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NEAR-TERM IMPROVEMENTS IN PARABOLIC TROUGHS: AN ECONOMIC AND PERFORMANCE ASSESSMENT

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PREFACE

This work was initiated under Task 3471.20 in FY 1980 and completed under Task 1006.00 in FY 1981 and was supported by Jim Rannels, Chief, Research and Technology Branch, Solar Thermal Technology Division, U.S. DOE, as part of the overall technology development effort under the Solar Thermal Program.

This effort represents an extension of previous work by both Sandia National Laboratories and the Solar Energy Research Institute in three areas. First, system benefits corresponding to selected component improvements are quantified for a realistic range of operating conditions over annual operating cycles. Second, an upper-bound allowable cost for each selected improvement is given. Last, an analysis of how much these components can increase the system's economic rate of return is made. This work does not focus on the details of component development nor on the best method of achieving component improvement, but rather provides and applies a framework to assess the resulting system annual benefits for one or a combination of component improvements from several perspectives. The individual improvements investigated in this study have been proposed and have been under development by others, principally Sandia Labs, for some time.

The authors would like to express their appreciation to those individuals at Sandia National Laboratories (primarily, Jim Banas) and to Bob Copeland and Chuck Kutscher of SERI, who reviewed previous drafts and provided valuable comments on this work.

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SUMMARY

Improved parabolic trough concentrating collectors will result from better design, improved fabrication techniques, and the development and utilization of improved materials. This analysis quantifies the performance potential of various parabolic trough component improvements from a systems viewpoint and uses this performance data to determine the worth of each improvement on an economic basis. The improvements considered are evacuated receivers, silvered-glass reflectors, improved receiver selective coatings, higher optical accuracy concentrators, and higher transmittance receiver glazings. Upper-bound costs for each improvement are provided as well as estimates of the increased solar-system rates of return that are made possible by these improvements.

Evacuated receivers and silvered-glass reflectors are shown to have the greatest potential for improving system performance. At an operating temperature of about 150°C, either improvement can increase system performance by about 20%. At higher operating temperatures, the performance potential of these improvements is even greater. Also, of all the improvements considered in this report, the evacuated receiver is shown to have the most cost leverage, because of both its potential for improved performance and because line-focus receiver costs are small relative to total system costs.

All the component improvements considered in this report have been evaluated in terms of average annual energy delivery enhancement. This approach reveals that the potential for near-term parabolic trough performance enhancement is quite high; in fact, significantly higher than previously thought possible because most prior analysis has been performed in terms of instantaneous performance or clear-day performance enhancement.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (concluded)

LIST OF TABLES

NOMENCLATURE

C	geometric concentration ratio
E	annual energy delivered by solar system per unit collector area
E_{coll}	annual energy collected by a single unshaded collector per unit collector area
E_{field}	annual energy thermal loss of solar system piping (both overnight and steady-state) per unit collector area
F_{shad}	shading factor to account for reduction in energy collection due to row-to-row shading in the collector field
I	total turn-key capital cost of the solar system per unit collector area
I_a	beam irradiance of sun upon aperture plane of collector
I_c	assembled (but not installed) collector cost per unit collector area
LF	levelizing factor for energy costs
M	levelized required revenue per total investment dollar
P_{f0}	price of energy in year zero
T_{abs}	absorber tube surface temperature
T_{amb}	ambient temperature
U_L	heat loss coefficient based on absorber tube surface area
W	annual system energy delivery per dollar of system capital cost
ε	solar effectiveness factor
η	instantaneous collector efficiency
η_o	collector optical efficiency
$\sigma_{con_\perp}$	rms angular deviation of concentrator from perfect parabola in transverse direction (transverse slope error)
$\sigma_{con_\parallel}$	rms angular deviation of concentrator from perfect parabola in longitudinal direction (longitudinal slope error)
σ_{disp}	equivalent rms angular spread, which accounts for imperfect placement of receiver

$\sigma_{spec_{\perp}}$	rms angular spread of reflected beam due to imperfect specularity of reflector material in transverse direction
$\sigma_{spec_{\parallel}}$	rms angular spread of reflected beam due to imperfect specularity of reflector material in longitudinal direction
σ_{track}	rms angular spread due to tracking error

SECTION 1.0

INTRODUCTION

There are basically three ways to enhance the cost effectiveness of parabolic-trough collectors: reducing their initial cost, increasing durability and reliability, and improving performance. Cost reductions will be possible as more efficient manufacturing techniques are implemented and as less expensive collector materials and simpler designs are developed. Through continued engineering development combined with field experience, increased collector system durability and reliability will also improve life-cycle economics. More durable reflectors, concentrator substrates, and selective absorber coatings are all being pursued for line-focus technologies. There has also been a significant effort to improve the performance of parabolic-trough collectors. Several studies [1-3] have documented these efforts and have predicted instantaneous efficiency or clear-day performance for individual parabolic trough component improvements. However, those reports* do not predict the expected annual energy benefit on a systems level and, therefore, do not take into account such effects as variable insolation levels, off-peak weather conditions, and increased system operating time resulting from component improvements. Increased operating time can result because the critical radiation intensity can be reduced, thus permitting earlier system startup and later shutdown. By considering all of these effects, a considerably higher estimate of improved performance, over that derived by considering only instantaneous efficiency, results. Hence, the attractiveness of specific component improvements can be significantly enhanced over that which has been presented in previous assessments.

This work extends the existing knowledge base regarding parabolic trough component improvements in three ways. First, the system benefits corresponding to the proposed improvements are quantified for a realistic range of operating conditions and for typical annual operating cycles. Second, an upperbound cost increase for each improvement is given. Third, an analysis of how much these improvements can increase a parabolic-trough system's rate of return is made. Thus, this work does not focus on the details of component development nor on the best methods of achieving those improvements, but rather provides insight into the system and annual operating benefits of specific, previously defined, promising component improvements. The development of specific component improvements considered here has been addressed by other researchers. The framework developed to address the questions on system annual benefits is, in itself, one of the major contributions of this work.

Improvements are explored in terms of increased performance and initial cost relative to current state-of-the-art parabolic-trough collector systems. Defining a state-of-the-art parabolic-trough system as a baseline provides for

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*A more recent report [4] considers the annual impact of concentrator optical accuracy for several geographical locations and concentrator reflectance for one location. However, the analysis was based on only one operating temperature.

easy comparison of next-generation performance improvements against current trough technology In this approach, many uncertainties--like those associated with discount, insurance, inflation, and fuel escalation rates, as well as lifetime taxes, subsidies, and O&M costs--are avoided. This simple procedure indicates the relative desirability of various improvements and can be used to recommend and support development of the most effective improvements, but it is not intended to be an exhaustive economic assessment. Further, if the reliability and lifetime of the systems with the various improvements can be made nearly comparable over the long term, the procedure provides a good estimate of the relative economic benefits of the various improvements. Also, this approach can yield results largely independent of climate and, therefore, it provides a general measure of an improvement's worth.

The system improvements considered in this report correspond to the most promising component improvements that were analyzed in a previous study [5]. However, no information was given concerning the relative cost effectiveness of these improvements. This report extends earlier work by comparing various performance improvements on a cost/performance basis. This report also considers improvements as they affect the performance of a parabolic-trough system rather than an individual trough module. The impact of trough end losses, row-to-row shading, and piping thermal losses (steady state and overnight) are included in this report.

SECTION 2.0

ANALYSIS

The basic analytical approach used in this paper is to relate various collector improvements to changes in both economic and performance measures of the entire solar energy system. First, improvements are evaluated according to their impact on overall system performance. Information is then derived on cost impacts and on the sensitivity of the system's rate of return to various trough improvements.

2.1 METHODOLOGY

The first performance/cost measure to be considered is the performance/cost ratio (W), defined as

$$W = \frac{E_s}{I} \ , \tag{1}$$

where E_s is the annual solar energy delivered by the system per unit area at the point of use, and I is the capital cost of the system per unit area. Increments in W, E_s, and I are related by using Eq. 1 to yield

$$\frac{\Delta W}{W} = \frac{\Delta E_s}{E_s} - \frac{\Delta I}{I} \tag{2}$$

When comparing the performance of different systems, it is convenient to define another quantity, called the normalized system performance (NSP), as

$$\text{NSP}^* = \frac{\text{Performance of Improved System}}{\text{Performance of Baseline System}} = \frac{\Delta E_s}{E_s} + 1 \tag{3}$$

It is also convenient to define similar expressions for comparing systems on the basis of their cost alone and on their performance/cost ratio. The normalized system cost is defined as:

$$\text{NSC} = \frac{\text{Cost of Improved System}}{\text{Cost of Baseline System}} = 1 + \frac{\Delta I}{I} \ . \tag{4}$$

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*This definition of NSP is analogous to the normalized performance index used in Ref. 5.

The normalized performance/cost ratio is defined as:

$$\mathrm{NPCR} = \frac{\text{Performance per Unit Cost of Improved System}}{\text{Performance per Unit Cost of Baseline System}} = 1 + \frac{\Delta W}{W} \quad . \tag{5}$$

The larger the performance impact of a component improvement, the larger will be its NSP value. The NSC value associated with the improvements indicates the system cost increase that resulted from the component improvement. Obviously, the smaller its value, the better. The NPCR value associated with each improvement accounts for both cost and performance. If an increase in system performance outweighs an increase in system cost, the component improvement's NPCR exceeds one. While the NPCR value carries the most significance in evaluating the merit of a particular improvement, it does require a knowledge of the improved component's cost. Because the components considered in this report are in various stages of development, current costs are not available. Instead, the merits of each improvement are explored for two special cases:

<u>Case 1</u>: A component improvement is made, but no increased cost is experienced. For this particular case, $\Delta I = 0$, and

$$\frac{\Delta W}{W} = \frac{\Delta E_s}{E_s} \tag{6}$$

or

$$\mathrm{NPCR} = \mathrm{NSP} \tag{7}$$

Thus, for this case the normalized performance/cost ratio equals the normalized system performance. This can be interpreted as providing an upperbound estimate for the NPCR--unless, of course, a performance improvement is obtained with a reduction in cost.

<u>Case 2</u>: The normalized performance/cost ratio remains constant (i.e., $\Delta W = 0$). For this situation

$$0 = \frac{\Delta E_s}{E_s} - \frac{\Delta I}{I} \tag{8}$$

or

$$\mathrm{NSP} = \mathrm{NSC} \tag{9}$$

Hence, for this case the normalized system performance is just the normalized system cost; that is, the increase in system cost exactly offsets the increase in system performance. This enables the user to determine how much a given improvement would cost while not having a negative impact on overall system cost effectiveness. This value, then, is an upperbound on the increased cost for an improvement.

We assume that the cost increments associated with particular improvements are independent. Then, the component cost data are utilized in the following way. Let the total increment in cost ΔI be allocated to that one component for which an improvement is proposed (i.e., the κ_{th} component). Also let

$$I = \sum I_j = I\left(\sum \lambda_j\right), \quad (j = 1, \ldots. n = \text{number of components}) \tag{10}$$

$$= \text{total installed system capital costs,}$$

where I_j is the cost of the jth component and where

$$\lambda_j = \frac{I_j}{I} \; (j = 1, \ldots.. n = \text{number of components}) \quad . \tag{11}$$

But, by definition,

$$\Delta I = \Delta I_\kappa \tag{12}$$

where κ corresponds to the component to be improved.

Hence

$$\frac{\Delta I_\kappa}{I_\kappa} = \frac{\Delta I}{\lambda_\kappa I} = \frac{NSC - 1}{\lambda_\kappa} = \left.\frac{NSP - 1}{\lambda_\kappa}\right|_{\Delta W = 0} \quad . \tag{13}$$

Thus, as Eq. 13 shows, if the normalized system performance is known, the upper limit cost increment that keeps the performance/cost ratio constant can be easily determined.

Another useful financial measure is the sensitivity of the internal rate of return to changes in performance and cost. Such a measure can be derived from the equation for rate of return (internal and after tax) given in Dickinson and Brown [6]. The equation can be written as

$$\frac{M(R)I}{\varepsilon E_s} - P_{f0} \cdot LF(R) = 0 \quad , \tag{14}$$

where $M(R)$, ε, P_{f0}, and $LF(R)$ are the levelized revenue per total investment dollar, the solar effectiveness factor, the price of fuel in year zero, and the levelizing factor for fuel, respectively. It is noted that both M and LF are functions of the internal rate of return R. Hence, an arbitrary variation in M and LF may be expressed as

$$\Delta M = \frac{\partial M}{\partial R} \Delta R \tag{15a}$$

and

$$\Delta LF = \frac{\partial LF}{\partial R} \Delta R \quad . \tag{15b}$$

Using Eqs. 14, 15a, 15b, and an arbitrary variation of ΔR in Eq. 14, the following expression may be derived:

$$\left(\frac{1}{M}\frac{\partial M}{\partial R} - \frac{1}{LF}\frac{\partial LF}{\partial R}\right)\Delta R - \left(\frac{\Delta E_s}{E_s} - \frac{\Delta I}{I}\right) = 0 \quad , \tag{16}$$

which can be rewritten as

$$\frac{\Delta R}{\frac{\Delta E_s}{E_s} - \frac{\Delta I}{I}} = \frac{\Delta R}{\left(\frac{\Delta W}{W}\right)} = \frac{1}{\frac{1}{M}\left(\frac{\partial M}{\partial R}\right) - \frac{1}{LF}\left(\frac{\partial LF}{\partial R}\right)} \quad . \tag{17}$$

The significance of this form is that the right-hand side is a function of financial parameters only (no cost data are needed) and is easily evaluated as a function of R with the definitions in Ref. 6. Thus, for any given R and an assumed set of financial parameters, the left-hand side of Eq. 17 is easily evaluated. Hence, the sensitivity of R to a change in performance/cost is easily determined. Equation 17 will be used in Sec. 3.3 to generate a family of parametric curves corresponding to commonly used financial parameters for IPH studies. The left-hand member of Eq. 17 can be read directly from these graphs for any assumed baseline value of R.

2.2 COST DATA BASE

Ideally, an accurate and detailed cost data base is required to investigate the performance/cost sensitivity of parabolic troughs to improvements. Unfortunately, there is no extensive, reliable data base from which costs can be obtained. Most of the cost studies performed to date give fairly accurate overall costs for demonstration projects, but the detail required at the component and subcomponent levels is missing. Costs have also changed as the designs have evolved; investments in demonstration projects very often do not reflect real costs that will be experienced in the future or even current replacement costs. Finally, the relative distribution of component costs within the system has been shown to vary considerably (and can be expected to continue to vary) for different configurations and applications.

Because of these complications, there are no perfect solutions to problems in making cost projections. However, enough data are available to provide a starting point from which parametric variations in performance/cost investigations can be studied. Clearly, as more definitive information becomes available, it should be utilized; the framework of this method makes incorporating new data easier.

Data from two sources provide the initial rough cost estimates used in this report. First, current and future estimates for the ratio of collector subsystem to total system costs were taken from Brown [7]. Current estimates were made from the only system-level data currently available. The future distribution was derived by Brown using learning-curve extrapolation approaches. Brown's estimates for the ratio of collector costs (I_c) to total system costs (I)* are:

$$\frac{I_c}{I} \simeq \begin{cases} 1/6 \text{ present} \\ 1/3 \text{ in } 1990 \end{cases}$$

Since this report deals with improvements for future implementation, the 1990 estimate for the I_c/I ratio will be used. However, results corresponding to present (or any other) I_c/I ratio can be extrapolated easily from results particular to the assumed condition. The 1990 estimate allows for significant cuts in both field-installation and indirect costs which are expected to occur as the solar industry matures.

A second set of data relates the relative costs of parabolic-trough components. The percentages of total uninstalled parabolic-trough cost allocated to the concentrator, receiver, drive, structure, and controls is given in Table 2-1. Both current and projected cost fractions are given. The current cost distribution was obtained from a survey of six major parabolic-trough collector manufacturers. Only the average cost fraction of each component is presented, because the individual data packages were considered proprietary by manufacturers. The projected cost distribution is based on 1985 component cost goals for mass-producible line-focus concentrating collectors [8]. Because the two cost distributions are so close, only the current cost distribution was used.

We must emphasize that this component-cost distribution is based on current collector designs. Should design changes occur that result in significant changes in the distribution of component costs, the component cost results in Sec. 3.2 will need to be adjusted accordingly.

2.3 TROUGH ANNUAL ENERGY PERFORMANCE

The performance measure used to compare each improved trough with the baseline trough is a long-term average of the system's annual energy delivery. Considering integrated system effects is important because a single component

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*I includes materials, labor, and indirect costs for the total turn-key system, while I_c includes the assembled (but not installed) cost of collector subsystem FOB only.

cannot adequately describe the total system performance. Further, the annual energy approach using actual averaged weather data with associated seasonal variations provides a more realistic basis for system comparison than instantaneous efficiency, clear-day performance, or an average over a short period of time.

Table 2-1. Parabolic Trough Component Cost Breakdown[a]

Component	Current Cost (% of Total)	Projected Cost (% of Total)
Concentrator	47	50
Receiver	13	15
Drive	12	15
Structure	13	10
Controls	11	10
Miscellaneous	4	--
Total	100	100

[a] Based on total FOB collector system cost data obtained from a survey of six trough collector manufacturers.

To make the analysis easily usable by system and component designers without requiring them to plug in detailed system and component information, a compromise between a detailed system model and a single-component system idealization is needed. The compromise used in the analysis considers major and system-component performance and loss impacts but does not consider system interaction effects due to variations in use patterns, storage, or parasitics. Thus, in this analysis we assume that the system can be characterized by use of a single average temperature and that the energy can be used at the load whenever it is generated. This is a reasonable assumption for process heat applications where the load and its temperature are very often constant or at least quite regular. Under these assumptions, the most important measurements to consider are the net annual collector subsystem energy delivery and the field piping losses.

In its simplest form, the system annual performance methodology used in this analysis can be expressed in the following manner:

$$E = E_{coll} \cdot F_{shad} - E_{field} \quad . \tag{18}$$

where E is the annual energy (per unit collector area) delivered by the solar system at its point of use (as defined earlier), and E_{coll} is the annual energy (per unit collector area) delivered by a single unshaded trough collector. F_{shad} is the reduction in the energy collected due to collector system shading and E_{field} is the annual energy loss (per unit collector area) due to piping (both overnight and steady-state).

Since the only positive contribution to E comes from E_{coll}, and since this analysis focuses on improvements associated with collector subcomponents, most of the detail in the analysis will be on the annual energy delivered by the collector. System losses associated with shading and field piping have been aggregated into only two parameters for this analysis. These system losses, set at typical values (see Sec. 2.4), were used for all of the trough systems in this study--baseline systems as well as improved systems. This simplification is justified in Sec. 3.4 where the results of this study are shown to be largely insensitive to system losses.

A detailed model of parabolic trough performance permitted an accurate prediction of the E_{coll} term of Eq. 18 and, most importantly, preserved the proper performance relationship between the optical and thermal improvements that were considered. This performance model is essentially the same as in Ref. 5. Briefly, steady-state receiver thermal loss is determined with a one-dimensional thermal model for a specified average temperature. The receiver is assumed to be of typical design--a selectively coated absorber tube surrounded by a glass jacket. Next, the optical characteristics of the concentrator are used to define the optical losses of the collector. The variation of optical efficiency with incidence angle, defined by the incidence angle modifier, is included in the model. Also, trough end losses (energy that is reflected by the concentrator beyond the end of the receiver) during nonnormal incidence is included [9]. The optical analysis can be done for either a given trough concentration ratio or, more generally, for the concentration ratio that is optimal for the trough at the specific operating temperature [10]. With both the optical losses and thermal losses defined, annual energy delivery can be determined using either hour-by-hour weather tapes or a utilizability method. Both methods provide approximately the same results, as shown in Ref. 5. A utilizability method [11] is used in this report because of its reduced calculation requirements, compared with hour-by-hour simulation. Basically, the model involves computation of the energy delivery of a collector for the central day of each month of the year. The concept of utilizability is used to account for total daily heat loss and the variability of insolation.

2.4 BASELINE TROUGH SYSTEM

The parabolic trough improvements considered in this report are evaluated relative to a baseline trough system which is representative of state-of-the-art parabolic trough systems. Both the configuration and performance of the baseline system are typical of current commercially available parabolic troughs. In particular, optical and thermal losses for the baseline system are typical of good available systems utilizing second-surface aluminized-film reflectors, with rim angles at or near 90°, and with a cylindrical glass tube surrounding an absorber tube with a black-chrome selective coating. The field losses assumed are consistent with the losses from installations of 5000 m^2 (53,800 ft^2) to 10,000 m^2 (107,600 ft^2) in aperture area. Losses and performance contributions associated with the collector (E_{coll})*, field piping

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*See Eq. 18 in Sec. 2.3.

(E_{field}), and field collector shading (F_{shad}), are discussed in more detail in the following paragraphs.

Losses associated solely with the collector and independent of collector field geometry are included in the E_{coll} term. These losses include reflectance losses of the concentrator, transmittance losses through the receiver glazing, absorptance losses from the absorber tube, and end losses. The baseline trough parameters (identical to those used in Ref. 5) that define these collector losses are listed below.

Receiver glazing transmittance (normal incidence)	0.9
Receiver glazing emittance	0.9
Receiver glazing thickness	2 mm
Black-chrome absorptance (normal incidence)	0.95
Black-chrome emittance	0.15(100°C), 0.25(300°C)*
Concentrator hemispherical reflectance	0.81
Reflector nonspecularity ($\sigma_{spec_\perp}$, $\sigma_{spec_\parallel}$)	1.6 mrad
Concentrator contour error ($\sigma_{con_\perp}$, $\sigma_{con_\parallel}$)	6.0 mrad
Tracking error (σ_{track})	2.2 mrad
Receiver/concentrator displacement error (σ_{disp})	2.0 mrad
Collector row length	24 meters
Absorber tube diameter	2.54 cm
Rim angle	90°

Field geometry losses are accounted for in the F_{shad} and E_{field} terms of Eq. 18. The row-to-row shading loss is significantly different between east-west and north-south oriented troughs. Rows of north-south oriented troughs should, in general, be spaced farther apart than east-west oriented troughs because shading losses are more severe in the north-south orientation. However, the optimum spacing is a function of many site-specific variables including land costs, latitude, operating temperature, and piping thermal losses. For the purpose of defining a baseline value of row spacing, a typical ground cover ratio** of 0.35 will be used. For this ground cover ratio at mid-latitudes the shading loss factor, F_{shad}, is equal to approximately 0.93 for north-south oriented troughs and 0.98 for east-west oriented troughs [12].

There are two kinds of collector field thermal losses that reduce the annual energy output of a trough system and that are included in this analysis (see loss term of Eq. 18). The first is the steady-state thermal loss from the field piping during normal collector operation. The second is the loss that

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*Emittance is assumed linear between these values.

**The ground cover ratio is defined as the ratio of system collector aperture areas to the system land area.

occurs during system shut-down. In this case, the field piping and heat-transfer fluid, which are at an elevated temperature, lose heat to the environment at an exponentially decaying rate. This occurs following every day of system operation. Hence, when the trough system begins operation again the following day, the collector field thermal mass must be reheated to the steady-state operating temperature. The energy required to reheat the thermal mass is equivalent to the overnight thermal loss.

Little information regarding these losses is available for operating systems. A survey of parabolic trough demonstration design reports yields predictions for steady-state thermal losses from piping that vary from less than 2% to more than 10% of the collected annual energy. Attempts to account for this spread on the basis of operating temperature and field size have been largely unsuccessful [9]. A recent study [10] of generic collector types provides very complete thermal loss data. These include detailed piping layouts, and relate the losses to operating temperature. This information has been used to define baseline annual thermal energy losses for a trough system, as shown in Table 2-2.

Table 2-2. Field Piping Heat Losses for a Parabolic Trough System

Average Temperature °C (°F)	Field Piping Losses, E_{field} ($MJ/m^2/yr$)
66 (150)	121
218 (425)	283
260 (500)	363

A linear fit of this data yields E_{field} ($MJ/m^2/yr$) = 120 + 0.65 (T_{avg} - 150), where T_{avg} is the average operating temperature of the collector (°F).

2.5 PARABOLIC TROUGH IMPROVEMENTS

Five potential component improvements for parabolic troughs have been considered in this report. Though there are many other possibilities, these five seem particularly promising. Improved troughs are defined by each of these improvements--taken one at a time. The five improvements are:

(1) Selective coating that decreases emittance to 0.05 (100°C), 0.15 (300°C)*;

(2) Back-silvered glass reflector; reflectance increased to 0.95, reflector nonspecularity decreased to 0.5 mrad;

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*Emittance is assumed to vary linearly between these values.

(3) Concentrator contour error decreased to 3 mrad;

(4) Evacuated annulus receiver; and

(5) Receiver glazing transmittance increased to 0.96.

Most of these improvements have been built and tested, but they are not fully developed nor have their system benefits been demonstrated over an extended operating period. The status of current development activity in the different improvement areas is highlighted briefly in the following paragraphs. More details on prior and current development as well as recommendations and a rationale for specific approaches can be found in the references.

2.5.1 Selective Coatings to Reduce Emittance

Several current research efforts are aimed at developing lower emittance selective coatings. Much of this development is for higher temperature applications (in excess of 300°C) [15], although their use below 300°C may prove beneficial. Several multilayer interference-type selective coatings show promise in yielding lower emittance values while maintaining a high absorptance [16]. A sputtered mixture of iron, chromium, and nickel carbides overlying copper have also yielded low-emittance coatings, although its accompanying absorptance is below 0.95 [17]. Sandia National Laboratories at Albuquerque (SNLA) is continuing work on black chrome with a study of the effects of known plating variables on the optical properties and thermal stability of the coating. While thermal stability is the chief concern, the study may identify plating variables which could yield a lower emittance black-chrome coating.

2.5.2 Back-Silvered Glass Reflectors

Back-silvered glass reflectors are undergoing rapid development. Most parabolic trough manufacturers are investigating replacement of their polished aluminum or aluminized mylar reflectors with glass ones and several companies are already offering glass reflectors as an option. Questions about durability and which type of glass reflector is the best choice have yet to be fully answered. Glass reflectors that are thermally sagged, chemically strengthened, or laminated to thin steel sheets are being investigated for use on parabolic troughs [18]. A reflectance of 0.95 may not be achievable with all types of glass reflectors but is close to their attainable upper limit. Major concerns are the failure of the mirror laminate at one of its interfaces, fracture of the glass, and corrosion.

2.5.3 Reduced Concentrator Contour Error

Reduced concentrator contour error can be attained with improved fabrication techniques and through the use of more stable concentrator substrates. Contour errors below 2.0 mrad rms have been demonstrated by SNLA on a fiberglass honeycomb panel fabricated on a precision mold. Several other concentrators under development at SNLA look quite promising in meeting a goal of having less than a 3 mrad rms contour error. For example, both stamped sheet metal and sheet molding compound (SMC) prototype concentrators have been fabricated with less than 3 mrad rms contour errors [19,20]. Whether this high optical quality can be maintained with high-volume production has yet to be demonstrated.

2.5.4 Evacuated Annulus Receivers

Evacuated annulus receivers are being investigated by Sandia National Laboratories, Albuquerque. SNLA has built two generations of prototype evacuated receivers in which the annuli between the absorber tubes and surrounding glass jackets are evacuated. The first-generation evacuated receivers suffered from several problems, including failure of the glass-to-metal seals and black-chrome outgassing. Their replacements have been installed and tested. The test data show higher heat losses than were expected [22]. The receivers are being examined to determine the cause of the thermal losses. Better coating facilities are being built at SNLA, which should provide improved process control and higher quality receiver glazings.

2.5.5 Receiver Glazing with Increased Transmittance

Some techniques that have been developed to increase glass transmittance for flat plate collectors could be adapted for cylindrical line-focus receiver glazing. Corning Glass has experimented with a gradient-index antireflection film on small samples of Code 7740 cylindrical glass. The results [23] indicate an increase in transmittance of about 6%. SNLA recently completed testing of a receiver tube assembly with an antireflective coating on the glass outer envelope. Only a 1% enhancement of peak efficiency was obtained. Both the oval shape of the glass tubes (because of processing difficulties) and the inconsistent quality of the coating have been cited as the cause of poorer than expected results [24].

SERI

SECTION 3.0

RESULTS

In general, trough component improvements can result in system performance improvements with some increase in costs. However, some component improvements may result from development and use of better materials or fabrication processes which may not involve cost increases. The results presented in this section are intended to provide insight into the cost/performance tradeoffs of component improvements and identify which improvements have the most potential.

Three types of information have been generated in this report. First, the performance benefits of individual improvements relative to state-of-the-art trough technology are shown. An index called the NSP is used for this purpose. Second, estimates of the upper-bound cost increases justified by performance improvements which just offset increased costs are shown. Third, the impact that the improvements have on a typical parabolic trough system's internal rate of return is shown. All of the results are displayed graphically so that key findings and trends are obvious and so that the user can evaluate an improvement of interest quickly. Further, all of the results are plotted as a function of average absorber-tube operating temperature. This is done so that the sigificance of operating temperature is apparent, which allows the user to evaluate improvements at temperatures specific to the application being considered.

3.1 PERFORMANCE INCREASES

As noted, the most significant measure of performance is system annual energy delivery. The increase in system annual performance that results from an improved collector component is given by a performance measure, the normalized system performance (NSP).

$$\text{NSP} = \frac{\text{Performance of Improved System}}{\text{Performance of Baseline System}} .$$

As shown in Sec. 2.1, when there is no increase in cost for an improvement, the normalized system performance/cost ratio is equivalent to the NSP. Thus, the NSP values given in this section can also be interpreted as upper-bound estimates of the amount each improvement can increase system cost effectiveness.

Figures 3-1 through 3-4 present NSP results for five improvements taken one at a time. These curves were generated for horizontal parabolic troughs--either north-south or east-west. The first three figures are for specific geometric concentration ratios of 15, 25, and 35, respectively. These figures are useful for evaluating improvements for a particular trough at its particular concentration ratio.

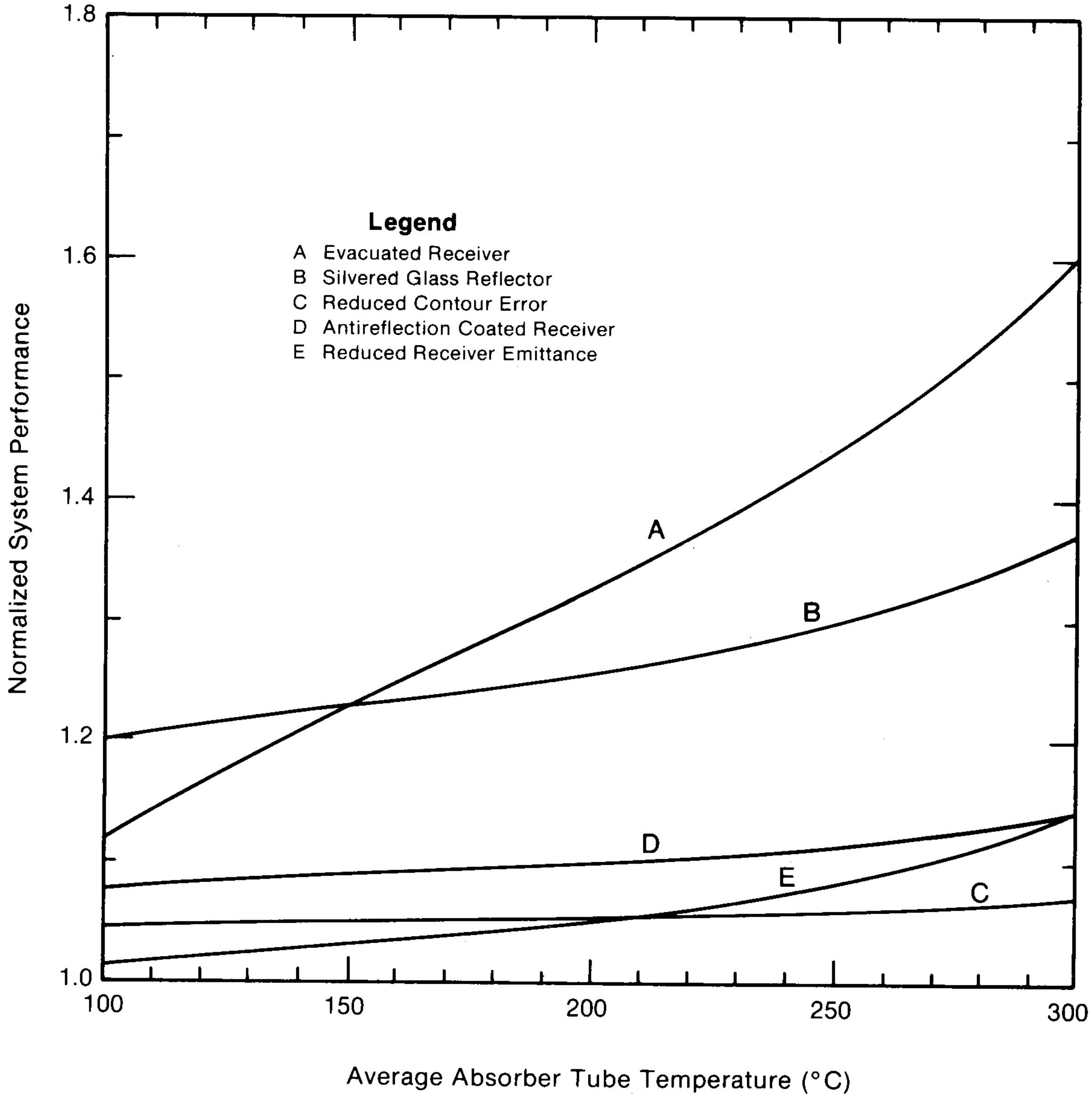

Figure 3-1. System Performance Increases vs. Absorber Temperature for Various Component Improvements of Horizontal Parabolic Troughs with Geometric Concentration Ratios of 15

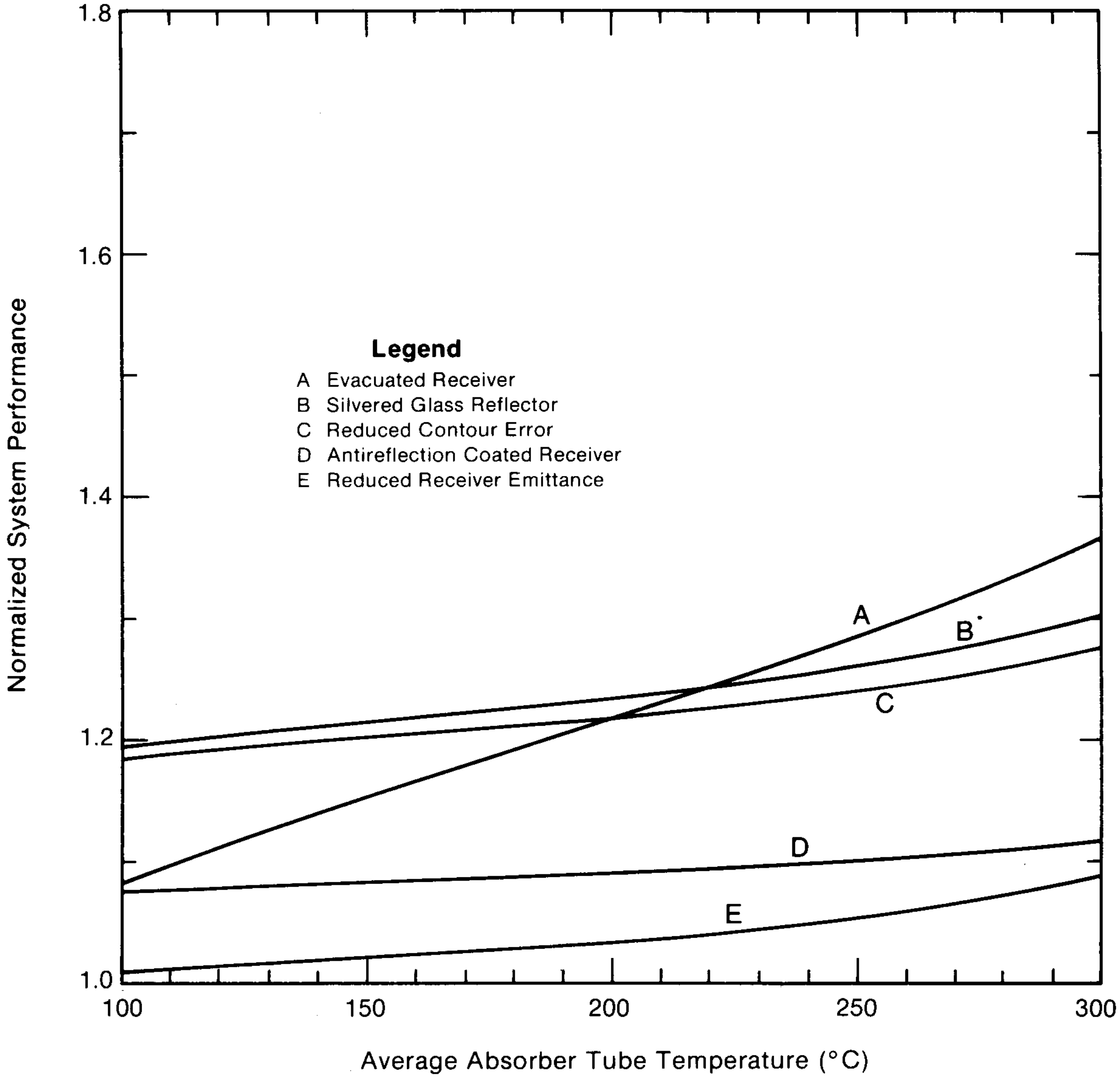

Figure 3-2. System Performance Increases vs. Absorber Temperature for Various Component Improvements of Horizontal Parabolic Troughs with Geometric Concentration Ratios of 25

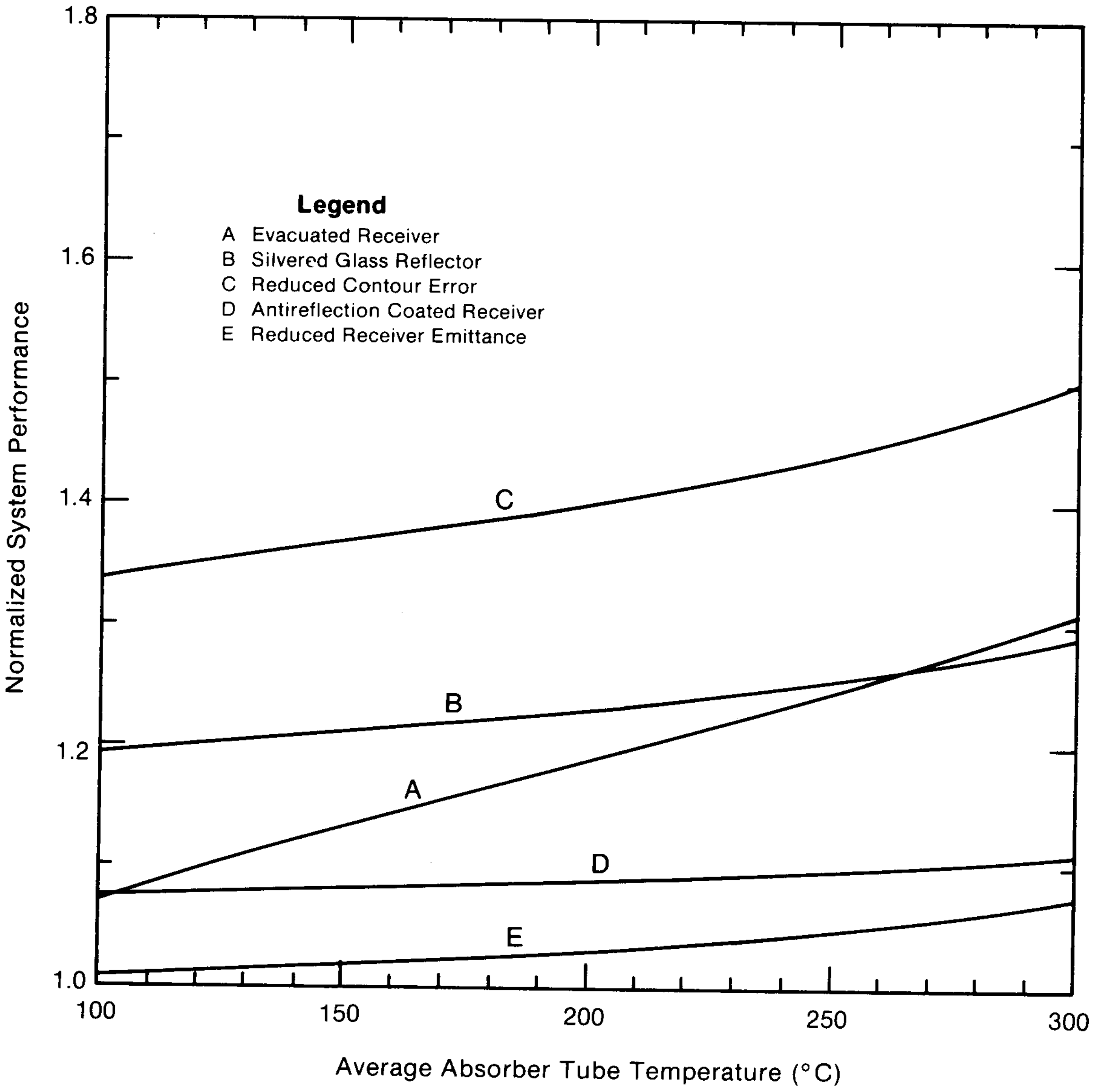

Figure 3-3. System Performance Increases vs. Absorber Temperature for Various Component Improvements of Horizontal Parabolic Troughs with Geometric Concentration Ratios of 35

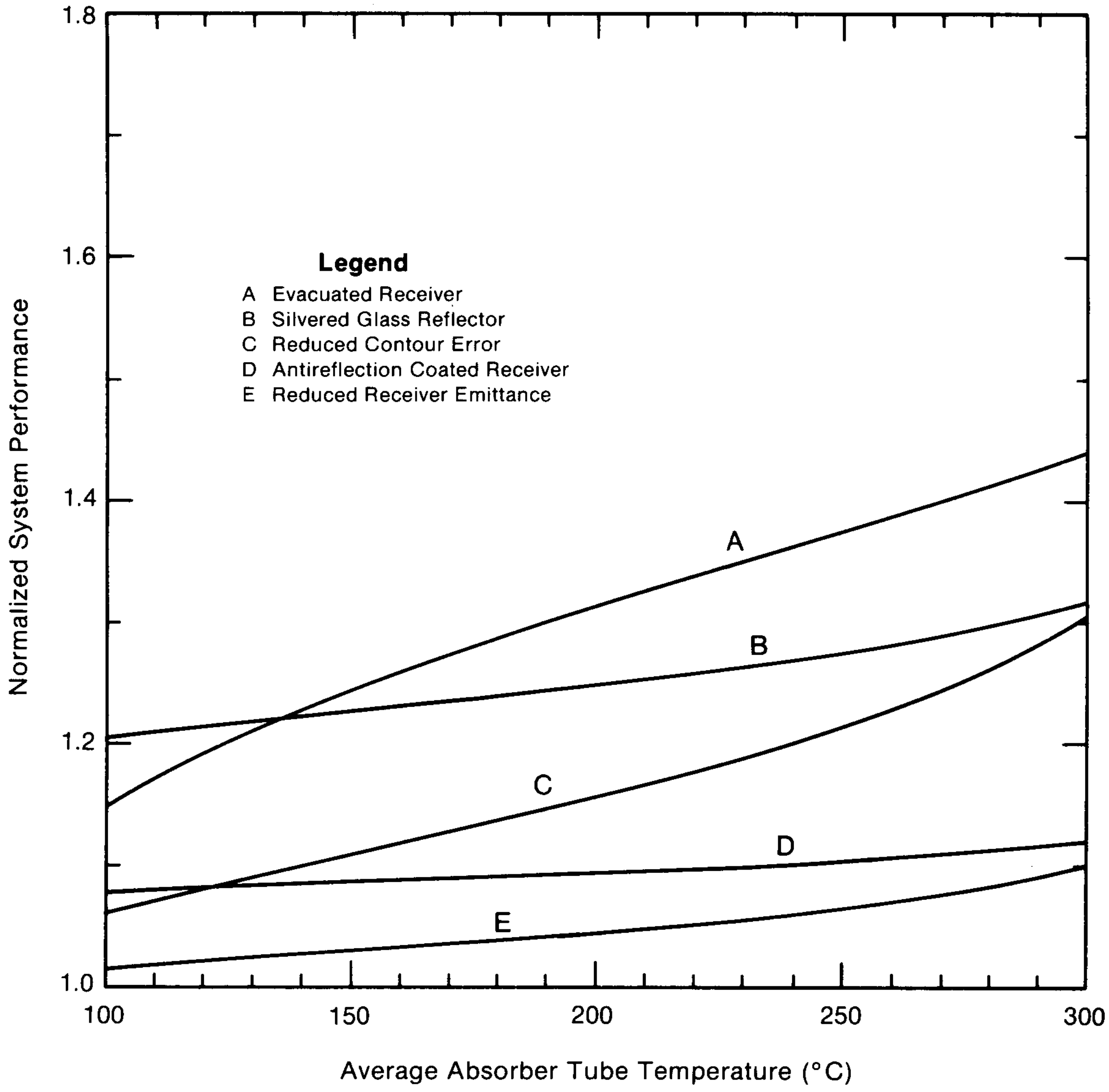

Figure 3-4. System Performance Increases vs. Absorber Temperature for Various Component Improvements of Horizontal Parabolic Troughs with Geometric Concentration Ratios Corresponding to Optimum Performance

The concentration ratio is shown to have a major impact on the magnitude of the various NSP curves. For relatively low concentration ratios, improvements that decrease receiver thermal loss are shown to be especially effective, while improvements to concentrator accuracy are shown to have little impact. However, troughs with high concentration ratios are shown to be less affected by improvements that decrease receiver thermal loss but highly sensitive to increased concentrator accuracies. The impact of optical efficiency improvements such as increased concentrator reflectance or receiver glazing transmittance are shown to be nearly independent of concentration ratio.

Figure 3-4 was not generated for a specific concentration ratio but rather for the particular concentration ratio that maximizes annual energy delivery at each temperature and for each set of trough optical and thermal characteristics. This is a somewhat more general case and allows for evaluation of improvements on an optimized trough configuration without the restriction of a fixed concentration ratio. This information should be especially valuable to manufacturers who already have troughs with a near optimal concentration ratio and who are likely to reoptimize their troughs following a major component improvement.

Several combinations of the individual improvements were also considered. Figure 3-5 was generated for improvements taken in combination with a back-silvered glass reflector. These combinations are near-term possibilities since improvements in glass reflector technology are being actively pursued. Figure 3-6 illustrates the significant jump in trough system performance that could result from other combinations of improvements.

All of the NSP curves are shown to increase with temperature. The curves associated with reduced thermal loss increase faster than those associated with increased optical efficiency. This occurs because low-temperature thermal losses are already small and further reductions are of little consequence. At higher temperatures, thermal loss increases and its reduction is of considerable consequence.

As noted earlier, if predicted performance benefits are based on an annual system perspective, as in this report, these benefits can considerably exceed those based only on clear-day instantaneous efficiency. This occurs because instantaneous efficiencies are determined when insolation levels are high and incidence angles are low. Annual performance calculations consider the effects of variable insolation levels, incidence angles, and off-peak weather conditions, as well as increased system operating time. The magnitude of this relative increase in predicted performance can be illustrated by comparing instantaneous performance and annual performance benefits for the same component improvements and baseline system. Consider an east-west trough with an operating temperature of 200°C and a concentration ratio of 15. Now, define a measure of improved instantaneous performance as the normalized instantaneous collector performance (NICP).

$$\text{NICP} = \frac{\text{Instantaneous efficiency of improved collector}}{\text{Instantaneous efficiency of baseline collector}} \quad .$$

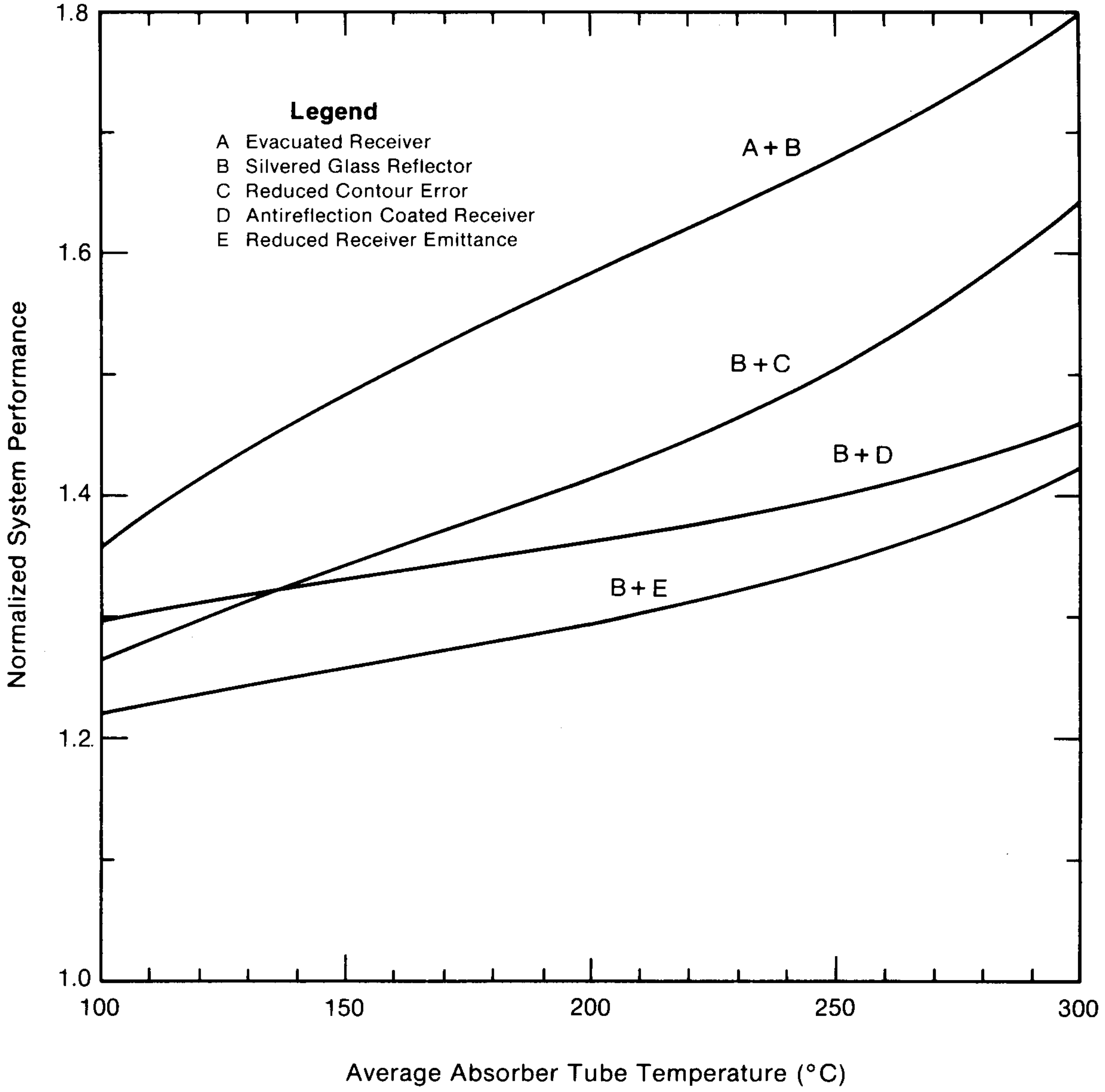

Figure 3-5. System Performance Increases vs. Absorber Temperature for Combined Component Improvements of Horizontal Parabolic Troughs with Geometric Concentration Ratios Corresponding to Optimum Performance

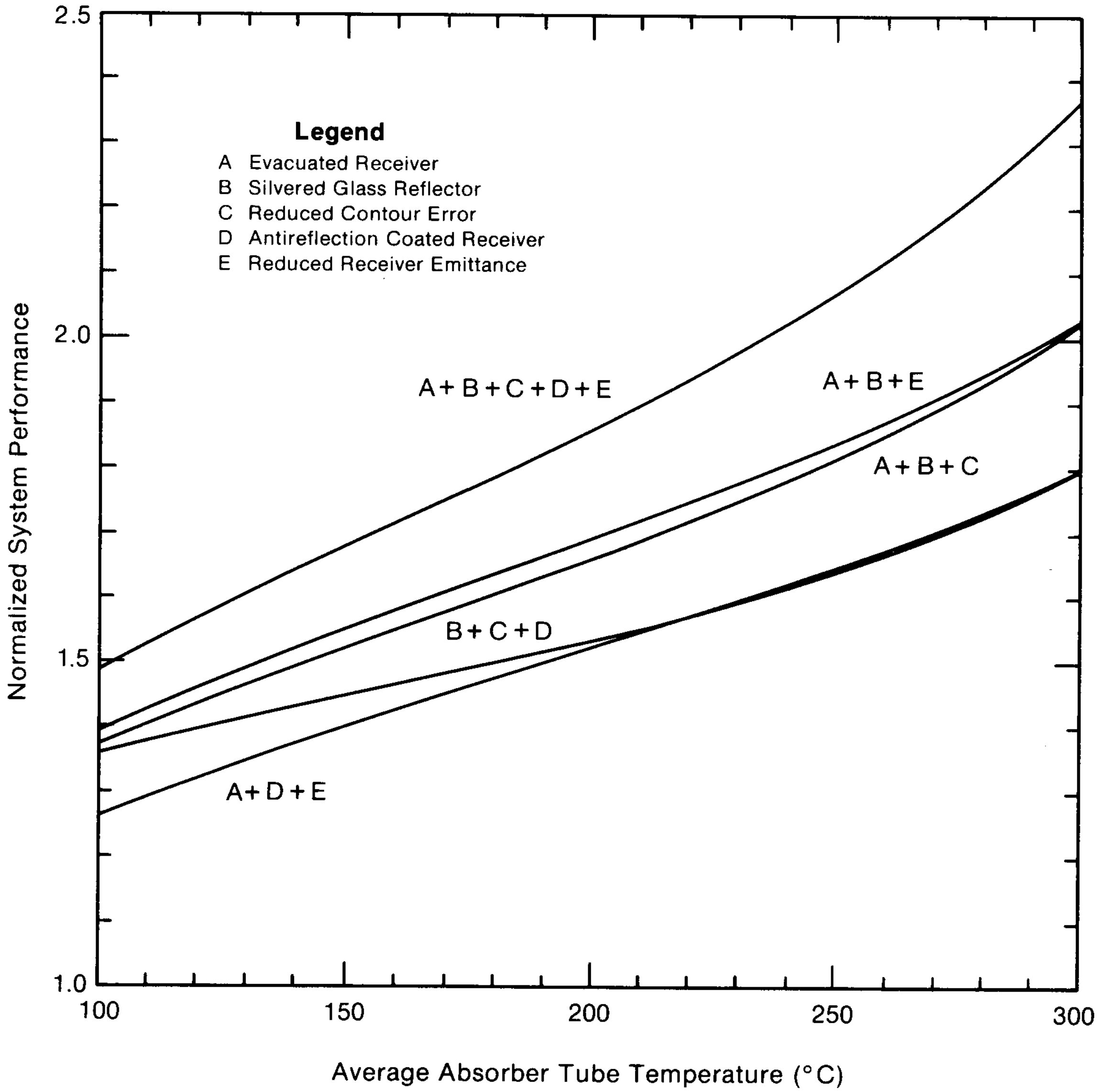

Figure 3-6. System Performance Increases vs. Absorber Temperature for Combined Component Improvements of Horizontal Parabolic Troughs with Geometric Concentration Ratios Corresponding to Optimum Performance

Assume that the normal irradiance on the collector is 100 W/m^2 for the instantaneous performance case. Then, NICP can be determined from the same collector parameters used in the annual energy analysis. The results of this analysis are summarized in Table 3-1.

Table 3-1. A Comparison of Predicted Performance Improvements Based on Instantaneous Collector Efficiency and Annual System Performance[a]

Component Improvement	NICP[b]	NSP	$\frac{NSP-1}{NCIP-1}$
Evacuated receiver	1.12	1.32	2.67
Reduced contour error	1.02	1.05	2.50
Silvered-glass reflector	1.20	1.25	1.25
AR-coated receivers	1.08	1.10	1.25
Reduced receiver emittance	1.02	1.05	2.50

[a] EW orientation:
Temperature of absorber tube = 200°C
Geometric concentration ratio = 15.
[b] Normal incident flux = 1000 W/m^2.

Comparing columns one and two in Table 3-1, we see a significant difference in the incremental performance predicted with the two approaches. The last column compares the predicted incremental performance directly. For example, for an evacuated receiver and the conditions noted, the annual energy prediction method would predict an incremental system improvement 2.67 times greater than that predicted by the instantaneous efficiency method. It is also interesting to note that, if this same comparison were made for a higher operating tube temperature, the relative difference would be even greater.

Another simple yet informative performance comparison involves the increased operating time that results from a collector improvement. Consider the performance improvement that results with an evacuated receiver over a single average day for the east-west trough operating at 200°C. The direct normal insolation profile for an average mid-April day in Denver is shown in Fig. 3-7. This insolation profile is based on long-term averages [11]. Note that the average direct insolation profile is considerably below that for a clear day. Next, the profile labeled "average available insolation" is simply the direct insolation in the aperture plane of the east-west trough as it tracks throughout the day. It accounts for the cosine losses. The third profile, labeled "average absorbed insolation," is the insolation actually absorbed by the receiver. It accounts for the trough's optical efficiency (which decreases away from solar noon), as defined by the baseline trough characteristics of Sec. 2.4. The two dashed lines correspond to the energy loss levels of the nonevacuated (upper line) and evacuated receivers. Thus,

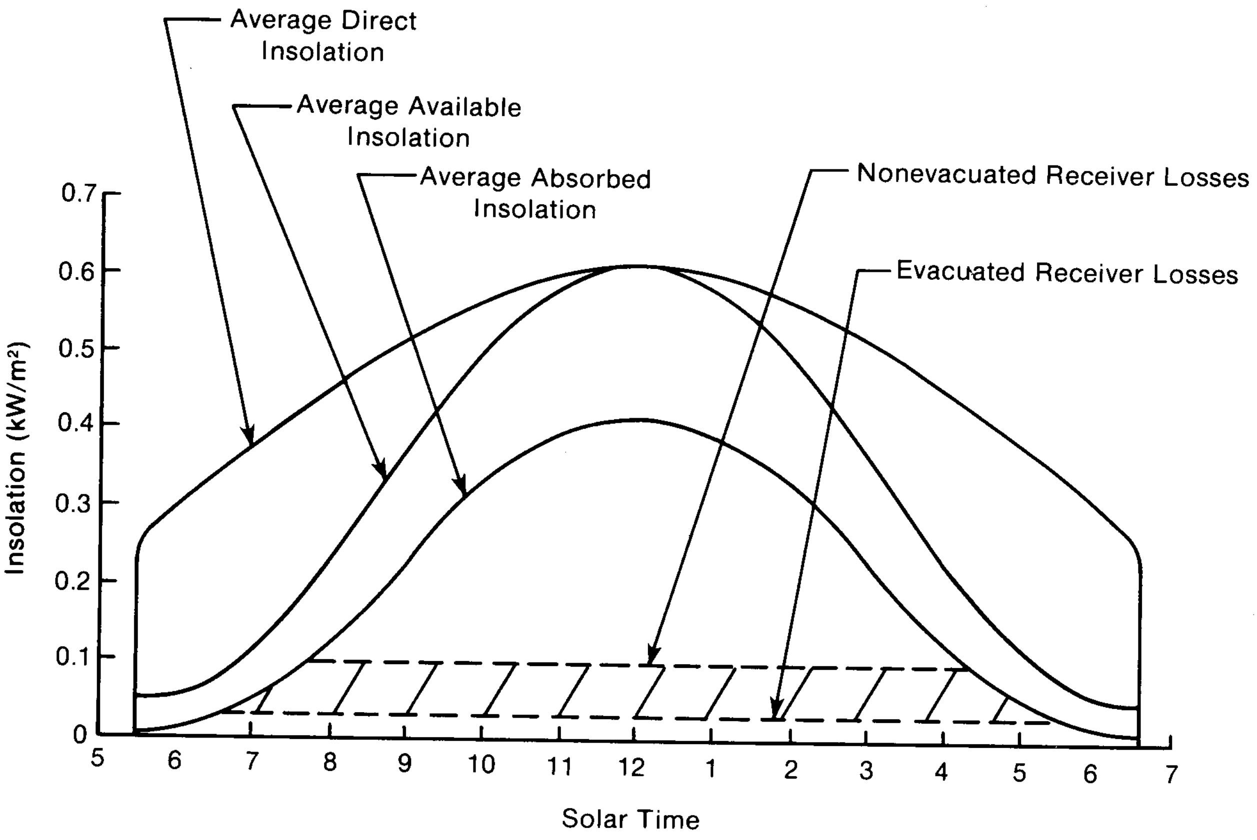

Figure 3-7. Parabolic Trough Performance on an Average April Day

the area between the abscissa and the respective dashed line corresponds to the energy loss for the particular receiver. Hence, the collected energy is represented by the area below the absorbed insolation profile and above the dashed line for the particular receiver of interest. The cross-hatched area represents the additional insolation usable by the improved collector. Not only is the available insolation used more efficiently, but the improved trough will sustain operation to a lower insolation level (critical intensity) and is thus capable of starting up earlier and shutting down later in the day. Integrating the collected insolation over the day results in a total of 1.7 kWh/m^2 for the baseline trough. Adding an evacuated receiver increases the collected energy to 2.3 kWh/m^2. The ratio of improved to baseline collectible energy is 1.36. This agrees very closely with the NSP of 1.33 determined for this improvement on an annual basis at 200°C (see Fig. 3-1).

Compare this result with the result based on clear-day instantaneous efficiency. Instantaneous efficiency can be expressed by the Hottel-Whillier-Bliss equation, as follows:

$$\eta = \eta_o - \frac{U_L}{C\,I_a}(T_{abs} - T_{amb}) \quad .$$

The value of U_L for an evacuated receiver at 200°C is about 2.5 W/m^2-°C and about 8.0 W/m^2-°C for the baseline nonevacuated receiver [8]. For a baseline optical efficiency of 0.68 and a parabolic trough concentration ratio of 25, the instantaneous efficiencies of the two parabolic troughs would be:

$$\eta\text{ (nonevac.)} = 0.68 - \frac{8.0}{25\ (900)}(200 - 10) = 0.612 \ ,$$

$$\eta\text{ (evac.)} = 0.68 - \frac{2.5}{25\ (900)}(200 - 10) = 0.659 \ .$$

A typical ambient temperature of 10°C has been assumed as well as a typical clear-day direct normal irradiance of 900 W/m^2.

Normalizing the instantaneous efficiency of the improved trough by the baseline trough instantaneous efficiency:

$$\frac{\eta\text{ (evac.)}}{\eta\text{(nonevac.)}} = \frac{.659}{.612} = 1.08 \quad .$$

This measure of performance enhancement is much smaller than the annual energy based value of 1.33. Thus, the evaluation of component improvements must be done on a long-term average basis if misleading results are to be avoided.

3.2 ALLOWABLE UPPER-BOUND COMPONENT COST INCREASES

Not all component improvements are attainable without increasing component costs. Improved components are beneficial only if an improvement in the performance/cost ratio is realized. (The positive change in the performance/cost ratio must offset the decrement to the performance/cost ratio due to increased costs.)

In this report, the performance/cost ratio is also expressed in terms of the normalized performance/cost ratio (NPCR in Eq. 5a). By holding NPCR constant and equal to one, we can calculate the upper-bound increase in component cost that a given improvement justifies. This corresponds to the situation wherein the increased cost of an improved system exactly offsets its improved performance, resulting in no net gain in delivered energy cost.

Upper-bound cost increases for several improvements are shown in Figs. 3-8 to 3-11 as a function of temperature. Each upper-bound cost increase for improvements is normalized by the baseline cost of the particular component. Figures 3-8, 3-9, and 3-10 correspond to fixed geometric concentration ratios of 15, 25, and 35, respectively. Figure 3-11 was generated for a continuously optimized concentration ratio in the same manner as Fig. 3-4.

As described in Sec. 2.2, these figures are based on current uninstalled parabolic trough cost breakdowns. The absolute dollar values of the components are not used, just their fractional contribution to total collector cost.

Further, a 3:1* ratio of system cost to uninstalled collector cost has been assumed. This corresponds to a future situation where installation and design costs are substantially reduced and should provide reasonably conservative upper-bound cost increases. Also, to ensure that component improvements will be cost effective for future trough systems and not just present-day systems, it is suggested that projected component costs be used with Figs. 3-8 to 3-11 rather than present-day costs.

The magnitudes of the upper-bound cost increases are shown to be substantial. Receiver improvements are shown to have significantly higher upper-bound cost increases relative to their baseline costs than do concentrator improvements. This occurs because the contribution of receiver costs to total costs is small relative to the contribution of the other components. Further, it is important to realize that collector costs are only a part of the total installed system costs. Thus, for example, a one-dollar-per-square-foot investment in an improved collector might improve system performance substantially but result in a comparatively small increase in total installed system costs.

As with the NSP figures of Sec. 3.1, concentration ratio has a significant impact. Receiver improvements that decrease thermal loss warrant higher cost increases for troughs with low concentration ratios than for those with high concentration ratios. Conversely, improved concentrator accuracies warrant higher cost increases for high-concentration-ratio troughs than for low-concentration-ratio troughs. This is the direct result of the sensitivity of trough performance to concentration ratio as discussed in Sec. 3.1.

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*Results corresponding to any other ratio can be obtained from these curves by a simple scaling procedure. For example, if the ratio is 6:1 then the allowable costs in Figs. 3-8 to 3-11 would all be multiplied by a factor of 2.

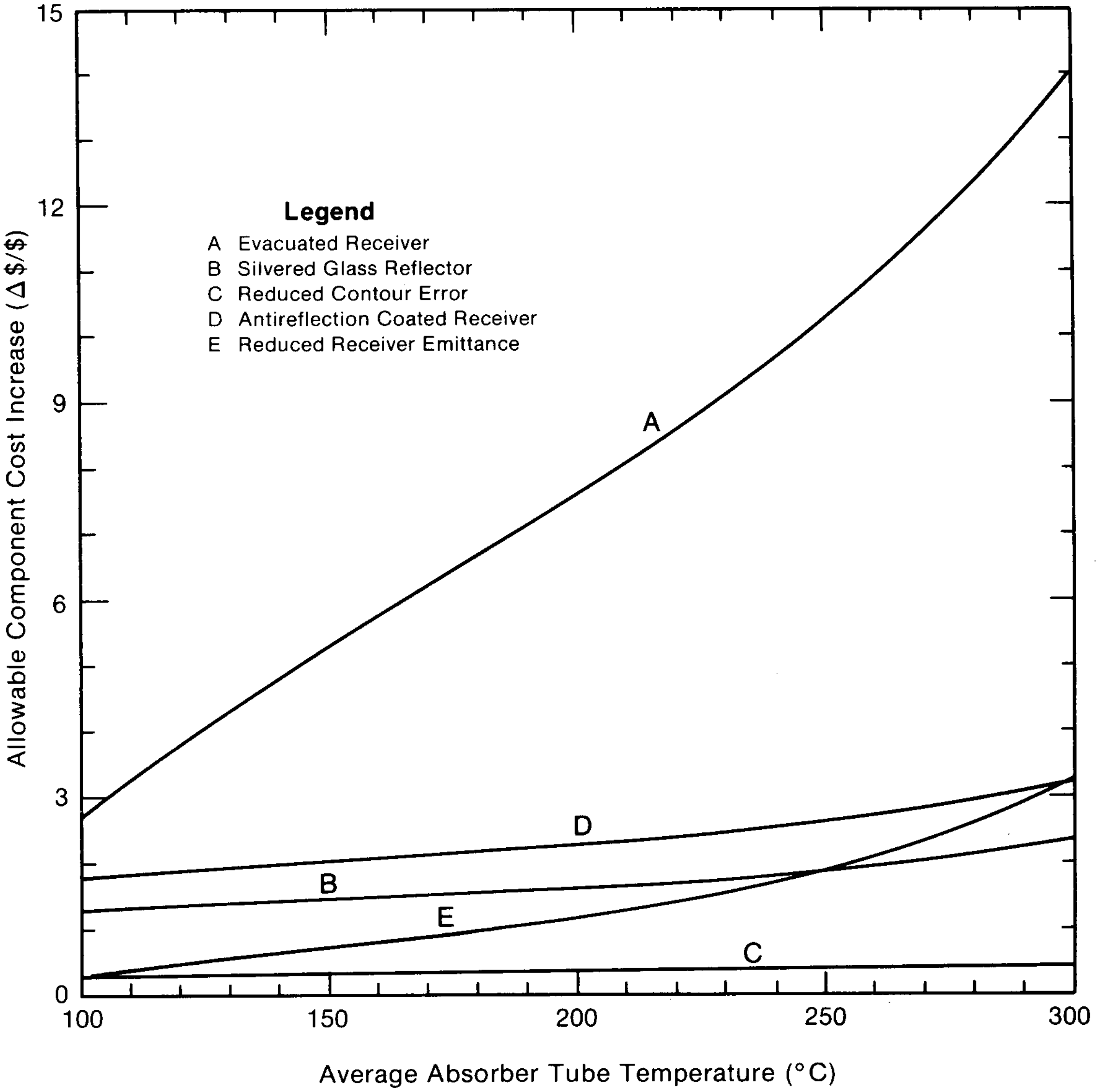

Figure 3-8. Upper-Bound Cost Increases vs. Absorber Temperature for Various Improved Components of Horizontal Parabolic Troughs with Geometric Concentration Ratios of 15

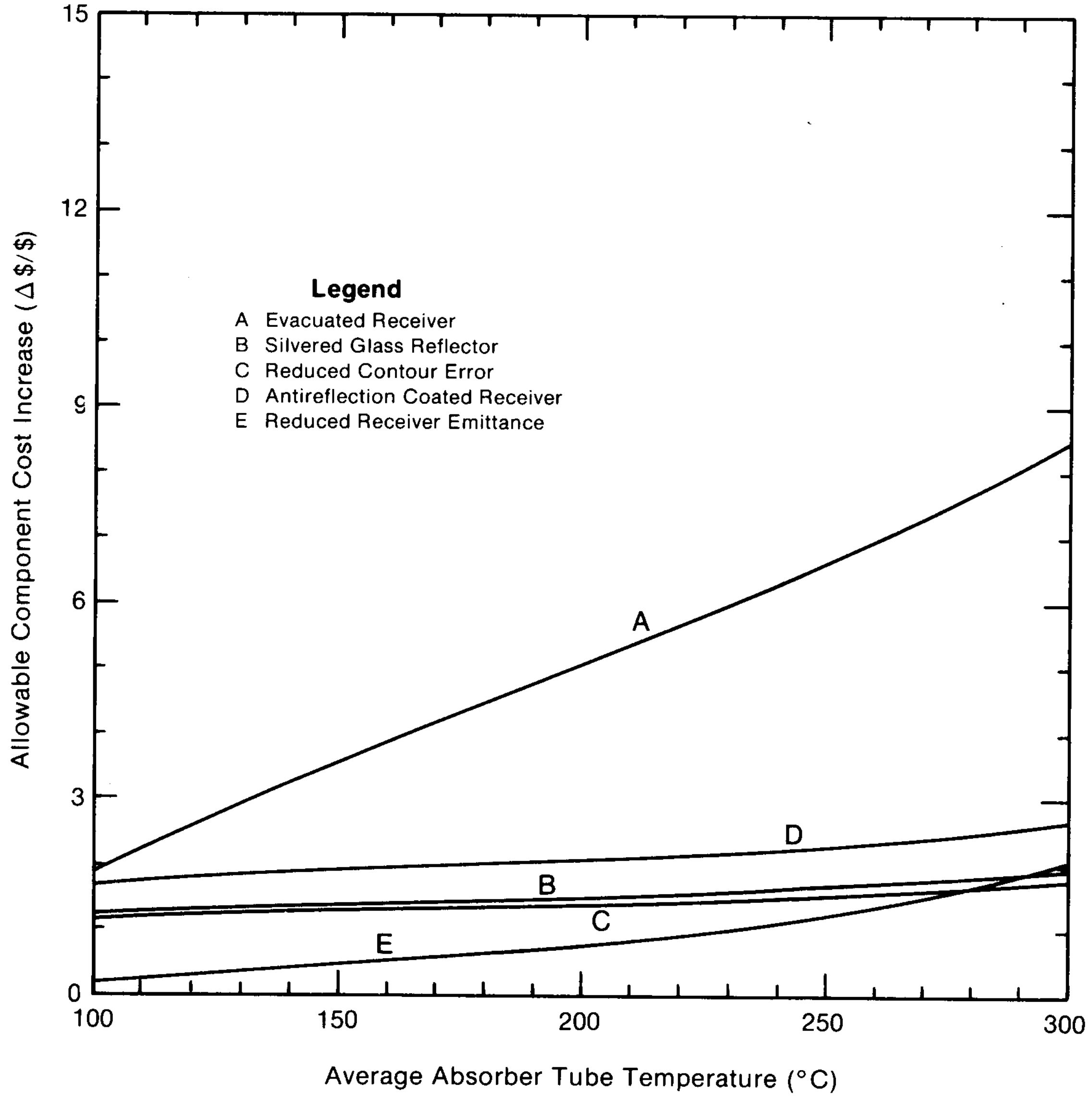

Figure 3-9. Upper-Bound Cost Increases vs. Absorber Temperature for Various Improved Components of Horizontal Parabolic Troughs with Geometric Concentration Ratios of 25

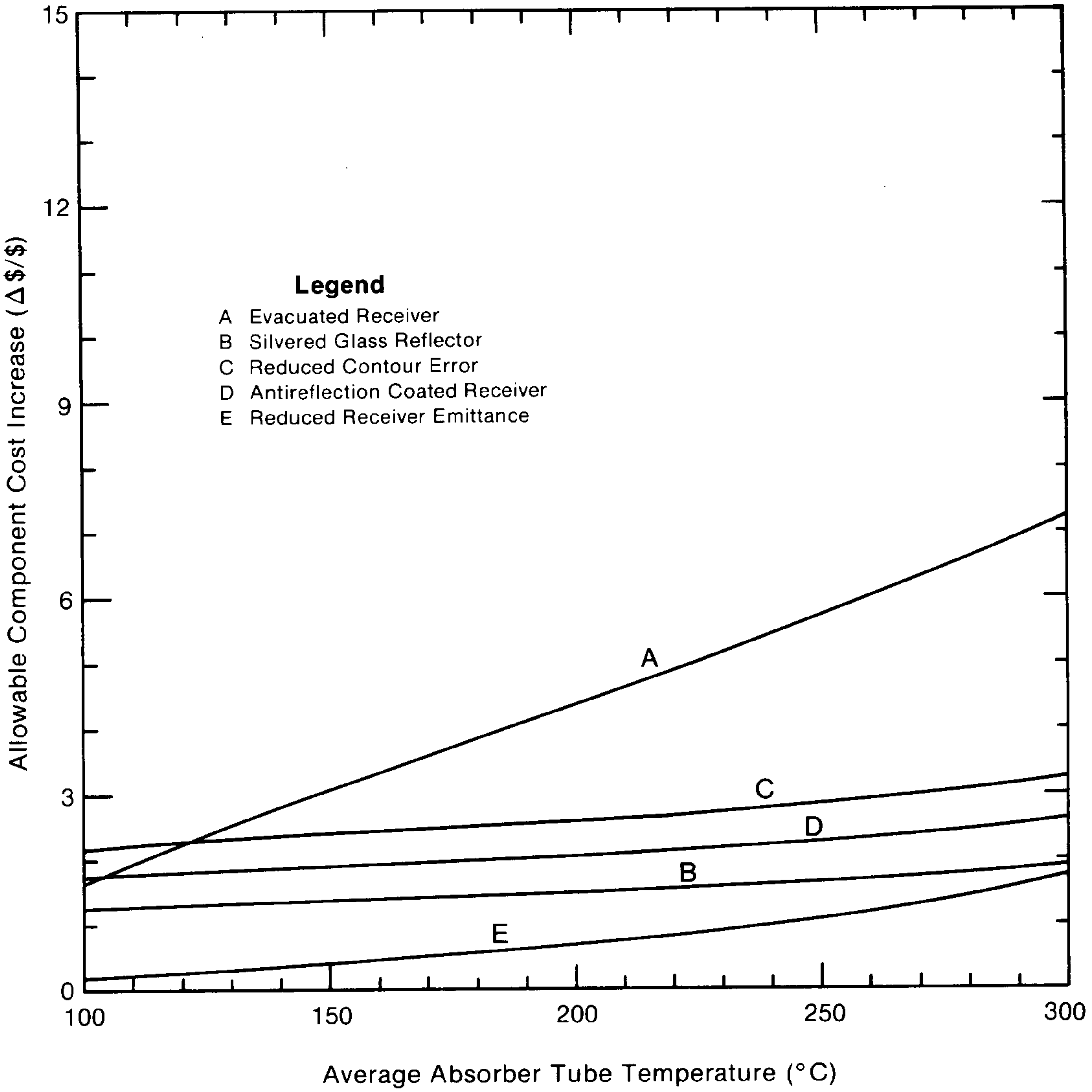

Figure 3-10. Upper-Bound Cost Increases vs. Absorber Temperature for Various Improved Components of Horizontal Parabolic Troughs with Geometric Concentration Ratios of 35

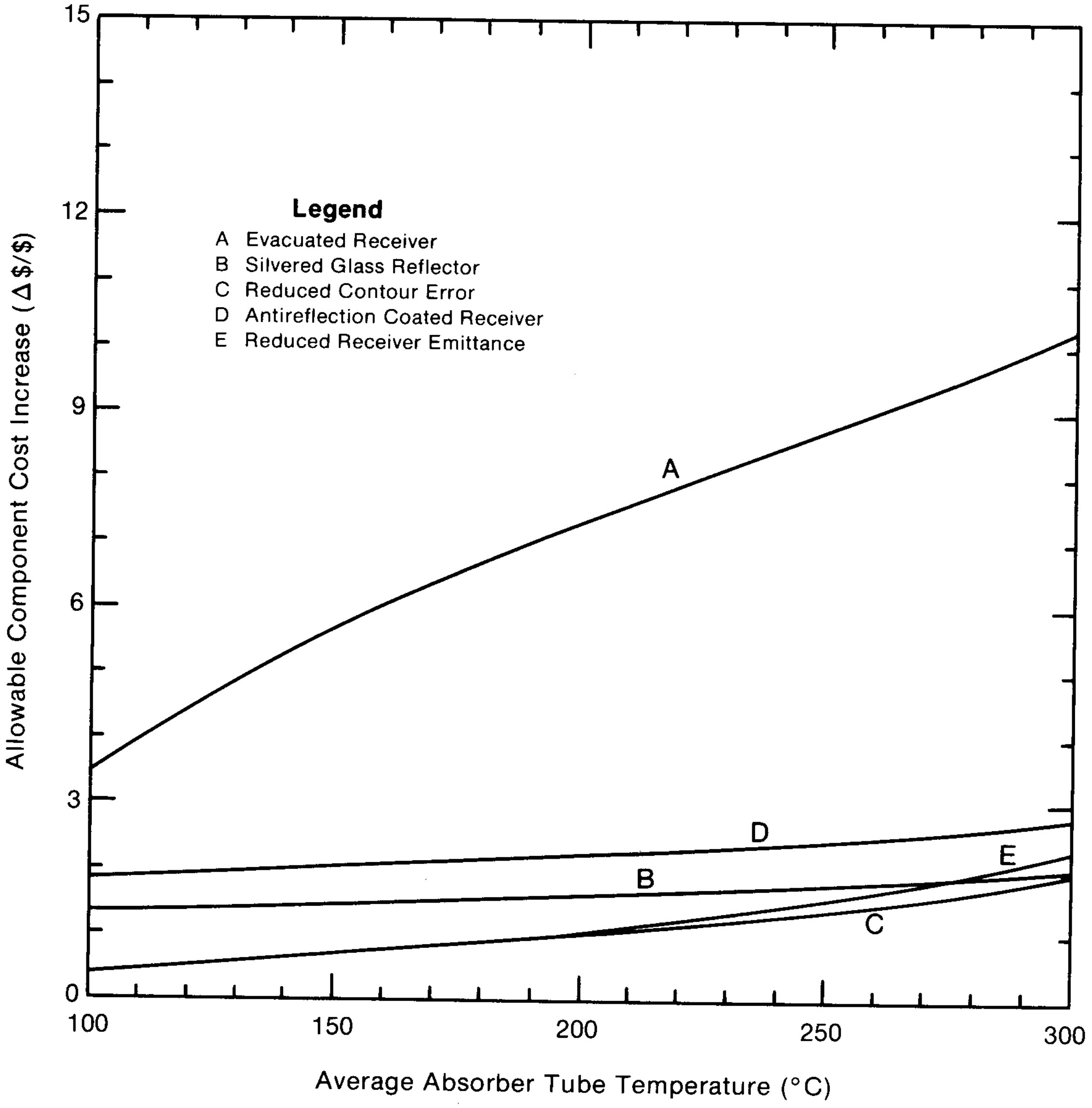

Figure 3-11. Upper—Bound Cost Increases vs. Absorber Temperature for Various Improved Components of Horizontal Parabolic Troughs with Geometric Concentration Ratios Corresponding to Optimum Performance

It is important to reemphasize that allowable cost increases that have been plotted represent upper bounds for an average system. It is generally not recommended that such costly improvements be developed and implemented. The upper-bound approach provides a cost range within which a designer can work to provide an improvement that will, in turn, improve the performance/cost ratio. The upper-bound cost increases were based on average component cost breakdowns and, therefore, represent the group, not a particular parabolic trough.

3.3 RATE OF RETURN INCREASES

The internal rate of return (R) is often used as a measure of the relative attractiveness of a solar investment. The improvements discussed in this report can increase solar system energy delivery and thereby result in an increase in the system's rate of return. As shown in Sec. 2.1 (Eq. 17), the sensitivity of R to a change in performance and/or cost can be evaluated easily as a function of financial parameters only. A parametric family of curves (Figs. 3-12 and 3-13) has been generated that allows the user to determine the increase in rate of return (ΔR) for any given performance/cost ratio increase and any assumed baseline rate of return. As a first approximation, performance increases without cost increases might be considered as in Sec. 3.1. Users can subsequently estimate cost increases, or upper-bound costs might be used as generated in Sec. 3.2. Cost increases can vary from zero to the upper-limit component costs given in Sec. 3.2.*

The two rate of return figures correspond to the cases of 100% and 70% equity, respectively. Financial institutions usually demand an analysis based on 100% equity to compare the relative benefits of various options before the effect of financing is considered. This is because financing and "leveraging" can lead to distortions** as well as large sensitivities to variations in the rate of return. Thus, it is felt that a 100% equity comparison leads to the least distorted picture of relative value of the alternatives. The 70% equity case corresponds to a typical debt-to-equity ratio ultimately sustained by many industries. As seen in Figs. 3-12 and 3-13, for a given change in the cost/performance ratio, higher initial rates of return lead to correspondingly greater improvements in rate of return. Larger fuel escalation rates also correspond to large R improvements in the rate of return.

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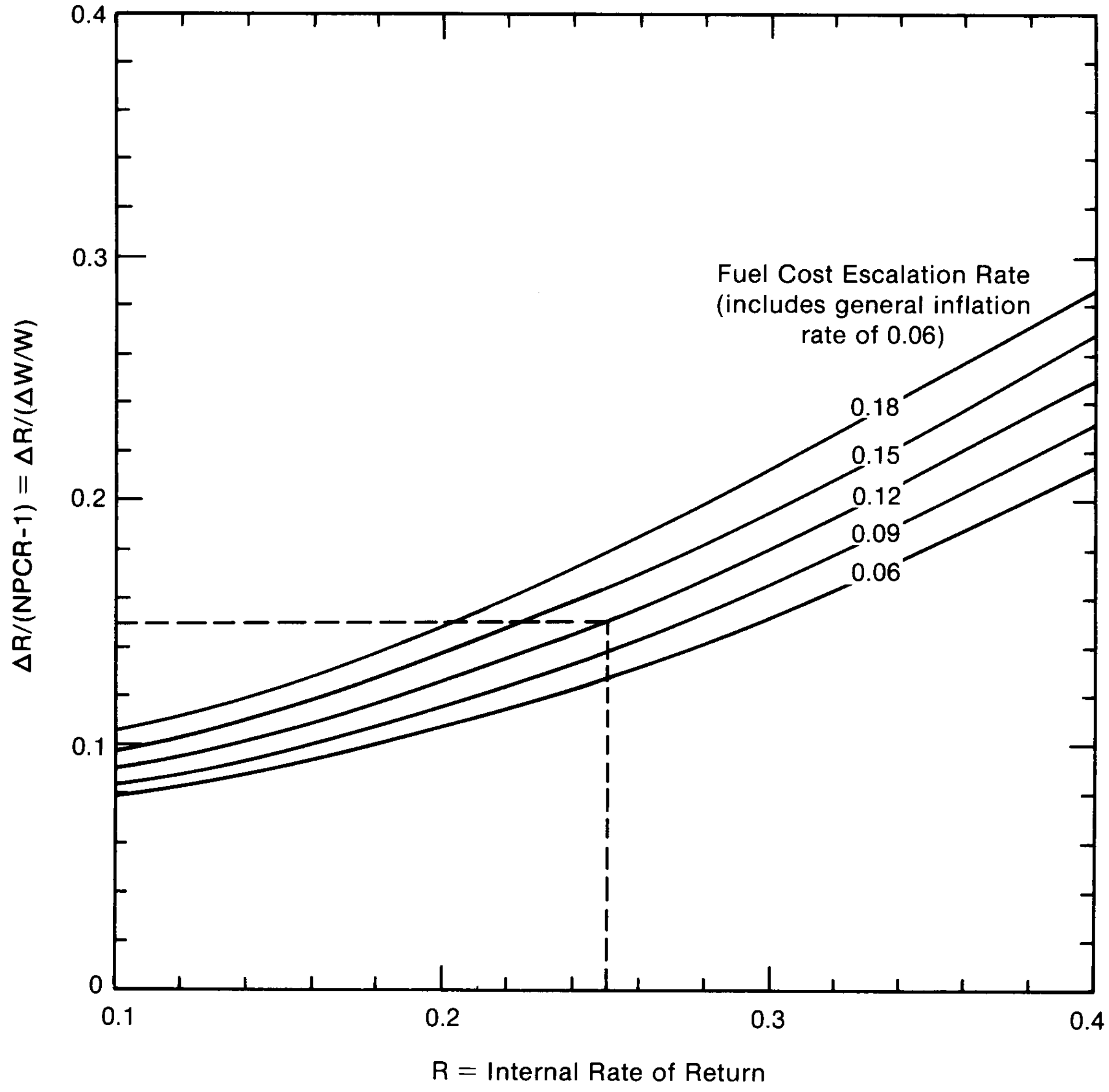
*It should be reemphasized that the costs being considered in the performance/cost ratio increment are total system increment costs.

**For example, leveraging with large loan fractions corresponding to decreasing M values with increasing R (see Ref. 6) can lead to an initial attractive cash-flow picture for the users. However, stock and bond prices as well as further credit availability are usually adversely affected, since financial institutions associate high risk with this situation. Because of these concerns, most large corporations constrain their own debt ratios.



The dashed lines in the figure indicate the following sample calculation: Assume that the fuel escalation rate is 0.12, the baseline rate of return on the investment prior to the improvement is 0.25, and the performance/cost ratio can be improved by 0.30 (=ΔW/W). Then, reading up from the rate of return axis (R=0.25) to the 0.12 fuel escalation rate curve and then over to the ordinate results in a ΔR/(ΔW/W) equal to 0.15. Solving for ΔR results in an increase in R of 0.045. Hence the new rate of return for the improved system will be (0.25 + 0.045) equal to 0.295.

Figure 3-12. Increases in Rates of Return vs. Baseline Internal Rate of Return for 100% Equity

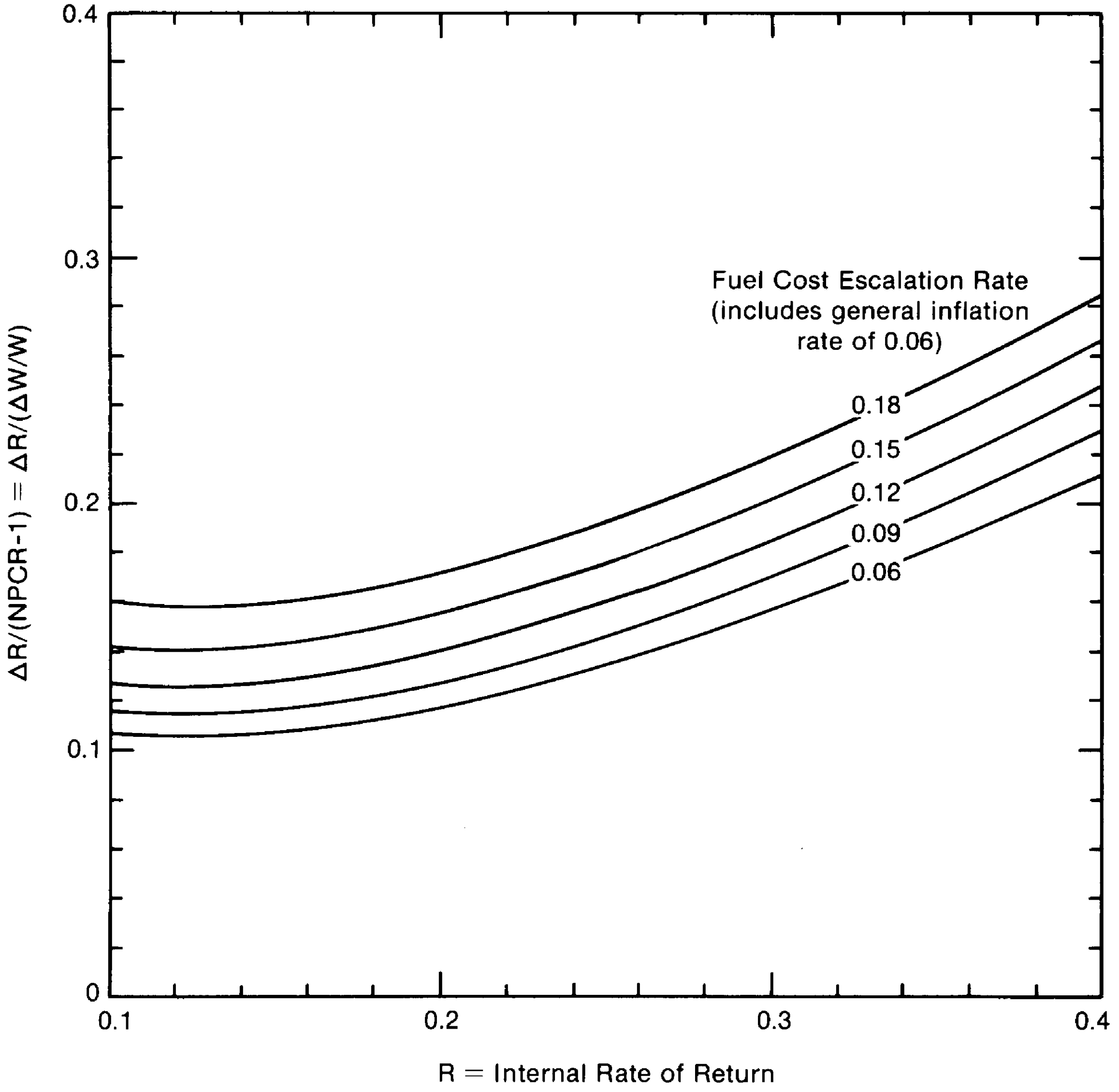


Figure 3-13. **Increases in Rate of Return vs. Baseline Internal Rate of Return for 70% Equity**

3.4 SENSITIVITY ANALYSIS

All the results presented in previous sections were generated for horizontal east-west parabolic trough systems operating in Denver, Colo., with average system losses. This section shows that these results have little sensitivity to large variations in tracking configurations, system losses, or system location. Therefore, they provide a good representation of the benefits for a wide range of user conditions.

Tables 3-2, 3-3, and 3-4 contain tabulated results showing the sensitivity of the NSP values to other orientations, system losses, and geographical locations. NSP variations are examined at low, medium, and high temperatures for three component improvements. The three improvements are an evacuated receiver, reduced concentrator contour accuracy, and a silvered glass reflector. They represent the three major areas for trough performance improvements--reduced receiver thermal losses, improved optical accuracy, and improved optical transmission.

Table 3-2 compares NSP values for the baseline troughs (having east-west rotational axes) with those having a north-south orientation. Both orientations are evaluated for a ground cover ratio of 0.35. This corresponds to a higher shading loss for the north-south orientation ($F_{shad} = 0.93$) than the east-west orientation ($F_{shad} = 0.96$). The differences in NSP are shown to be very small, 2% or less. Thus, the NSP values of this report are generally applicable to horizontal parabolic troughs regardless of orientation.

Table 3-2. Sensitivity of NSP to Trough Orientation for Three Representative Component Improvements

Component Improvement and Temperature (°C)	Baseline NSP East-west	North-south[a] NSP	North-south[a] % Change in NSP
Evacuated receiver			
100	1.15	1.13	-2
200	1.32	1.30	-2
300	1.44	1.47	2
Reduced contour error			
100	1.06	1.05	-1
200	1.15	1.16	1
300	1.30	1.33	2
Silvered glass reflector			
100	1.20	1.20	0
200	1.25	1.25	0
300	1.31	1.32	1

[a] North-south troughs are assumed to be mounted with a row-to-spacing identical to the baseline east-west troughs. For the baseline ground cover ratio of 0.35 the resulting shading loss factor, F_{shad}, is about 0.93.

Table 3-3. Sensitivity of NSP to System Losses for Three Representative Component Improvements

Component Improvement (°C)	Baseline NSP	Increased System Losses $F_{shad} = 0.96$, E_{field} Doubled		Decreased System Losses $F_{shad} = 1$, E_{field} Halved	
		NSP	% Change in NSP	NSP	% Change in NSP
Evacuated receiver					
100	1.15	1.15	0	1.15	0
200	1.32	1.34	2	1.31	-1
300	1.44	1.50	4	1.41	-2
Reduced contour error					
100	1.06	1.06	0	1.06	0
200	1.15	1.17	2	1.15	0
300	1.30	1.34	3	1.28	-2
Silvered glass reflector					
100	1.20	1.21	1	1.20	0
200	1.25	1.26	1	1.24	-1
300	1.31	1.36	4	1.29	-2
			Average = 2%		Average = -1%

Table 3-4. Sensitivity of NSP to Geographic Location for Three Representative Component Improvements

Component Improvement (°C)	Baseline NSP Denver	Albuquerque, N. Mex.		Blue Hill, Mass.		New Orleans, La.		Glasgow, Mont.	
		NSP	% Change in NSP	NSP	% Change in NSP	NSP	% Change in NSP	NSP	% Change in NSP
Evacuated receiver									
100	1.15	1.14	-1	1.18	3	1.17	2	1.16	1
200	1.32	1.30	-2	1.37	4	1.36	3	1.34	2
300	1.44	1.42	-1	1.53	6	1.52	6	1.45	1
Reduced contour error									
100	1.06	1.06	0	1.07	1	1.07	1	1.06	0
200	1.15	1.15	0	1.18	3	1.18	3	1.17	2
300	1.30	1.29	-1	1.36	5	1.36	5	1.31	1
Silvered glass reflector									
100	1.20	1.20	0	1.21	1	1.21	1	1.21	1
200	1.25	1.24	-1	1.26	1	1.26	1	1.25	0
300	1.31	1.30	-1	1.35	3	1.36	4	1.32	1
			Average = -1%		Average = 3%		Average = 3%		Average = 1%

Table 3-3 compares NSP values of the baseline trough system with a trough system having either larger or smaller system losses. System losses include row-to-row shading losses, steady-state piping thermal losses, and overnight thermal losses. Values for the baseline system are discussed in Sec. 2.4. Departures from these baseline values can alter the predicted NSP values. However, the sensitivity of NSP to system losses is quite small. For a system with doubled row-to-row shading losses and doubled thermal losses, the NSP values increase by only about 2% on the average. A system with no row-to-row shading losses and halved thermal losses decreases the NSP values by only about 1% on the average. Therefore, the baseline system values for system losses are not critical. Any trough system with reasonable losses is closely represented by these results.

The sensitivity of NSP to geographical location is shown in Table 3-3. The differences in NSP values for four other cities are tabulated against the baseline NSP values for Denver. These four cities were chosen because of their wide differences. Albuquerque, N. Mex., represents a high insolation area with a low latitude. Glasgow, Mont., is in a high insolation area at a high latitude. New Orleans, La., and Blue Hill, Mass., are low insolation locations at a low and high latitude, respectively. The monthly average temperatures and clearness numbers were taken from Ref. 25. Even for these extreme locations, the sensitivity of NSP is small. Cloudier climates result in the largest errors. Also, the errors are shown to increase with operating temperature. However, it is important to note that the baseline NSP values are generally conservative. Only for low-latitude, high-insolation locations such as Albuquerque do the baseline NSP values overpredict performance benefit from an improvement.

The insensitivity of NSP to parabolic trough orientation, system losses, and geographic location indicates the general applicability of the NSP curves of Sec. 3.1. Differences from these predicted NSP values will be small relative to the NSP values themselves.

SECTION 4.0

CONCLUSIONS

From the analysis presented in this report, we see that parabolic trough improvements corresponding to the components considered are likely to increase system performance substantially above levels previously thought possible. Further, it has been demonstrated that the normalized system performance, as developed and used in this analysis, is reasonably insensitive to changes in the geographic location, field and shading losses, and orientation of the collector system. Hence, the analysis has generality that can be extended beyond the range of operating conditions considered in this report. The relative attractiveness of various component improvements are viewed here from an annual system performance perspective.

Advanced troughs that incorporate several of the improvements discussed in this report can yield up to 50% more annual energy delivery at low temperatures. At higher temperatures, the potential for improvement is even greater; annual energy output can be doubled, in some cases. Evacuated receivers and silvered glass reflectors offer the greatest potential for improving performance. The evacuated receiver, in particular, has enormous cost leverage because line-focus receivers are inexpensive relative to total system cost. The evacuated receiver's upper-bound cost increase relative to the baseline receiver cost (see Figs. 3-8 to 3-11) is higher than that of the other improvements at all but the lowest operating temperatures. While silvered glass reflectors also offer a potentially large performance improvement, the cost leverage associated with them is not as substantial as that for evacuated receivers, because of the higher fraction of collector cost associated with the concentrator. While antireflection (AR) coated receivers offer approximately a 10% increase in annual performance, they would be cost-effective even at double the receiver cost. Concentrator contour-error reduction is important if higher operating temperatures are to be efficiently attained. The increase in performance that occurs with a concentrator contour error reduction of from 6 mrad to 3 mrad outweighs the economic penalty that occurs if the cost of the concentrator is doubled. However, for lower concentration ratio troughs intended for use at lower temperatures, the performance benefit is much smaller (see Fig. 3-8). Thus, more accurate concentrators are only attractive if higher-temperature operation is intended. The performance impact of a lower-emittance selective coating is a strong function of trough operating temperature. For low-temperature operation, the reduction in thermal losses due to a lowered selective surface emittance is very small and, therefore, the improvement is of little consequence. However, at operating temperatures in excess of 250°C, the improvement is significant enough that the coating cost can double the receiver cost and still provide an increase in overall system cost-effectiveness.

All the component improvements considered in this report have been evaluated in terms of average annual energy delivery enhancement. This approach reveals that the potential for near-term parabolic trough performance enhancement is great. These performance enhancements are significantly larger than previously thought because most analysis has been performed in terms of instantaneous performance or clear day performance enhancement. While instantaneous efficiency is the commonly used performance measure, it does not adequately describe performance. Instantaneous efficiencies are determined when insolation levels are high and incidence angles are low. When annual performance is considered, the influence of lower insolation and off-peak performance is accounted for.

For most of the operating ranges considered in this report, the upper-bound allowable cost increases are quite large. Incremental allowable component cost increases are often greater than two and can be as high as a factor of 15 times the baseline-component costs. This means that there is a large cost margin within which the designer can work and still provide an improvement in system performance/cost. Note that the ratios of component costs used in this report are based on limited (but the best available at the time of the analysis) data, which may well change as the technology evolves. However, the analysis presented here can be scaled easily to account for new information as it becomes available. Further, it does not seem likely that new data will change the trends presented here significantly.

We reemphasize that this study has not investigated the development issues associated with, nor the cost of implementing, the component improvements addressed. Actual hardware problems associated with some of these development issues can be quite complex and difficult to resolve. Thus, the potential benefits cited, although quite significant, are based on analysis and represent only part of the story. Nevertheless, the magnitude of predicted potential benefits is such that further development effort appears warranted, especially in the area of evacuated receivers. Further, our analysis does quantify the relative benefits of various improvements corresponding to a wide range of expected operating conditions. Therefore, it should help trough developers to select the most beneficial improvements for their products that are within their ability to implement.

SECTION 5.0

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APPENDIX

LINE-FOCUS RECEIVER HEAT LOSS COEFFICIENTS

The accuracy of the receiver heat-loss coefficients developed in Ref. 1, and used again in this report, is sometimes questioned because the coefficients are based on a constant outside ambient temperature of 10°C. While the heat-loss coefficients do vary with ambient temperature, the variance is small when the coefficients are expressed as a function of absorber temperature itself rather than as a function of ΔT (absorber temperature above ambient). This interesting fact is shown in Figs. A-1 and A-2 for the baseline nonevacuated receiver. Heat-loss coefficients for the baseline ambient temperature of 10°C are compared with the coefficients which result from both an increase and a decrease in ambient temperature of 20°C. The total receiver heat loss is the sum of two components--a conduction/convection loss and a radiation loss. The conduction/convection heat loss as a function of ΔT is essentially linear and can be obtained by multiplying the heat loss coefficient, U_L, by the ΔT above ambient to arrive at total conduction/convection heat loss.

However, the receiver radiation loss is driven by the fourth power of the absorber temperature and, hence, is not primarily dependent on ΔT but is, to a greater extent, dependent on simply T (absorber temperature). Therefore, the curves in Fig. A-2, which show the heat loss coefficient as a function of absorber temperature, yield better agreement.

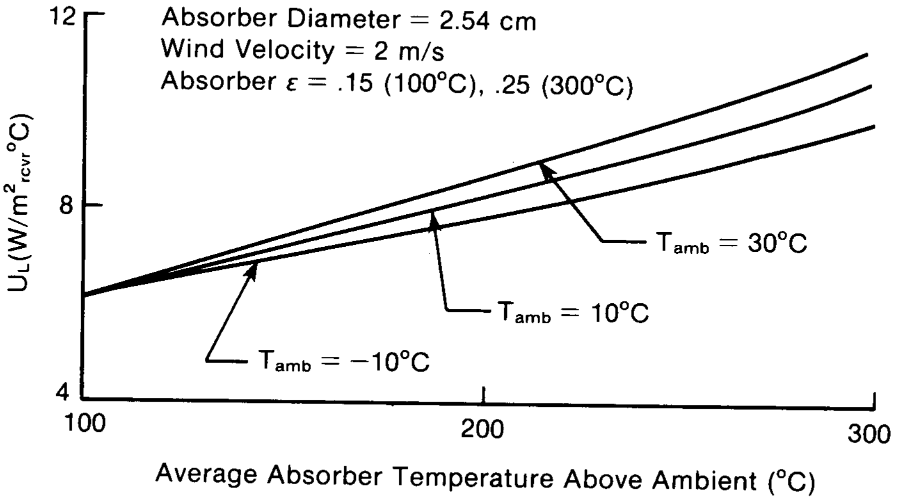

Figure A-1. Heat-Loss Coefficient vs. Absorber Temperature Above Ambient
(Nonevacuated Receiver)

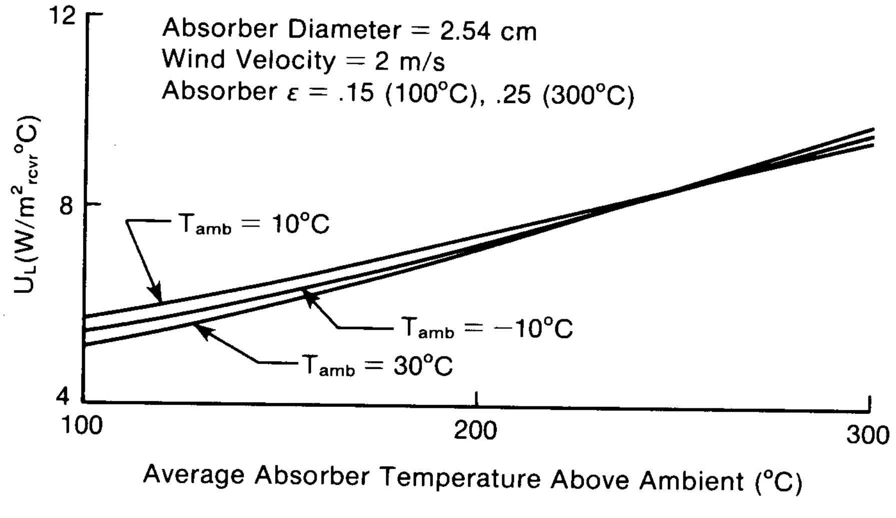

Figure A-2. Heat-Loss Coefficient vs. Absorber Temperature
(Nonevacuated Receiver)

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Improved parabolic-trough concentrating collectors will result from better design, improved fabrication techniques, and the development and utilization of improved materials. This analysis qualifies the performance potential of various parabolic-trough component improvements from a systems viewpoint and uses these performance data to determine the worth of each improvement on an economic basis. The improvements considered are evacuated receivers, silvered-glass reflectors, improved receiver selective coatings, higher optical accuracy concentrators, and higher transmittance receiver glazings. Upper-bound costs for each improvement are provided as well as estimates of the increased solar system rates of return that are made possible by these improvements. The performance and economic potential of some of these improvements are shown to be substantial, especially at higher collector operating temperatures.

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