondary is quite dramatic, particularly at focal ratios near 1.0 where the efficiency of such a compound configuration exceeds that of a true paraboloid without a secondary at all focal ratios. The optimum performance with a secondary occurs at a somewhat larger focal ratio (F/D = 0.8 to 1.0) than typical for conventional designs. This behavior suggests that the combination of a secondary with a stretched membrane primary may be particularly advantageous.
- The methodology for the rational optimization of performance versus costs is based on the constraint that at the optimum, the relative incremental performance gains with respect to a particular performance parameter should balance the incremental costs associated with improvements in that parameter. Under this constraint it is shown that, as long as the cost of the secondary remains small, and unless all costs are virtually independent of optical errors, a two-stage thermal system, so optimized, must always be cost effective relative to the corresponding single-stage system.

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1.0 INTRODUCTION

1.1 Background

A variety of nonimaging optical devices [1], similar in principle to the well-known compound parabolic concentrator (CPC), can be deployed in the focal zone of image-forming primary concentrators. Such two-stage configurations have the capability of approaching the thermodynamic limit on geometrical concentration for a given angular field of view. (Here, geometric concentration is defined as the ratio of the collecting area of the primary to the area of the target receiver aperture in the focal plane.) This limit is the maximum possible concentration allowed by physical conservation laws and is impossible to achieve with a focusing primary by itself. In a point-focus reflecting geometry, this typically means that the nonimaging secondary can deliver an additional factor of two to four in concentration above that possible with the primary alone. In general, this is accomplished without doing anything to the primary. Nonimaging secondaries thus offer the optical designer an additional degree of freedom unavailable with any conventional approach. This unique capability can be used to increase either the total concentration or the effective angular field of view of the concentrating optics (or perhaps some of each). For solar thermal applications, these parameters are related respectively to increased performance (thermal efficiency) or relaxed optical tolerances (mirror slope error, angular tracking, etc.).

The two-stage concentrator concept, and in particular the secondary element, has been under development for a relatively short time compared with traditional design techniques. Since the combination of a compound elliptical concentrator (CEC) with a primary paraboloid was first formally suggested by our group in 1980 [2], a number of significant advances have been made. The flow-line or "trumpet" concentrator [3], in which the reflector is a hyperboloid of revolution, was developed as an alternative type of secondary both analytically [4,5] and experimentally [6,7]. Measurements carried out on one of the test-bed concentrators (an 11-m-diameter faceted primary parabolic dish), then at the Jet Propulsion Laboratory Edwards Air Force Base, demonstrated that a trumpet increased the effective intercept factor at a geometric concentration ratio of 4800 from 0.72 to 0.96, a relative gain of 33% in collected energy. Although active water cooling was simple and quite effective in these tests, some problems were encountered with uncooled secondaries, so a preliminary study was carried out to evaluate effective methods of passive thermal control and to determine the effect of the secondary on flux and directional distributions in the focal plane [8,9]. During recent DOE-sponsored work [10,11], we returned to the investigation of CPC-type secondaries with the objective of developing a combination of a high concentration secondary and long-focal ratio primary with potential for low cost. A conceptual two-stage design based on this concept was developed, and several versions of a 5X CPC, both passively and actively cooled, were fabricated and tested at the Advanced Component Test Facility at Georgia Tech [10,11]. The motivation for the present work is to provide a systematic evaluation of the potential performance and cost benefits associated with these two-stage designs for a wide range of design configurations.

1.2 Objectives

Specifically, the objectives of the most recent work have been to

- Develop generalized performance models for dish-thermal systems with and without secondaries
- Analyze quantitatively, using these models, the performance trade-offs associated with secondaries relative to conventional single-stage designs over a wide range of design parameters
- Identify the potential for reducing the cost of delivered thermal energy relative to other current or projected designs
- Explore preliminary questions relevant to the application of secondaries to advanced conceptual designs, in particular central receivers.

The performance trade-offs are studied in the context of a model incorporating the fundamental optical properties of the secondary and their impact on the optical and thermal performance of the overall concentrator system. Considerations involving thermal control and the interaction with receiver design are not addressed in this study. Since the secondary is ultimately a relatively small part of the full system, it is anticipated that in those areas for which significant benefit may be predicted, any necessary development effort can then be considered.

Similarly, potential cost reductions are examined in terms of the impact on the rest of the system, such as increased energy delivery or less stringent design requirements, but a detailed study of the costs associated with the secondary itself is deferred.

The effort was divided into three activity areas:

- Performance Modeling: This constituted the major portion of our work. We used computer ray-trace optimization of one- and two-stage concentrator designs to model system performance as a function of mirror surface optical error, primary focal ratio, receiver design operating temperature, and sun off-track error.
- Industry Interaction: We worked with representatives of one particular commercial dish manufacturer (LaJet) to design a variety of secondaries for possible use in the next generation version of their design with the objective of evaluating the impact of the relaxed tolerances on the primary structural design and ultimately on system costs. The results of this work are summarized in a report attached to this document as an appendix. Although not otherwise related to the content of the main body of this report, the discussion and figures in the appendix provide an example of the shapes and dimensions of typical nonimaging secondaries relative to one another and to some actual cavity aperture sizes in a practical context.
- Advanced Concepts: In this area we began to address the potential implications of the properties of secondary optical elements for both innovative dish concepts and central receiver applications. However, this activity was eventually assigned low priority relative to the others and systematic efforts have been deferred for the present.

The remainder of this report is devoted to a detailed summary of the results of the performance modeling studies and an analysis of potential cost trade-offs associated with nonimaging secondaries. Section 2.0 describes the performance model and Section 3.0 uses it to illustrate a variety of performance gains provided by secondaries as a function of operating and design variables. Section 3.4 discusses other benefits, such as increased off-track capability, which could be provided by a secondary if the efficiency of a single stage is already near optimum. Section 3.5 treats the special case where the primary contour is spheroidal rather than paraboloidal, a case of some relevance to potential applications with stretched membrane primaries. Section 4.0 describes a simple performance-cost optimization methodology and applies it to evaluate potential cost benefits of secondaries. Sections 5.0, 6.0, and 7.0 discuss the implications and conclusions resulting from the analysis and review the recommendations for future research.

2.0 METHODOLOGY FOR OPTIMIZING THERMAL PERFORMANCE

The performance model we have developed for optimizing point-focus solar thermal concentrators both with and without secondaries uses a methodology patterned after an approach originally introduced by Jaffe [12,13]. However, we have incorporated two very important new features.

First, we have used Monte Carlo ray-trace calculations to determine the focal plane distributions, which in turn are used to evaluate the trade-off between energy intercepted by apertures of different sizes (related to the geometric concentration ratio) and receiver heat losses. Jaffe approximates these distributions by single parameter Gaussian normal functions for which the scale of the radial distribution in the focal plane is approximately related to the root-mean-squared optical error distributions, which are also represented as Gaussian distributions. Our approach not only provides a better representation of the actual focal plane distributions, but it allows treatment of non-Gaussian optical error distributions, deviations from axial symmetry (e.g., off-track bias), and nonparabolodial contours.

Second, we model the secondary optical efficiency to take account of variations in throughput as a function of the fraction of energy it intercepts. Jaffe simply assumed one constant value, typically between 0.9 and 0.95, independent of the relative size of the secondary compared with the scale of the focal plane distribution. This is an artificially severe representation, particularly for Gaussian distributions, since it always introduces an optical loss for the two-stage system, whether or not the secondary is actually doing anything. We do not, in general, calculate the secondary efficiency by directly ray-tracing through it for each and every performance calculation. However, the approximation used is accurate to a fraction of one percent and is more than adequate for the kind of trade-off analysis done here. If necessary, we can do detailed ray-tracing through the secondary later for those cases where this small correction may be of interest.

The basic procedure can be understood as follows. The net instantaneous thermal efficiency of a single-stage system is represented by

$$\eta(Cl_{geom},T) = \eta_1(Cl_{geom},\delta,F/D) - Q_{loss,1}/IA_p, \qquad (2\text{-}1)$$

where the optical efficiency of the primary is

$$\eta_1 = \rho_1\Gamma_1(Cl_{geom},\delta,F/D) \qquad (2\text{-}2)$$

and the receiver heat loss without a secondary is

$$Q_{loss,1} = A_r[H(T - T_a) + \sigma_{SB}(T^4 - T_a^4)] \ . \qquad (2\text{-}3)$$

In these relationships,

A_p = the area of the primary dish = $\pi(D/2)^2$

A_r = the area of the receiver aperture (without secondary) = πr_1^2

Γ_1 = the fraction of the target plane energy intercepted within a circle of radius r_1

Cl_{geom} = A_p/A_r = geometric concentration ratio of the single stage (without secondary)

H = receiver aperture convective heat loss coefficient

T = receiver operating temperature

T_a = ambient temperature

ρ_1 = reflectivity of the primary mirror surface

I = instantaneous beam insolation

F = focal length of the primary

D = diameter of the primary

σ_{SB} = Stefan-Boltzman constant

f/No. = focal ratio = F/D

δ = standard deviation of the total effective optical error distribution.

In particular, following Jaffe, we can write

$$\delta^2 = (4\sigma^2_{slp} + \sigma^2_{spec} + \sigma^2_{sun}) \, , \tag{2-4}$$

where σ_{slp}, σ_{spec}, and σ_{sun} characterize the angular scales of the circular Gaussian functions used to represent the slope error, specularity, and characteristic sun shape distributions. Specifically, δ and σ are the standard deviations of the one-dimensional functions, which are the projections of the corresponding full two-dimensional rotated distributions. In contrast to Jaffe's work, we first calculate the instantaneous efficiency for nominal aligned "on-sun" operation and do not include a random tracking error in Eq. 2-4. Note that the heat loss model, again following Jaffe [12,13], assumes that both radiative and convective losses scale directly with receiver aperture area. Later in the analysis, we will analyze the performance in terms of a well-defined off-track angle.

For a particular set of optical parameters, the procedure is to select a large number of rays randomly located with uniform probability on the circular dish aperture and with random angular deviations relative to the paraxial direction governed by a Gaussian or other probability distribution. Each of these rays is then reflected off the primary and its location in the target plane is determined. The distributions in Cartesian and polar coordinates are accumulated for a large number of rays, typically between 1000 and 10,000 rays depending on the statistical accuracy desired. These are then used to determine the intercept factors as a function of (variable) receiver aperture sizes. For each value of receiver radius r_1 the corresponding heat loss from Eq. 2-3 and the net thermal efficiency from Eq. 2-1 are determined as a function of receiver operating temperature. These results are then tabulated and used to determine the maximum efficiency at each temperature resulting from the trade-off between intercept factor and heat loss. It is this ray-trace optimized efficiency that is analyzed as a function of design parameters in all the sections that follow.

The effect of a nonimaging secondary is included in the above analysis in a parallel set of calculations incorporating two modifications.

First, for each value of target radius, a second value of the relative heat loss is calculated, corresponding to a receiver aperture reduced in area by a factor equal to the secondary concentration ratio C2. That is the value given by Eq. 2-3 multiplied by a factor of 1/C2. The acceptance angle θ_C for a nonimaging optical element is the extreme angle for which it is designed to transmit a light ray [1]. This defines the conical field of view "seen" by the element and determines its maximum theoretically allowed geometric concentration,

$$C2_{MAX} = 1/\sin^2 \theta_C \ . \tag{2-5a}$$

In fact, neither trumpets nor CPCs can reach this limit without losses in a three dimensional geometry. Furthermore, they become large and impractical as they approach it, so they are usually "truncated" by terminating the reflector for lengths somewhat less than the maximum analytically required values and over designed slightly to reduce losses near the edge of the acceptance. In our model, we take C2 for a secondary to be given by

$$C2 = 1/\sin^2 (\phi + 2.5°) \ , \tag{2-5b}$$

where ϕ is the rim angle corresponding to the particular value of F/D. This is slightly less than the maximum concentration allowed and represents a good approximation to values typically achieved with reasonably truncated secondaries. See, for example, the trumpets and CPC secondaries selected for the geometries discussed in the appendix.

Second, the effective net optical efficiency is reduced by a factor η_2, to account for losses due to the secondary. For the parametric analysis, this is approximated by

$$\eta_2 = [\Gamma_2 + \rho_2(\Gamma_1 - \Gamma_2)]/\Gamma_1 \ , \tag{2-6}$$

where

Γ_2 = the fraction of energy in the target plane intercepted by a circle of radius, $r_1/(C2)^{1/2}$, corresponding to the exit aperture of the secondary.

ρ_2 = the reflectivity of the secondary.

This relationship effectively approximates the average number of reflections in the secondary by the fraction intercepted by the secondary (or alternatively, it assumes that rays initially directed toward the exit aperture pass through it with no reflections, and those directed between the exit aperture and the effective secondary collecting aperture experience only one reflection before passing out the exit aperture). This is a very good approximation in the case of the trumpet. Note that net efficiency given by Eq. 2-6 approaches unity in the limit that Γ_2 approaches Γ_1 as they both approach unity. We should also mention that Eq. 2-6 neglects shading of the primary by the secondary. For almost all cases of practical interest this is expected to be a negligible incremental effect since shading due to the receiver (and engine) will usually be larger and has been neglected in this model for all systems. Even if, in some case, the entrance aperture of a trumpet extends beyond the shadow of the receiver, the relative magnitude of the loss will be a few times $1/(C_{1geom})$ or usually a small fraction of one percent.

The optimization procedure then proceeds by calculating and tabulating the resulting overall system efficiency with a secondary as a function of r_1, and the corresponding maximum net thermal conversion efficiency as a function of temperature is found. Note that for the case with a secondary, r_1 becomes the effective target radius seen by the primary and corresponds to the so-called "virtual target" provided by a trumpet or the entrance aperture of a CPC.

To test the accuracy of the approximation of Eq. 2-6, a detailed trace of 10,000 rays through several different complete configurations, each including an appropriately truncated trumpet, was carried out. For example, for the baseline configuration and a trumpet of what we determined to be near optimum size, the results show that of 8229 rays, that would have entered the target aperture in the absence of the trumpet, 7701 (94%) still pass through the trumpet exit aperture without reflection. Of the remainder, 515 or 6% will undergo one or more reflections and 13 (<0.2%) are lost because they miss the trumpet entrance aperture. An additional 1272 rays that would otherwise have been lost are picked up by the trumpet and reflected through the exit. Of the total of 1797 collected rays that undergo one or more reflections, 1593 experience only a single reflection. The net optical gain provided by the trumpet (net energy with trumpet/net energy without) in this case is 1.141. The effective net trumpet efficiency relative to the virtual target from the detailed ray trace is 0.9851 compared with a value of 0.9902 calculated from Eq. 2-6. (Only about half of this is due to reflection losses. The remainder is due to the small intercept loss from those rays that miss the trumpet entrance aperture, and this could be reduced or eliminated, if desired, by reducing the concentration slightly and changing the truncation.) In all cases, the difference between the simple approximation and the ray trace result is negligible compared with the overall optical gains. For the case of a trumpet secondary, which would be the secondary design of choice for short and moderate focal ratios, the use of Eq. 2-6 thus provides a very accurate analytical method for carrying out performance optimization studies without the need for a detailed ray trace of each possible secondary size. At longer focal ratios, where a CPC secondary might be used, the approximation will not be as accurate because of higher reflection losses, but the optical gains will be even larger, so the relative error introduced by the approximation will remain negligible.

One of the problems with quantitative evaluation of the effect of secondaries has been that there are so many variables. The approach of Jaffe and our own here serves to alleviate this problem somewhat by optimizing first with respect to the variation in geometric concentration (receiver aperture) as just described for every case considered. The analysis is further organized by selecting a baseline design for reference holding all variables, except one fixed, and studying the effect of variations in this one parameter on the (concentration) optimized efficiency. For purposes of illustration, we have defined a baseline reference design with the parameters listed in Table 2-1. We chose nominal values for the key parameters, which are round numbers characteristic of what we think might be a typical two-stage configuration. In particular, we chose F/D = 0.6, T = 1000°C, and σ_{slp} = 5 mr. Since our purpose

Table 2-1. Parameters for Baseline Thermal Concentrator Performance Analysis

Dish diameter	11 m
Focal length	6.6 m
Focal ratio (F/D)	0.6
Rim angle	45.24 deg
Primary slope error[a]	5 mr
Specularity error[a]	1.5 mr
Sun size[a]	2.73 mr
Shape of angular incidence distribution	Gaussian
Primary reflectivity	0.9
Secondary reflectivity	0.95
Receiver operating temperature	1000°C
Absorbtivity of cavity aperture	1.0
Emissivity of cavity aperture	1.0
Aperture convective loss coefficient	16.0 W/(m^2 °C)
Ambient temperature	20°C
Direct normal insolation	800 W/m^2

[a]Standard deviation of the one-dimensional projection of the corresponding two-dimensional circular normal distribution.

has been to develop compound systems with potential low cost through the use of secondaries to relax primary optical tolerances, we have assumed a relatively large characteristic slope error. Nevertheless, it should be kept in mind that although slope errors somewhat smaller than this value are achievable for many mirror technologies on a local scale, a significantly larger effective value may result for a fully assembled dish. The value of 0.95 for the secondary reflectivity is somewhat high but not unrealistic for some of the new mirror technologies being developed. In any case, the relatively low average number of reflections, confirmed by detailed ray-tracing, results in very high effective secondary efficiencies (e.g., the seventh column of Table 2-2) that are only weakly dependent on secondary reflectivity. The value of the aperture convective heat-loss coefficient is taken directly from Jaffe and held fixed throughout the analysis.

The basic optimization procedure is illustrated for the baseline case in Figures 2-1 and 2-2 and Table 2-2. Figure 2-1 is a representation of the focal plane distribution calculated by tracing 3000 rays. Table 2-2 lists the variation of several parameters, including efficiency, with and without a secondary as a function of target radius r_1, at the baseline receiver operating temperature of 1000°C. The numbers in the fourth and sixth columns (NumAcc and NexInt) are, respectively, the number of traced rays intersecting the focal plane inside r_1 and, if a trumpet is present, inside its exit

Table 2-2. Thermal Optimization for Baseline Case

Operating temperature is 1000°C; Ambient temperature is 20°C

Bin	Radius	C1	Num Acc	Γ	NexInt	η_2	Q_{Loss}	Relative Q_{Loss}	Eff_1[a]	Eff_2[b]
0	0.0133	169765	37	0.012	6.1	0.958	92	0.001	0.010	0.010
1	0.0267	42441	156	0.052	94.1	0.980	368	0.005	0.042	0.043
2	0.0400	18863	342	0.114	197.0	0.979	827	0.011	0.092	0.094
3	0.0534	10610	553	0.184	334.6	0.980	1470	0.019	0.147	0.152
4	0.0667	6791	839	0.280	489.8	0.979	2297	0.030	0.221	0.230
5	0.0801	4716	1158	0.386	679.0	0.979	3308	0.044	0.304	0.316
6	0.0934	3465	1421	0.474	896.6	0.982	4503	0.059	0.367	0.386
7	0.1068	2653	1700	0.567	1132.7	0.983	5881	0.077	0.433	0.459
8	0.1201	2096	1960	0.653	1331.8	0.984	7444	0.098	0.490	0.525
9	0.1335	1698	2185	0.728	1532.9	0.985	9190	0.121	0.535	0.580
10	0.1468	1403	2377	0.792	1736.7	0.987	11120	0.146	0.567	0.623
11	0.1602	1179	2542	0.847	1929.1	0.988	13233	0.174	0.589	0.658
12	0.1735	1005	2646	0.882	2099.8	0.990	15531	0.204	0.590	0.674
13	0.1869	866	2759	0.920	2254.4	0.991	18012	0.237	0.591	0.690
14	0.2002	755	2847	0.949	2393.7	0.992	20677	0.272	0.582	0.698
15	0.2136	663	2894	0.965	2515.9	0.993	23526	0.309	0.559	0.693
16	0.2269	587	2921	0.974	2602.5	0.995	26558	0.349	0.527	0.680
17	0.2403	524	2949	0.983	2682.4	0.995	29775	0.392	0.493	0.666
18	0.2536	470	2964	0.988	2764.4	0.997	33175	0.436	0.453	0.647
19	0.2670	424	2978	0.993	2829.6	0.998	36759	0.483	0.410	0.626
20	0.2803	385	2984	0.995	2872.5	0.998	40527	0.533	0.362	0.602
21	0.2937	351	2990	0.997	2901.6	0.999	44478	0.585	0.312	0.575
22	0.3070	321	2992	0.997	2921.6	0.999	48613	0.639	0.258	0.546
23	0.3204	295	2996	0.999	2942.3	0.999	52933	0.696	0.203	0.517
24	0.3337	272	2997	0.999	2956.5	0.999	57436	0.755	0.144	0.485

[a] One stage; without secondary

[b] Two stage; with secondary

aperture (of radius $r_1/\sqrt{C2}$). The columns headed Q_{Loss} and Relative Q_{Loss}, are the heat loss, first in watts and then normalized to the power collected by the primary for a cavity receiver of radius r_1.

Figure 2-2 is a plot of the corresponding calculated efficiencies as a function of primary geometric concentration ratio $C1_{geom}$. The maximum value reached by each curve occurs when the loss in intercept with increasing concentration is precisely balanced by the corresponding reduction in heat losses. This balance clearly depends on receiver temperature and the shape of the focal plane distribution as well as the optical properties of the system.

The single most important result of these comparative optimizations is that, for literally any case of practical interest, the efficiency of the two stage is always greater than the single stage if all the other design parameters are the same. The performance enhancements with a secondary, which will be evident in all the optimized efficiency curves presented, are a direct measure of

```
Dish Diameter = 11.0M;      Focal Length =  6.6M;      F/Number =  0.600

Slope Error =  5.00mr, Specularity = 1.50mr,Sunsig = 2.73mr
Rim Angle =  45.24deg:      Total Optical Sigma is   10.47 mr

Duff-Lameiro Factor is   1.4483;    Focal Scale Rho is   0.08343 M

Primary Concentration for Rt=3Rho(Gamma=0.989) is   483X C2 is 1.83X

NRays is   3000. Nstrange =    0,NrOut is  3, NxOut is  0, NyOut is  1


  Form of input Optical Distrubution is Gaussian

   Radial Distribution in Focal Plane;   Full scale Equal 4 Rho

 37 119 186 211 286 319 263 279 260 225 192 165 104 113  88  47  27  28  15  14   6   6   2   4   1
        X-Y Distribution in focal plane:   Full scale equals + or - 4Rho
  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
  0  0  0  0  0  0  0  0  1  0  1  0  0  1  0  0  0  0  0  0  0  0  0  0  0
  0  0  0  0  0  0  0  0  0  0  0  1  0  0  1  0  0  0  0  0  0  0  0  0  0
  0  0  0  0  0  0  0  0  3  1  1  0  4  3  0  3  0  0  0  0  0  0  0  0  0
  0  0  0  0  0  0  0  0  0  1  3  3  4  3  2  3  1  2  0  0  0  0  0  0  0
  0  0  0  0  0  0  0  2  3  7  3  3  8  9  6  5  4  2  2  0  0  0  0  0  0
  0  0  0  0  1  3  1  4  2 11 10  5 13 14 10  7  7  6  2  3  1  0  0  0  0
  0  0  1  1  1  0  5  3 11 11 23 18 20 28 17 12  8  6  5  1  0  0  1  1  0
  0  0  1  0  1  3  1  9 15 24 16 29 31 30 27 26 18  6  4  1  0  0  0  0  0
  0  0  0  0  0  4  5 10 14 22 42 41 50 38 28 31 19 13  3  3  0  1  0  0  0
  0  0  0  1  0  3  3 13 21 25 39 46 67 41 53 23 13  3  8  3  1  0  1  0  0
  0  0  0  1  5  4  5 11 17 43 37 50 50 43 39 34 25 10  8  2  1  0  0  0  0
  0  0  0  0  1  4  4  8 22 35 40 44 55 46 45 26 25 10  2  4  3  1  1  0  0
  0  0  0  1  0  3  7 13 19 26 48 36 42 37 35 15 23 11  6  3  2  3  0  0  1
  0  1  0  0  0  1  6  6 15 19 27 34 31 34 27 24  9  5  3  2  2  0  0  0  0
  0  0  0  0  1  2  4  4 11 16 15 22 20 18 18 14  6 10  2  0  1  0  0  0  0
  0  0  0  0  0  0  2  4  5  5 10 19 12 12 10  7  6  3  0  0  1  0  1  0  0
  0  0  0  0  0  0  1  0  4  4  3  6  8 10 10 11  3  1  0  3  0  0  0  0  0
  0  0  0  1  0  0  0  2  1  0  4  2  3  4  2  0  0  0  0  0  0  0  0  0  0
  0  0  0  0  0  0  0  0  1  0  1  1  2  2  0  1  0  1  0  1  0  0  0  0  0
  0  0  0  0  0  0  0  2  0  0  0  1  0  0  2  0  0  0  0  0  0  0  0  0  0
  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0  0  0  1  0  0  0  0  0  0
  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
```

Figure 2-1. Partial Output of Monte Carlo Ray-Trace Program for Baseline Case. The assumed optical error distribution is Gaussian and the resulting radial and X-Y position distributions in the focal plane are indicated. The corresponding thermal efficiency optimizations are shown in Table 2-2.

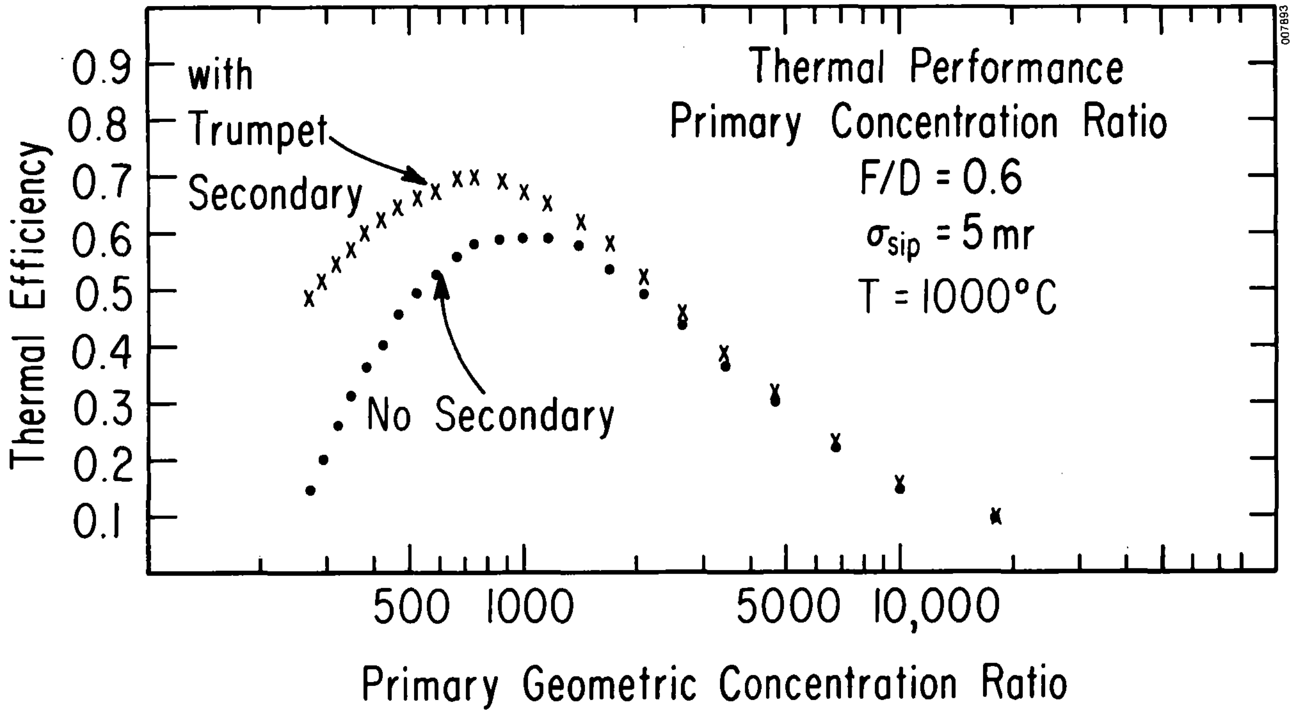

Figure 2-2. Illustration of the Optimization Procedure for the Baseline Case. The combined effect of optical and thermal lsoses, as a function of effective focal plane target size (primary concentration ratio), is shown with and without a secondary. For a given target size, the secondary improves the efficiency by reducing the heat losses substantially more than the associated optical losses.

the relative importance of the additional factor of two to four in concentration made possible by the secondary. The potential for improvement with a secondary can be understood very simply in terms of this relationship. If the marginal benefits of additional concentration are large, the performance gain is large; if these are small, the gains are small but usually significant.

In subsequent sections, we investigate the variation of the optimized efficiency, both with and without secondaries, in response to changes in one specific design variable while holding the others constant at their baseline value (Table 2-1) unless otherwise stated. We will be particularly interested in the effects of slope error, focal ratio, shape of effective angular error distribution and primary contour.

3.0 PERFORMANCE TRADE-OFFS WITH AND WITHOUT SECONDARIES

3.1 Effect of Slope Error

The optimized thermal conversion efficiencies, determined by the procedures described in Section 2.1, are shown as a function of primary Gaussian slope error at fixed temperature in Figure 3-1. The sun shape and specularity errors are also approximated as Gaussian distributions but held constant as are the other baseline values in Table 2-1. The optimized baseline values as σ_{slp} = 5 mr without and with a secondary are 0.59 and 0.70, respectively. As slope error is reduced, the optimized efficiency for both cases improves with the two stage always remaining somewhat above the single stage, although the absolute and relative separations decrease as one approaches the limit of zero slope error. This is very similar to the behavior with respect to temperature at constant slope error as shown in Figure 3-2 and in both cases is a consequence of the diminishing importance of marginal increases in concentration when thermal losses are a relatively small fraction of the optical gain.

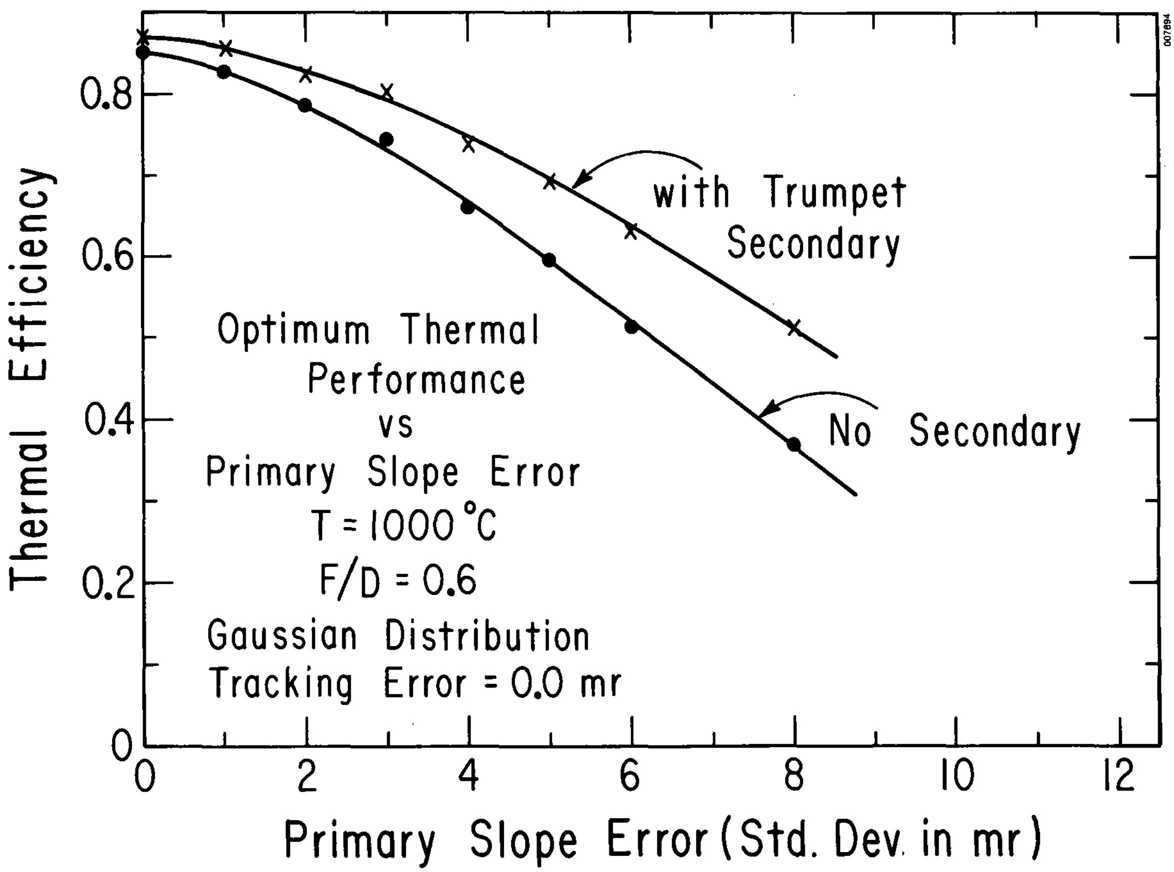

Figure 3-1. **Performance Improvement Provided by a Trumpet Secondary for the Baseline Case when the Primary Slope Error is Varied and the Temperature is Held Constant.** At small slope errors the primary alone can achieve a high enough concentration to reduce heat losses to a negligible amount, so that the additional concentration with a secondary increases the efficiency only slightly. In this high performance limit, a secondary can still be employed to increase tracking tolerances.

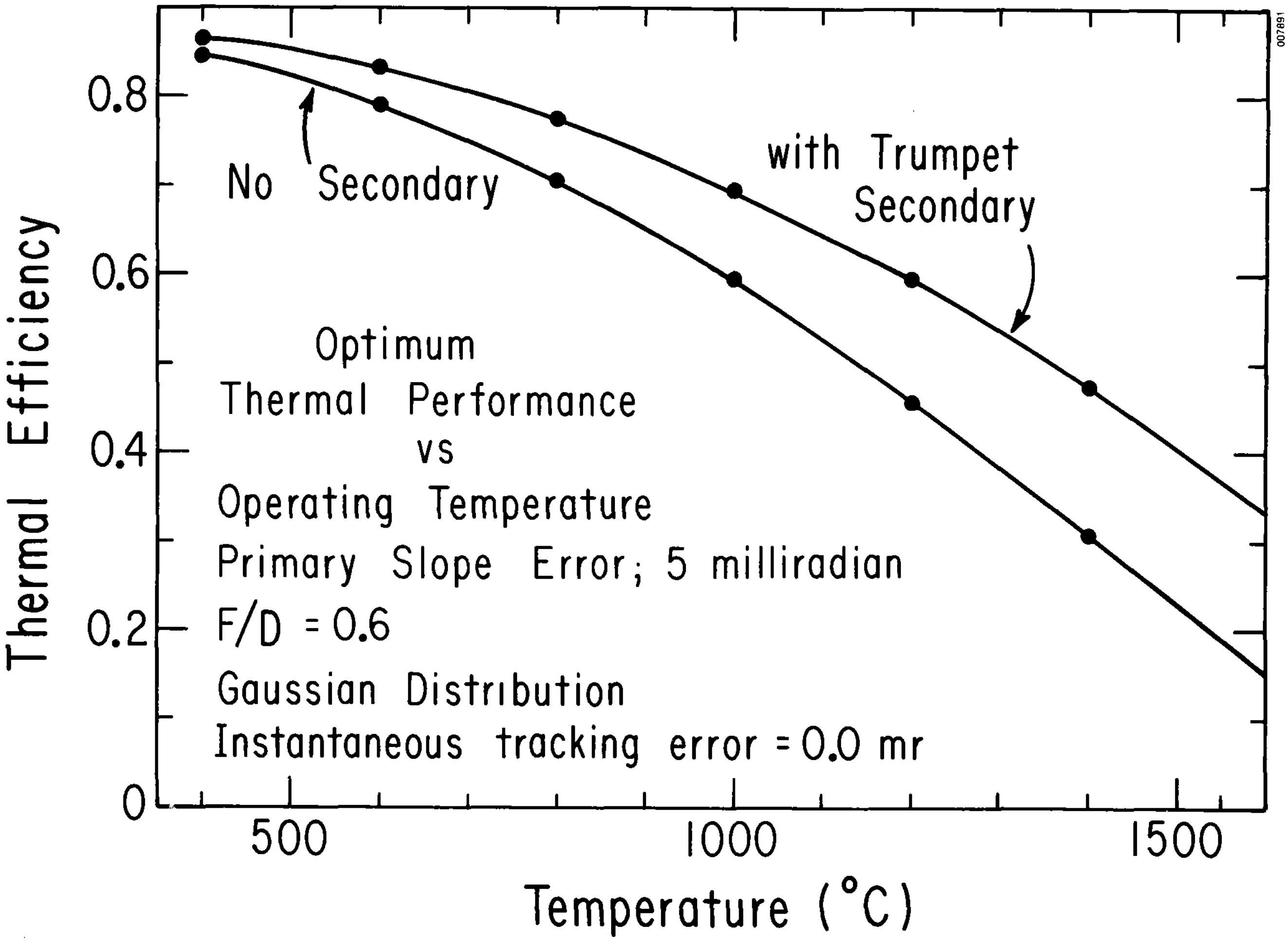

Figure 3-2. Performance Improvement Provided by a Nonimaging Trumpet Secondary as a Function of Design Temperature. The primary is a reference baseline paraboloid (Table 2-1) with relaxed optical errors with characteristic slope error 5 mr. The solid points are optimized efficiencies calculated by balancing thermal losses against intercept gains using a focal plane distribution determined by Monte Carlo ray tracing.

This general feature of all of our analysis is illustrated more clearly in Figure 3-3, where the optimized efficiencies are shown as a function of temperature, as in Figure 3-2, but now removed from our baseline operating point and corresponding to a primary slope error of only 2 mr. Here one needs to go to higher temperatures to see substantial relative gains with a secondary, but some gain is provided at all temperatures and all characteristic slope errors.

3.2 Effect of Focal Ratio

There are two effects expected to be important [10,14] as one varies the design focal ratio of the primary:

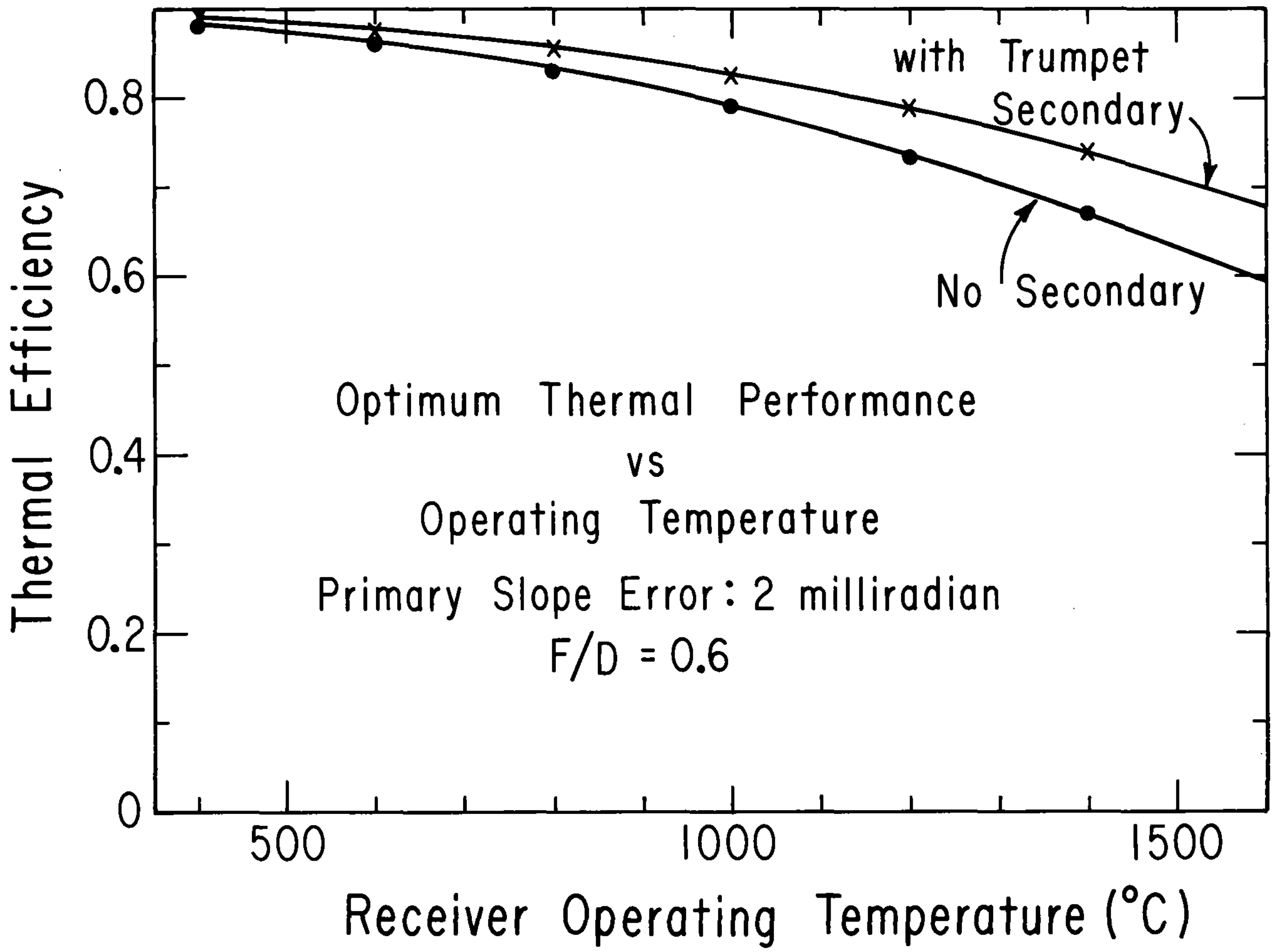

Figure 3-3. The Performance Benefit as a Function of Temperature with Slope Errors at a Low Level. The benefit becomes more appreciable at very high temperatures. (This is the same as Figure 3-2 except for a Gaussian slope error of 2 mr).

- Although the image size of an extended object produced by a parabola decreases with increasing rim angle, the off-axis optical aberrations (coma) increase. The combination of the two effects is a minimum at a rim angle of 45 deg, in that, for perfect optics, the corresponding "focal patch" size is smallest relative to the primary diameter. This means that, for a 100% intercept factor, the maximum geometric concentration occurs for this geometry, which corresponds very closely to F/D = 0.6. Thus, for a single-stage paraboloid with some distribution of optical errors, we expect performance to be optimum near this value of F/D.
- If we add a secondary, the acceptance angle θ_C required for it to "see" the primary decreases with longer focal ratio, permitting higher secondary concentration ratios (Eq. 2-5). This effect more than offsets the decreasing concentration ratio of the primary, so the combined two-stage concentration asymptotically approaches the thermodynamic or "ideal" limit as F/D increases. To the extent that the thermal efficiency depends on concentration, we should expect the performance of a two-stage system to exhibit a similar relationship relative to its focal ratio.

As we shall see, the shape of the focal plane distribution and its role in the trade-off between intercept factor and thermal losses affects this behavior somewhat, but the general trends are still as expected.

The calculated optimized efficiencies for a high and a low temperature delivered by a primary mirror with characteristic focal ratio of 5 mr are shown with and without secondaries as a function of slope error in Figure 3-4. No distinction is made here between possible types of secondary, since their general properties are similar and a detailed ray-trace study comparing their characteristics as a function of concentration and acceptance angle has not yet been carried out (see Section 7.0). In practice, a trumpet would be used at the shorter end of the range, since its reflection losses are smaller [4,6]. The optimized design would change to a CPC type somewhere above F/D = 0.7, since in this limit the trumpet cannot achieve the necessary high secondary concentration without prohibitive shading losses [5,10].

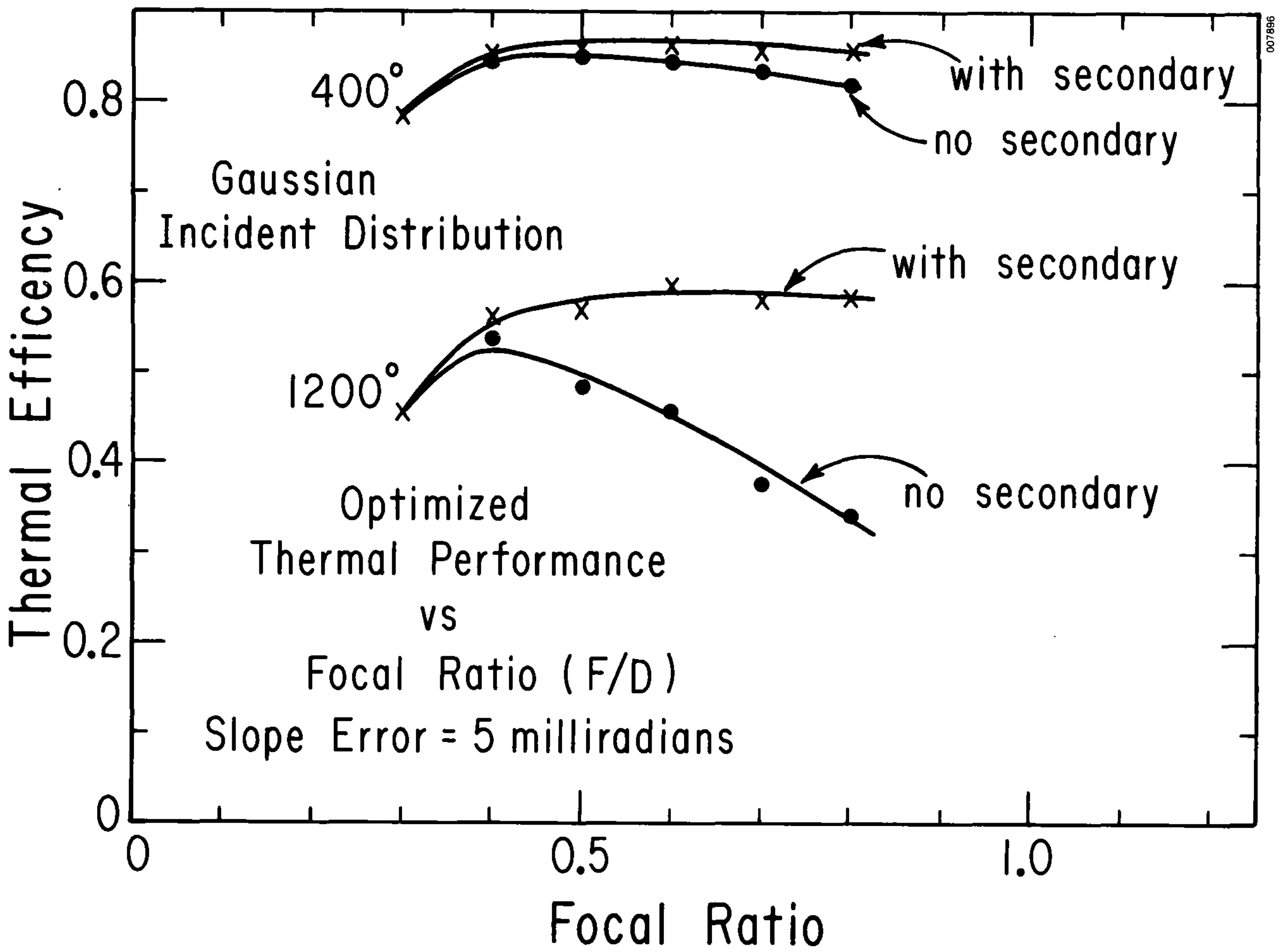

Figure 3-4. Variation of the Optimized Thermal Performance at Low and High Temperature with and without a Nonimaging Secondary as a Function of Primary Focal Ratio. At high temperatures and longer focal lengths, where concentration to reduce thermal losses is necessary, the two stage maintains respectable performance, while the loss of concentration of the primary alone causes its performance to fall off. The precise shape of these curves depends on the shape of the optical error distribution.

There are a number of notable features in Figure 3-4. The performance of the two stage is flat or slowly increasing as focal ratio increases, while the single-stage efficiency gradually falls off. The separation between the two curves is quite large at high temperature but small at low temperature where the single-stage performance is only weakly dependent on focal ratio. As before, this is an indication of the relative lack of importance of increased concentration at low temperature. However the single-stage efficiency peaks near F/D = 0.4 rather than 0.6. We interpret this as being due to the assumed Gaussian optical error distribution function, which has relatively long tails with very little energy in them. As one shortens the design focal length, the effect of these tails is relatively less pronounced than if the distribution were more sharply bounded. As a result, there is a very subtle effect in which the trade-off between intercept and thermal losses allows higher geometric concentrations without as much loss as at longer focal lengths. We do not feel too much should be made of this effect since it is strictly true only if the optical errors are really Gaussian and also applies only to the case where the overall macroscopic contour of the full primary is truly paraboloidal. We feel that in reality, the commonly used values for single-stage primary focal ratios, corresponding typically to $0.5 \le F/D \le 0.7$ are near the optimum for a single stage. We investigate some consequences of this behavior further in the next section.

3.3 Effect of Shape of Optical Error Distribution

The ray trace procedure was developed with the capability of specifying different probability functions for the angular incidence distribution. For the most part, Gaussian distributions with a characteristic deviation δ were used, but to investigate the effect of the shape of the focal plane distribution on the optimization procedure, other shapes were tried. In particular, we show in Figure 3-5 results for performance versus focal ratio with and without secondaries and at two different temperatures for the case when the probability is uniform within a cone of half-angle θ_{max}, a so-called "pill-box" distribution. (We use this term even when the cone is much larger than the angular size of the sun.) For consistency, note that such a distribution will have the same polar standard deviation as a circular Gaussian with

$$\delta_{opt} = \theta_{max}/2 . \tag{3-1}$$

We have used this relationship to define the pillbox distribution corresponding to the Gaussian distribution used to derive the results in Figure 3-4. Note that the curves in Figure 3-5 are similar to those in Figure 3-4, but that the single-stage optimum has shifted to F/D = 0.5 and that the improvement due to the secondary increases more strongly with increasing F/D.

The differences between Gaussian and pill-box distributions are compared directly at a receiver temperature of 1000°C in Figure 3-6. Note in particular that the more sharply bounded distributions develop higher efficiencies (since they permit higher concentrations with high intercept factors), and the relative gain with secondaries and at longer focal ratios is slightly more pronounced. Again, we do not want to place undue emphasis on these features but simply point out that particular optimization results may be quite sensitive to such effects.

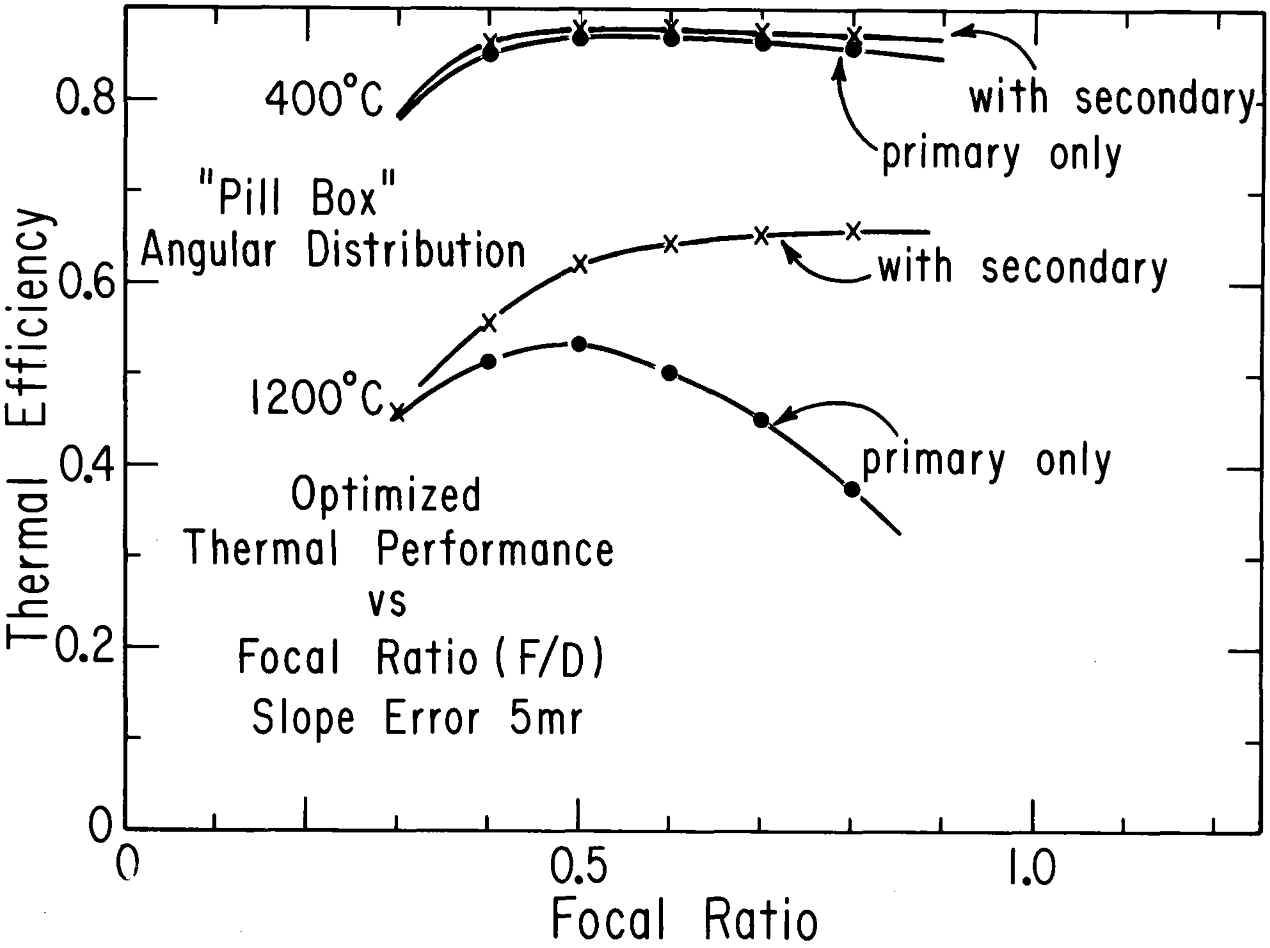

Figure 3-5. The Same as Figure 3-4, Except that the Optical Error Distribution is a Flat "Pill-Box" with the Same Angular Standard Deviation. At high temperatures, the single-stage optimum is shifted towards larger focal ratios and the secondary is more effective than in the case with Gaussian errors.

3.4 Off-Track Tolerances with and without Secondaries

3.4.1 The Limit of Small Slope Error and High Performance

We have already noted that the relative efficiency gain with a secondary is marginal in the limit of small slope errors or low receiver operating temperatures or both. This, of course, is because in this limit one already has all the concentration needed to reduce heat losses to a negligibly small fraction of the optical gain with the primary alone, and the additional factor of 2 to 3 from the secondary will not substantially improve the instantaneous performance. However, in this limit there are other optical benefits from a secondary that do not show up on an efficiency graph such as Figures 3-1, 3-2, or 3-3. In particular we refer to increased circumsolar collection and relaxed tolerance for off-track errors. We have analyzed the latter effect as an illustration of the magnitude of this kind of benefit.

Our generalized ray-trace procedure allows us to calculate the net efficiency as the center of the optical error distribution is moved off-axis by a given

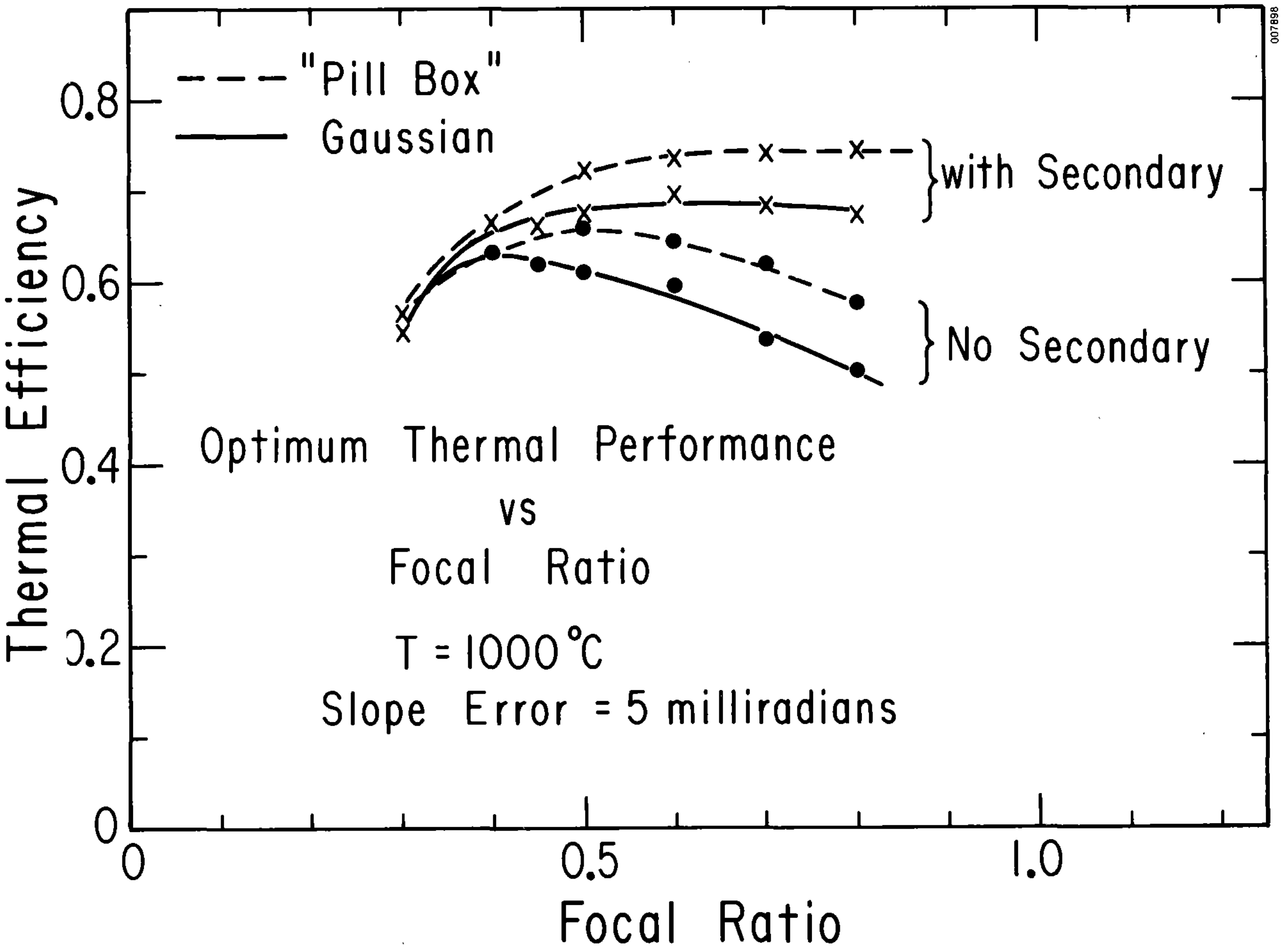

Figure 3-6. A Comparison of the Focal Ratio Dependence for the Two Different Optical Error Distributions at the Same Temperature with and without Secondary.

prespecified angle. This allows determination of the actual angular acceptance function of the concentrator for the analysis of tracking errors rather than the usual procedure of simply approximating them by a random Gaussian function. It should, of course, be noted that if secondaries are to be operated regularly in such a mode, particular care must be taken to provide adequate thermal control. We have not addressed such operational questions under this study. We also note that our approximation for secondary efficiency (Eq. 2-6) may not be as accurate for these asymmetric cases, but the uncertainty should be no more than about 1%. We are in the process of carrying out more detailed ray traces for the passage through the secondary to determine these effects precisely. The results of these off-axis efficiency calculations are shown in Figure 3-7 for a case corresponding to a high performance limit (1-mr slope error with other parameters as in Table 2-1).

For the single-stage system, the instantaneous efficiency is maximized as before for a perfectly aligned concentrator (zero tracking error), yielding an efficiency of 0.83. Then, the actual efficiency for a concentrator with this aperture is calculated as the pointing direction is moved systematically off the sun. As the plot shows, the efficiency drops to 0.9 times its on-sun optimum at an off-track angle of 4.9 mr.

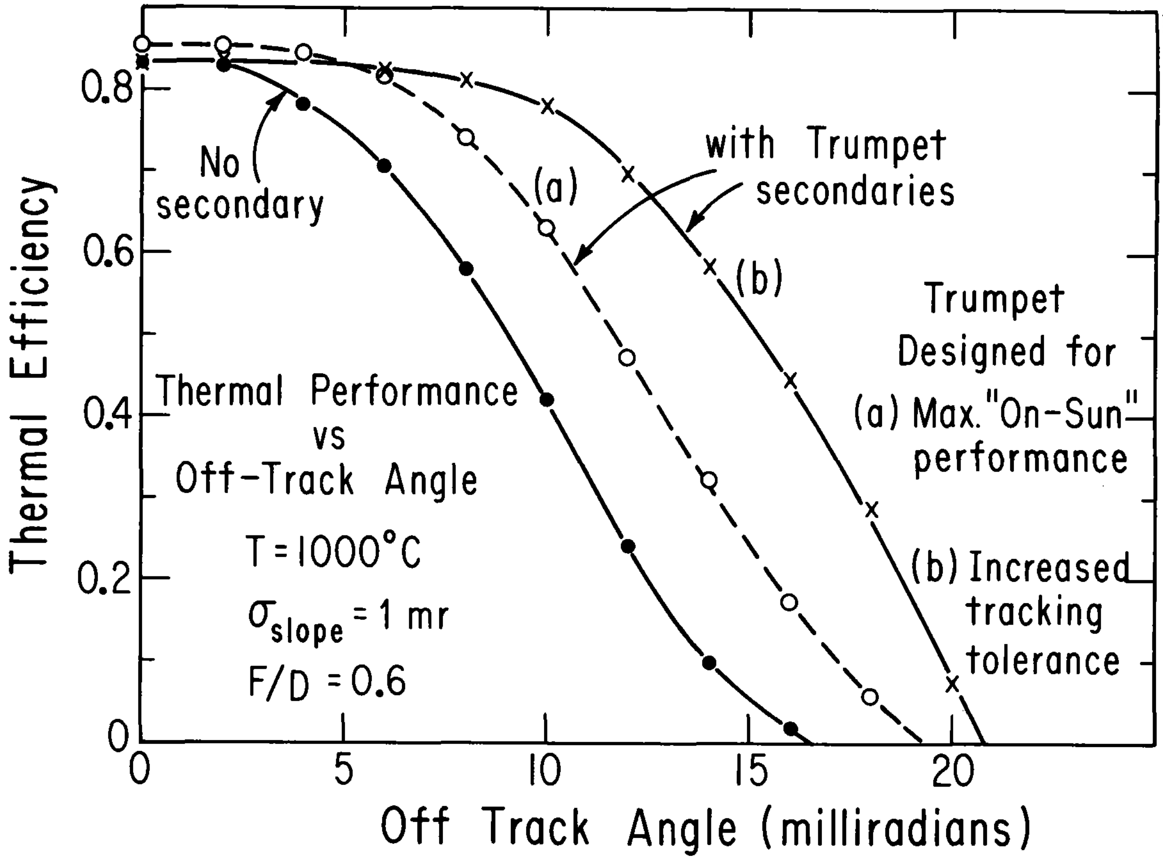

Figure 3-7. Thermal Performance with and without Secondaries versus Tracking Bias Error in the "High Performance Limit" of Very Small Slope Error. The secondary which maximizes the two stage on-sun efficiency provides a small increase in angular acceptance as well, but a two stage system designed to have the same on-sun efficiency as the optimized single stage, can nearly double the allowed off-track error.

There are several possible strategies for selecting a trumpet and receiver aperture to turn this F/D = 0.6 dish into a two stage. The first is to maximize the on-sun performance as before, which yields an efficiency of 0.85, only marginally better than with no secondary for the reasons we have been discussing. The performance with this secondary is also shown in Figure 3-7 as a function of off-track angle (curve a) and does exhibit somewhat wider angular acceptance, dropping to 0.9 times its on-sun value at an off-track angle of 7.5 mr, 1.5 times larger than with no secondary. A second strategy would be to choose the secondary and receiver aperture combination that has the same efficiency as the optimized single stage. The off-track performance for this case is indicated by curve b in Figure 3-7. The performance for this case drops to 0.9 times its on-sun maximum at 11 mr, about 2.3 times larger than with no secondary. It would seem that in this high performance limit, the latter option represents the better choice and indeed does offer potential advantages with respect to the single stage alone, although there is no efficiency gain at all! An intermediate choice (not shown) might be simply to fit a secondary to the optimized single-stage design, in which case there would be both a small performance gain and some increased off-track tolerance, but each less than the corresponding maximum possible.

3.4.2 Design Choices for Moderate to Large Slope Error

If a particular application does not correspond to the high performance limit, the considerations are somewhat different. We show in Figure 3-8, the efficiency as a function of off-track angle for the single-stage baseline case. Also shown are two curves, a and b, for two-stage systems designed according to the same criteria as in Section 3.4.1. Here the choice is not so clear. The slope error is large enough so substantial performance gain is provided by the efficiency optimized secondary and an increase by a factor of 1.6 in off-track tolerance as previously defined is also provided. On the other hand, maintaining the same efficiency with the two-stage as the optimized single stage improves the off-track tolerance by a factor of 2.4. Here, the large performance gain coupled with appreciable relaxation of tolerances would seem to favor the first choice for most applications.

3.5 Performance Benefits for Secondaries Combined with Spherical Mirrors

For some time we have been suggesting that the optimum application for secondaries may lie in their combination with potentially inexpensive approximations to a paraboloidal figure, rather than with a true paraboloid [10,14].

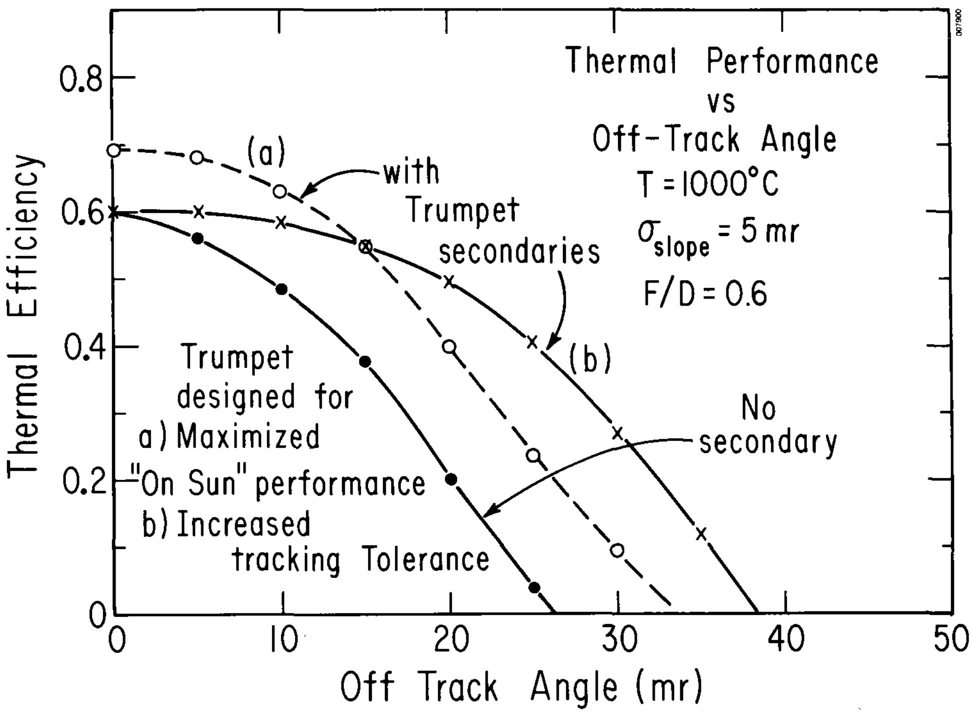

Figure 3-8. The Same as Figure 3-7 Except for the Baseline Parameter Values (relaxed Slope Error). In this case, the performance improvement and somewhat increased tracking tolerance for the performance optimized two stage (a) would seem to outweigh the benefit of maximizing the tracking tolerance alone(b).

One example of such a configuration is a set of flat mirror tiles arranged appropriately to be tangential to an imaginary paraboloidal surface. Another possible example is a spheroidal mirror. Both of these cases (and perhaps many others) share some common features that make their combination with secondaries particularly attractive. First, they become better approximations to a paraboloid at longer focal ratios. Second, they appear to be less problematic to fabricate at longer focal ratios (fewer facets required in the first case, a shallower draw in the second). Since the secondary concentration ratio is increasing at longer focal ratios, just slightly more than enough to compensate for the increasing image size due to the primary, it certainly seems like an ideal marriage! As a preliminary study of the kinds of performance that might be possible with such a compound design, we replaced the paraboloidal primary with a simple spherical mirror in our ray trace code and carried out a set of optimization studies similar to those already discussed. The procedures and preliminary results are summarized in the next two subsections.

3.5.1 Location of Optimum Receiver Aperture Plane

When a concave spherical reflecting surface with radius of curvature K is used as a focusing mirror, its paraxial focal length is

$$F_o = K/2 \ . \tag{3-2}$$

However, for large rim angles or short effective focal lengths, rays reflected of the outer edge of the spherical surface will be focused at a point somewhat inside F_o, designated as F_e. This means that the focal plane distribution will change shape between these two foci, and any optimization procedure that depends on this shape must take this variation into account.

For a spherical mirror with a Gaussian standard slope error of 5 mr and $K = 1.2D$ or $F_o/D = 0.6$, we calculated the optimized thermal efficiency over a range of actual target plane locations between F_o and F_e for three different temperatures. The results are shown in Figure 3-9. The optimum location for all three temperatures is about 2/3 of the distance from F_o towards F_e.

3.5.2 Comparative Performance versus Focal Ratio

As one considers large values of F_o for fixed D, F_o and F_e move closer to one another, and the variation in between them becomes less severe than in the case shown in Figure 3-9. Therefore, as an approximation, we evaluated the optimized performance at a distance 2/3 of the way between F_o toward F_e for values of F_o/D between 0.6 and 1.2. The results are plotted in Figure 3-10 for the spherical analogue of our baseline case.

These preliminary results appear quite encouraging. The two-stage performance levels off at a value about 35% better than the best single stage. The latter occurs at a nominal focal ratio of 0.7 although the two stage is almost independent of F/D for values >0.8.

Such designs or some variations on this theme, may offer a very attractive path to economical delivery of solar thermal energy, particularly in view of recent developments in stretched membrane technology.

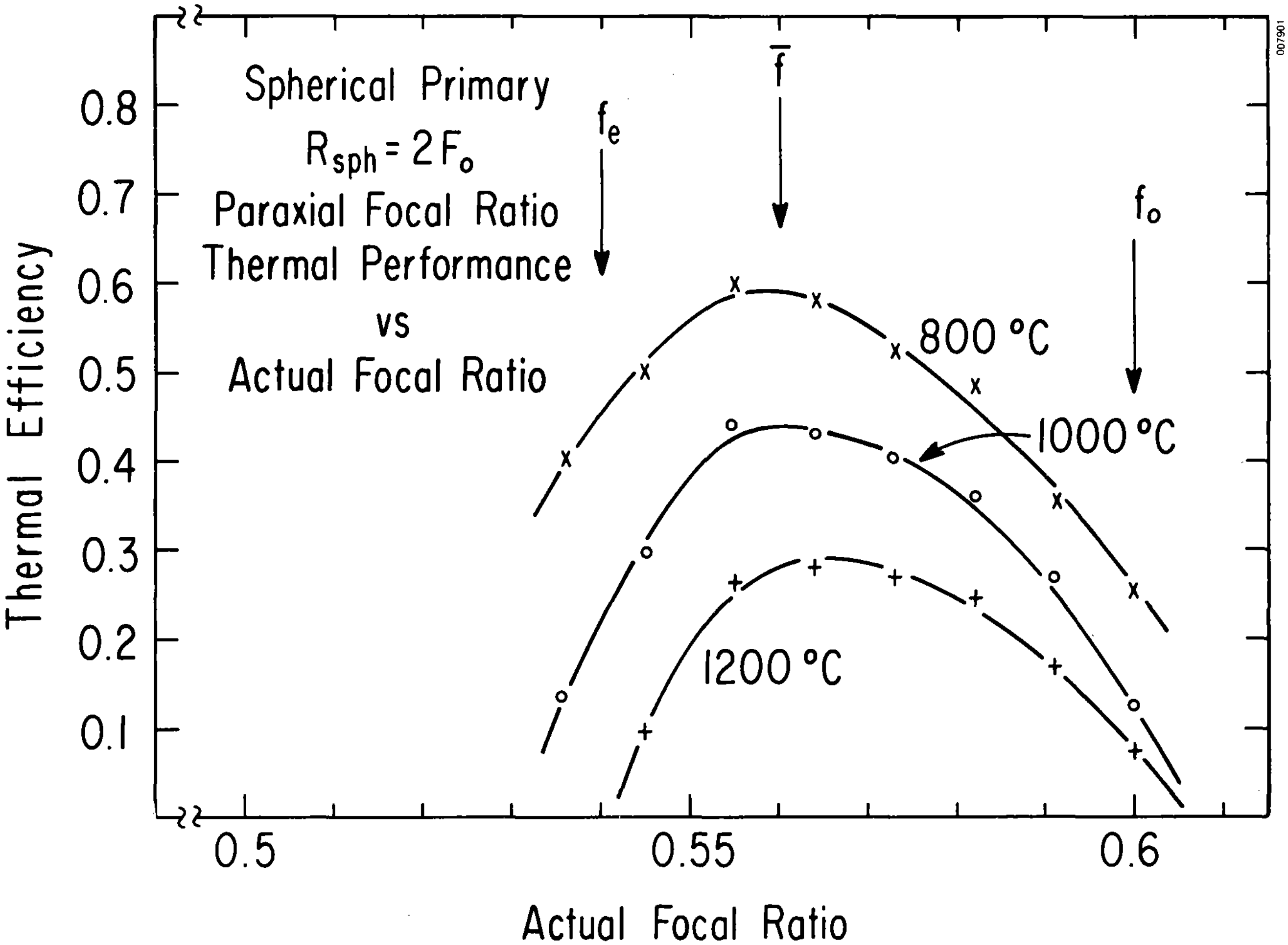

Figure 3-9. Ray-Trace Optimized Thermal Performance of a Single-Stage Dish Concentrator with a Spheroidal Primary of Nominal Focal Ratio of 0.6 as a Function of Actual Cavity Aperture Plane Location for Three Different Temperatures. The best performance for all three temperatures lies roughly at f lying two-thirds of the way from the paraxial focal point (f_o = 0.6) towards the focal point where rays from the very edge of the dish cross the axis (f_e).

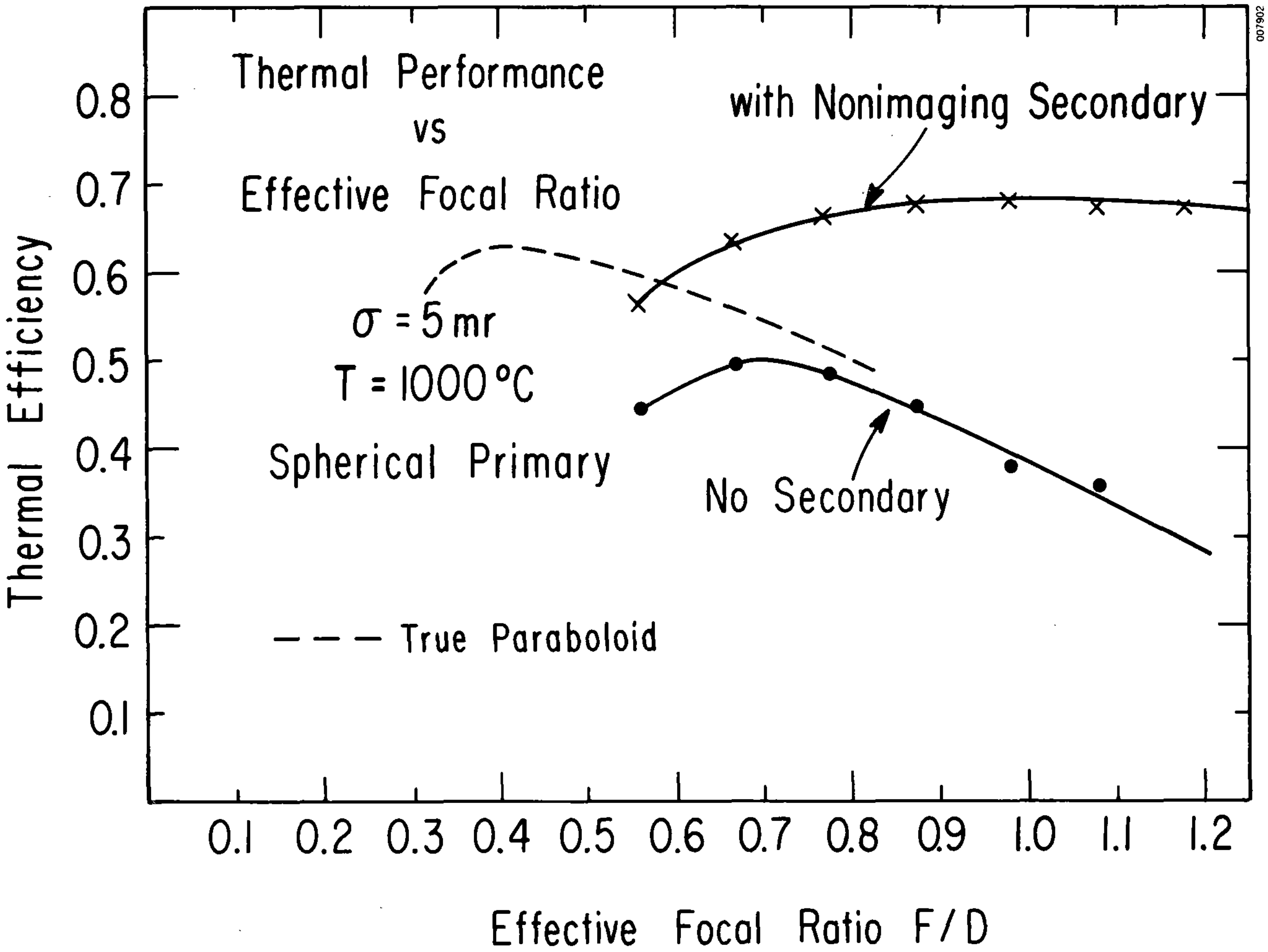

Figure 3-10. Thermal Performance for the Baseline Optical Errors and Operating Temperature for Single- and Two-Stage Concentrators Using a Spheroidal Primary as a Function of Actual Focal Ratio. The corresponding optimized performance for a single-stage paraboloidal contour is shown for reference. The spheroidal two stage at moderate to long focal ratios is dramatically better than the spheroid alone and even exceeds the performance of the short focal length paraboloid. We suggest that this may have possible applications with stretched membrane primaries not requiring preforming.

4.0 SIMPLE MODEL FOR RATIONAL ECONOMIC OPTIMIZATION

4.1 Performance Versus Cost Trade-offs

We have previously noted [10,14] that the practice of maximizing the efficiency of a solar thermal system with respect to some design parameter may not yield the most cost-effective configuration. That is, designs that allow the use of inexpensive materials and construction techniques may not (and probably will not) approach the performance of the most efficient systems one could build. Despite the self-evident nature of these statements, one common approach has been simply to determine those parameter values required for maximum or near maximum efficiency and to select the corresponding designs as baseline or reference configurations. This practice is probably the result of the lack of quantitative information on cost as a function of various design parameters. Unfortunately, it may result in selecting a development path that leads away from our ultimate goal of minimizing the cost of delivered energy. In fact, insofar as we are aware, the only serious attempt to incorporate cost as a function of performance parameters is a recent study of one- and two-stage systems by Gray [15]. However, even here the cost model was based on very limited and perhaps out-of-date information as we have subsequently pointed out [16].

Relevant to our discussion here, we also note that as a side effect, the approach of maximizing efficiency also results in the definition of baseline systems, which have relatively low thermal losses and thus show only small improvement with increases in concentration. When a secondary is added to such a system, the marginal gain is usually small. We feel that this approach can be quite misleading in that it implicitly ignores the costs of achieving the high performance in the first place and at the same time implicitly understates the value of a secondary.

To illustrate quantitatively the relationships discussed above, we have developed in preliminary form a methodology for performance versus cost optimization. For purposes of analysis, it assumes that the costs as a function of some particular design parameter can be described by a known function, even though at present this is usually not the case. However, the approach provides new insights into the search for cost-effective approaches and emphasizes the sensitivity of design choices to the detailed structure of the cost functions. We feel that the basic concepts are quite general and, in fact, can be applied in very many areas of solar system optimization not restricted to solar thermal applications. Finally we will see that when a system is optimized according to this methodology, the addition of a secondary should yield significant economic benefits unless the concentration of the primary is virtually independent of cost.

The fundamental objective, of course, is to maximize the energy delivered per dollar. The most sophisticated approach would be to deal with annual energy delivery and annualized costs; however, for a preliminary analysis it should be sufficient to work with instantaneous efficiency and initial costs since these are directly related to the annualized quantities. We will first develop the approach generally and in subsequent sections apply it to the special case of optimization versus slope error. In particular, we define the quantity R, the energy per unit cost by

$$R(u) = \eta(u)/P(u) \ , \tag{4-1}$$

where η is the instantaneous solar conversion efficiency under some fixed set of operating conditions (e.g., delivery temperature and insolation) and P is the system cost per unit collection area. The quantity u represents some design parameter on which both efficiency and cost depend. In our simple model the most cost-effective system will be that for which R is a maximum. It is important to note that η is fundamentally bounded (it cannot be greater than unity) whereas P is not. It is quite possible that in the very region in which $\eta(u)$ is approaching its limit, P(u) will be increasing rapidly. If this is the case, maximizing $\eta(u)$ alone is clearly a misguided strategy.

More formally we solve for the condition of maximum R(u) by setting the derivative with respect to u equal to zero as follows:

$$\begin{aligned} \frac{dR}{du} &= \frac{1}{P}\frac{d\eta}{du} - \frac{\eta}{P^2}\frac{dP}{du} \\ &= \frac{\eta}{P}\left(\frac{1}{\eta}\frac{d\eta}{du} - \frac{1}{P}\frac{dP}{du}\right) \\ &= \frac{\eta}{P}\left[\frac{d(\ln\eta)}{du} - \frac{d(\ln P)}{du}\right] = 0 \ . \end{aligned} \tag{4-2}$$

Thus, optimum cost effectiveness occurs at that value of u for which the logarithmic derivatives of η and P are equal. Application of this method requires not only that both η and P are known but that they can be represented by continuous and differentiable functions. In practice, these idealized conditions are unlikely to be met, particularly for the cost function. On the other hand, a great deal can be learned simply by representing the behavior by appropriate parametric models. Clearly the optimum will depend strongly on the shape of both functions.

The procedure is illustrated graphically in Figure 4-1 for a case in which both functions are monotonically decreasing with increasing u. The efficiency approaches a limiting value (here 0.85 for illustration) as u goes to zero and falls off slowly as u increases. In contrast, P is nearly constant at large u but begins to increase relatively rapidly as it approaches zero. We have deliberately chosen these forms to emphasize the effects noted above; nevertheless, such qualitative behavior is not at all unreasonable. The ratio R and both logarithmic derivatives are sketched in the bottom two panels of the figure. Note that for such functions the optimum is rather broad but occurs for values of η which are significantly below its limiting value. To the left of the optimum, marginal increases in cost more than offset the small incremental gains in efficiency, while to the right of the optimum, cost savings are too small to make up for the loss in performance.

4.2 Application to One- and Two-stage Systems

As a concrete example of the application of the economic methodology outlined in the preceding section, we compare the baseline (Table 2-1) one- and two-stage systems optimized with respect to primary slope error. The efficiency functions for each are those determined by our ray-trace optimization procedure in Section 2.0 and are reproduced in Figure 4-2. Also shown is an analytic

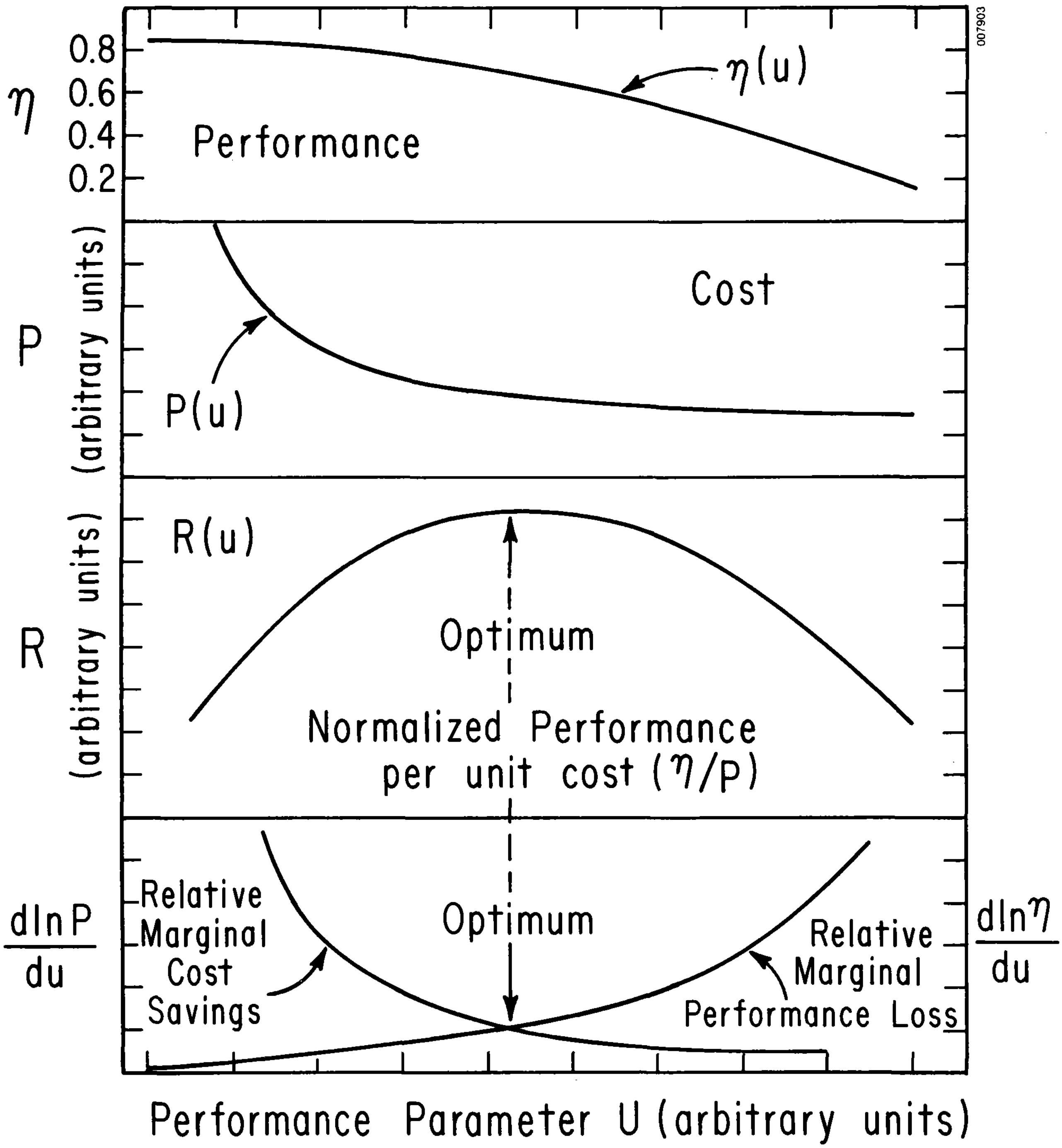

Figure 4-1. Schematic of a Proposed Model for the Rational Optimization of Performance and Cost Trade-Offs. It is required that the relative marginal cost and performance variations as a function of changes in some design parameter u, on which they both depend, be equal. The possibility that the cost may be increasing rapidly in the same region where the performance is approaching its upper limit has important implications for the location of the optimum.

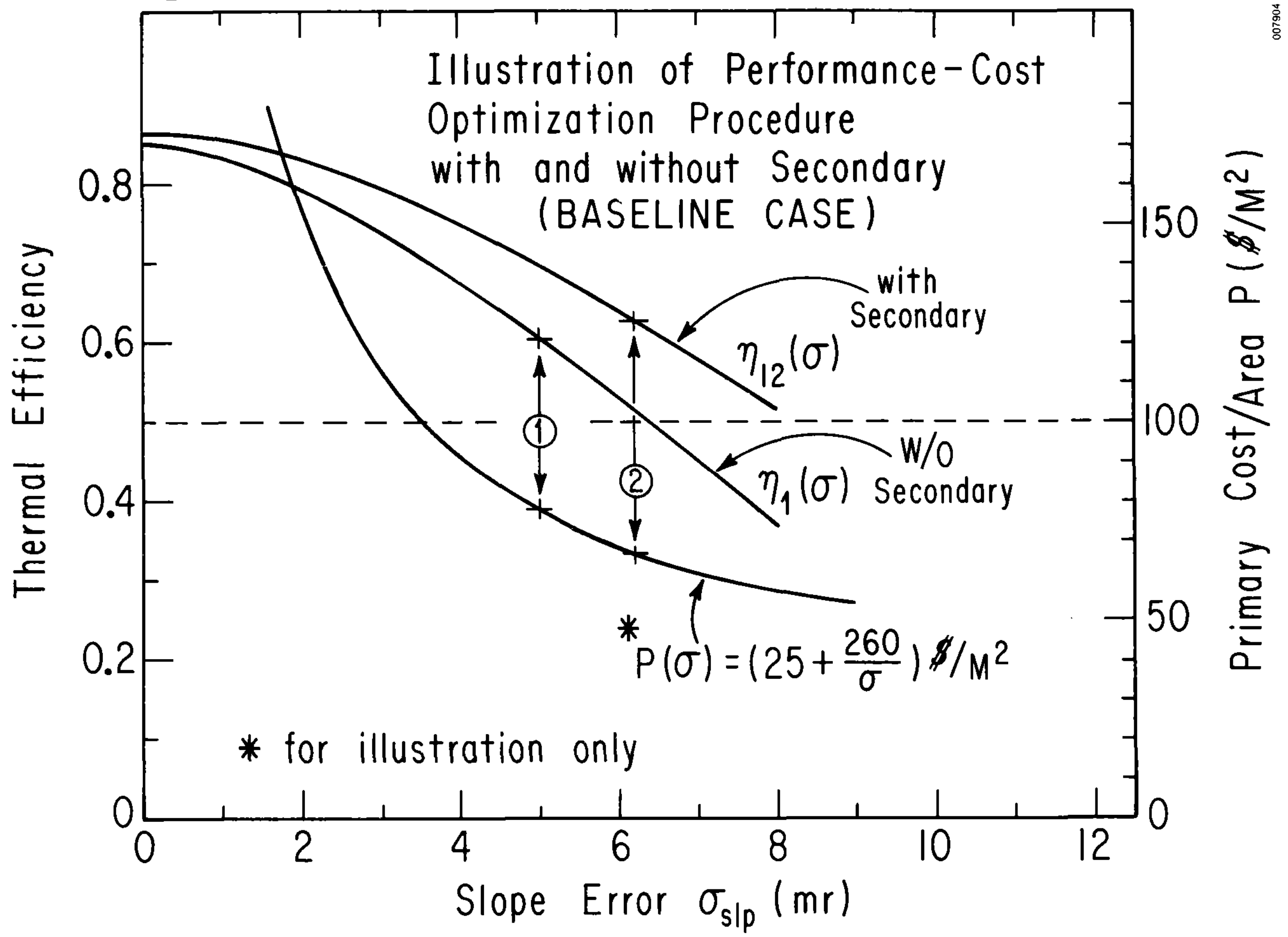

Figure 4-2. Application of the Proposed Cost Model to the Evaluation of the Marginal Cost Benefit of Using Secondaries. The performance of the baseline systems, with and without secondaries from the earlier analysis, is shown as a function of slope error. For illustration only an analytic curve showing a possible dependence of cost on slope error is also shown.

function relating primary mirror cost to its characteristic slope error chosen for purposes of illustration. It has the form

$$P(\sigma) = C + D/\sigma , \qquad (4\text{-}3)$$

where the values of the constants, C($\$25/m^2$) and D($\$260/m^2$ mr), are those introduced by us in our comment (16) on Gray's work (15) to show the sensitivity of his conclusions to the shape of the assumed cost function. Any particular cost value given by Eq. 4-3 for 2 mr < σ_{slp} < 8 mr lies within the range of uncertainties bounded by present day estimates. See for example the recent work of Murphy et al. [17]. The corresponding variation with slope is also accommodated within this range. However, we emphasize that there exist no quantitative data to allow accurate formulation of a reliable cost function and in its absence we are limited to parametric illustrations such as presented here.

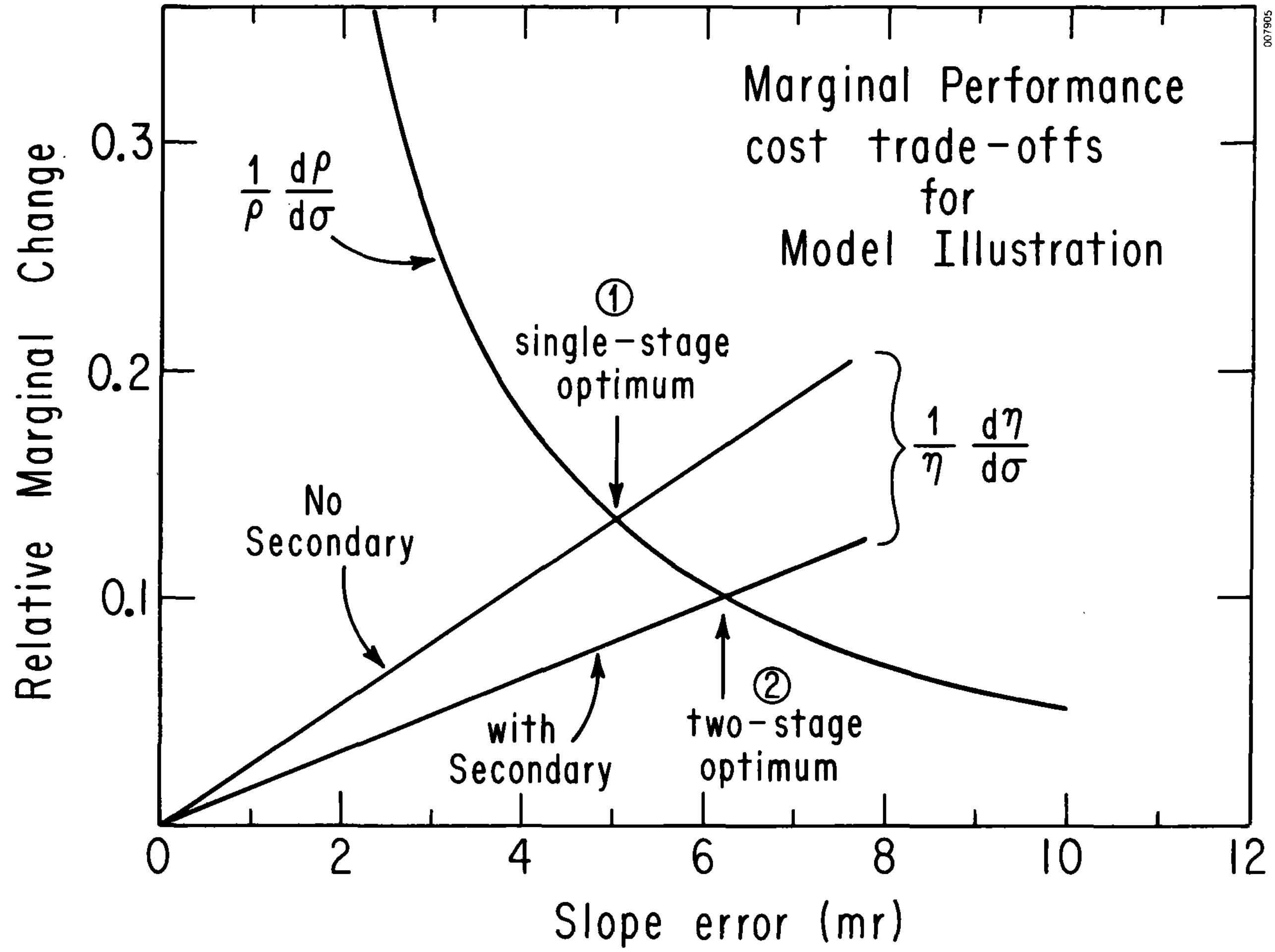

Figure 4-3. Absolute Values of the Logarithmic Derivatives with Respect to Slope Error of the Illustrative Cost Function and the Efficiency Functions with and without a Secondary from Figure 4-2. The application of the cost model requires that the intersections of these curves define the optima.

Proceeding with the illustration, we show in Figure 4-3 plots of the logarithmic derivatives of optimized efficiency with and without a trumpet secondary and of the cost function in Eq. 4-3. The optima occur at the corresponding intersections of the two curves at different values of the slope error as indicated in both Figures 4-2 and 4-3. Using the values of η and P read from the graph, we find for the corresponding optimum values of R

$$R_1(\sigma=5.0) = 0.605/(\$78/m^2) = 0.78\%\ pts/(\$/m^2)$$

and

$$R_2(\sigma=6.2) = 0.630/(\$67/m^2) = 0.94\%\ pts/(\$/m^2)\ .$$

This corresponds to a relative gain of 20% in energy per unit cost for the two-stage system over the single-stage system. The optimum slope error values are 5.0 and 6.2 mr, which are significantly larger than the values of 1-3 mr often regarded as representative of what needs to be achieved for large dishes.

Although the exact value of the calculated benefit is dependent on the shape of the cost function, the value found is roughly indicative of the magnitude of the benefit that can be achieved if the cost has any appreciable variation over the range from 1 to 5 mr where the performance is really varying quite slowly. For example, consider the case where the values of the constants in the cost function (Eq. 4-3) are changed to C = $\$69/m^2$ and D = $\$100/m^2$ mr, those used by Gray [15]. Even though this describes a much weaker relative dependence of cost on slope error, the values of the optimum slope errors with and without a secondary change to 3.2 and 4.0 mr, respectively, and the corresponding relative gain in R is about 9% with a secondary.

Only if the cost is essentially independent of slope error, as represented by the horizontal dashed line in Figure 4-2, are the above conclusions substantially altered. In this limit, of course, there is no marginal cost for reducing slope error, and marginally increasing the concentration is free. Formally in terms of the model, the logarithmic derivative of the cost function is always zero, and the optimum indeed does occur at maximum efficiency and very small slope error. Even in this limit, the benefit of the secondary would still consist of a small gain in efficiency or increased tracking tolerances and circumsolar collection as discussed earlier. However, we feel it is unlikely that when all different possible mirror technologies and primary configurations are evaluated, the fully assembled dishes with characteristic optical errors of 1 or 2 mr will all cost the same as those with errors of perhaps 5 or 6 mr. Our analysis shows clearly that it is in this latter regime that a secondary really has the greatest potential.

4.3 General Features of the Cost/Performance Model

As will be found by inspecting any of the performance comparison curves found from our ray-trace optimization procedure, the efficiency of the two-stage system at a given value of a particular design parameter (e.g., slope error or focal ratio) always lies above that for the single stage even if only by a small amount. (It should be noted that in the high-performance limit, some practical secondaries might introduce a small loss in throughput of $\leq 1\%$ due to truncation and intercept losses. However, a detailed ray trace shows that this loss is typically $\leq 0.3\%$, and if it were necessary to avoid even this small loss, trumpet secondaries that eliminate these losses can be designed for a small sacrifice in secondary concentration.)

This relative performance gain at a fixed value of the performance parameter is $\Delta\eta/\eta_1$, where $\Delta\eta$ is the vertical separation between the two curves and η_1 is the efficiency of the single stage alone. This provides a lower limit on the relative gain in cost effectiveness of a secondary (still neglecting, for now, the cost of the secondary itself) when added to an existing single-stage system. If the single-stage system is truly cost optimized, this lower limit will generally be valid independent of the shape of the cost function (unless the cost is actually decreasing with increased performance). To see this, consider that

$$\frac{R_2}{R_1} = \frac{\eta_2(\sigma_2)P(\sigma_1)}{\eta_1(\sigma_1)P(\sigma_2)}$$

$$= \frac{P(\sigma_1)[\eta_1(\sigma_1) + \Delta\eta + (d\eta_2/d\sigma)\Delta\sigma + \ldots]}{\eta_1(\sigma_1)[P(\sigma_1) + (dP/d\sigma)\Delta\sigma + \ldots]}$$

$$= 1 + \frac{\Delta_\eta}{\eta_1(\sigma_1)} + \frac{1}{\eta_1}\frac{d\eta_2}{d\sigma}\Delta\sigma - \frac{1}{P(\sigma_1)}\frac{dP}{d\sigma}\Delta\sigma + \ldots \tag{4-4}$$

to first order. Here, the subscripts 1 and 2 refer to the single- and two-stage systems, respectively, σ_1 and σ_2 are slope error values of the cost optimized systems, and $\Delta\sigma = \sigma_2 - \sigma_1$.

Note that

$$(1/P)\ [dP(\sigma_1)/d\sigma] = (1/\eta_1)\ (d\eta_1/d\sigma) \tag{4-5}$$

from the condition for optimum, so that we can write

$$\Delta R/R = (R_2/R_1) - 1 \tag{4-6}$$

$$= \Delta\eta/\eta_1 + (\Delta\sigma/\eta_1)\ [d\eta_2/d\sigma - d\eta_1/d\sigma]\ .$$

Both $d\eta_2/d\sigma$ and $d\eta_1/d\sigma$ are negative quantities, but the magnitude of $d\eta_1/d\sigma$ will be $\geq d\eta_2/d\sigma$, so that the difference between the terms in brackets will be ≥ 0 (e.g., Figures 3-1 and 4-3 illustrate this graphically). Therefore, we will always have

$$\Delta R/R \geq \Delta\eta/\eta_1\ . \tag{4-7}$$

This is important because it shows explicitly that when a secondary is added to a single-stage system, which is rationally optimized with respect to cost performance trade-offs, the relative cost benefit must always be at least as great as the relative efficiency gain. This emphasizes that any analysis that finds the relative cost benefit provided by a secondary to be smaller than the relative efficiency gain (as in Gray [15]) cannot have been derived for a properly cost-optimized single-stage system.

4.4 Secondary Cost Estimates

In Sections 2.0 and 3.0, we showed that except in the limits of either low receiver operating temperature or high optical quality, there is a significant performance advantage of an optimized two-stage system over an optimized single stage. For the baseline example (F/D = 0.6, T = 1000°C), this performance gain relative to a single-stage system varies from about 5% at a slope error of 2 mr to about 40% at 8 mr. We showed in the previous subsection that this relative performance gain is a lower limit on the overall relative cost benefit that could be delivered with a two-stage system, depending on the shape of the cost functions involved. In all of this analysis, we have, up to now, neglected the cost of the secondary itself. It is interesting to use these results concerning performance and cost benefits as a measure of the value of the secondary and to compare these with preliminary, order of magnitude, estimates of what actual secondaries might cost as a very preliminary indication of their potential cost-effectiveness.

First, consider what secondaries might cost. They will generally be on the order of one hundred to several hundred times smaller in size and weight than the primary. For example, the geometric concentration ratio of the primary relative to the optical target provided by the secondary for the optimized two-stage baseline (Table 2-2) is 755X. The actual surface area to optical target area ratio ranges from a factor of 2-3 for a CPC to perhaps 5-10 for a trumpet, which would correspond in this example to a secondary from 75 to 375 times smaller than the primary. The secondary need not be structurally massive since it only has to support its own weight. The optical surface need not be very accurate since the slope error tolerances are on the order of a few degrees (these need only be small compared to the secondary acceptance angle which is greater than or equal to the rim angle ϕ). They may need to be actively cooled [8,9]; however, this need not be expensive particularly when used in conjunction with focal-mounted heat engines in which case the cooling might be integrated into the engine cooling system. Passive cooling where possible should be simple and inexpensive. The reflecting surface does need to be highly reflective and stable in a high flux environment, which does introduce a potential cost uncertainty into consideration. However, based on all of these facts it seems to be reasonable to expect that secondaries could be manufactured for about 1% to 2% of the primary cost. This, in turn, should be substantially less than 1% of the total overall system cost. This is not at all unreasonable for a design modification that increases net system output by 5% to 40%.

These considerations are supported independently by cost experience gained in the two hardware experiments conducted so far [6,10]. For example, Table 4-1 summarizes the actual costs and projected costs for secondary CPCs built and tested at the ACTF at Georgia Tech. The prototypes, of which only a few were made, essentially were handmade and cost roughly \$500 to \$1000 each for passively cooled versions (not including tooling for the mandril on which the shells were spun). Even for these experimental prototypes, this cost is probably less than our estimated 1% to 2% of primary cost when derived with respect to present day, recently available state-of-the-art 11-m dishes (e.g., Advanco or McDonnell-Douglas). The projected costs of about \$100 to \$200 in volume production are even substantially less than 1% of what a commercial 11-m dish system would need to cost to be competitive with conventional electricity generation! Even if these preliminary estimates are off by a factor of two or more, it is clear that secondaries have the potential to deliver a value, typically about an order of magnitude more than they cost.

As another way of quantifying the cost benefit of secondaries, one can estimate the associated incremental cost/watt. Assuming a typical performance benefit for an optimized (with respect to heat engine operating temperature) solar electric conversion system, Kritchman [18] found a typical increase in system electrical output of 10% through the use of a trumpet secondary. If we apply this to a nominal 11-m dish electric system delivering 25 kW peak, without a secondary, this would correspond to an incremental gain in peak capacity of 2.5 kW. If the required secondary cost \$500, this yields an incremental cost/peak-watt of 20 cents. As part of the case study of secondary potential

Table 4-1. Cost of Secondaries

Actual costs for experimental CPC's as built (not including tooling).

	Aluminum	Copper
Spinnings	$100	$300
Reflector surface (silver or aluminum	200	300
Polishing	100	200
Additional labor and materials	50	50
Total each secondary	$450	$850

Rough estimate for volume production

	Aluminum	Copper
Cone structure and substrate	35	100
Additional labor and material	50	50
Reflecting surface @ $50/m^2	40	40
Total	$125	$190

Costs of cooling, if needed, could vary widely from negligible (~$20/unit) up to several hundred dollars, but probably not more even for semiactive closed loop system. (Cooling load is only 1-2 kW.)

for state-of-the-art commercial dishes, an evaluation of performance improvement from a secondary on the proposed LaJet "innovative concentrator" designs indicated gains in intercept of from 4 kW to as much as 10 kW. If a larger secondary costing $1000 were employed this would still correspond to an incremental cost per peak watt of 10 to 30 cents. These numbers are quite low compared to the same kind of cost parameters associated with many other solar system technical components.

5.0 DISCUSSION OF RESULTS AND DESIGN APPLICATIONS

In an effort to examine the potential of nonimaging, maximally concentrating secondaries for point-focus solar thermal applications, we have carried out a parametric study of the performance and cost trade-offs of one-stage and two-stage solar dish configurations. The performance model, developed as part of this work, uses a Monte Carlo ray-trace procedure to determine the focal plane distribution for a given primary focal ratio and optical error distribution and then optimizes the resulting trade-off between thermal losses and effective optical intercept factor as a function of receiver operating temperature. The cost model maximizes performance per unit cost, assuming that both are functions of a given design parameter. Significant performance and potential cost benefits with secondaries are found for a wide range of design parameters.

5.1 Performance

The performance effects are analyzed as a function of deviations from a baseline configuration typical of one for which we expect secondaries to be useful. In particular, for a primary paraboloid with F/D = 0.6 and a Gaussian slope error standard deviation of 5 mr operating at 1000°C, relative efficiency improvement is 18%. This relative performance gain increases (or decreases) if either operating temperature or slope error are increased (or decreased) respectively relative to their baseline values.

The results show clearly that the effects of operating temperature and optical slope error are closely coupled. Since concentration reduces heat losses and the intercept function depends on optical errors, the optimized efficiency is coupled to operating temperature and slope error in a similar manner. For example, Figures 3-2 and 3-3, which show the performance dependence and comparative improvement with a secondary at fixed focal ratio, as a function of temperature, are virtually identical in shape to Figure 3-1, which shows the same thing as a function of slope error. The combination of operating temperature and slope error could be thought of as defining a single parameter for which the potential improvement is a monotonically increasing function. In the limit that this parameter is large, the secondary provides dramatic improvement; in the limit that both temperature and slope error are small, the improvement is relatively small. However, this serves to illustrate that at any achieved value of optical quality, there will always be temperatures for which a secondary will be highly advantageous. Similarly, for any reasonable design operating temperature, a new range of acceptable optical quality will be made available with a secondary. Note that, in the context for which we have been advocating the use of secondaries, namely reasonably high operating temperatures and relaxed slope errors, the benefits are substantial. Finally, it should be emphasized that all of these calculated effects depend on the assumed heat loss model (Eq. 2-3 with the radiative and convective parameters in Table 2-1). If in fact the convective heat losses from the aperture are substantially higher, the relative gains resulting from the use of a secondary will be even greater in all configurations than those calculated here.

For most of the parameter range considered, that is, for slope errors greater than about 2 mr or operating temperatures greater than about 600°C, the relative gain of a system using a secondary concentrator is always ≥5%. Even in the limit of very high optical quality ($\sigma_{slp} \leq 1$ mr) or very low operating temperatures ($T \leq 400°C$), there is a small residual improvement of 1% to 2%. In this "high performance limit," there is an alternative receiver aperture and secondary optimization strategy for which the off-track tolerance can be doubled relative to a single-stage configuration while maintaining the identical efficiency. In this case, although there are no instantaneous performance gains, the annual energy collection will be increased due to increased acceptance of circumsolar radiation. Therefore, no matter what the operating temperature or achievable slope errors, there is always some potential benefit with a secondary, either through increased efficiency or increased angular acceptance or usually some of both.

Variations of performance and incremental benefit with a secondary as a function of focal ratio are more complicated to summarize. This is because, as we have noted, the precise shape of the relationships depends somewhat on the form of the optical error distribution so that the optima for the single stage are not so well defined. Furthermore, although the concentration of the two-stage system is continuously increasing toward longer F/D, the relative decrease in the effective secondary optical efficiency as it intercepts a larger fraction of the focal plane distribution approximately cancels the benefit in reduced heat losses, so that the performance of the two-stage system is roughly independent of focal ratio. However, there are really two domains of interest.

The first is the short focal length regime where a trumpet can provide substantial additional concentration and thermal performance with negligible optical losses. Note that, for fixed operating temperature and optical error, the performance of the two-stage system at moderate focal ratios (F/D between 0.6 and 0.8) is substantially better than the best single-stage system at shorter focal ratios (F/D between 0.4 and 0.6) regardless of the shape of the error distribution. For the baseline case, the relative advantage of the two-stage system is about 0.10 for the Gaussian distribution and 0.14 for a pillbox.

The second lies at longer focal length (F/D 0.8 to 1.0) where a higher concentration CPC in a two-stage system would develop performance comparable to that of a two-stage trumpet design at shorter focal ratio, but the performance of a single-stage design in this range would not be acceptable. Here, the performance advantage of the two-stage system relative to the single stage, if for some reason both are required to have moderate to long focal ratios, is very dramatic. For example, for a focal ratio of 1.0, the efficiency of the two-stage system for the baseline case is about a factor of two better than the single-stage system. In this context, we mention again the interesting properties of near spherical stretched-membrane reflectors with long focal lengths and multifaceted concentrator designs.

The performance benefits demonstrated here are illustrative of the effect of secondaries in general. However, it should be recognized that all of this analysis is based on one idealized configuration, namely a primary whose basic contour is a true paraboloid and a very simple model for the optical errors, namely, a single circular Gaussian incorporating all the effects of sun shape, nonspecularity, and slope and contour errors. In particular, we point out that since the results of the optimization procedure depend on the shape of the focal plane energy distribution, care must be taken to understand the tradeoffs in the context of a specific design. An accurate determination of the relative optimum for a single-stage system and the performance benefits with a secondary for real, not generalized, designs requires both a quantitative description of the optical error distribution and detailed specification of the proposed optical configuration. An actual practical point-focus concentrator might involve many deviations from our simple model, such as a primary concentrator composed of facets or gores, a nonparabolodial shape, optical errors that are neither circularly symmetric or Gaussian, etc. For such a configuration, the quantitative effect of a secondary can be expected to be somewhat different than shown here. The trends found here should be typical, however, and perhaps the benefits with practical designs will be even greater.

5.2 Cost/Performance Sensitivities

We have shown that the precise choice of design parameters for a rationally performance-cost optimized system depends critically on the shape of the assumed cost function. As a consequence, the predicted relative cost benefit expected from a secondary depends on the primary mirror costs as a function of the reflector characteristic slope error. Despite the lack of quantitative information about such relationships, some very general conclusions can be drawn. The first is that as long as there is significant cost variation over the interval where the performance is also varying significantly, the optimum for a single-stage system will lie in this range. Second, the optimized two-stage design will lie at both a somewhat higher efficiency and a larger slope error than the optimized single-stage design (as in the specific examples given above). Third, even in the complete absence of cost information, the relative performance gain with a secondary provides a lower limit on the economic benefit that can be expected and a corresponding guide to an upper limit for allowed secondary costs.

The examples presented here yielded optimum slope errors from 3 mr to 6 mr and corresponding relative cost reductions of 9% to 20%. If costs increase even more strongly with decreasing slope error between 10 and 2 mr than we have assumed, the optimum single-stage design could lie at slope error values substantially larger than are usually discussed. Furthermore, the relative cost benefit with a two-stage design in such a case would be substantially greater than the performance benefit at fixed slope error in this range. This suggests potential reductions in the cost of delivered energy of 20% to 40%. On the other hand, if costs are independent of decreasing slope error, down to the highest quality optical surface, the benefits of secondaries will be only those of the "high performance limit." These are more difficult to quantify but nevertheless real. However, it must be pointed out that current technologies have not apparently reached this limit.

All of the above serves to emphasize the importance of understanding performance cost trade-offs in trying to choose among alternative paths towards the ultimate goal of low-cost solar thermal energy. For purposes of discussion we have illustrated the consequences of the optimization model developed here with a particular analytic form for the cost function (Eq. 4-3). It is quite possible that, in fact, real mirror technologies will not be able to be described so simply. That is, there may be discontinuities in the functions or their derivatives which would make an analysis such as outlined here difficult. Another possibility might be that only a relatively narrow range of costs and achievable slope errors will characterize a particular mirror technology such that each approach would be represented by a single point or small spot on the graph. Whatever the case, as long as the trend is such that lower costs are associated with larger slope errors (or alternatively, with design strategies for which the two-stage efficiencies remain "respectable"), it is clear that secondaries can provide a very effective cost reducing design option.

In general, an approach such as developed here can be particularly useful in defining both cost and performance goals. It emphasizes that accurate knowledge of the cost structure associated with all design trade-offs is essential both for choosing an optimized cost-effective design and for fully appreciating the relative merit of two-stage designs. Probably no single approach can provide the dramatic cost breakthrough still necessary for solar energy to compete favorably with conventional high temperature thermal sources. However, perhaps a number of different innovative technologies can be combined synergistically, to deliver acceptable performance at greatly reduced cost. Based on all the results presented here it appears to us that secondaries can play a major role in several such design paths. A combination of a stretched-membrane primary together with a properly designed nonimaging secondary to correct for nonideal shape and optical properties seems to be a particularly promising example of such an approach. In this connection we emphasize again the superior performance of the two-stage design with a spherical primary at longer focal ratios as shown in Figure 3-10. In this regime, the shape of a stretched membrane with no preforming will be approximately spherical to first order and the relative performance will be as modeled. At shorter focal ratios the membrane will deviate significantly from both spherical and especially paraboloidal shapes and the performance will be poor without preforming, which may, in turn, be expensive. The combination of a simple stretched membrane with a secondary at a focal ratio of 0.8 to 1.0 provides not only better performance than a short focal length, single-stage paraboloid (see the data in Figure 3-6 and the dashed line in Figure 3-10), but saves the cost of preforming.

6.0 CONCLUSIONS

Based on the assumptions defined in the main body of this report and the exercising of the models developed, we reached the following conclusions:

- Based on a simple model for the secondary effective optical efficiency (net throughput), the optical efficiency of a trumpet secondary, to a very good approximation, for energy that would have been intercepted by a given receiver aperture in its absence approaches unity (typically >0.995 based on ray trace). Unless the optimized intercept factor is at least this close to unity, one can never lose performance by adding such a secondary; one can only gain or break even.
- Based on a comprehensive set of performance calculations, we found that, in general, the optimized thermal efficiency for a two-stage system lies significantly above that for a single-stage system if all other characteristic parameters are the same for both. For example, curves showing the thermally optimized instantaneous performance with and without a secondary are compared in Figure 3-2 as a function of receiver operating temperature. These curves are for a paraboloidal dish with a focal ratio of 0.6 and a reflector surface with a characteristic root-mean-square Gaussian slope error of 5 mr. The gain with a secondary varies from 2.5% (a relative gain of 3% in energy delivered) at 500°C to 13.5% (a relative gain of 30%) at 1200°C. Curves such as those in Figure 3-2 are shown to be a general feature of comparisons between one- and two-stage systems.
- Analysis shows that there are subtle effects that need to be taken into account when defining a final "optimized" configuration. This is based on a preliminary exploration of the sensitivity of the optimized performance for both types of systems as a function of other design parameters, in particular focal ratio, under different assumptions about the shape of the optical error distribution.
- Based on investigation of the relative performance of one- and two-stage systems in the limit where there may be only a small relative efficiency gain (e.g., low operating temperatures), we found that in such cases one can design for a large gain in off-track tolerances, typically about a factor of two, relative to those corresponding to single-stage systems.
- Based on investigation of the relative performance of the two types of systems when the primary is spheroidal rather than paraboloidal, we found that the optimum performance with a secondary is much better than the best performance with no secondary, and this optimum performance occurs at a somewhat larger focal ratio (f/No. 0.8 to 1.0) than typical for conventional designs. This may have important implications for the use of primaries utilizing stretched-membrane technologies.
- Using a methodology for the rational optimization of performance versus cost, we found that unless all costs are virtually independent of optical errors, a two-stage thermal system, so optimized, must always be cost-effective relative to the corresponding single-stage system (provided, of course, that the relative costs of the secondary itself remain small compared to the primary). The method is based on what should be a self-evident constraint; namely that at the optimum, the relative incremental performance gains, with respect to a particular performance parameter, should balance the incremental costs associated with improvements in that parameter.

- Different sets of both secondary trumpets and CPCs were designed for the LaJet Innovative Concentrator configurations. These secondaries have geometric concentration ratios of just under 2X for the 95 facet design and somewhat over 2X for the 67 facet case. Optimized sizes and truncation ratios were determined for either increasing the overall system concentration ratio or increasing the diameter of the effective target seen by the primary and thus relaxing the optical tolerances. This work, summarized in a preliminary report and provided to LaJet, is attached here as an appendix and is not discussed further in the main body of this document.

7.0 RECOMMENDATIONS FOR ADDRESSING REMAINING UNCERTAINTIES

Our investigations to date have indicated the very favorable potential for significant cost and performance advantages using secondary concentrators. Further, we have not identified nor do we anticipate any fundamental limitations to effective implementation of the concept. There are, however, a number of important questions that must be addressed before the potential of the concept can be fully realized. Moreover, by addressing new capabilities, an even more cost-effective application of secondaries may arise. Specifically, these questions concern obtaining a better understanding of the optical and thermal properties of compound concentrators and identifying technical engineering solutions having to do with practical implementation of the concept. We discuss each of these areas below and finally review briefly some longer term conceptual possibilities.

7.1 Analytic Design Questions

There are three analytic areas that need immediate development if secondaries are to be used to assist in the development of a truly cost effective dish concentrator system in the relatively near term.

7.1.1 Secondaries and Innovative Concentrator Configurations

The interaction between the optical properties of proposed new primary concentrator technologies and nonimaging secondaries needs to be understood. We refer in particular to stretched-membrane reflectors, but work in this area may be appropriate for other potentially low-cost approaches involving multifaceted or Fresnel reflector designs. In general, these new configurations are not paraboloidal, and the focal plane distributions will not be the same as those modeled in this work. It is particularly noteworthy that the coupling between optical properties and fabrication costs may be quite strong for such designs. We have previously pointed out [14] a feature that is clearly supported by the analysis in this report, namely that for an optimized two-stage system one cannot simply optimize the single-stage system and then add a secondary. One must understand the overall performance of the primary combined with a properly matched secondary as a function of design parameters, (e.g., focal ratio) and optimize the entire compound concentrator as a system.

7.1.2 Comparative Performance of Trumpets, CPCs, and CECs

In this study, the nonimaging secondary has been treated generically, with both concentration ratio and optical throughput represented by approximate analytic functions. These are very accurate in the case of a trumpet, but less so for CPC-type concentrators. CPCs and the closely related compound elliptical concentrators (CECs) have skew ray losses and a considerably higher average number of reflections whose effect can only be determined precisely by ray tracing each case. The trumpet has no skew ray losses and a low average number of reflections; however, it is limited to shorter focal ratios and low secondary concentration ratios. A ray-trace analysis of properly truncated versions of each type of secondary as a function of primary focal ratio and secondary reflectivity is needed to define the appropriate focal length regime for each, as well as to develop a precise quantitative representation of long focal length two-stage designs.

7.1.3 Spatial and Directional Distributions at the Secondary Exit

Theoretical considerations and some preliminary ray-trace calculations show that, in general, a secondary tends to reduce spatial nonuniformities in the target plane and to spread out the directional distribution. Such effects would have a general impact on receiver design constraints; however, they are not very well understood at this time. A systematic investigation based on ray trace calculations for each type of secondary needs to be carried out to understand the general features of both spatial and directional distributions and how they vary with design configuration.

7.2 Practical Design Questions

For some time we have been concerned about overcoming a number of potential practical obstacles to successful use of secondaries for solar thermal applications. In general, these do not depend on the details of the optical design, but have to do instead with severe thermal requirements imposed on the secondary by its location in a region of concentrated solar flux and its proximity to the receiver. Again there are three specific areas that stand out as requiring further attention.

7.2.1 Dissipation of Thermal Loads on the Secondary

We have just completed a relatively thorough analysis of this problem for trumpet secondaries [8,9] with support from Sandia National Laboratories. Ray trace computations were used to determine the solar flux distribution on a trumpet reflector side wall in a baseline reference configuration and scale. A thermal model was developed to analyze resultant heat flow under passive thermal control. It was found that there exists domains whose boundaries depend on both total system power and concentration ratio, in which thermal control by passive means should be readily achievable with careful design. At very high concentrations or very large system powers some form of active cooling will most likely be required. The work needs to be extended quantitatively to other scales and to CPC-type secondaries, for which the problem is quite different. In addition, practical methods for active or semiactive cooling need to be explored.

7.2.2 Development of Appropriate Secondary Reflector Materials

The materials used for secondary concentrator reflector surfaces must meet much different specifications than is usual for solar reflectors. They must maintain a high reflectivity for a long time in a high flux and possible high temperature environment. The experimental secondaries previously built and tested by our group used electroplated silver, vacuum-deposited silver with an overcoat of MgFl or vacuum-deposited aluminum with an overcoat of SiO for the reflector surface. The first of these is not likely to provide a practical material, since it oxidizes and degrades if left to itself, although it can be restored to its initial reflectivity with occasional polishing. The other two surfaces, although more practical, have somewhat lower reflectivities than optimum. The experimental Solgel silver reflector surfaces under development at Sandia may provide an attractive solution. They are highly reflective (ρ = 0.95), and preliminary tests carried out by Sandia [19] indicate that they can maintain this reflectivity up to temperatures above 300°C. Work in this area should be continued and extended with this application in mind.

7.2.3 Thermal Isolation of the Secondary from the Receiver

The experimental tests of secondaries carried out so far have been carried out with low-temperature receivers (cold water calorimeters) in order to make direct measurements of the energy throughput. In actual operation with a hot receiver, there are two closely related concerns that have not yet been addressed. The first is the effect of the secondary on the receiver heat loss. Whether the secondary is actively or passively cooled it must be maintained at a relatively low temperature with respect to the receiver temperature, and if the secondary is not properly isolated from the interior of the cavity, it could provide an undesirable thermal loss path. The second is the effect of the hot cavity aperture on the temperature distribution on the secondary, particularly at its exit aperture. The temperature even at this point must be maintained below safe operating limits for the reflector surface and substrate. Careful attention to proper thermal isolation of the secondary from the receiver should solve both of these problems.

7.3 Advanced Concept Development

7.3.1 Central Receiver Applications

We have de-emphasized for the present the systematic design of optimized non-imaging terminal concentrators for central receivers. A preliminary study at SERI [20] found some improvement simply with flat reflector augmentation. One can do considerably better if one can use curved mirrors designed according to the "edge ray principle" of nonimaging optics [1]. Obviously, the geometry is very much different from the cases of point-focus dish concentrators studied here, but the fundamental design principles are the same. One is not trying to achieve as high a secondary concentration in the central receiver case, and one has some additional design options available, such as the use of asymmetric configurations. Therefore, there remains considerable potential for further development of this concept. Systematic analysis of representative geometries should be able to define a set of candidate designs for evaluation by ray trace methods. These designs may offer advantages commensurate with those found for dish systems.

7.3.2 A New Hybrid Secondary Concentrator

The vector-flux formalism led to the invention of the trumpet concentrator [3] by describing lines of energy flow, which, in turn, defined the location of reflector surfaces corresponding to an ideal concentrator. We have recently noted that when the same formalism is used to examine the properties of a CPC, there are families of flow lines that suggest a new kind of ideal concentrator that is a hybrid between a CPC and a trumpet having some of the geometrical features of each. We do not understand the optical properties of these devices except that they will be ideal in two dimensions and closely approaching ideal in three dimensions. They may combine some of the advantages of trumpets (small or negligible skew ray losses) with those of CPCs (smaller sizes and higher possible concentration ratios) and be particularly suitable for point-focus secondaries. A systematic study of the optical properties and truncation behavior of these new devices using ray-trace techniques could identify significant advantages with respect to existing secondary designs.

The broad analysis presented in the preceding sections clearly supports the general conclusion that optimized two-stage concentrators generally have some performance or cost benefits relative to an optimized single-stage system; relative benefits are quite substantial in a wide variety of possible configurations. This conclusion provides the justification for pursuing the research and development directions outlined here.

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APPENDIX

Preliminary Design of Secondaries for the LaJet Innovative Concentrators

SUGGESTED SECONDARY DESIGN ALTERNATIVES FOR THE LaJET 95 AND 67 FACET INNOVATIVE CONCENTRATOR CONFIGURATIONS

Prepared by

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Abstract

We have designed two sets of secondary concentrators for both the 67 and 95 facet Innovative Concentrator configurations. The first set increases intercept with constant receiver aperture, allowing for relaxed system tolerances; the second decreases receiver aperture while maintaining constant intercept, for the purpose of improving receiver performance. Each set consists of two alternative trumpet designs and a CPC. Preliminary tradeoffs among these designs are outlined.

INTRODUCTION

As is well known, a paraboloidal point focus concentrating dish of rim angle ϕ falls short of the maximum achievable geometric concentration ratio by a factor of approximately

$$\frac{C_{dish}}{C_{ideal}} = \sin^2\phi \cdot \cos^2\phi \qquad (1)$$

For example, if $\phi = 45°$, this ratio is about 1/4. A properly designed nonimaging secondary can increase the concentration ratio by a factor

$$C_2 = {}^1/\sin^2\theta \qquad (2)$$

where θ is the acceptance angle of the secondary ($\theta \geq \phi$) and thus develop a two-stage concentration considerably closer to the allowed limit. In the limit that $\theta \simeq \phi$ and ϕ small (long focal length) the two-stage concentration can come very close to the ideal. In general, the increased power of the secondary can be used either to relax the optical tolerances for a given concentration or to increase system concentration while maintaining the same tolerances.

The LaJet Innovative Concentrator consists of nearly spheroidal facets arranged to approximate a paraboloid and is being developed in two configurations, a large 95 facet design with a rim angle of 45° and a smaller 67 facet version with a rim angle of 39°.

We have proposed three secondary designs for each of four cases: A) 95 facet relaxed tolerance (95RT); B) 95 facet increased concentration (95 IC); C) 67 facet relaxed tolerance (67 RT); and D) 67 facet increased concentration (67 IC). For each of these cases, a maximally concentrating trumpet, a smaller, lower concentration trumpet, and a CPC have been designed, making a total of twelve secondary designs.

SECONDARY CONSIDERATIONS

Initially, in designing the secondaries, the main objective was to maximize the concentration ratio of the secondary. In fact, the maximum possible concentration ratio is determined by the thermodynamic limit (equation 2 above). Of course, θ must be no less than the rim angle of the primary, and must be slightly larger to accommodate extreme rays.

Another limitation upon the concentration ratio is the size of the secondary. In the limit that the asymptotic angle of a hyperboloid is equal to the rim angle of the primary, the untruncated secondary reaches to the very edge of the primary. The effect upon the untruncated height of a CPC is less drastic, but nevertheless significant. It is primarily for this reason that lower concentration trumpet designs and CPC designs have been included.

The height of an un-optimized trumpet of a given asymptotic angle is determined by the point of intersection of the hyperbolic mirror surface and the extreme ray connecting the edge of the primary with the edge of the virtual target. However, great savings in the size, cost, and shading caused by the trumpet can be achieved by truncating the reflector at the point at which the flux reflected by the primary is equal to that of the sunlight striking the back surface. This reduces the entrance aperture of the secondary, somewhat reducing its intercept factor typically by no more than 1 percent, while the reflector is reduced to approximately 1/3 of its original height.

This truncation point is determined by raytracing the system and examining the flux incident along the secondary wall. For convenience, we have traced a system with a full paraboloidal primary, whose optical tolerances are scaled to produce a focal plane distribution similar in size to that of the Innovative Concentrator designs. In fact, this is a conservative approximation because while the focal plane distribution is similar in size and shape (gaussian), it is of greater intensity than that of the Innovative Concentrator, resulting in a slightly larger secondary than would otherwise be produced -- while at the same time there is no corresponding shading of central mirror surface.

The primary criteria for truncating the CPC are size and concentration ratio, for unlike the trumpet, concentration is directly affected by truncation. However, removing the upper portion of the reflector decreases concentration only slightly. For example, removing the upper 50 percent of the secondary CPC typically decreases concentration by only about 10 percent.

It is important to note that the CPC has a higher average number of reflections and thus greater reflection losses and heat loading than does a trumpet in an otherwise similar geometry. Cooling the secondary may be a proportionately greater problem, particularly when the significantly smaller surface area of the CPC is considered.

The optical tolerances of the system for which these secondaries are designed can be characterized by the standard deviation of the angular distribution of sunlight leaving the surface of the primary, which is, to a good approximation, a gaussian distribution. The center of this distribution at any given point is a ray reflected by a perfect surface from a point source on the optical axis of the primary at infinity. This distribution results from the size of the source (sun), slope errors (deviations from a perfect paraboloidal reflecting surface due to both the shape and alignment of the facets and imperfections in the mirror surfaces), specularity spread, and pointing errors. For each of the concentrator configurations discussed below, a corresponding total angular error tolerance, σ_{tot}, has been estimated. This quantity is the maximum total spread which will produce a focal plane distribution with an intercept near unity (0.98) for the appropriate corresponding target (receiver aperture, trumpet, virtual target or CPC entrance), and represents the total optical tolerance budget of the primary.

RECOMMENDED SECONDARY PROFILES

We have developed designs for practical nonimaging secondaries for each of the four cases outlined above (95 RT and IC and 67 RT and IC) and the resulting profiles are shown in Figures 1-4. The detailed geometrical parameters for each subcase and for the reference (no secondary) designs are listed in Table 1. For each case trumpets with acceptance angles (asymptote angles) equal to $\theta = \phi + 1°$ and $\theta = \phi + 4°$ and a CPC with $\theta = \phi + 1°$ have been selected. In the case of the CPC this is sufficient to accommodate the extreme ray from one edge of the primary to an opposite edge of the CPC extreme aperture within the acceptance. This condition is satisfied for both trumpets as well and, in addition, results in reasonably sized secondaries when the truncation procedure, based on the ray traced flux distribution on the secondary, is applied as outlined above. Note the trade-off between material requirements and concentration associated with an increase in acceptance angle of 3° between the two trumpets.

The CPCs shown are all untruncated and in practice would be shorter in height by 30 to 50%, with a small loss in concentration. In particular note that the truncated height corresponding to the same concentration as the lower concentration trumpet is indicated in all figures. In all cases the truncated CPC is considerably smaller and more manageable than the corresponding trumpet. This is offset by slightly higher optical losses (reflection and skew ray) and cooling requirements for the CPC. Also note that both trumpets and CPCs are shown relative to a fixed receiver with their exit apertures coincident. In the frame of the primary, the CPC (and receiver) would be displaced relative to a trumpet because the CPC entrance aperture must be in the focal plane whereas for a trumpet both virtual source and exit aperture lie in the focal plane.

At the present time emphasis is on the use of secondaries to relax tolerances (Figures 1 and 3). The final design recommendation should be based on further optical ray trace analysis at Chicago after a preliminary ranking by LaJet of the three suggested alternatives based on hardware, mounting, material, structural, and aesthetic considerations.

Nomenclature:

C_2 = geometric concentration of secondary equal to $(^{d_v}/_{d_r})^2$

d_r = maximum diameter of focal spot: equivalent to diameter of virtual target (trumpet) or CPC entrance aperture when secondary used, otherwise equal to receiver aperture

σ_{tot} = maximum allowed root mean squared angular spreading of a point source associated with <u>all</u> broadening effects (sun size, slope, alignment, specularity, and pointing errors) for corresponding focal spots of given size.

ϕ = rim angle of primary

θ = design acceptance angle of secondary concentrator

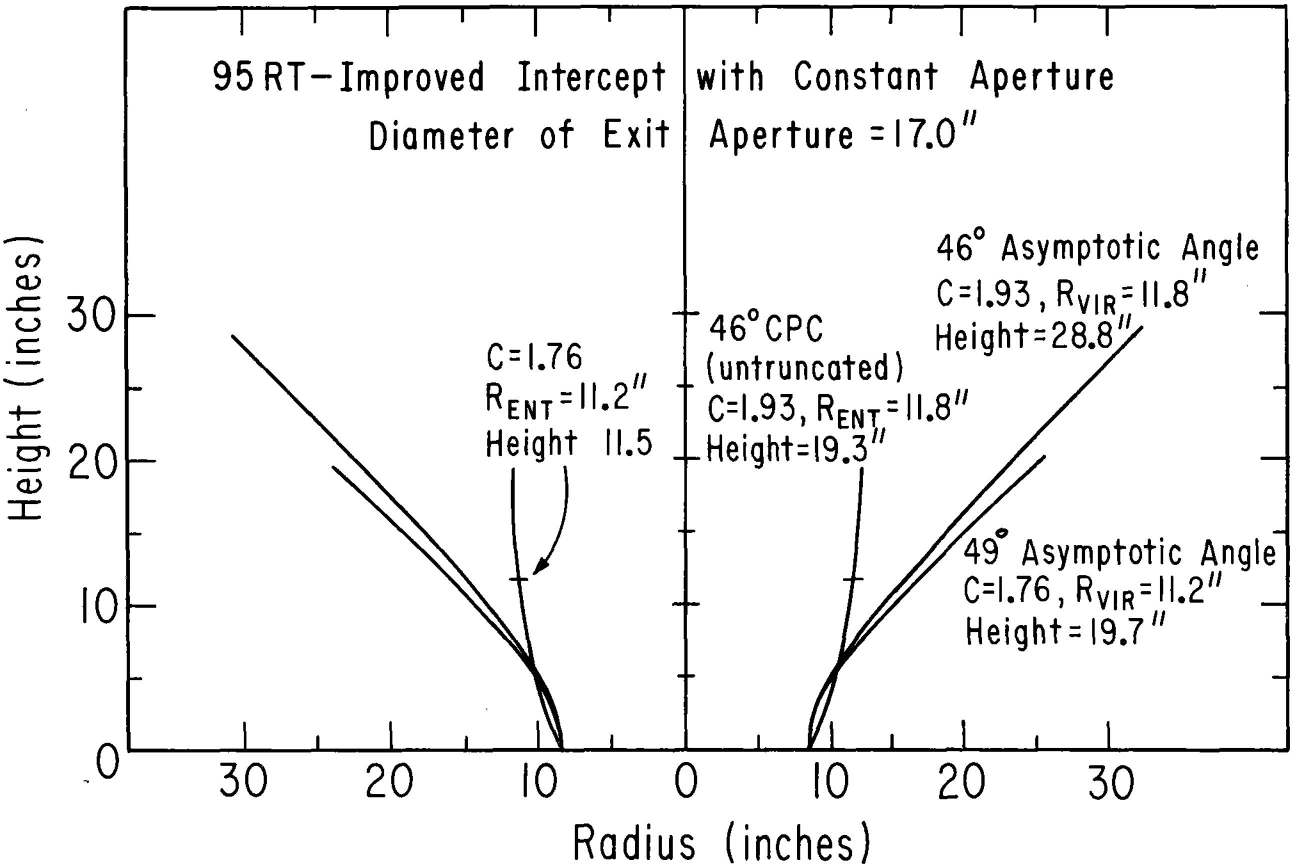
TABLE I

LAJET INNOVATIVE CONCENTRATOR

SYSTEM GEOMETRICAL PARAMETERS FOR VARIOUS SECONDARY ALTERNATIVES

DESIGN	SECONDARY	C_2	d_r	d_v	σ_{tot} (mr)
Present 95 facet (ϕ = 45°)	none	-	17.0"	17.0"	5.5
95 RT	Trumpet (46°)	1.93	17.0	23.6	7.8
	Trumpet (49°)	1.76	17.0	22.4	7.1
	CPC* (46°)	1.93	17.0	23.6	7.8
95 IC	Trumpet (46°)	1.93	12.2	17.0	5.5
	Trumpet (49°)	1.76	12.8	17.0	5.5
	CPC* (46°)	1.93	12.2	17.0	5.5
Present 67 facet (ϕ = 39°)	none	-	11.0	11.0	4.2
67 RT	Trumpet (40°)	2.42	11.0	17.1	7.1
	Trumpet (43°)	2.15	11.0	16.1	6.9
	CPC* (40°)	2.42	11.0	17.1	7.1
67 IC	Trumpet (40°)	2.42	7.0	11.0	4.2
	Trumpet (43°)	2.15	7.6	11.0	4.2
	CPC* (40°)	2.42	7.0	11.0	4.2

*untruncated


95RT—Improved Intercept with Constant Aperture
Diameter of Exit Aperture = 17.0"
46° Asymptotic Angle
C=1.93, RVIR=11.8"
Height=28.8"
46° CPC
(untruncated)
C=1.93, RENT=11.8"
Height=19.3"
C=1.76
RENT=11.2"
Height 11.5
49° Asymptotic Angle
C=1.76, RVIR=11.2"
Height=19.7"
Height (inches)
Radius (inches)
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10
20
30
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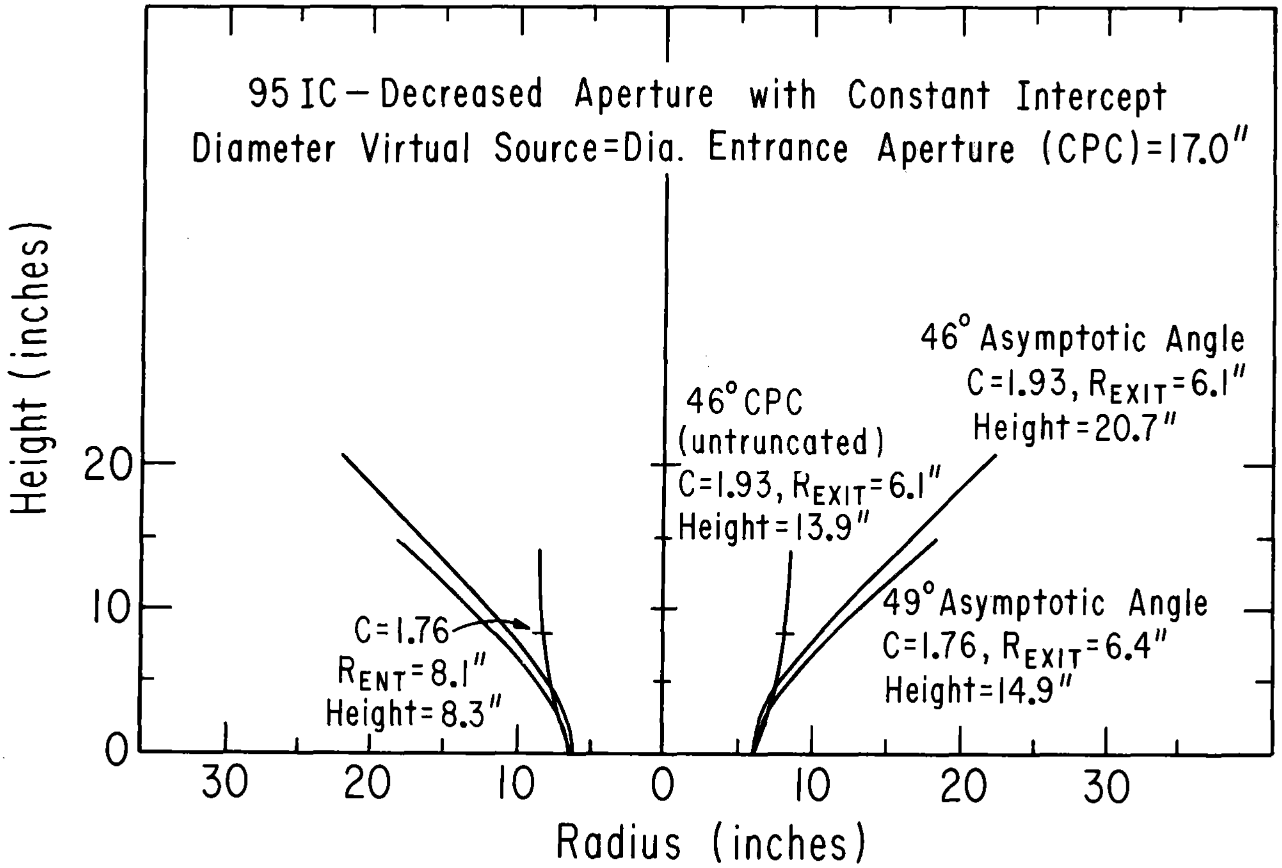
95IC—Decreased Aperture with Constant Intercept
Diameter Virtual Source=Dia. Entrance Aperture (CPC)=17.0"
46° Asymptotic Angle
C=1.93, REXIT=6.1"
Height=20.7"
46° CPC
(untruncated)
C=1.93, REXIT=6.1"
Height=13.9"
49° Asymptotic Angle
C=1.76, REXIT=6.4"
Height=14.9"
C=1.76
RENT=8.1"
Height=8.3"
Height (inches)
Radius (inches)
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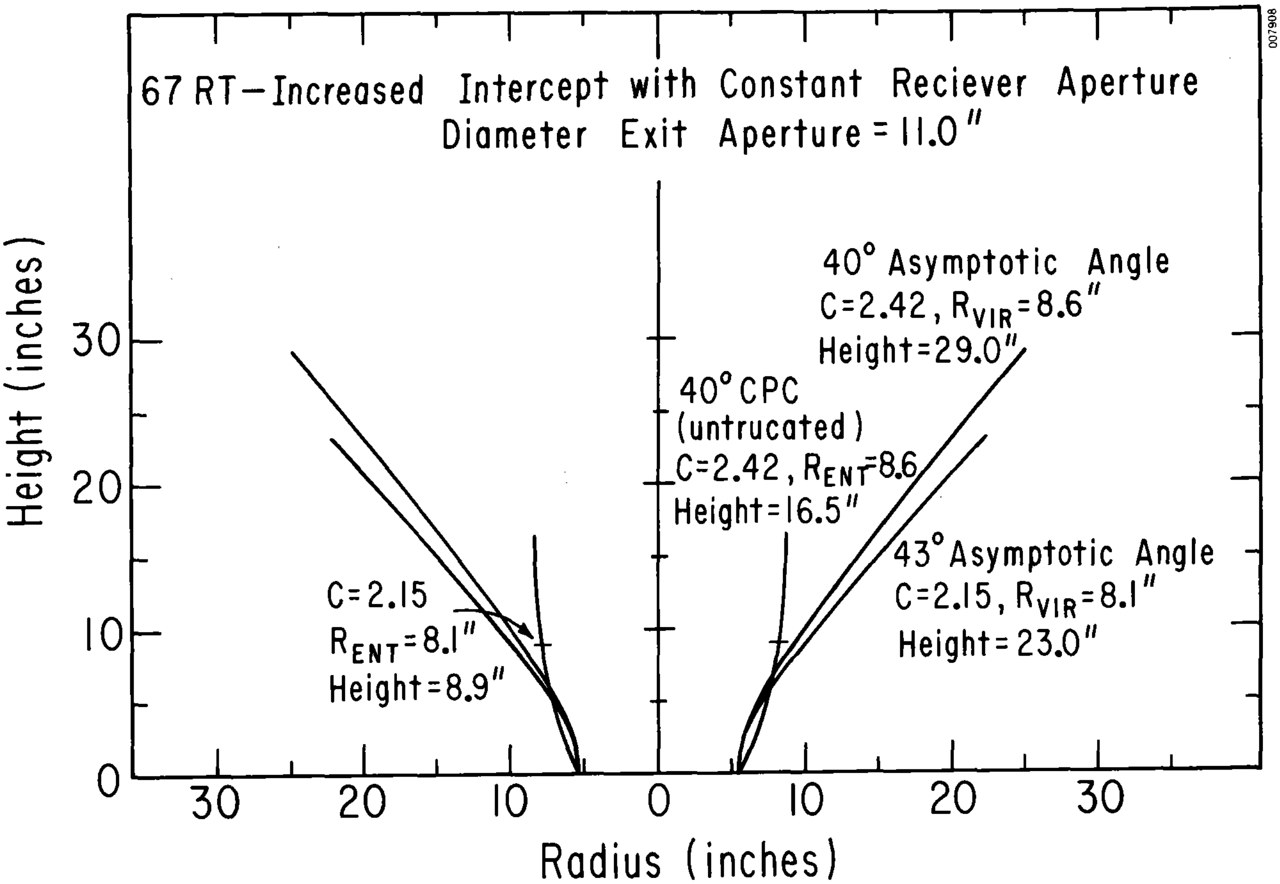
10
20
30
007907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67 RT—Increased Intercept with Constant Reciever Aperture
Diameter Exit Aperture = 11.0"
40° Asymptotic Angle
C=2.42, R_{VIR}=8.6"
Height=29.0"
40° CPC
(untrucated)
C=2.42, R_{ENT}=8.6
Height=16.5"
43° Asymptotic Angle
C=2.15, R_{VIR}=8.1"
Height=23.0"
C=2.15
R_{ENT}=8.1"
Height=8.9"
Height (inches)
Radius (inches)
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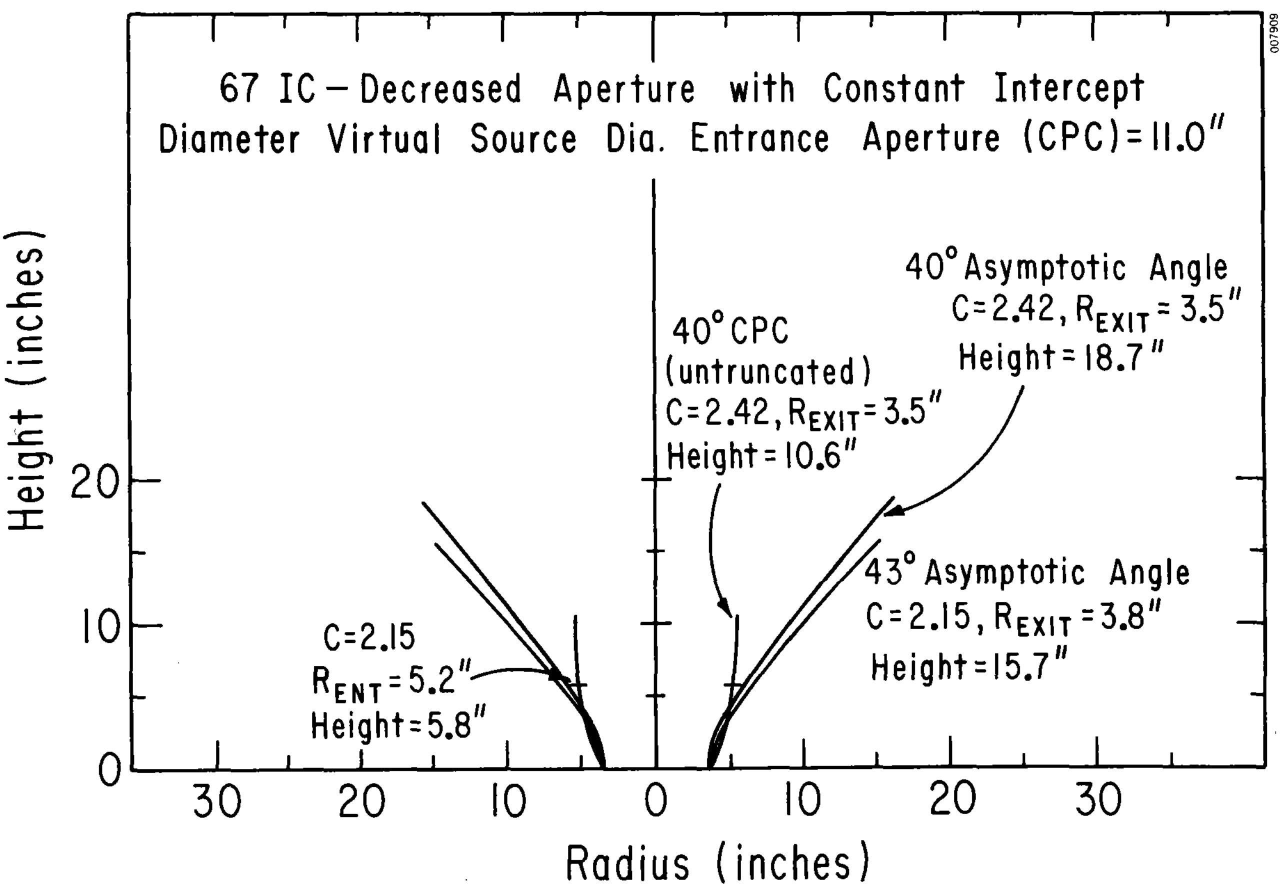
10
20
30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67 IC—Decreased Aperture with Constant Intercept
Diameter Virtual Source Dia. Entrance Aperture (CPC)=11.0"
40° Asymptotic Angle
C=2.42, R_{EXIT}=3.5"
Height=18.7"
40° CPC
(untruncated)
C=2.42, R_{EXIT}=3.5"
Height=10.6"
43° Asymptotic Angle
C=2.15, R_{EXIT}=3.8"
Height=15.7"
C=2.15
R_{ENT}=5.2"
Height=5.8"
Height (inches)
Radius (inches)
0
10
20
30

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15. Supplementary Notes

Technical Monitor: Allan Lewandowski

16. Abstract (Limit: 200 words)

Using nonimaging secondary concentrators in point-focus applications may permit the development of more cost-effective concentrator systems by either improving performance or reducing costs. Secondaries may also increase design flexibility. The major objective of this study was to develop as complete an understanding as possible of the quantitative performance and cost effects associated with deploying nonimaging secondary concentrators at the focal zone of point-focus solar thermal concentrators. A performance model was developed that uses a Monte Carlo ray-trace procedure to determine the focal plane distribution of a paraboloidal primary as a function of optical parameters. It then calculates the corresponding optimized concentration and thermal efficiency as a function of temperature with and without the secondary. To examine the potential cost benefits associated with secondaries, a preliminary model for the rational optimization of performance versus cost trade-offs was developed. This model suggests a possible 10%-20% reduction in the cost of delivered energy when secondaries are used. This is a lower limit, and the benefits may even be greater if using a secondary permits the development of inexpensive primary technologies for which the performance would not otherwise be viable.

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