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A COMPREHENSIVE COMPUTER-BASED METHOD FOR DESIGN OF PARABOLIC TROUGH SOLAR COLLECTORS FOR TECHNICALLY LESS DEVELOPED COUNTRIES

TECHNICAL REPORT 2

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Any opinions, findings, conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the U.S. Agency for International Development (USAID).

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EXECUTIVE SUMMARY

Although in the U.S. solar energy is still not considered cost-effective for many applications, the situation appears to be more favorable in developing countries. Solar energy conversion systems require a large initial investment and as much as 60 percent of this initial expense is for labor. Since labor costs in developing countries are much lower than in industrially developed countries, the cost of solar systems can be considerably less. Therefore, a solar industry, utilizing local labor and materials as much as possible, may be cost-effective today for many applications in developing countries.

Parabolic trough collectors (PTC's) are capable of supplying thermal energy over a wide range of temperatures (up to 300°C) and presently are the leading solar technology in the intermediate temperature range. In the U.S., where most of the PTC research has been performed and the present PTC state-of-the-art has been developed, the main design objectives have been the 'maximization of thermal efficiencies' and 'mass-production suitability'. However, these criteria are not compatible with the goals and design objectives of most developing countries, which favor labor-intensive designs and production techniques. Consequently, in order to be cost-effective, different 'optimum' PTC designs should be developed for different design environments. Moreover, in a developing country, the need for solar power may vary from electricity for rural applications (e.g., farm irrigation) all the way to industrial process heat (IPH) generation. It is therefore necessary to have a design method that is both comprehensive and flexible to cope with changes in: (a) the application and (b) the design environment.

In this report, a design methodology for the design of PTC's for different design environments (economic, technical, geographic) with different constraints and set of objectives, is presented. It is shown that this design method can be used to develop optimum error-tolerant PTC designs for developing countries. In this method, the number of iterations in the design cycle are minimized and hence the cost of design effort is reduced.

Implementation of the design methodology is demonstrated with two illustrative examples: PTC designs for the U.S. design environment and for a developing country design environment. The results from the design methodology are validated by comparing the optimum PTC design for the U.S. design environment given by the design method with PTC designs currently available in the U.S. market; they are found to compare favorably.

Abstract

A comprehensive method is presented for the design and optimization of Parabolic Trough Collectors (PTC's) for different design environments. This method, in addition to the usual performance related parameters, has options to include and process qualitative and/or quantitative information, thereby, enabling the designer to cope with change (e.g., change from a high-technology design environment to a low-technology design environment) in an efficient manner. The development consisted of:

- a comprehensive optical model which was presented in the first technical report [1]. In this model, particular emphasis was placed on the modeling of different kinds of errors (operational, manufacture, assembly, materials, etc.).
- a multi-objective rational design and optimization approach. In this design procedure, in addition to the usual performance related parameters, special emphasis is placed on the inclusion of information about the design environment, such as the design goals, the design objectives, the intrastructure and the limitations (e.g., social economical and/or technological limitations) of the design environment.

A two-level design structure (macro-level and micro-level) is introduced for handling changes in the design environment. At the macro-level of design, design decisions and optimization aspects based on capabilities and objectives of the design environment (e.g., selection of the method of fabrication and selection of materials) are analyzed. At the micro-level of design, environment

independent design decisions and optimization of the components of the subsystems based on technical considerations alone (e.g., optimization of the gap width between the glazing and the absorber surface of the receiver subsystem to minimize convection and conduction losses) are analyzed.

A mathematical structure, i.e., a decision support procedure, for the design problems at the macro-level of design is presented. This decision support procedure allows for quantitative assessment of both the usual performance related parameters and the qualitative information such as availability and technological capability of the design environment. An optimization method for the micro-level design is developed in which a seven-step procedure for optimizing the concentration ratio is given. In this procedure, all-day average efficiency of the collectors is maximized. The use of the method for designing PTC's for different design environments (i.e., countries) is demonstrated by illustrative examples.

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LIST OF SYMBOLS

A_a	Reflector aperture area
A_{ij}	j_{th} attribute rating for the i_{th} alternative; a numerical value associated with an attribute of a particular alternative
A_j^{max}	Maximum attribute rating of attribute j
A_j^{min}	Minimum attribute rating of attribute j
A_r	Absorber tube area
C	Concentration ratio, $C = W/\pi D$
C_o	Optimum concentration ratio
C_o'	Optimum concentration ratio for sensitivity analysis
$\langle\cos\theta\rangle$	All-day average incidence factor
C_p	Specific heat at constant pressure
D	Absorber tube diameter
$D_{g,i}$	Diameter of inner surface of glass jacket (glazing)
$D_{g,o}$	Diameter of outer surface of glass jacket (glazing)
d_r	Distance between the actual focus and the center of the absorber tube
$(d_r)_x$	d_r along the lateral axis of the reflector
$(d_r)_y$	d_r along the optical axis of the reflector
d^*	Universal non-random error parameter due to receiver mislocation ($= (d_r)_y/D$)
d_i^+	Amount by which constraint i has exceeded goal (overachivement)

List of Symbols (Continued)

d_i^-	Amount by which constraints i is short of goal (underachivement)
f	Focal length of the reflector
g	Acceleration due to gravity
h_w	Heat-transfer coefficient due to wind
H_d/H_h	Ratio of diffuse to hemispherical irradiation
I_b	Beam solar irradiation
$\langle I_b \rangle$	All-day average beam insolation
$\langle I_b \cos\theta \rangle$	All-day average beam insolation and incidence factor product
k_{air}	Thermal conductivity of air
k_{ef}	Effective conduction coefficient due to conduction and natural convection in an annular space
k_{gas}	Thermal conductivity of the gas in the annular space of the receiver
k_{glass}	Thermal conductivity of glass
K_h	Sky clearness index
$K(\theta)$	Incidence angle modifier
$\langle K(\theta) \rangle$	All-day average incidence angle modifier
ℓ	Annular gap width
L	Absorber tube length
$\dot{m}$	Working fluid flow rate
P_i	Priorities of goals; their subscripts serve to identify priority level for the goals
q_L	Heat loss per receiver surface area

List of Symbols (Continued)

q_{net}	Net heat flux absorbed by the absorber
$\langle q_{net} \rangle$	All-day average net heat flux absorbed by the receiver
$\dot{Q}$	Heat loss rate
R_{ij}	Normalized j_{th} attribute rating for the i_{th} alternative
T_a	Ambient temperature
T_{abs}	Absorber temperature (collector operating temperature)
$T_{f_{in}}$	Inlet temperature of working fluid
$T_{f_{out}}$	Outlet temperature of working fluid
$T_{g,i}$	Temperature of inner surface of glazing
$T_{g,o}$	Temperature of outer surface of glazing
U_L	Heat-loss coefficient for receiver based on absorber surface area
V_{wind}	Wind velocity
W	Reflector aperture width

Greek Symbols

α	Absorptance of selective coating
β	Reflector misalignment and tracking error angle
β^*	Universal non-random error parameter due to angular errors ($= \beta C$)
γ	Intercept factor at normal incidence
γ_o	Optimum intercept factor
γ_θ	Instantaneous (incidence angle dependent) intercept factor
δ	Solar declination angle

List of Symbols (Continued)

ε_{abs}	Emissivity of selective coating
$\varepsilon_{g,i}$	Emissivity of glazing inner surface
$\varepsilon_{g,o}$	Emissivity of glazing outer surface
ζ	Half optical cone angle (angular aperture)
η_o	Optical efficiency
$\langle\eta_c\rangle$	All-day average collector efficiency
$(\eta_c)_{noon}$	Overall collector efficiency at solar noon
θ	Angle of incidence of the sun's rays on the collector aperture measured from the normal to trough aperture
$\theta_\perp$	Incidence angle projected to x-y plane
$\theta_\parallel$	Incidence angle projected to y-z plane
θ_c	Incidence angle on the aperture at the cut-off time
θ_{noon}	Incidence angle at solar noon
λ	Latitude
μ	Angular shift of the mean of the standard distribution
ρ	Average specular reflectance of the reflecting surface
σ	Energy distribution standard deviation
σ^*	Universal random error parameter ($= \sigma C$)
τ	Transmissivity of the glass jacket
$(\tau\alpha)_n$	Effective transmittance-absorptance factor at normal incidence
ϕ	Trough rim angle (see Fig.2.2)
ω	Hour angle (subscript c designates hour angle at cut-off time).

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Chapter One

GENERAL INTRODUCTION

1.1 Background

The continuing expansion of fossil fuel reserve estimates in the 1960's, lulled the world into a false sense of energy security. During this period, the U.S. and the other industrialized nations of the west based their entire economic growth on the nonrenewable energy resouces, and the developing countries of the world followed their lead by initiating many fossil-fuel-intensive development programs to accelerate agricultural production through the use of irrigation, chemical fertilizers and hybrid seeds, and to provide for industrial development through rural electrification and road construction. Nevertheless, the energy crisis of 1973 and the subsequent ten-fold increase in oil prices has greatly decreased the attractiveness of many fossil-fuel-intensive development and economic growth programs in both industrialized and developing countries.

In response to the energy crisis, interest in solar energy and other alternative energy sources was intensified, and the development of indigenous fossil fuel resources,

conservation programs, improvements in energy conversion and efforts to utilize renewable sources were initiated. This intensified research and development in renewable energy sources resulted in the demonstration of the technical feasibility of many alternative energy options.

Nonetheless, in the U.S. and other industrialized countries, where solar know-how and technology exists, at present, solar energy is cost-effective for only a limited number of applications (e.g., domestic hot water) [1,2,3]*. The economic value of a solar energy utilization system, is equivalent to the incremental cost of the cheapest competing energy source that supplies the energy to accomplish the same task as the solar system. At the present time with government orchestrated energy pricing policies, tax exemptions, etc., especially favorable to conventional energy, it is difficult to make a true cost estimate. However, rough estimates of collection efficiencies, material costs, etc., recently indicate that in the U.S., for example, thermal energy from a solar system would cost more than that from a conventional source.

The situation, however, appears to be more favorable in developing countries. The major share of the cost of solar energy lies in repayment of the initial capital investment for the installed cost of the conversion system

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*Numbers in brackets refer to references in Reference section.

that can transform insolation into a form of energy that can perform useful tasks. As much as 60 percent of the large initial expense of the solar energy conversion systems is for labor [4]. Since labor costs in the developing countries are much lower than in industrially developed countries, the installed cost of a solar system could be considerably less. Furthermore, since many developing countries have no indigeneous oil resources, the price of the cheapest competing energy source, which is usually imported oil, is considerably higher than, for example, in the U.S. Thus, a solar industry, utilizing local labor and materials as much as possible, may be cost-effective today or in the near future for many applications in developing countries.

1.2 Industrialized versus Developing Countries

Of the existing solar technologies, parabolic trough and flat plate solar collectors have a more-or-less fully developed technology, and they are commercially available in the U.S. Parabolic Trough Collectors (PTC's) are capable of supplying thermal energy over a wide range of temperatures (up to about 305°C), and therefore they can be used for a variety of applications ranging from electricity for rural applications (agricultural pumping) all the way to industrial hot water and steam production. Consequently, at present, they are the best candidates

for widespread use in developing country energy applications.

In mounting an effort to encourage the utilization of PTC's in developing country energy applications, however, it is important to be fully aware of the differences in design philosophy and design objectives between industrialized and developing countries. In an industrialized environment* like the U.S., design goals and objectives for PTC's included [5]:

- High performance -- thermal efficiences of 60-70% at 600°F (305°C);
- Designs suitable for mass-production;
- Low-costs achieved with low-labor, mass-production materials and processes.

On the other hand, in a semi-industrialized and technically less advanced environment (e.g., developing countries), design goals and objectives for PTC's include the use of:

- designs which require small capital investment in new production facilities and raw material and which depend heavily on local labor;
- locally available materials and technology with minimum dependence on imported materials and components;

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*Throughout this report 'environment' is defined as a country (or region) with certain given economic and technical capabilities.

- designs that require no sophisticated maintenance.

The problem is then to satisfy the goals and objectives of designs in developing countries with an'information base' derived from industrialized countries. However, the questions that need to be answered first are:

1. Is the current 'information base' in PTC technology comprehensive and flexible enough to be used in developing PTC designs suitable for developing country energy applications?

2. Can the design methodology used for designing PTC's in the U.S. be duplicated for designing PTC's for applications in developing countries?

An extensive search of literature and communication with the researchers in the world's leading laboratory in PTC technology, Sandia National Laboratories, Albuqurque, N.M., unveiled a wealth of scientific information on PTC analyses and performance evaluations [6- 14]. These included numerous studies on optical and thermal analyses as well as studies on manufacturing techniques, selective coatings, methods for reducing slope errors, flexible hose design, materials improvement, wind loading, etc.

With regard to design methods and optimization aspects of PTC's, however, very few studies were found to exist [15- 18]. After carefully studying the available literature, it was

concluded that:

- state-of-the-art PTC modeling was not comprehensive enough to be utilized for performance simulations in a comprehensive design method which would incorporate changes in the design environment, and
- a comprehensive design method for designing PTC's (i.e., a method which would incorporate different environmental goals and objectives along with technical and manufacturing constraints to produce an 'optimal' design) did not exist.

The development of comprehensive simulation models for optical and thermal analysis of PTC's were presented in a previous technical report [1] issued as a result of this project. It was shown that the developed optical and thermal analysis models could be used for analysis of designs in both industrialized and developing country design environments. Therefore, in this report the attention will be directed at developing comprehensive design methods in which the analysis models developed in reference [1] could be used effectively.

In the following section the reasons for the deficiencies that existed in the PTC design methods at the beginning of this investigation are discussed.

1.3 Discussion of the Problem

1. In the U.S., PTC designs have emerged as the result of an evolutionary process. Design decisions concerning the

environmental goals, objectives and constraints were made implicitly in an ad hoc manner as the PTC technology evolved. Consequently, the 'optimum' PTC designs for the U.S. design environment were developed without the use of a structured formal design method. However, now that the PTC technology development is more-or-less complete and the adaptation of this technology to different design environments that have different goals, constraints and objectives (namely, developing countries) is being proposed, there is a need to formalize the design method of PTC's.

2. As a direct consequence of the 'low-labor mass-production' goal of the U.S. design environment, research efforts were invested in the development of one 'standardized' PTC design for all applications and geographic locations throughout the U.S. The 'transportable', 'standard' PTC design concept is emphasized in almost all the available studies. For example, Treadwell [14], in a study investigating the influence of geographic location on the PTC performance, stated:

> "... a single-axis tracking parabolic trough solar collector could have a common optimum design for use in all regions of the U.S. This determination has an impact upon mass-production of troughs since different geometric configurations might be optimum for different regions of the U.S. and could result in multiple production lines and controlled distribution. Neither is

> necessarily compatible with the desired cost reductions that could result from <u>large volume production</u>."

Sandia researchers, for example, chose a 2m-aperture width 90°-rim angle reflector and a 2.5cm-diameter cylindrical receiver with selective coating for their 'high quality' PTC design.

In developing country design environments, big mass-production facilities and large-volume production (which require efficient transportation-distribution systems too) may be out of question. Instead, small-scale labor-intensive, 'distributed production shops' may play a more important role in cost-effectiveness and hence widespread use of PTC's. Therefore, different geometric configurations can be considered for different locations (just the opposite of the ONE optimum design philosophy stated above). In fact, in such environments 'redesigning' PTC's for different applications and locations may be a <u>must</u> to compensate for performance reductions resulting from poor manufacture and/or poor maintenance. However, redesigning PTC's for every 'new' application and location may prove to be a very tedious and elaborate job. Therefore, it is desirable to have a comprehensive design method which can produce an optimum PTC design quickly and effectively with no (or few) iterations.

1.4 Objectives and Outline of Study

The main objective of the study is to develop a rational approach to formalize the design method of PTC's. This formal design method is required to be comprehensive and general-purpose. Therefore, it should incorporate:

- a general-purpose, comprehensive PTC performance simulation model,
- options to handle changes in the design environment, i.e., changes in: design goals, design objectives, infrastructure, social limitations, economic limitations and technological capabilities;
- as much of the existing PTC 'information base' as possible;
- information about the previous design experiences;
- an effective method for multi-objective optimization to produce an optimal design for a given design environment with few iterations.

The development of the formal design method for PTC's is presented in the next six chapters.

In Chapter Two, an introduction to the PTC design problem is presented. PTC subsystems and problem areas are identified. Interaction between the subsystem designs and the multi-objective nature of the overall design problem is highlighted.

In Chapter Three, the characteristics of the conventional design method are explained. The shortcomings and disadvantages of the conventional design process are discussed

and the need for a new approach for multi-objective design of PTC's is established.

In Chapter Four, a computer-based design method is proposed, and its characteristics are explained. The building blocks of computer-based design are given; the multi-level nature of design problems is highlighted; and the role of decision making in design is discussed. A two-level design structure (macro-micro) is introduced for handling changes in the design environment effectively. A systematic approach for formulating decision support problems is also presented.

In Chapter Five, the structure of the design problems at the macro-level of design for PTC's is presented. An optimization method for micro-level design is developed. A seven-step procedure for optimizing the concentration ratio is given in which the analysis models from reference [1] are used.

In Chapter Six, the implementation/validation of the design method is given. Illustrative examples are presented; PTC designs for the U.S. design environment and a developing country design environment are developed.

Concluding remarks, discussions and recommendations are given in Chapter Seven.

Chapter Two

INTRODUCTION TO PARABOLIC TROUGH COLLECTOR DESIGN

2.1 Introduction

A PTC consists of a cylindrical parabolic reflecting surface (reflector), a receiver assembly centered along the reflector's focal line and a tracking system. The receiver assembly usually has two components; an absorber surface and a transparent outer cover (glazing). The collector tracks the sun on a continuous basis focusing the sun's rays onto the absorber surface which becomes heated and transfers energy to the fluid flowing through it. The heat transferred to the fluid can provide energy for many types of practical energy applications.

2.2 Design of PTC Subsystems

As shown in Figure 2.1, three major subsystems and consequently three design problems can be identified in the design of PTC's. These are:

1. Reflector design.
2. Receiver design.
3. Tracking system design.

In addition to these, design of various support structures and controls, such as flex tubes and collector stands can be thought of as a fourth design problem area. However,

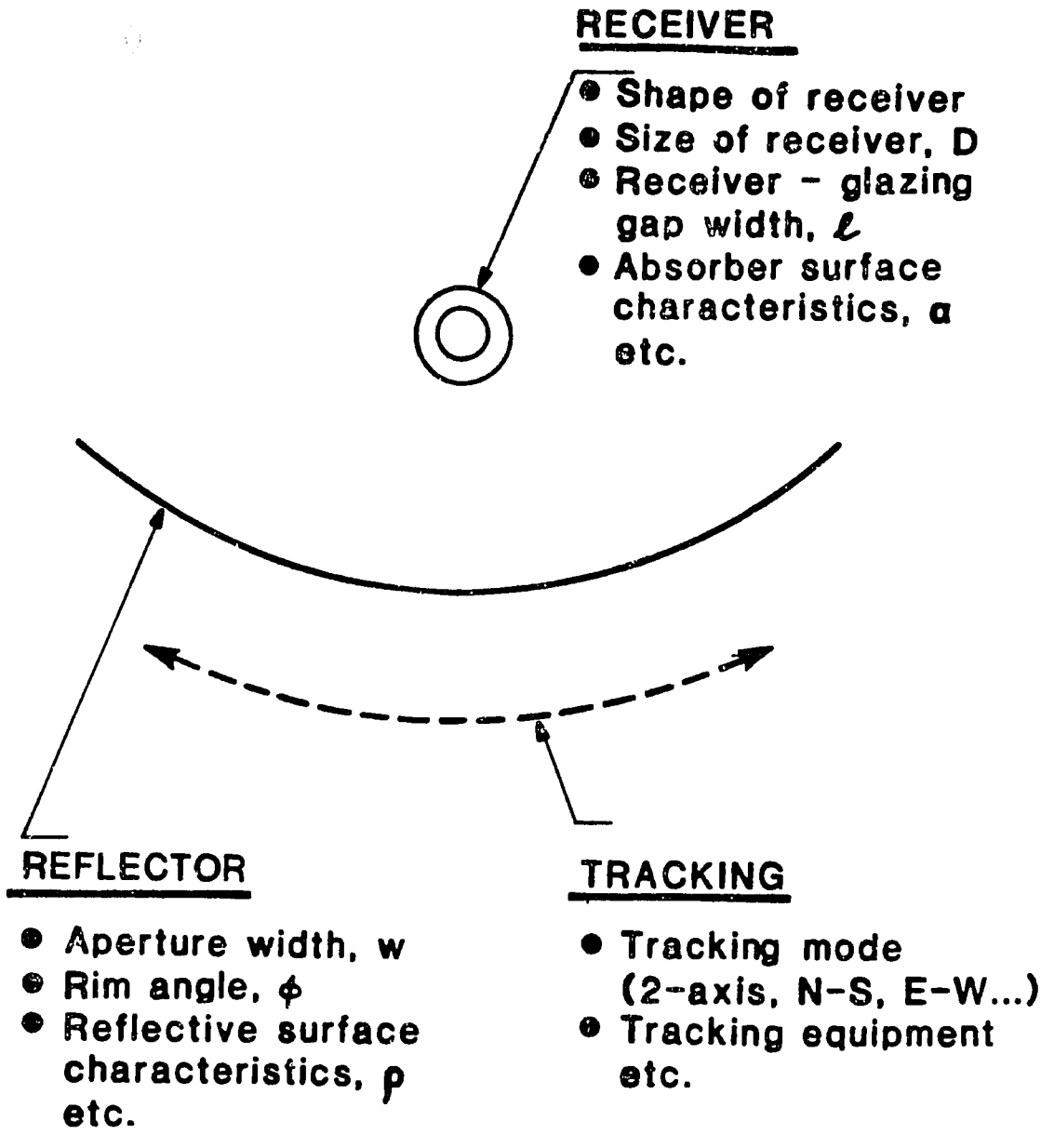


Figure 2.1 Subsystems of a parabolic trough collector system.

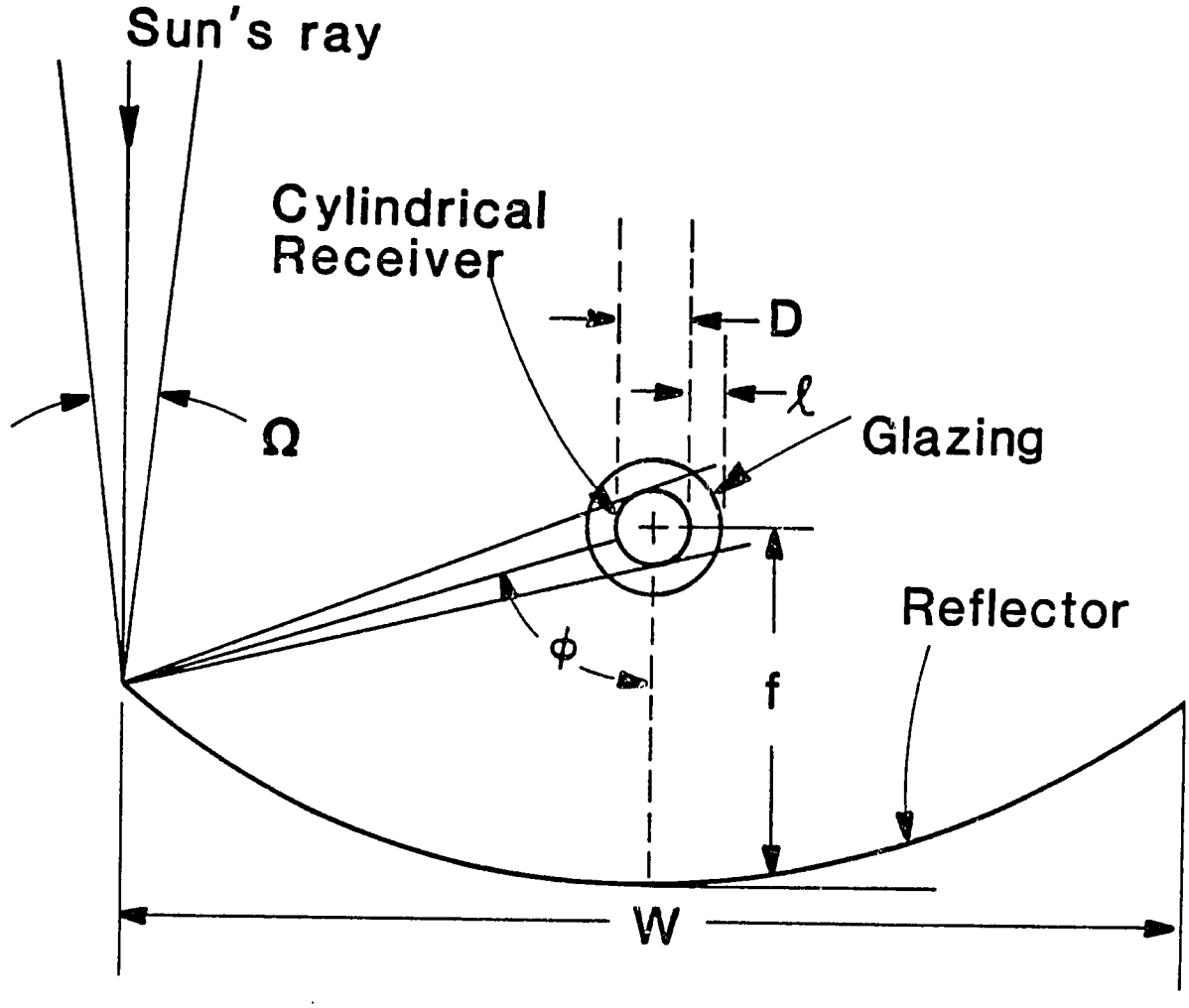
since the design of such components does not directly affect the optical and/or thermal performance of the PTC system, this group of design problems will not be directly addressed in this report.

Common terminology for PTC's and some of the primary design variables for the subsystems are shown in Figure 2.2. In the following sections, description of the subsystems, their respective design parameters and the criteria on which their designs may be based are presented.

2.2.1 Reflector Design

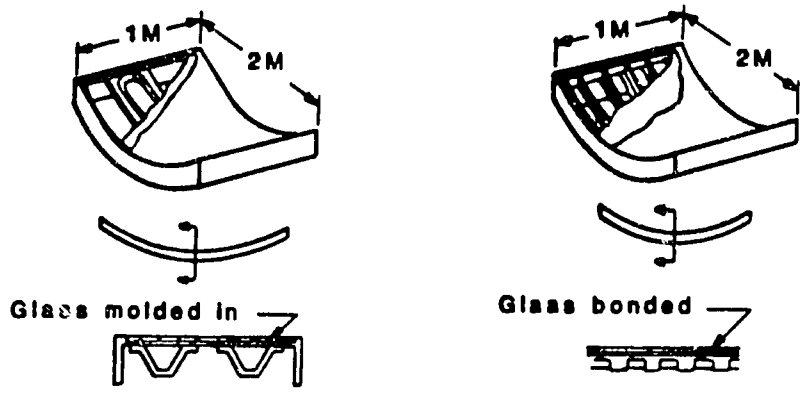
The reflector consists of a reflecting surface and a supporting structure.

The reflecting surface is composed of a thin sheet of material one surface of which is reflective. The supporting structure is usually either a ribbed frame or a sandwich structure. A ribbed supporting structure is particularly suitable for mass-production and consists of a ribbed frame panel attached to a sheet metal skin supporting the reflecting surface. Two ribbed supporting structure concepts are shown in Figure 2.3a; one with reflective material (glass) molded in and one with glass bonded to the surface. A sandwich structure usually requires a laborious production scheme and consists of a front skin, which is usually the reflecting material, a center core and a back skin. Construction of several typical sandwich structures (fiberglass core, plywood laminate, aluminium honeycomb core, and paper core) are shown in Figure 2.3b.

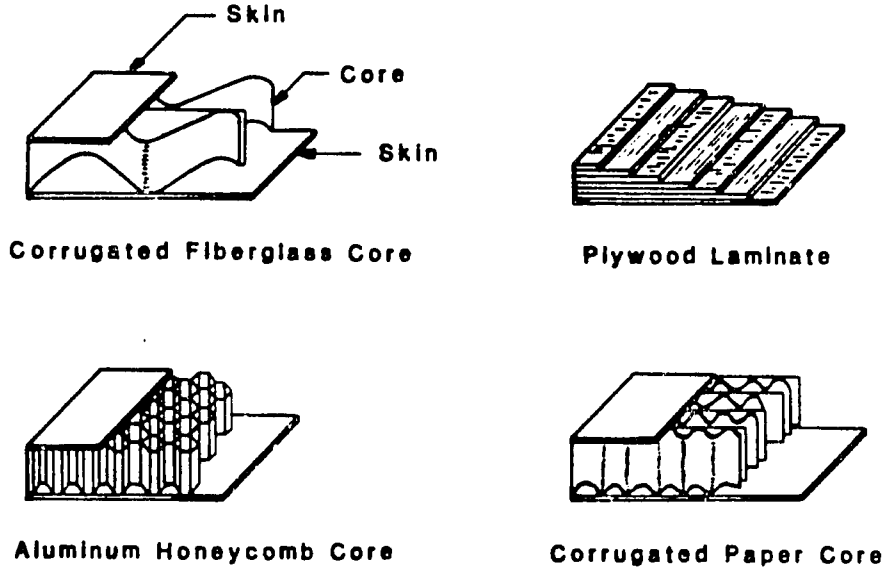


f = Focal length
ϕ = Rim angle
W = Aperture width
D = Receiver diameter
Ω = Acceptance angle
ℓ = Gap width

Figure 2.2 Common terminology and some of the primary design variables of a parabolic trough collector.



(a) Ribbed supporting structures (Budd Co., from Ref. 5)



(b) Sandwich supporting structures (Ref.19)

Figure 2.3 Typical reflector supporting structures.

Design parameters for the reflector design are the reflectivity of the reflecting surface and the geometry (rim angle and aperture width) and contour accuracy of the reflector. For a given application, the designer must design the reflector based on several constraints and criteria such as:

- technological capability of the design environment,
- availability, size and cost of materials,
- design goals of the environment (low-labor mass-production or labor-oriented production),
- manufacturing constraints and/or preferences (e.g., maximum press and mold sizes, ease of manufacture, etc.),
- weight of the reflector,
- wind loading considerations (e.g., stiffness, i.e., mechanical strength of the reflector),
- technical constraints or preferences such as the sensitivity of the geometry to various optical errors, and
- size of the receiver (from the receiver design)

2.2.2 Receiver Design

The receiver consists of an absorbing surface and a transparent outer cover (glazing).

The absorber surface will usually be coated with a selective coating which has a high absorptivity-to-emmissivity ratio. The glazing serves for a double purpose; protecting the coating from environmental degradation and reducing heat losses from the absorber surface.

The shape of the receiver is not critical and any would do (cylindrical, flat, V-shaped, elliptical, etc.), as long as its surface area is small. Over the years, several different receiver geometries have been investigated by researchers. Some of these are shown in Figure 2.4. Preliminary analyses, however, have indicated that a cylindrical receiver geometry is more practical (than, for example, a flat receiver geometry) and easier to manufacture. In fact, ordinary steel tubes available in market place can be used. Moreover, experience and data gathered from collectors with cylindrical receivers have been very favorable. Therefore, for all practical purposes, cylindrical receiver geometry can be taken as the 'optimum' geometry for PTC's.

Since the primary function of the receiver is to absorb and retain as much of the concentrated energy as possible, every effort should be made, besides keeping its surface area to a minimum, to reduce heat losses. The options for heat loss reduction may include:

(i) Evacuating the annulus between the absorber tube and glazing (to eliminate conduction and convection losses).

(ii) Using heavy gases in the annulus (to supress convection losses).

(iii) Covering part of the absorber surface with insulating material (to reduce, mostly, radiation losses, see Figure 2.4b).

Among these options, (iii) is found to be ineffective;

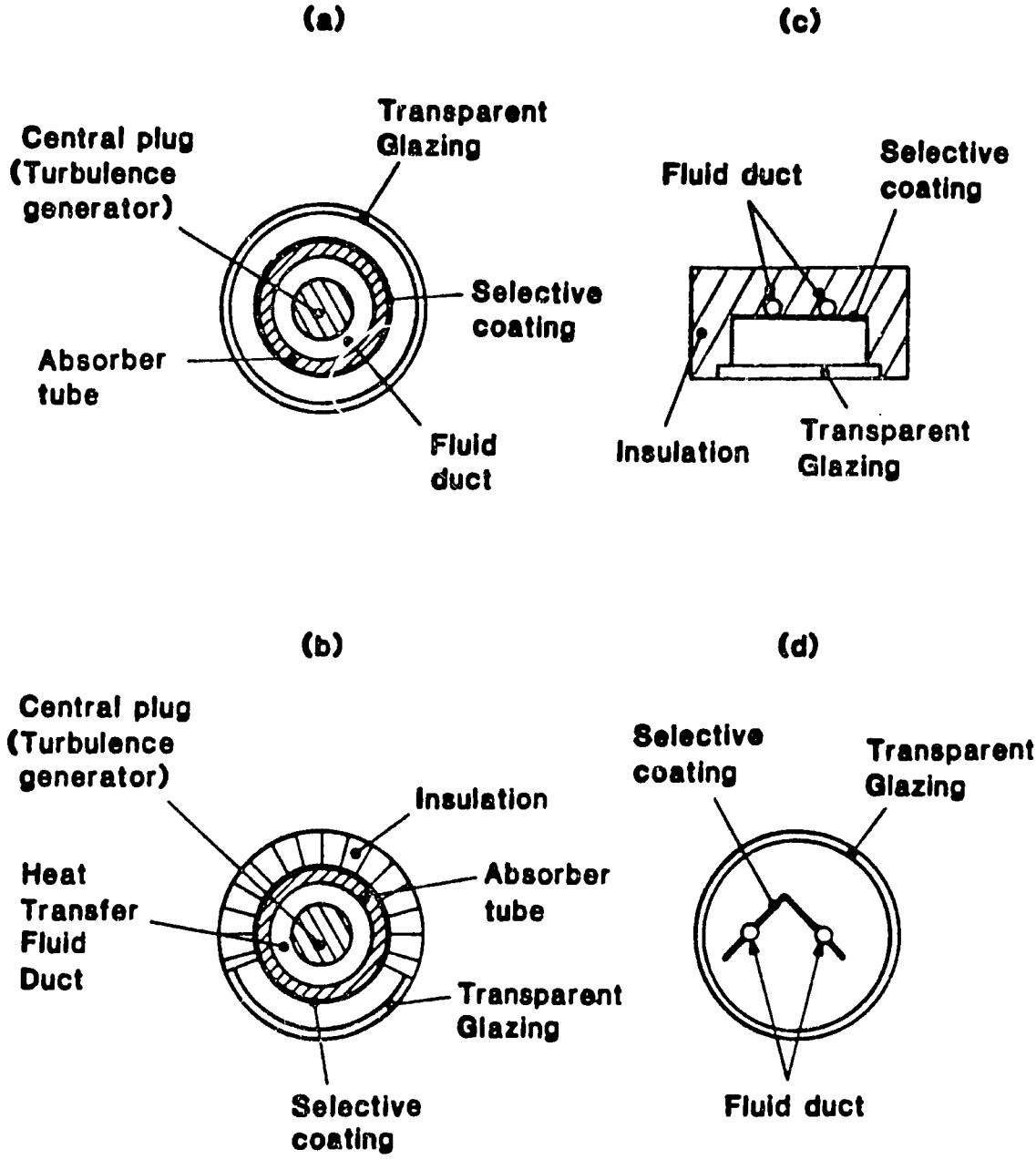


Figure 2.4 Different receiver designs.
(a) Cylindrical receiver with no insulation[5],
(b) Cylindrical receiver with back insulation[10],
(c) Flat receiver[21],
(d) V-Shaped receiver[22].

experience with such receivers have been very unfavorable [20], and therefore they are not recommended unless the absorbing surface has high emissivity [10,23] (greater than 70%). On the other hand even though the remaining two options are found to be effective, they are, unfortunately, at present impractical. Due to leaks, it is very hard to maintain a vacuum or heavy gas in the annulus. The technology in this area is still developing. However, preliminary data and analysis show that efficiency improvements up to 10% can be realized with an evacuated receiver and up to 4% improvement is possible with heavy gasses [23].

In the present work, only cylindrical receivers with no insulation, as shown in Figure 2.4a, are considered. Therefore, the design parameters for receiver design are the absorber tube diameter, the gap width (ℓ, see Fig. 2.2), the absorptivity-to-emmissivity ratio of the selective coating and the transmissivity of the transparent glazing.

As in the reflector design, for a given application, the designer must design the receiver based on several criteria and constraints such as:

- Availability, size and cost of materials.
- Technological capability of the design environment.
- Stiffness of the receiver.
- Size of the reflector (from the reflector design), etc.

2.2.3 Tracking System Design

The tracking system (tracker) will consist of a motor, a gear box and several sensors. The sun may be tracked either along one-axis or two-axes and the design of the tracker (size, power, sophistication and accuracy) will depend on the tracking mode employed. Four alternative tracking modes for PTC's are shown in Figure 2.5.

There are several tracker design concepts. For example, the tracker might be a simple feedback system consisting of a differential photocell sensor mounted on the collector feeding an analog amplifier which, in turn, controls a geared down motor to rotate the collector. As another example, the tracker might be a micro-computer controlled open-loop system with position feedback. In this case a digital clock supplies solar time to a micro-computer programmed to compute the tracking angle. Feedback is provided by a digital shaft encoder on the solar collector's axis of rotation. A geared down motor controlled by the micro-computer maintains a minimum difference between the computed tracking angle and the actual tracking angle.

As part of the tracking system design, the designer will have to choose a tracking mode (N-S, E-W, etc.) and determine the length of a ΔT-string first, and then design or choose the tracker.

Selection of the tracking mode is usually a difficult problem which requires a precise knowledge of the application

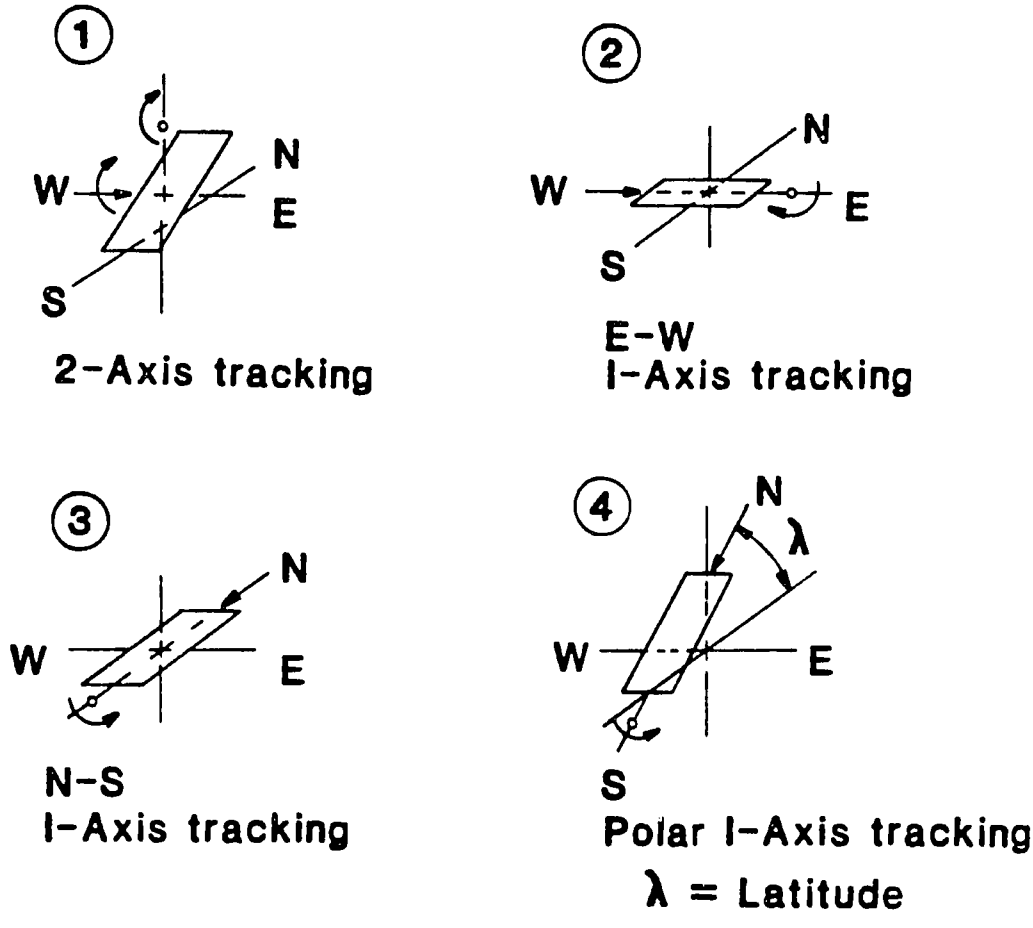


Figure 2.5 Alternative tracking modes for parabolic trough collectors.

and involves several criteria. The criteria for selecting a tracking mode may include:

- Size and orientation of the available land.
- Required annual (or seasonal or daily) heat delivery.
- Relative cost with respect to alternative tracking modes, (e.g., foundation cost, plumping cost, etc.).
- Type of tracker required.
- Consequences of failure, etc.

The design (or choice) of the tracker will then depend on:

- Tracking requirement (tracking mode and length of the ΔT-string).
- Required tracking accuracy.
- Availability, cost, etc.

2.3 Design Synthesis of the PTC System

In the preceding sections the design variables and the design criteria and constraints for the design of PTC subsystems are presented. As shown, the design of each subsystem involves multiple objectives, and there is interaction between them (i.e., design of a PTC subsystem cannot be carried out independently).

With a given requirement for heat delivery at a specified output temperature, the designer must design the subsystems based on their respective criteria and several system goals and constraints such as total cost, total weight and efficiency of conversion. For this, it is necessary to

have a design method in which the multiple design objectives and interactions among subsystems can be dealt in a rational and effective manner. Moreover, this method should be such that, in addition to the usual performance related parameters (e.g., reflector geometry, receiver diameter, etc.), it should incorporate information about the design environment (goals, constraints, objectives, etc.), thereby enabling the designer to cope with change in an efficient manner. Also, it should be a flexible method which can be used

- to design a PTC system which satisfies certain specifications;
- to design components (subsystems) of a PTC system;
- to modify an existing design of a system or component to satisfy a revised set of specifications;
- to modify an adequate design in order to obtain a superior design;
- to incorporate new technology or changes required as a result of field tests.

As is the case in any design, however, development of such a method will first require the development of a good analysis model (i.e., a comprehensive performance simulation model). Such an analysis model was presented in Reference 1. Therefore, this report will emphasize the development of the mathematical underpinnings of the models of use in design synthesis.

2.4 Summary

In this chapter an overview to the PTC design problem was given. PTC subsystems, constraints and criteria for design

of the subsystems and primary design variables for each subsystem were identified.

Interaction between the subsystem designs and multi-objective nature of the overall design problem were highlighted. Consequently, the need for a comprehensive approach for designing PTC's was established. The characteristics of conventional design methods is presented in the following chapter.

Chapter Three

CHARACTERISTICS OF CONVENTIONAL DESIGN METHOD

3.1 Introduction

In this chapter, the conventional design process and its characteristics are discussed. Then, the shortcomings and disadvantages of the conventional design process are discussed and the need, for a rational approach (which incorporates multiple objectives) in the design of PTC's for developing countries, is established.

3.2 Conventional Design Process

As many engineering systems are, by definition, made up of inter-related subsystems, they are often too complex to be handled in their entirety. It is, therefore, necessary to decompose a system into smaller subsystems.

In the conventional design process, the problem, after the system is decomposed into smaller subsystems, is one of sequential design. In other words, the conventional design process may be viewed as the cyclical approach to design. This is illustrated in Figure 3.1 and elaborated in Figure 3.2.

As shown in the Figures 3.1 and 3.2, the conventional design cycle comprises of four operational stages - Feasibility, Preliminary Design, Detailed Design and Revision - through which the design is developed to completion using an iterative (cyclical) scheme. Each of the four design stages are briefly

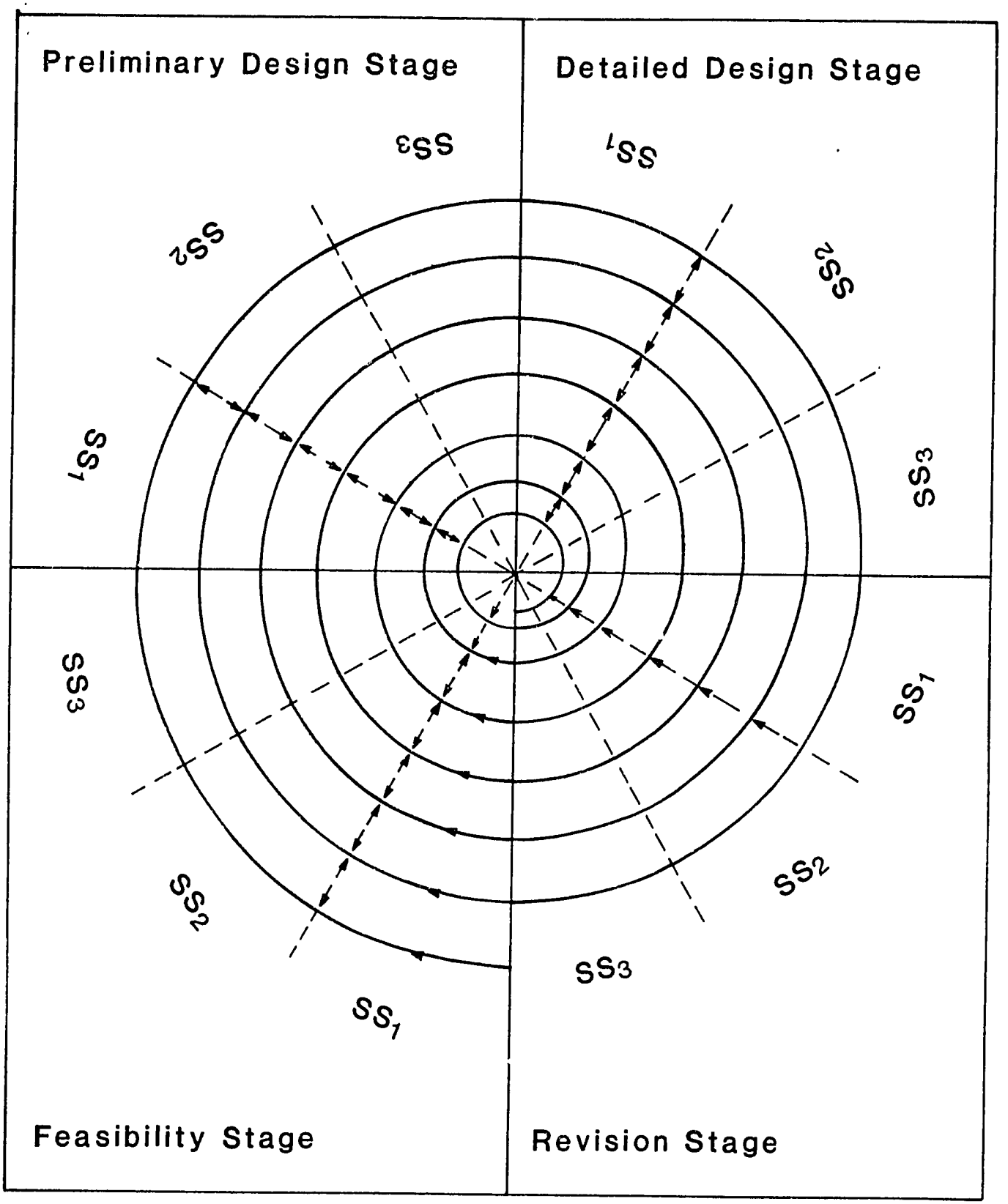


Figure 3.1 A cyclic approach to design (from [24]).

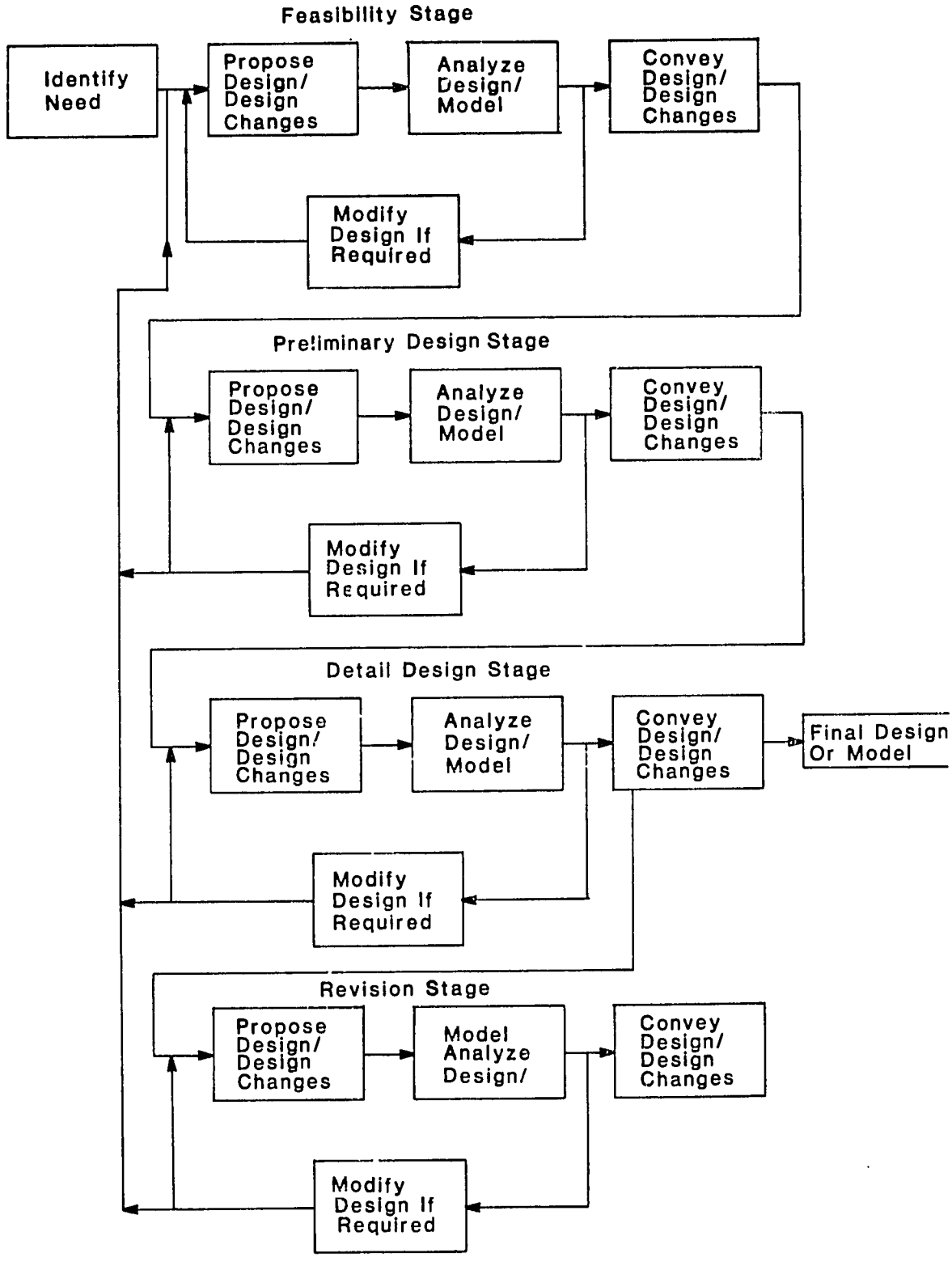


Figure 3.2 The four stages of the conventional design process (from [25]).

discussed in the following sections [26].

Feasibility Stage

In this stage, the engineers study needs and requirements and determine whether the problem is technically, economically and financially feasible. General ideas and concepts about the design are generated and evaluated. The input of this stage is all the available information from all related sources, not necessarily only engineering information. The output of this stage is the result of the evaluation of the design. Usually, the output of this stage is a written or oral report which includes a statement of recommendation. The recommendation is either to accept or to reject the project. If the project is accepted, it will be carried on to the next stage of design which is the preliminary stage. However, if the project is rejected, no further design activities will take place until it is reinitiated.

Preliminary Design Stage

The preliminary stage of design is divided into two parts. First, the best alternative is selected from the feasible alternatives developed in the feasibility stage, based on technical and economic criteria. In the second part this alternative is developed to the stage where the basic characteristics of the system are established. All major design, such as material, power source, basic dimensions, etc., are made in the preliminary design stage.

Detailed Design Stage

The detailed design stage consists of all the activities required to produce the complete, detailed specifications of the elements recommended for the final product or process. The output of the detailed design stage consists of engineering drawings, material lists, assembly instructions and quality control documents. All decisions about the performance, construction or appearance of the final product are finalized in this stage.

Revision Stage

Once the product or process has been placed in service, or upon the completion of a prototype, field experience may form a basis for further design improvements. This process is called the revision stage.

3.3 Characteristics of the Conventional Design Process

In the cyclical (conventional) approach to design, the principle of iteration is prevalent as shown by the arrows in Figures 3.1 and 3.2. Iteration is used to improve the design at each stage of the process. There is also iteration between the design stages. The designer may proceed through the stages to the detailed design and then be forced to return to the feasibility stage because the design does not meet all the requirements. This is usually because of the sequential nature of the process which leaves out the interaction between the subsystems. Nonetheless, through subsequent iterations, interactions

between the various subsystems (SS_1, SS_2, SS_3, etc. in Figure 3.1) can be accounted for - interactions that were overlooked in the first pass are usually captured in the subsequent design cycles - and therefore a properly functioning system (as judged by the specifications) can finally be obtained. A certain degree of 'optimality' may also be achieved but only with a considerable additional amount of time, effort and resources.

Figure 3.2 shows that the activities within each design stage to be essentially the same, which tends in practice to result in considerable repetition of the design effort. This problem is compounded since each stage of the design process is usually undertaken by a separate design group. The design tasks within each stage of the design process are completed sequentially by specialized engineering teams. Only those tasks which are independent, i.e., do not affect any other design task, can be completed simultaneously or out of sequence.

3.4 Shortcomings of the Conventional Design Method and the Need for a New Design Process for PTC Design in Developing Countries

Some of the major characteristics of the conventional design method as applied to PTC designs for developing countries are discussed below.

1. Due to its sequential and iterative nature, this process requires a large expenditure in time and human resources. Therefore, the cost of undertaking

such a complex and elaborate effort can only be justifiable for objects which are to be produced in large volumes such as cars, planes, tractors or ships. The prototype troughs, Figure 3.3, installed at Sandia National Laboratories in New Mexico can be cited as an example of the outcome of such an iterative design, research and development effort.

2. In this process, the design is usually optimized (or further optimized) by small improvements from one generation of the product to the next. Acurex collectors 3011-01, 3011-02 and 3011-03 can be cited as examples of the improvements from one generation of the product to the next. Table 3.1 shows the design changes that took place from 3011-01 Acurex Prototype Collector to 3011-02 Acurex Production Collector. Table 3.2 shows the comparative performance of two different generation of Acurex collectors, namely, 3001-03 and 3011-03. As shown in these tables, small design changes take place from one generation of the product to the next, and hence the design is optimized in small steps.

3. In the conventional design process, decisions related to environmental constraints, preferences, capabilities and goals are hidden in various stages of the process. In other words, environment-related decisions (e.g.,

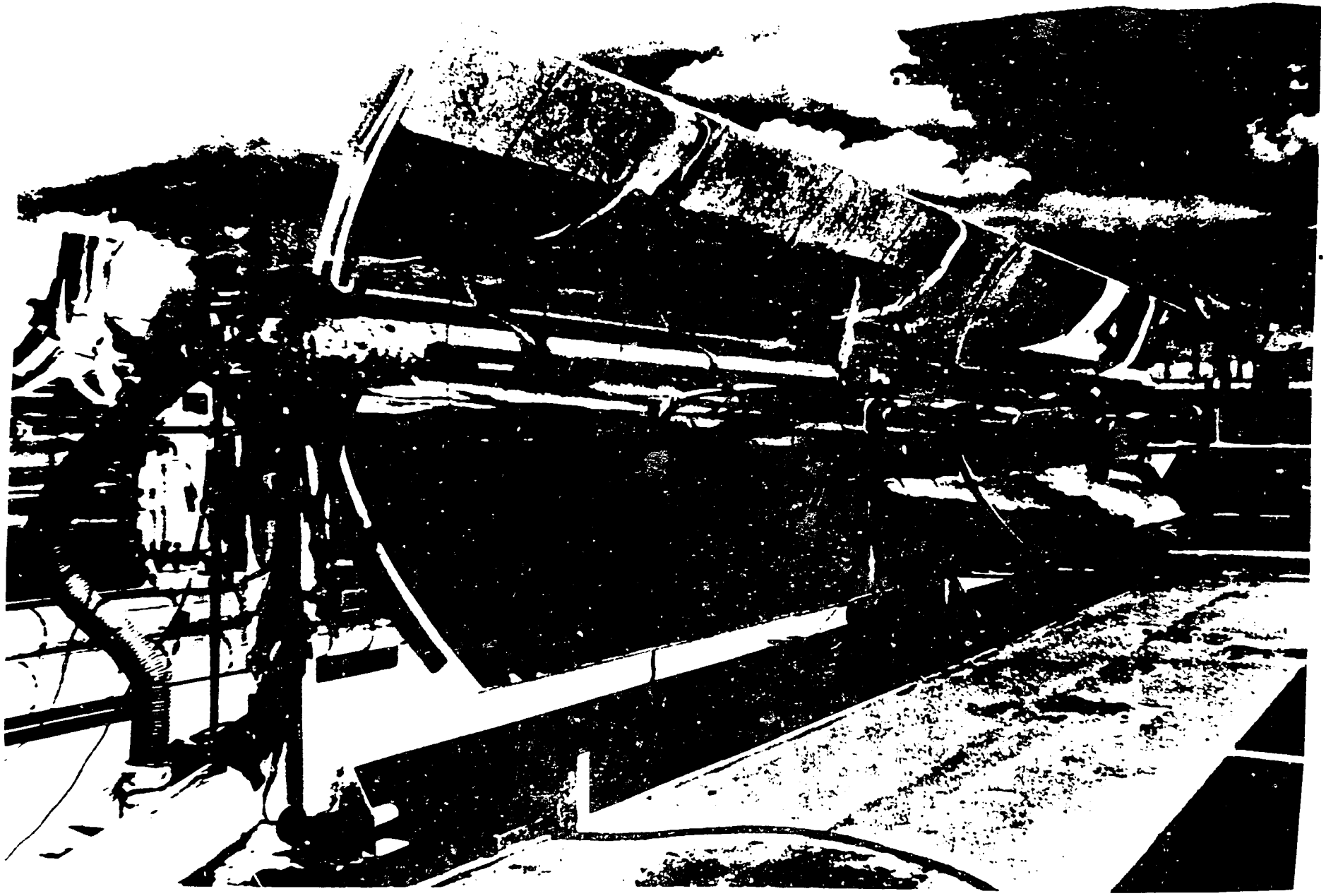


Figure 3.3 Parabolic trough solar collectors installed at Sandia National Laboratories, Albuquerque, New Mexico.

TABLE 3.1 ACUREX 'PRODUCT ENHANCEMENT' PLANS*

3011-02 Production Collector -- Changes from 3011-01 Prototype

- Antireflective receiver glazing[a]
- Eight modules per group (six)[b]
  - -- Recent wind data allow extension
- One piece rib (three)
- Three glass sheets per panel (two)
  - -- Sheet interfaces are no longer at the maximum stress location
- Welded end cranks on both ends of torque tube (one bolted)
  - -- Deformation in production processes found to be insignificant
- Receiver plane tracker mount
  - -- Improved daily performance
- Stainless-steel receiver tube (carbon steel)
  - -- Improved black chrome processes and life
- Five rib-to-flange rivets (nine)

Under Development

- Evacuated receiver
- Improved receiver selective coatings
- Improved reflective systems
- More flexible master control
  - -- Interact with process load
  - -- Integration of energy output

[a] Incorporated into MISR system
[b] Parentheses refer to 3011-01

* Taken from Reference 27.

TABLE 3.2 COMPARATIVE PERFORMANCE AND COSTS OF ACUREX 3001-03 AND 3011-03 COLLECTORS*

Parameter	Collector		Percent Change
	3001-03	3011-03	
Module size	6 ft x 10 ft	7 ft x 20 ft	--
Group length	120 ft	120 ft	--
Row spacing	20 ft	20 ft	--
Reflective surface	FEK	Mirror glass	--
Normal efficiency			
• Optical intercept	0.64	0.81	27
• T_{ave} = 372°F (189°C)	0.57	0.68	20
• T_{ave} = 572°F (300°C)	0.46	0.59	29
Gross output[a] (million Btu/ft^2-yr)	0.323	0.433	34
System losses	10 percent	10 percent	--
Net output[a] (million Btu/ft^2-yr)	0.291	0.390	34
Collector system cost	--	--	32
Shipping cost	--	--	71
Installation cost	--	--	76

[a]Phoenix, Arizona; T_{ave} = 372°F

*Taken from Reference 27.

technological capabilities, socio-economical restrictions, import regulations, etc.) are made implicitly at various stages of the design process and the outcome of the process, the final product, has built-in environmental preferences, capabilities and goals. For example, Sandia's prototype collectors shown in Figure 3.3 are optimized for the U.S. design environment, and therefore they have built-in preferences to U.S. technology and built-in requirements for competitiveness in the U.S. market (e.g., low-labor production, suitability for mass-production, modularity, transportability, etc.).

In the conventional design process, a decision made at the feasibility stage concerning the method of construction (due for example to economic competitiveness of the product and/or technological capabilities of the environment) undoubtedly affects the final design. Therefore, the process and its outcome has little or no flexibility to changes in design environment. The whole process, from beginning to the end, has to be repeated for every new design environment.

As discussed above, development of a technically feasible and economically competitive design for a given design environment, using the conventional design process, is a lengthy task.

Furthermore, in this process, the 'optimum' design* (for a particular design environment) is usually achieved by considering the environmental objectives one-at-a-time. Therefore the process, inherently, involves excessive iterations which make the undertaking of such a task worthwhile only for design of objects which can (or will be) produced in large volumes (as indicated earlier).

For developing countries, however, large volume production of a 'standardized' trough design may be out of question; different optimum trough designs may have to be developed for different applications and geographic locations (or regions), with probably little or no standardizations in the designs. Furthermore, design goals and environmental constraints (e.g., technical, social, etc.) may vary considerably within the same country (e.g., urban design environment versus rural design environment). Therefore, for the present design problem, it is required to have a design methodology (or process) which has the following features:

- It should produce an optimum design with few if any iterations, thus reducing the time, effort and cost

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*The 'optimum' design for a given design environment is defined as one which meets all the design requirements/specifications as well as achieving as far as possible all the environmental preferences and goals.

involved in the design process. Thus, the 'redesign' of troughs for every new application and location becomes feasible.

- It should single-out environment-related decisions hence enabling the designer to cope with changes in the design environment effectively.

In order to display the above features, the 'new' design method should incorporate:

- a computer, not necessarily a mainframe, for speedy handling of design calculations; (Computer hardware requirements should be targetted to a small (and cheap) computer that is available in developing countries too.)
- some sort of division in the overall design problem in order to achieve the best distinction between the analyses and decisions that are environment independent and those that are environment dependent;
- decision support problems (or procedures) to handle 'hard' information (based on scientific principles) as well as 'soft' information (experience-based insight of the designer);
- multiple-objective optimization in order to identify the feasible design space and aim at the target, the common optimum based on all the environmental objectives, quickly and effectively.

In the following chapter, a computer-based design method which

has the preceding features is proposed and its characteristics are explained.

3.5 Summary

In this chapter, first, the stages and characteristics of the conventional design method were presented. Then, the shortcomings of the conventional design method and the need for a new multi-level and multi-objective design process for PTC design in developing countries was established.

Chapter Four

A COMPREHENSIVE COMPUTER-BASED DESIGN METHOD FOR SOLAR APPLICATIONS IN THE DEVELOPING COUNTRIES

4.1 Introduction

In this chapter, a comprehensive computer-based design method is proposed for designing solar systems for solar applications in developing countries. This computer-based approach enables a designer

- to design a system with minimum number of iterations;
- to handle changes in the design environment effectively, i.e., account for changes in the design objectives and incorporate changes in the environmental constraints;
- to incorporate previous design experiences into the design and hence make viable design decisions;
- to optimize the design as efficiently as possible.

In the following sections, the structure and method of formulation for the computer-based design method will be presented.

4.2 Overview of the Computer-based Design Concept

The computer-based design approach is shown in diagram form in Figure 4.1. In this approach, the computer is indispensible since it is the basis for the approach [26]. In the figure, the computer is shown at the center of the design process under the control of the design team and linked to the data base. The

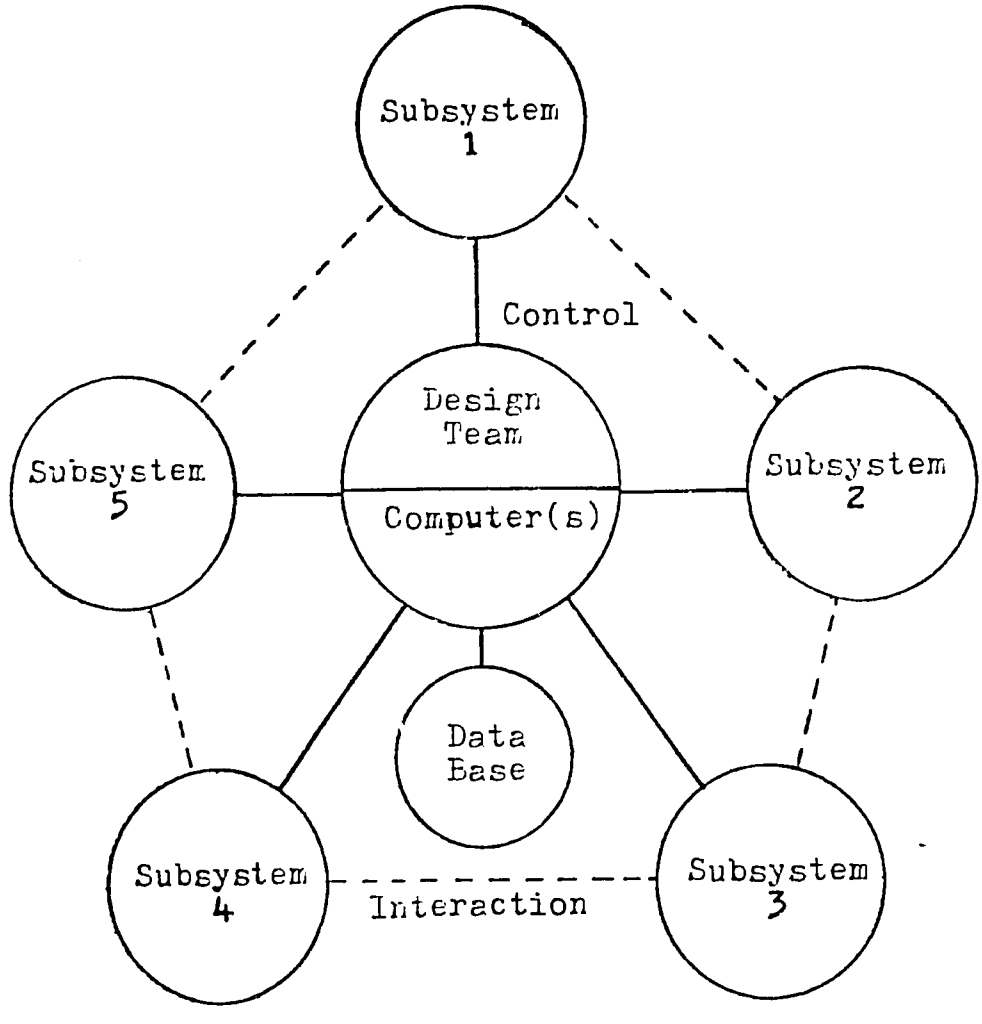


Figure 4.1 Computer-based Design (from [26]).

subsystems shown represent actual components of the whole system or individual aspects of the design. (In PTC design, for example, three of the subsystems might be the reflector, the receiver and the tracker.) The subsystems are shown surrounding the computer to indicate that they are all of equal importance, all directly co-ordinated by the computer, and are all handled simultaneously. The individual subsystems are not independent and there is interaction among them.

The advantages of this computer-based method are as follows [26]:

- interaction among subsystems leads to a superior design in all aspects with few iterations,
- multiple design objectives can be dealt with in a rational and effective manner,
- duplication of design effort is reduced to a minimum,
- a division in the design problem as environment-related design activity and environment-independent design activity (i.e., multi-level design) can be incorporated,
- the expenditure in time and human resources is reduced, and
- the method produces 'optimal' designs instead of simply acceptable (or functioning) designs. (Since all the design activities are carried out on the computer, concurrent access to optimization software at different stages of the system/subsystem designs yield superior designs.)

The data base is an important component of the computer-based design process; it provides data for all analysis and synthesis activities. The data, in the data base, include all the information relevant to the design problem at hand. For design of solar collectors, for example, the data base should include data on:

1. methods of construction and manufacturing techniques (their availability, cost, etc.);
2. available equipment (e.g., pipes, pumps, heat exchangers flex hoses, trackers, etc.);
3. available materials and their properties (e.g., selective coatings, glazing tubes, glass covers, reflective surfaces and mirrors, etc.);
4. labor (e.g., labor skills, costs, etc.);
5. regulations and other constraints (e.g., standards, import regulations, taxes, safety codes, etc.).

In the computer-based design process, all the design activities are carried out using the computer. Thus, the data base is accessible for all design subsystems at all times.

The traditional phases of design, i.e., feasibility, preliminary, detailed and revision, have no clear definition in computer-based design. Each design activity is completed to the greatest possible accuracy and reliability at any given time. The enormous speed and relatively low cost of the computer means

that a detailed design may be produced for less cost in terms of time and money, than a simple conceptual design using the traditional approach.

4.3 Building Blocks of Computer-based Design

In the following subsections, the building blocks and the underlying philosophy of the computer-based design concept are presented. First, the relationship between design and decision making is discussed: the common characteristics of engineering systems are identified, and the types of problems encountered in the design of engineering systems are described. Second, the design structure of the engineering systems for computer-based design is given.

4.3.1 Design and Decision Making

Engineering systems can be characterized by the following descriptive statements [25]:

- the problems associated with the systems are multi-disciplinary;
- the problems require multi-level decisions;
- there are multiple measures of merit;
- the measures of merit may not be equally important to the final decision;
- all of the information required for making a decision leading to an adequate design may not be available;

some information may be 'hard' (i.e., based on scientific principles) and some information may be 'soft' (i.e., based on the perceptive judgment of designer).

Problems encountered in the design of engineering systems can be categorized as [28]:

- Analysis problems
- Synthesis problems
- Problems requiring intuition, experience, etc.
- Non-technical problems

Analysis is the process of testing a concept (design) for its capacity to satisfy demands placed on it. Analysis pertaining to various disciplines can usually be performed independently of each other. For example, the optical and thermal analyses of PTC's (presented in the first technical report [1]) were carried out independently of each other. Analysis is unidisciplinary in nature; scientific and mathematical principles are used to develop hard information on the system's performance.

Synthesis is the process of creating or modifying an existing concept to satisfy the demands on the system. Unlike analysis, this process requires interaction among the various scientific disciplines and therefore requires information which is multidisciplinary in nature. Scientific as well as experience-based insight and intuition form the information base of the synthesis process.

Analysis problems generally provide one unique answer. The solutions are either 'right' or 'wrong' depending on the

information and knowledge available for solving these problems. For synthesis problems, however, there is no (one) 'right' or 'wrong' answer. Instead there may be many possible solutions; some of which are adequate, others which are inadequate and a few which are superior.

The task in solving a synthesis problem is to identify the set of superior solutions. Undoubtedly, this would require making decision(s), at some stage of the process, so as to eliminate the weaker solutions and keep the superior ones for further consideration. Therefore, it can be deduced that design activities deal mostly with decision making, and a 'good design' is usually the outcome of a series of good decisions. Since impulsive decision making is usually unproductive and is not conducive to good decision making, the structuring of all information available for a problem is essential in making good decisions. It is possible to structure all the available information, technical as well as non-technical, in the form of Decision Support Problems [29]. The types of decision support problems (DSP's) that will be discussed in this report are:

- Selection DSP
- Compromise DSP
- Coupled Selection-Compromise DSP

Briefly, selection entails choosing one alternative from a number of feasible alternatives without modification whereas compromise seeks to improve a particular alternative through modification. Selection and Compromise DSP's will be discussed in greater detail in later sections.

4.3.2 Multi-level and Multi-objective Design [24]

It is often necessary to decompose an engineering system into smaller subsystems in order to allow for its analysis and design. It is, however, important that these subsystems are organized in a way that all the interactions among them are retained. This therefore requires that some sort of a hierarchy is established among the subsystems. The structure of a three-level design system is shown in Figure 4.2. An example of a design system is shown in Figure 4.3; the PTC system is subdivided into four hierarchical levels. The main system is represented by (1,1). (The main system is also known as the parent system -- PS -- of level 1 [24].) The PS is divided into three subsystems (SS):

$(SS)_{21}$ -- Reflector

$(SS)_{22}$ -- Receiver

$(SS)_{23}$ -- Tracking

Then each one of the subsystems are further divided as shown in the figure.

For each subsystem in the design system, a decision support problem is formulated in terms of subsystem variables. For the PTC system (Figure 4.3), for example, the reflector supporting structure involves, as one of the DSP's, the 'selection' of the appropriate material to build the structure which will withstand the wind loads and environmental conditions (among other things). As another example, the 'selection' of the absorber surface coating properties, which will allow the

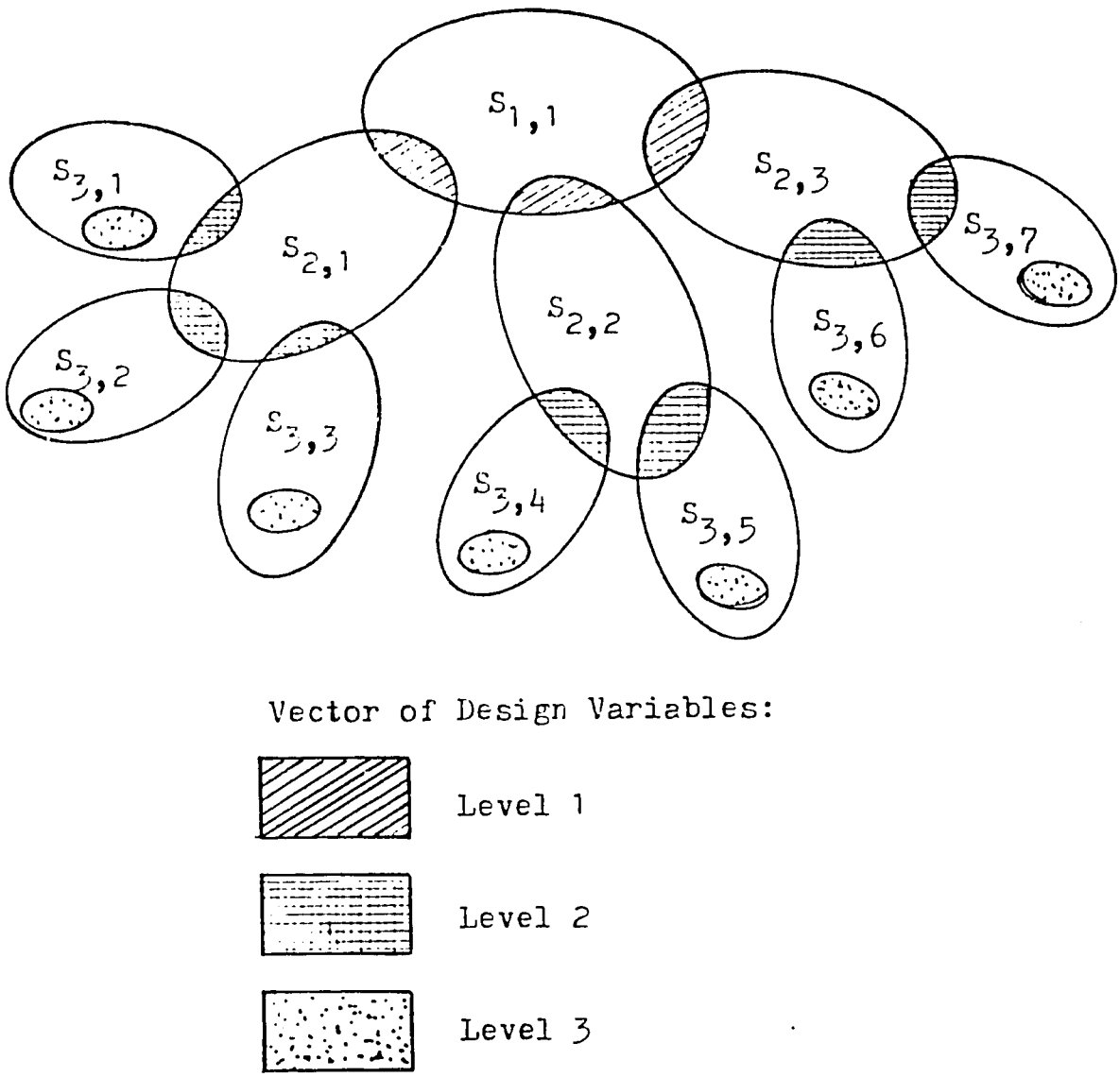


Figure 4.2 A Venn Diagram for a Three-level System (from [25]).

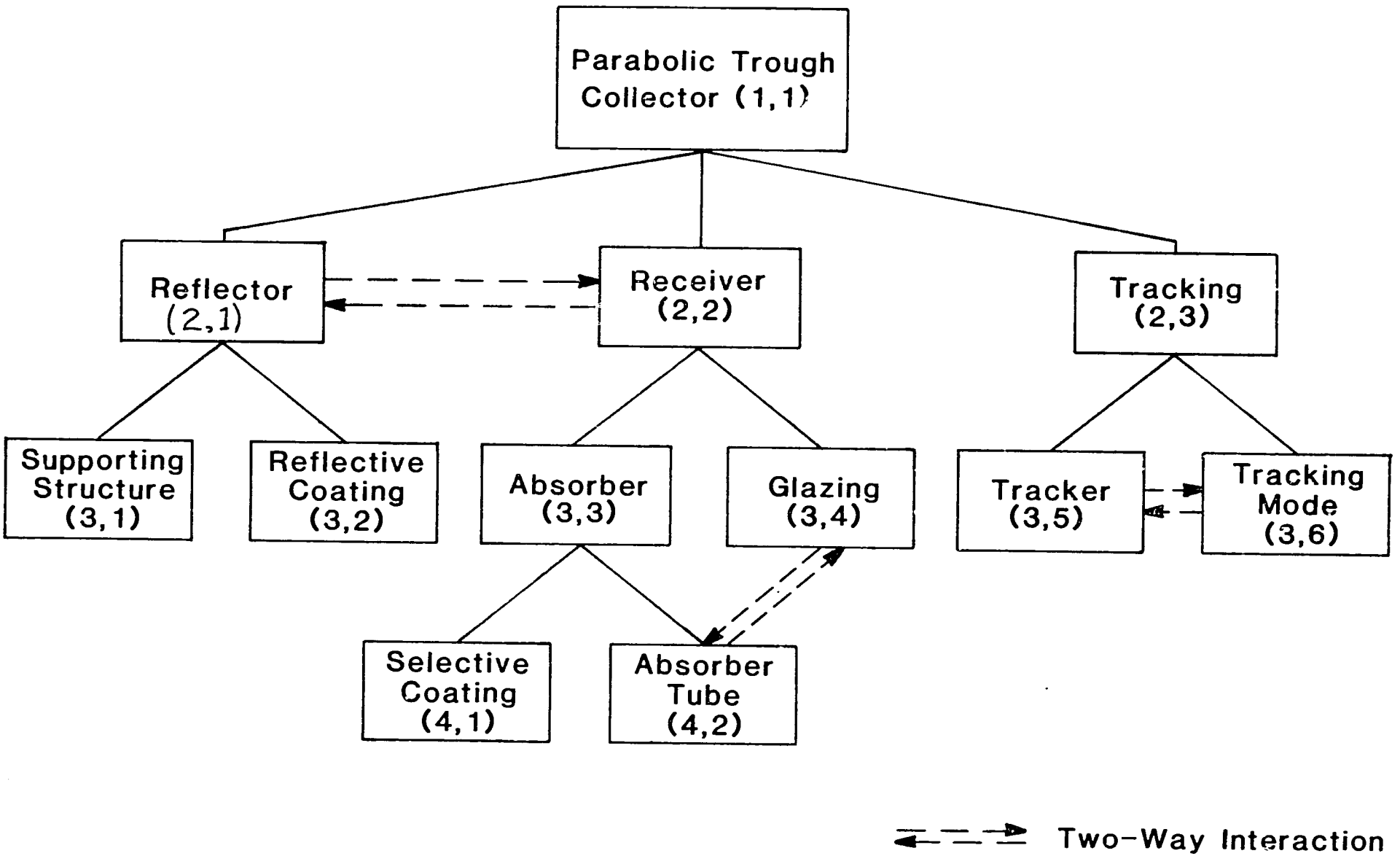


Figure 4.3 Multi-level design system of a parabolic trough collector.

collector to operate at the required operating temperature, can be cited. Thus, the design problem is transformed to a set of decision support problems, and then the DSP's are integrated into one multi-objective problem.

Once the problem is constructed as a multi-objective problem, then it can be solved on a computer. In this way, all variables in all subsystems are determined simultaneously, and the system objectives are satisfied simultaneously according to the assigned hierarchy. Thus, the interactions among subsystems are accounted for; the number of iterations and duplication of design effort are minimized; and therefore the cost of design effort is reduced. Also, this computer-based method ensures that the outcome is a superior (i.e., optimum) system as judged by the specifications.

Since the computer storage requirements and computational demands of the computer-based scheme described above, however, are enormous for a complex design problem such as the PTC design and are beyond the present computational capabilities of most developing countries, a scaled-down version of the computer-based multi-level method is presented in this report. Instead of the four-level design system shown in Figure 4.3, a simpler two-level design system is described. The higher-level is 'macro-level design' and the lower level is called 'micro-level design'. This two-level, macro-micro design scheme will bring about adequate division and hierarchy in the design problem so as to allow for the handling of changes in design environment, and will not require as much computational resources as the four-level design system. The macro-micro design scheme is

explained further in the following subsection .

4.3.3 Macro-Micro Design Structure [30]

In Chapter Two, it was shown that the design of the PTC subsystems (reflector, receiver and tracking system) all involved multiple objectives and constraints. Some of these constraints and objectives, however, are common to all three subsystems (e.g., technological capability and availability). This is because each subsystem design must:

a. comply with the environmental goals and objectives (e.g., low-labor mass-production or labor-oriented production) and, at the same time,

b. satisfy the social, economical and/or technological limitations of the design environment.

The rest of the constraints and objectives, i.e. those which are not common to all three subsystems, are mostly technical and/or performance related and are independent of the design environment. Therefore, in order to deal with the design environment changes in an efficient manner, one can separate out the environment-dependent decisions from the environment-independent ones and, consequently, divide the design problem into two major parts.

- A macro-level design problem which deals with the design decisions and optimization aspects based on capabilities, objectives and limitations of the design environment (e.g., selection of the method of fabrication and selection of materials for PTC design).
- A micro-level design problem which deals with the environment independent design decisions and

optimization of the components of the subsystems based on technical considerations alone (e.g., optimization of the gap width between the glazing and absorber surface of the receiver subsystem of PTC's to minimize convection and conduction losses).

In the PTC design, for example, one can identify a number of macro-level and micro-level design problems. (The partitioning of the PTC design problem as macro- and micro-level design problems is shown in Figure 5.1.) In the receiver subsystem design, for example, the decision on the choice of an evacuated or a non-evacuated receiver design will be made based primarily on the technological capability and goals of the environment (macro-level design). The decision on the size of the gap width, however, will be made based primarily on, as mentioned, technical considerations (micro-level design). As another example, in the reflector subsystem design, the decision on the type of reflector supporting structure (ribbed or sandwich) and method of construction will be made based primarily on environmental goals and constraints (macro-level design). The size of the reflector, however, will be chosen based primarily on technical considerations (micro-level design).

The design problems at macro- and micro-level are structured in the same way as multi-level multi-objective scheme, i.e., by partitioning the design problem into a series of DSP's. The following section presents an approach for formulating DSP's.

4.4 A Rational Approach for Formulating Decision Support Problems

It is the engineer's task to partition a design problem into a set of decision support problems. Having done so, the hierarchies of these problems (e.g., macro-micro) are to be identified so that decisions can be made in proper order.

Although DSP's occur at different phases and levels in the design system, the structure of the problems and methods of their solution and validation remain the same. For the formulation of decision support problems, the following six-step approach is proposed by Mistree and Muster [29].

1. A story

The story contains information on objectives, requirements and specification for each design system. The information available is usually incomplete. The first step is to write an abstract of the story that summarizes the technical aspects of the system problem. Subsystems are identified and abstracts that summarize the technical needs of each subsystem are written.

2. Problem statements

The transition from the abstract (of any subsystem) to a set of problem statements is an unstructured process where success depends almost entirely on the judgment exercised by the engineer. In this step, the design and systems defined in the story are characterized and written in terms of a set of

problem statements. Problem statements should describe, in technical terms, the decisions needed to be made by the engineer. Each problem statement should be written so as to lead to a single decision support problem. Problem statements should be self-contained, completely accurate and non-contradictory.

3. Structuring the DSP's

From the problem statements, the problems are structured as word problems. Keywords are used to emphasize the elements of the problem.

The Compromise DSP is stated as follows:

Given
- An initial design
- The requirements that need to be satisfied by the design for feasibility
- The goals of the design -- these need to be achieved as far as possible
- The relevant assumptions

Find
- The values of the design (independent) variables
- The values of the deviation variables (they indicate to what extend each of the goal is achieved).

Satisfy
- The system constraints -- the requirements that must be met for feasibility
- Goal constraints -- the goals that are desirable but not necessary to achieve (i.e., to be achieved as far as possible).

- Bounds -- upper and lower bounds on the design variables -- and -- upper and lower bounds on the deviation variables

Minimize
- The difference between the specified goals and the estimated performance of the design.

The Selection DSP is stated as follows

Given
- The specifications
- The assumptions related to the proposed model

Identify
- The feasible alternatives
- The principle attributes that the alternatives should possess

Rank
- The alternatives in order of preference based on the ratings ascribed to each attribute and the relative importance of the attributes.

Further details on structuring the DSP's can be found in Appendices A and B, together with solved sample problems for PTC's.

4. Mathematical formulation of DSP's

After the word problems have been written, the problems can then be formulated in mathematical form in order that a computer can be used to solve the problems. For details of the mathematical formulations of Selection and Compromise DSP's see Appendices A and B, respectively.

5. Numerical solution

In this step, the principal activity is to prepare data to be used for solving (numerically) the DSP by means of some

calculating tools. Calculating tools used may be a calculator, a microcomputer or a main-frame computer depending on the size and complexity of the problem.

6. Post-solution analysis to validate the results and conclusions

The numerical solution obtained from step five is only a partial solution of the decision support problem. This is because the problem is invariably formulated using incomplete information. Therefore, to assure that the solution is valid and the design will perform well in the real environment, post-solution analysis need to be done. The post-solution analysis includes validation of the solution and effect on the solution due to small changes in parameters of constraints. Using the numerical solution and the post-solution analysis information, an engineer is able to make better decisions.

4.5 Characteristics of Software for Decision Support Problems [29]

As stated before, the decision support problems may differ from one problem to another. However, most problems can be categorized as either Selection or Compromise DSPs. Compromise DSPs, especially in engineering, require complex computations. Selection DSPs, when they are not related to other problems, can be solved directly using little computational effort. When Selection DSPs need to be solved together with other (say Compromise) DSPs, they may require some modification. The generic formulation for Selection and Compromise DSPs are presented in Appendices A and B. The

software needed for solving DSPs, therefore, should handle the problems formulated in the generic form and provide, at least, some sensitivity information to support the engineer's decision. Software for solving DSPs are available for specific types of problems. Linear Programming packages such as LINDO [31], are ideal for solving Compromise DSPs in which all functional relationships are in linear form. Compromise problems of other types usually require specific software to obtain a solution. A computer program written by Cawsey [32] for a mainframe computer system solves stand-alone Selection DSPs. The same type of software with sensitivity analysis information provision was written by Ganesan [33] in BASIC for a micro-computer system. A program SLIP2 [34] which is written in FORTRAN is available for the mainframe computer system. This program is capable of solving all Compromise DSPs likely to occur in engineering. A recent computer program by Ittimakin [28], SLPPC (Sequential Linear Programming for Personal Computers), can be used to solve decision support problems (Compromise and Selection) on a micro-computer.

4.6 Summary

In this chapter, characteristics and essential features of a computer-based design approach were presented. The advantages o the computer-based design method over the conventional design metho were discussed.

A two-level (macro-micro) design structure was proposed for structuring design problems that involve changes in the design environment. It was shown that decision support problems need

to be formulated for solving design problems at the macro- and micro-level of design. A rational approach for formulating decision support problems was presented together with a survey of available software for solving decision support problems. (Note: Detailed descriptions of decision support problems are presented in Appendices A and B.)

Chapter Five

DESIGN METHOD FOR PARABOLIC TROUGHS FOR DEVELOPING COUNTRIES

5.1 Introduction

As discussed in chapter Two, for a given design environment, and a given requirement for heat delivery at a specified output temperature, the designer must design the PTC's based on several constraints and objectives [35, 36]. These constraints and objectives will include such things as:

- cost,
- durability,
- reliability,
- environmental goals and objectives,
- manufacturing constraints,
- social, economical, and/or technological limitations of the design environment, etc.

In most cases, the information available to the designer at the preliminary stage of design will be:

- incomplete,
- contradictory, and
- both qualitative and quantitative in nature.

The designer will be required to design and optimize the PTC system by using whatever information is available to him at this stage. However, this task will not be an easy one and will

involve numerous design decisions. For example, the designer will be required to choose the dimensions of the subsystems, the 'best' components for the subsystem designs, the 'best' fabrication technique, the 'best' method of assembly, etc., based on the goals, objectives and limitations of the design environment as well as his intuition, previous design experiences, and technical considerations (i.e., optical and thermal aspects of the design). Therefore, the designer would need a structured design method to assist him in handling the synthesis and analysis aspects of the design effectively and to support his design decisions.

As discussed in Chapter Four, the multi-objective design problem at hand can be structured by the use of decision support problems (DSP's) and a two-level (macro-level and micro-level) design structure. As explained in section 4.3.3, this two-level, macro-micro design scheme will bring about adequate division and hierarchy in the design problem so as to allow for the handling of changes in design environment.

The overall set-up of the macro-micro design problem for PTC's is shown in Figure 5.1 and can be summarized as follows [35]:

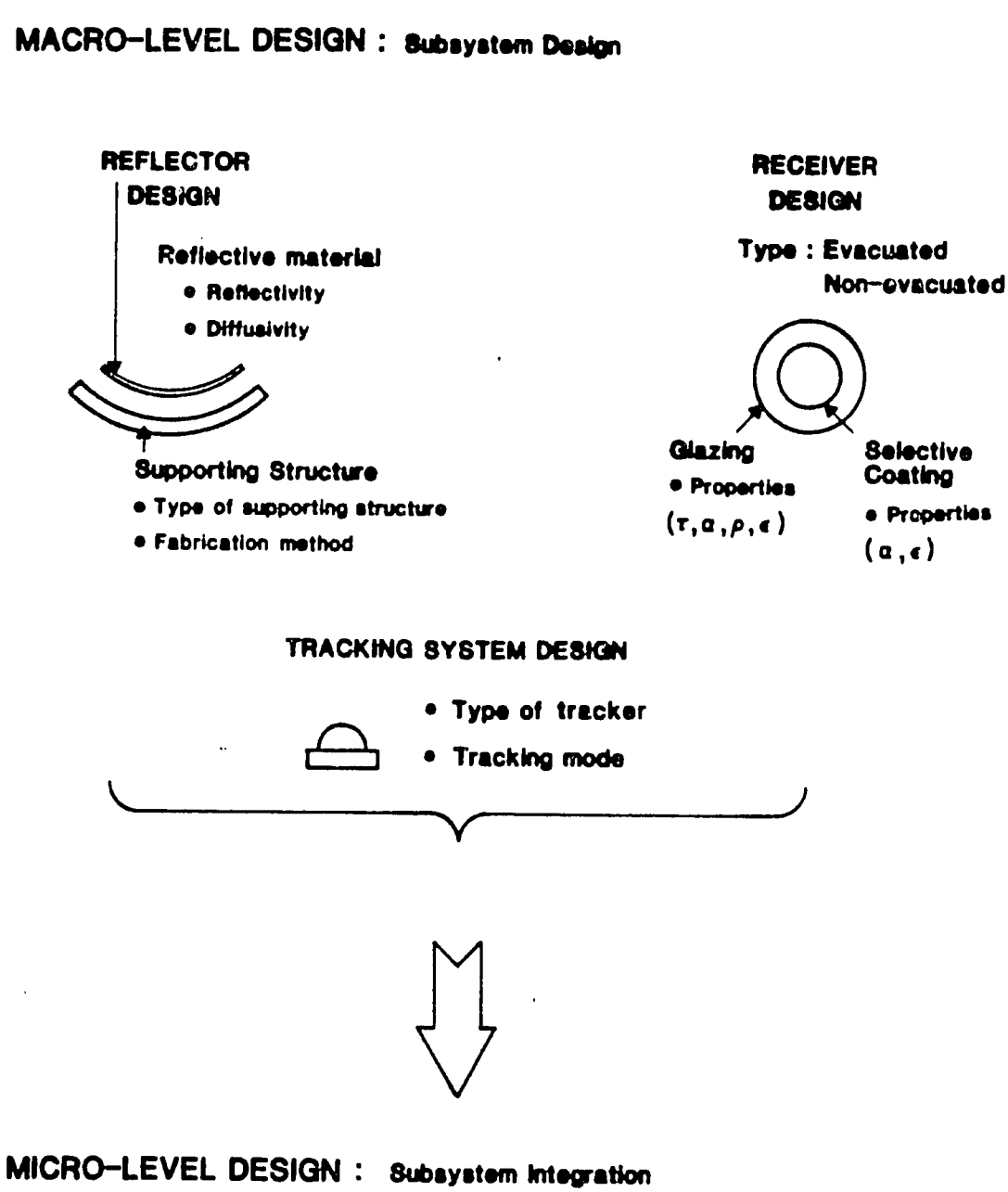
- At the macro-level of design, the design problem is comprised of a number of selection DSP's which provide a means for optimizing various components (and/or subsystems) independently. The multiple objectives and constraints such as

environmental goals (mass-production or labor-oriented production), cost and availability considerations, weight and manufacturing constraints, etc., are dealt with in a sequential manner in the selection DSP's. These are included in the selection models as attributes (criteria) and rated against each other. Consequently, as a result of these trade-off evaluations the selected 'optimum' component (or subsystem) designs are the best possible for the given design environment or application.

- At the micro-level of design, interaction among subsystems is accounted for, and a system design is obtained by the use of compromise-type DSP's. The component (or subsystem) designs selected as optimum at the macro-level of design are integrated in such a way to optimize one or more performance-related system objectives like thermal efficiency. The instantaneous and all-day thermal efficiency of parabolic troughs are optimized at micro-level design.

In the following sections, the macro-level and micro-level design models for PTC's are presented.

Figure 5.1 **PARABOLIC TROUGH COLLECTOR DESIGN**



5.2 Macro-Level Design

As explained in section 4.3.3, at the macro-level of design the designer must make decisions concerning the subsystems (and/or the overall system) based on environmental goals, constraints and limitations.

Design decisions for PTC subsystems at macro-level of design are given in Table 5.1. Design variables that will be affected by these decisions are also shown. For each component of every subsystem, at least one decision has to be made at the macro-level of design. Therefore, a total of seven selection DSP's are required. In addition to these, a separate model will be required for determining the error tolerances for the design. These are explained in detail in the following subsections.

5.2.1 Macro-Level Subsystem Design

Tracking System Design

Table 5.2 summarizes the macro-level design of the tracking system. In this table, typical alternatives for tracker mechanism and tracking mode are listed. The attributes (criteria) for selecting a tracker mechanism and a tracking mode are also listed.

For a given design environment, the tracker mechanism will be selected by setting-up and solving a selection DSP using the listed alternatives and attributes. Similarly, the tracking mode will be selected by setting-up and solving

TABLE 5.1 MACRO-LEVER DESIGN OF PTC's

SUBSYSTEM	DECISION is needed on	DESIGN VARIABLE(S) AFFECTED
REFLECTOR	Type of supporting structure	σ slope, n
	Properties of reflecting material	ρ, σ_{mir}, n
RECEIVER	Type of receiver (evacuated , nonevacuated, etc.)	q_L
	Absorber surface characteristics (absorptivity , emissivity, etc.)	α, q_L
	Glazing (transmissivity, emissivity, etc.)	τ, q_L
TRACKING	Type and accuracy of tracker	β
	Tracking mode	K (θ) $I_b \cos\theta$

TABLE 5.2 MACRO-LEVEL DESIGN OF TRACKING SYSTEM

COMPONENT	ALTERNATIVES	ATTRIBUTES
TRACKER	• Shadow-band • Micro-computer programmed • Flux-detector feedback • etc.	• Cost • Maintenance requirement • Availability • Tracking mode (one-axis or two-axes) • Technology requirement • Accuracy, etc.
TRACKING MODE	• Two-axes • N-S one-axis • E-W one-axis • Polar one-axis	Resources • Annual energy output • Seasonal variations in output • Hourly variations in output Relative Cost • Field cost • Tracking cost • Tracker mechanism • Structure and foundation cost • Plumbing cost, etc. Consequences of Failure • Reliability for continued output • Design safety, etc.

another selection DSP using its respective alternatives and attributes.

Briefly, in a selection DSP first each alternative is rated against each attribute using a preset logical scale. Then, relative importances for attributes (weights) are calculated by ranking them according to their importances. Finally, merit values for alternatives are calculated using the ratings and relative importances of the attributes. The steps involved in structuring and solving selection DSP's are presented in greater detail in Appendix A where the process is demonstrated for the selection of the tracking mode for a typical application using a relatively simple selection model.

In this example, it is shown that the environmental design goals and design objectives, the application-specific requirements and the experience-based insight of the designer can be effectively incorporated by the relative importance values (weights) assigned to the attributes. Therefore, the outcome of the selection process, the selected candidate is the 'best' in all aspects.

After solving the two tracking system selection DSP's, the designer will obtain the 'best'

- type of tracker mechanism, and
- tracking mode

for the given design environment and application.

Reflector Design

Table 5.3 summarizes the macro-level design of the reflector subsystem. Some typical alternatives and attributes for selection of supporting structure and reflective material are shown. In a manner similar to that used for the tracking mode and tracker mechanism selection, for a given design environment, the designer will choose the 'best' alternative based on the ratings and relative importances of the attributes. The relative importances assigned to the attributes will, like before, depend on the environmental goals and limitations, the application-type and site, as well as, the experience-based insight of the designer and the performance goals for the overall system. For example, with regard to selection of the reflective material, one of the more important attributes will always be its reflectivity. An increase in the reflectivity of the reflective material increases the the amount of energy reflected and consequently increases the efficiency directly, independent of all the other design parameters. Therefore, a higher relative importance will have to be assigned to this attribute in the selection of the reflective material.

As another example, if high wind speeds are present at the particular application site, the stiffness attribute in the supporting structure selection DSP will have a higher relative importance to account for that. Thus, the model will always output the 'best' possible candidate which

TABLE 5.3 MACRO-LEVEL DESIGN OF REFLECTOR SUBSYSTEM

COMPONENT	ALTERNATIVES	ATTRIBUTES
TYPE OF SUPPORTING STRUCTURE	• Ribbed frame , • Aluminum honeycomb , • Paper core, • Plywood laminate , • Fiberglass core, • etc.	**MATERIALS** • Cost, • Availability, • Weight, **STABILITY AND STRENGTH** • Stability under temperature cycling, • Stability to humidity • Mechanical strength of the structure (stiffness) , **FABRICATION METHOD** • Suitability to labor oriented production , • Suitability to low-labor mass-production, • Technology requirements for production **ACCURACY** • Accuracy as manufactured • Sensitivity to labor skills, etc.
REFLECTIVE MATERIAL	• Back-silvered thin glass, • Aluminum • Polished stainless steel • Back -silvered plastic • etc.	• Cost • Available sizes (dimensions) • Availability, • Strength to impact, • Reflectivity • Diffusibity (nonspecularity) • Stability to environmental degradation,

satisfies the environmental considerations as well as application-specific goals and limitations.

After solving these two selection DSP's the designer will obtain the following information about the reflector design:

- Reflectivity and diffusivity of the reflecting material (ρ, $\sigma_{mir,n}$)
- Type and fabrication method of the reflector.

However, the actual size of the reflector (aperture width) is not known yet. This will be determined at the micro-level of design.

Receiver Design

Table 5.4 summarizes the macro-level design of the receiver subsystem; typical alternatives and attributes for the three receiver components are shown. As for the macro-level tracking system and reflector design, the 'best' candidate will be chosen based on the ratings and the relative importances of the attributes.

As discussed earlier (in the case of mirror selection), material properties, e.g., reflectivity, will sometime play a primary role in the selection of the 'best' component of a subsystem. In the case of receiver design, material properties will play a major role in the selection of the selective coating and the glazing. For the selective coating selection, the two properties which will play major roles in

TABLE 5.4 MACRO-LEVEL DESIGN OF RECEIVER SUBSYSTEM

COMPONENT	ALTERNATIVES	ATTRIBUTES
TYPE OF RECEIVER	• Non-evacuated, • Evacuated, • Back-filled with heavy gases, • etc.	• Availability of techology, • Performance, • Cost, • Ease of manufacture, • Stability, • Overall effectiveness, • etc.
ABSORBER SURFACE CHARACTER-ISTICS	• Available selective coating in the design environment	• Cost, • Absorptivity, • Emissivity, • Stability to environmental degradation, • Degradation temperature, (decomposition temperature) • etc.
GLAZING	• Available transparent tubes in the design environment	• Cost, • Transmissivity, • Reflectivity, • Absorptivity, • Emissivity, • Availability, • Weight, • Temperature tolerances • Thickness, • etc.

the decision are the solar absorptivity and the infrared emissivity. For the glazing selection, probably solar transmissivity will be the most important property; solar absorptivity as well as infrared emissivity and reflectivity of the glazing material will also play some role in the selection. Nonetheless, as shown in Table 5.4, the final choices of the selective coating and the glazing will be made only after considering the cost, durability and availability as well.

After solving the three selection DSP's for the receiver, the designer will obtain the following information about the receiver design:

- Type of receiver,
- Solar absorptivity and infrared emissivity of the selective coating (α, ε)
- Transmissivity, emissivity and absorptivity of the glazing.

The actual sizes of the absorber tube and the glazing, however, are not known yet. These will have to be determined later, when considering the micro-level of design. In fact in this case, the two design problems (macro- and micro-design) will be coupled since the choice of the absorber tube and glass envelope sizes will depend on the standard tube sizes available in the market place as well as the technical considerations. This is explained further in the following sections.

TABLE 5.5 DETERMINATION OF ERROR TOLERANCES

TYPE OF ERROR TOLERANCE	Its average value is chosen based on :
RANDOM, $\sigma_{tot,n}$ [mrad]	• Type of supporting structure employed, • Method of construction (labor oriented production or low-labor production), • Diffusivity of reflecting surface, • Random tracking errors, • Intensity distribution of sun .
ANGULAR NON-RANDOM, β [deg]	• Accuracy of chosen tracker , • Method of assembly (possible rotation of reflector's vertex-to-focus axis during assembly),
MISLOCATION NON-RANDOM, $[\epsilon_r]_y$ [cm]	• Manufacture tolerance (method used in drilling holes in receiver supports), • Method of assembly in the field , • Transportation of collector to the field (reflectors may open-up/deflect if stacked on top of each other during transportation), • Operational tolerance (sagging due to weight and thermal effects).

5.2.2 Determination of Error Tolerances

The importance of selecting realistic values for error parameters (error tolerances) to carry out the preliminary design of the PTC cannot be overemphasized. Particularly, the need for realistic choices for error tolerances becomes increasingly important when one is designing the PTC's for technically less advanced design environments like developing countries. In such environments, labor-oriented production techniques and/or use of unskilled labor may give rise to gross errors that may not be expected in technically advanced design environments. Therefore, anticipating the different types of errors and incorporating information about their effects (on the performance) into the design process during the preliminary design stage is of greater importance when designing PTC's for such environments.

In Reference 1, a detailed description of different types of errors and their sources of origin were presented and three error parameters -- one random, σ, and two non-random, β and $(d_r)_y$ -- were introduced for the characterization of different types of errors.

Table 5.5 summarizes the factors that should be considered when determining the values for the error parameters for the preliminary design of the PTC's. Once the macro-level design of the tracking system, the reflector subsystem and the receiver subsystem are completed, the designer can determine the values for the error parameters using this information and Table 5.5.

5.3 Micro-Level Design

At the micro-level of design, the designer will integrate the subsystem designs and optimize their dimensions (sizes) based on technical considerations to obtain a 'system' design. It is at this level of the design that thermal and optical aspects of the design are brought together and considered simultaneously.

The set-up for both macro- and micro-level design problems and their respective design parameters are shown in Figure 5.2. The macro-level design decisions are, as shown, direct inputs to the micro-level design. The outcome of the micro-level design problem, the final design, therefore, will automatically have built-in tolerances and biases to such things as environmental goals, objectives, limitations, availability, etc., and, at the same time, it will be a performance-wise optimized design. As suggested by the dotted lines, however, there will be some interaction between the macro- and micro-level design problems.

In the following subsections, steps followed for structuring and solving the micro-level design problem are presented and discussed.

5.3.1 Micro-Level Optimization Philosophy

At the micro-level of design, given the macro-level design, i.e., given the:

- Material properties, (ρ, τ, α),

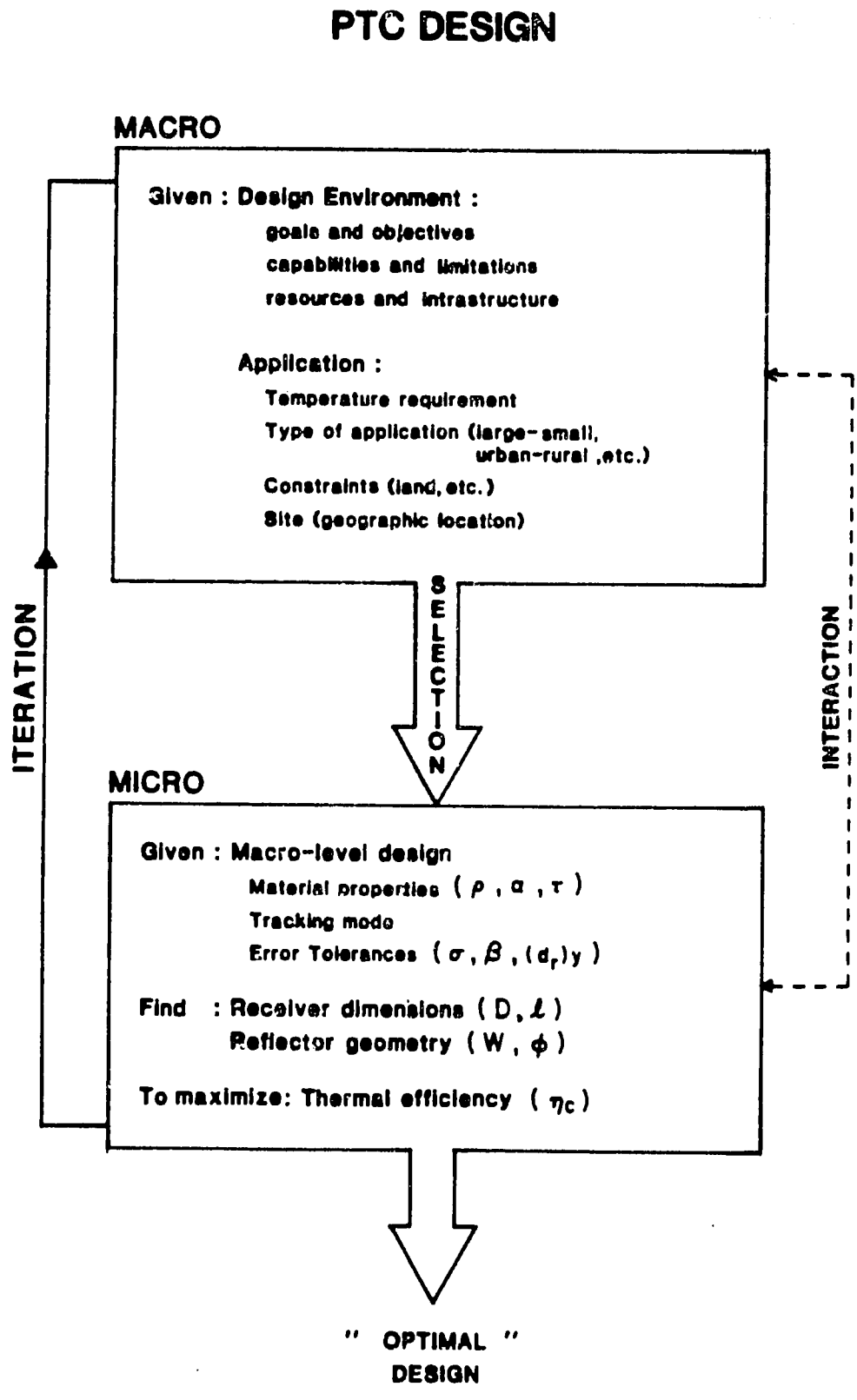


Figure 5.2 Set-up of the macro-level and micro-level design problems.

- Error Tolerances (σ, β, $(d_r)_y$),
- Receiver type (evacuated, non-evacuated),
- Operating condition (temperature requirement, I_b and tracking mode).

the designer will be required to optimize the reflector geometry (aperture width and rim angle) and the receiver dimensions (absorber diameter and gap width) based on technical considerations.

It is usually more convenient to carry out the optimization using the relative sizes of the reflector aperture and the absorber tube, i.e., the geometric concentration ratio. Therefore, the optimization parameters, i.e., the micro-level design parameters, will be rim angle, gap width and concentration ratio (ϕ, ℓ, and C, respectively).

Rim Angle

The optimum rim angle based on random errors alone is in the range of 80° - 120° [1]. However, as shown in Reference 1, first technical report, the optimum rim angle is sensitive to non-random errors as well. Fortunately, however, the range of optimum rim angles based on both random and non-random errors was found to be broad (in the range of 105° - 120°) for intercept factors greater than 75%. Therefore, the designer can enjoy some flexibility and determine the rim angle after looking at some other considerations as:

- ease of manufacture,

- mechanical strength of the reflector, etc.

Thus some interaction (or consulting) with the macro-level design may be necessary.

Gap Width

As discussed in Reference 1, for a nonevacuated receiver the width of the gap between the absorber tube and the glazing should be made as large as possible without initiating convection. It will usually be optimized if the corresponding Rayleigh number is approximately 1000. In Figure 5.3, it is shown that for absorber temperature of 200°C the optimal gap width is between 0.7 to 1.2 cm. Nonetheless, the final choice of the gap width will be determined after looking at the available 'standard' absorber and glass tube sizes in the design environment. (This will bring about interaction between macro- and micro-level designs.)

As shown in Figure 5.3, for an evacuated receiver, the heat loss coefficient is not a function of the gap width and therefore the spacing between the absorber tube and the glazing can be made as small as practical. Nevertheless, if the designer chooses the gap width as if the vacuum did not exist (i.e., based on nonevacuated receiver considerations) a drastic performance drop can be avoided in the case of an accidental loss of the vacuum in the annulus.

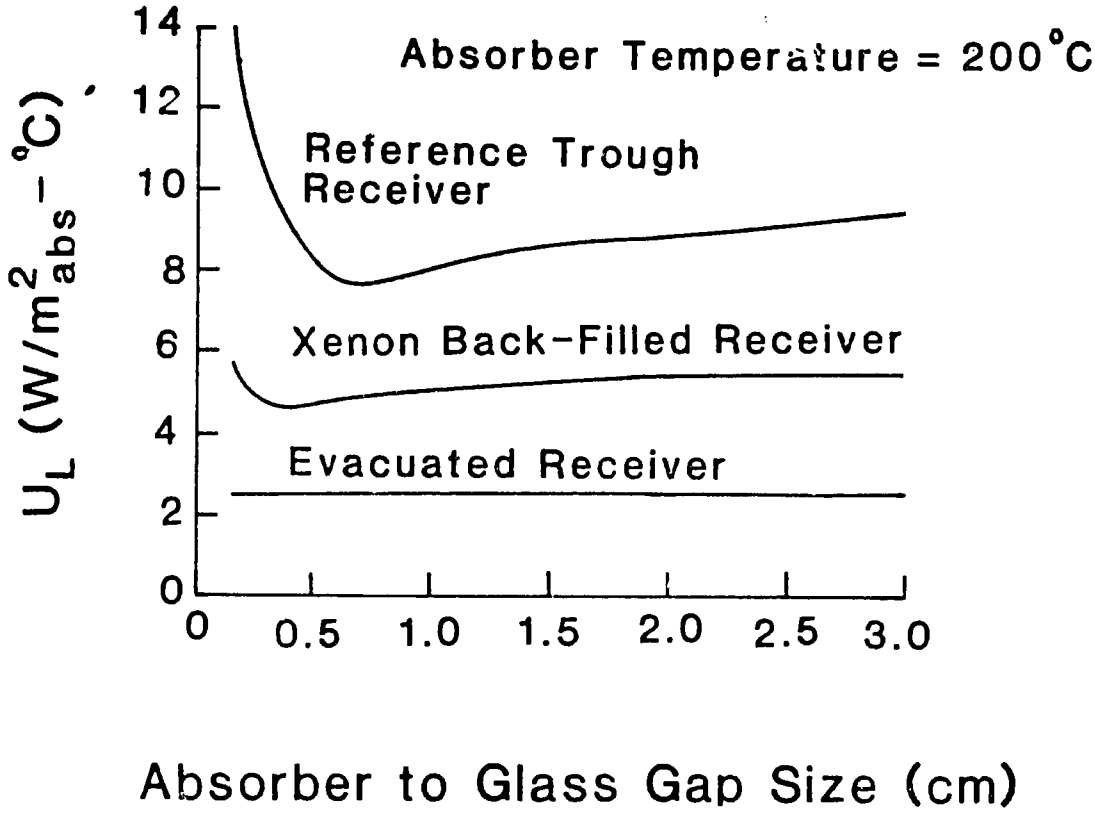


Figure 5.3 Annulus gap sizing for an absorber temperature of 200°C (from [1]).

Concentration Ratio

Concentration ratio is an important parameter in the micro-level optimization process; its determination will require information about the trade-offs between thermal and optical behavior of the trough.

Lower concentration ratios will permit a greater amount of the reflected energy to intercept the absorber tube. However, low concentration ratios will also increase the absorber tube surface area, relative to the aperture area, and result in increased heat loss per unit area of aperture. Conversely, high concentration ratios will reduce heat losses (per unit area of aperture) but increase optical losses, i.e., the fraction of the incident solar radiation that is intercepted by the absorber will decrease. Therefore, at the optimal concentration ratio, the incremental heat loss should be equal to the incremental loss of intercepted solar radiation.

Concentration ratio can be optimized by keeping one of the dimensions (absorber diameter or reflector aperture) fixed while varying the other. Conceptually, it is more convenient to carry out the optimization by fixing the absorber diameter and varying the aperture area of the reflector. Then, as explained in Chapter Four, only a single number, the heat loss rate q_L in W per m^2 of receiver surface area, will be needed to characterize the thermal properties of the receiver subsystem [18]. Moreover, the receiver dimensions (absorber and glass tube diameters) can be chosen first

based on some additional considerations such as:

- availability of different 'standard' steel and glass tube sizes, their stiffness-to-weight ratio, and
- absorber tube sizes that can be electroplated with selective coating using the available technology in the design environment, etc.

Of course, this will again bring about some level of interaction between the macro- and the micro-levels of design (dotted lines in Figure 5.2). Details of the set-up of the concentration ratio optimization problem are presented in the following section.

5.3.2 Optimization of Concentration Ratio

In Appendix C, it is shown that the net flux collected by the receiver, q_{net}, is given by:

$$q_{net} = K(\theta)\ I_b \cos\theta\ [\rho(\tau\alpha)_n]\ \gamma - \frac{q_L}{C} \tag{5.1}$$

At the optimal concentration ratio C_0 the derivative of q_{net} with respect to C equals to zero.

$$\left.\frac{dq_{net}}{dC}\right|_{C=C_0} = 0 \tag{5.2}$$

Therefore:

$$K(\theta)\ I_b \cos\theta\ [\rho(\tau\alpha)_n]\ \left.\frac{\partial\gamma}{\partial C}\right|_{C=C_0} + \frac{q_L}{C_0^2} = 0 \tag{5.3}$$

Once the rim angle is chosen, the intercept factor, γ , becomes a function of the universal random and non-random errors, i.e., for given ϕ:

$$\gamma = fn(\sigma^*, \beta^*, d^*) \tag{5.4}$$

Then the derivative of γ with respect to C equals to:

$$\frac{\partial\gamma}{\partial C} = \frac{\partial\gamma}{\partial\sigma^*}\frac{\partial\sigma^*}{\partial C} + \frac{\partial\gamma}{\partial\beta^*}\frac{\partial\beta^*}{\partial C} + \frac{\partial\gamma}{\partial d^*}\frac{\partial d^*}{\partial C} \tag{5.5}$$

The third term in Eq.(5.5) is equal to zero (see Figures 5.4 and 5.5), therefore, the equation can be rewritten as:

$$\frac{\partial\gamma}{\partial C} = \sigma\frac{\partial\gamma}{\partial\sigma^*} + \beta\frac{\partial\gamma}{\partial\beta^*} \tag{5.6}$$

Substituting Eq.(5.6) into Eq.(5.3) and rearranging gives

$$\beta\sigma^{*2}\frac{\partial\gamma}{\partial\sigma^*} + \sigma\beta^{*2}\frac{\partial\gamma}{\partial\beta^*} = -\frac{q_L\ \sigma\ \beta}{K(\theta)\ I_b\ \cos\theta\ [\rho(\tau\alpha)_n]} \tag{5.7}$$

The other requirement that has to be satisfied for optimal concentration ratio is:

$$C_o = \frac{\sigma^*}{\sigma} = \frac{\beta^*}{\beta}$$

or

$$\frac{\beta^*}{\sigma^*} = \frac{\beta}{\sigma} \tag{5.8}$$

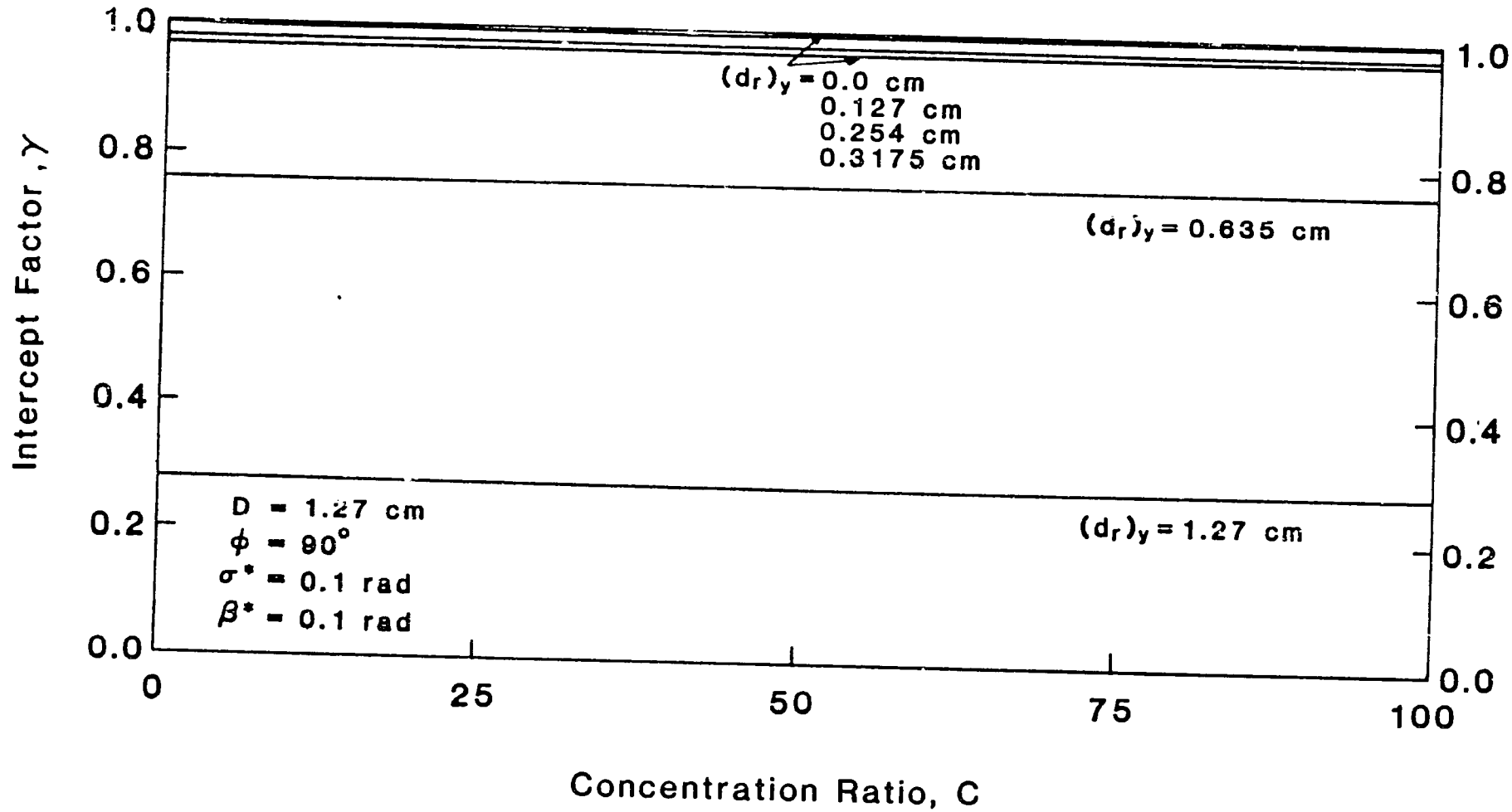


Figure 5.4 Intercept factor as a function of concentration ratio and receiver mislocation for D = 1.27 cm (from [1]).

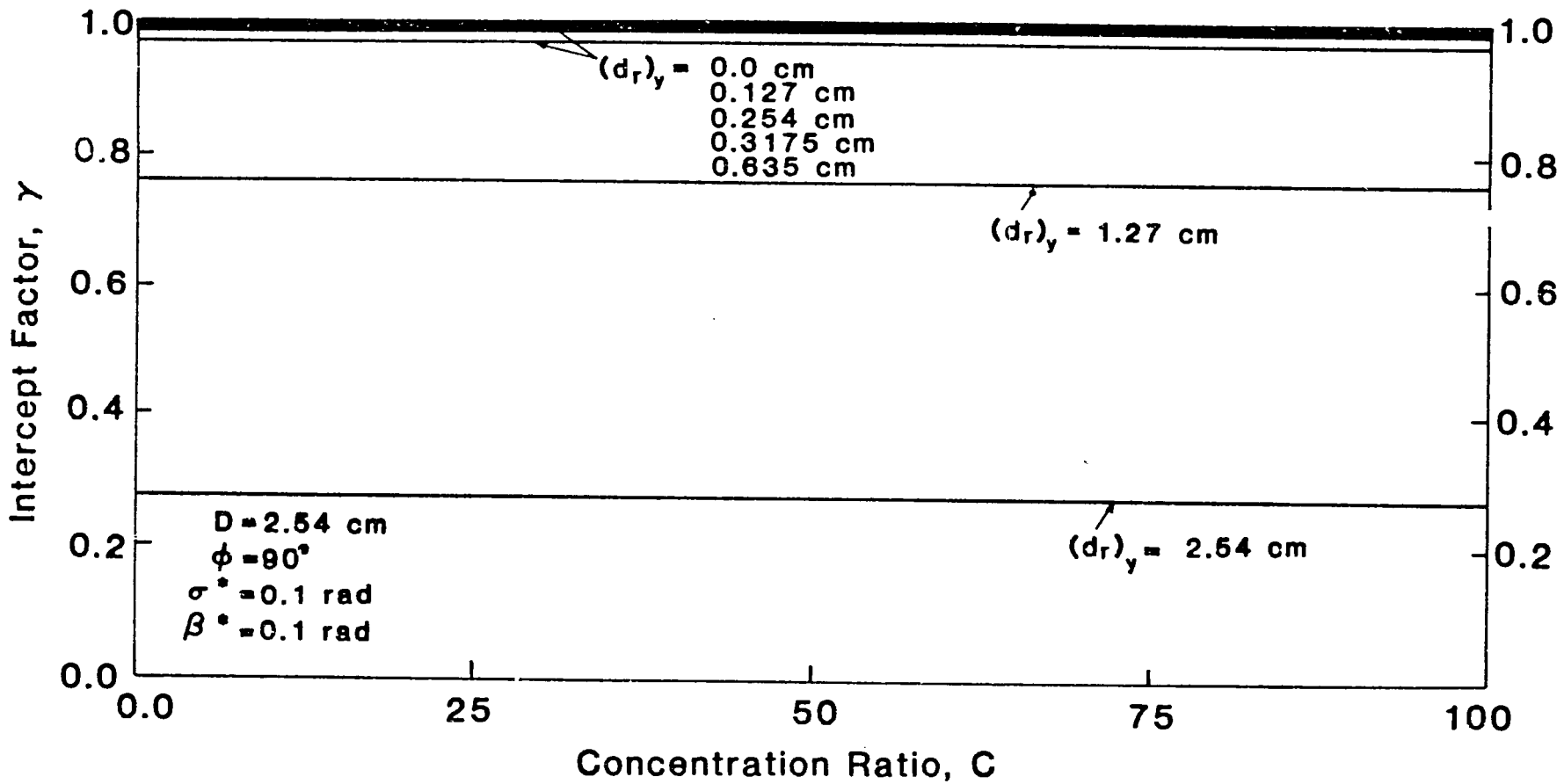


Figure 5.5 Intercept factor as a function of concentration ratio and receiver mislocation for D = 2.54 cm (from [1]).

Solving Equations (5.7) and (5.8) simultaneously will give the optimal concentration ratio.

The right hand sides of Eqs.(5.7) and (5.8) contain all known quantities, i.e, quantities known from the macro-level of design. These are:

q_L = Heat loss per unit of receiver surface area $[\frac{W}{m^2}]$,

σ = Random error tolerance [rad],

β = Angular non-random error-tolerance [rad]

$\rho(\tau\alpha)_n$ = Material properties at normal incidence,

$I_b\cos\theta$ = Product of design beam insolation and incidence factor $[\frac{W}{m^2}]$,

$K(\theta)$ = Design incidence-angle modifier.

The value of the last two parameters, $K(\theta)$ and $I_b\cos\theta$ will depend on the selected tracking mode and the insolation level at the application site as well as the optimization criterion. For a selected tracking mode, the concentration ratio can be optimized based on either

(i) peak insolation at solar noon, or

(ii) all-day average insolation.

For case (i):

$$I_b \cos\theta = [I_b \cos\theta]_{noon}$$
$$K(\theta) = [K(\theta)]_{noon} \qquad (5.9)$$

For case (ii):

$$I_b \cos\theta = \langle I_b \cos\theta \rangle = \text{All-day average}$$
$$K(\theta) = \langle K(\theta) \rangle = \text{" " "} \tag{5.10}$$

Optimizing based on peak insolation at solar noon (i.e., maximizing the instantaneous solar noon efficiency) is not very realistic because such an optimization would leave out the abberation effects (off-axis operation). In an optimization based on all-day average insolation, however, such effects can be accounted for (through an all-day average incidence angle modifier) and a more realistic optimum can be obtained. (Rabl et. al. [18] have shown that optimizing for a clear equinox day (clearness index $K_h = 0.75$) with the ambient temperature at the yearly average corresponds very closely to the optimum based on maximum annual energy delivery). Therefore, optimizing the concentration ratio based on all-day average values of $K(\theta)$ and $I_b \cos\theta$ is recommended. Eqs.(5.7) and (5.8), however, can be used for either kind of optimization. In the following section, optimization based on all-day average insolation will be illustrated.

The partial derivatives $\frac{\partial\gamma}{\partial\sigma^*}$ and $\frac{\partial\gamma}{\partial\beta^*}$ in Eq.(5.7) can be determined from the optical model. For a chosen rim angle and fixed d^* values, the intercept factor γ can be plotted as a function of σ^* and β^*. For example, Figures 5.6 to 5.10 show such plots for $\phi = 105°$ (which is the lower limit of the range of optimum rim angles based on both random and non-random

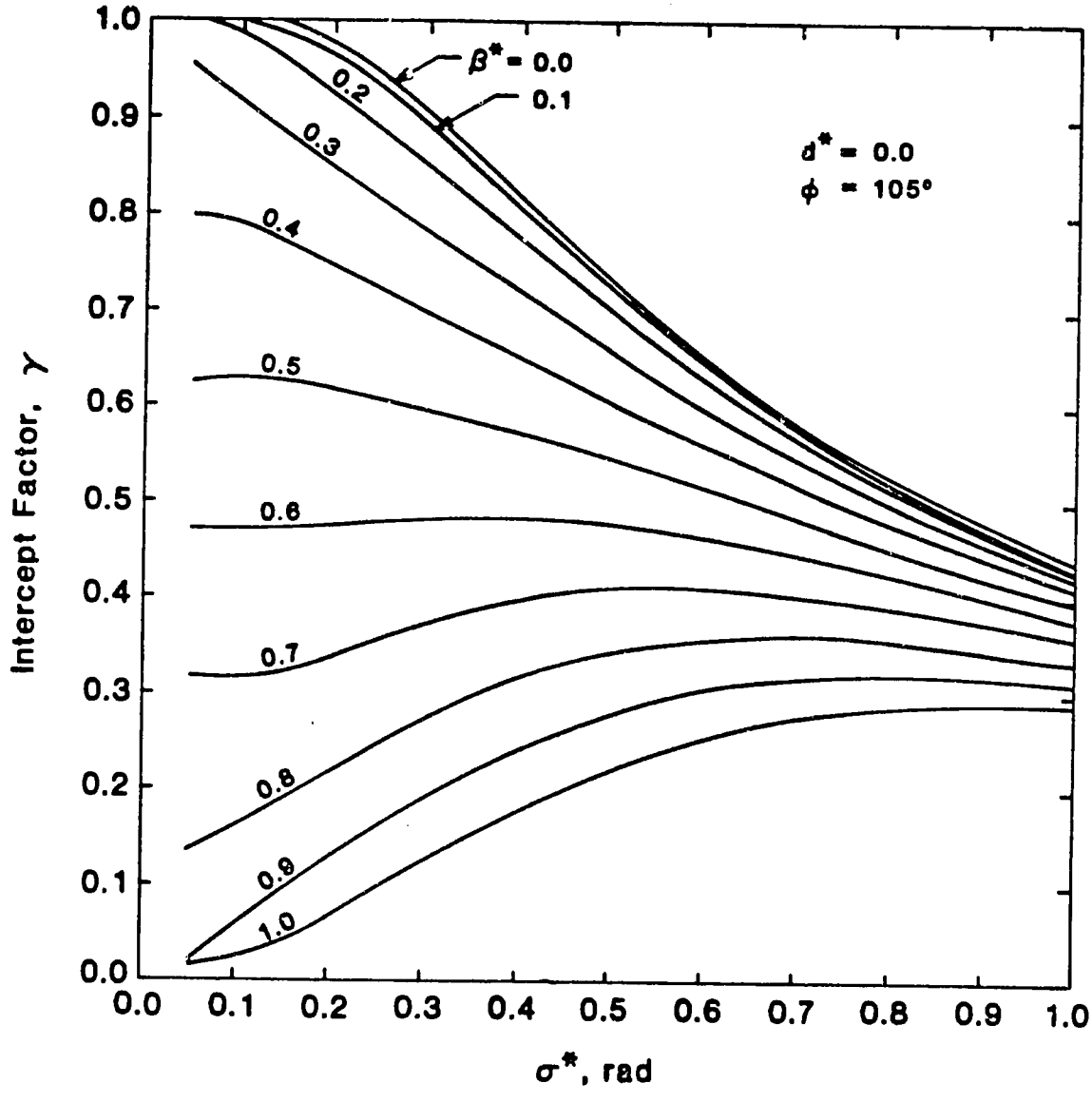


Figure 5.6 Intercept factor as a function of the universal random error parameter σ^* and the universal non-random error parameter β^* for $\phi = 105^\circ$ and for $d^* = 0.0$.

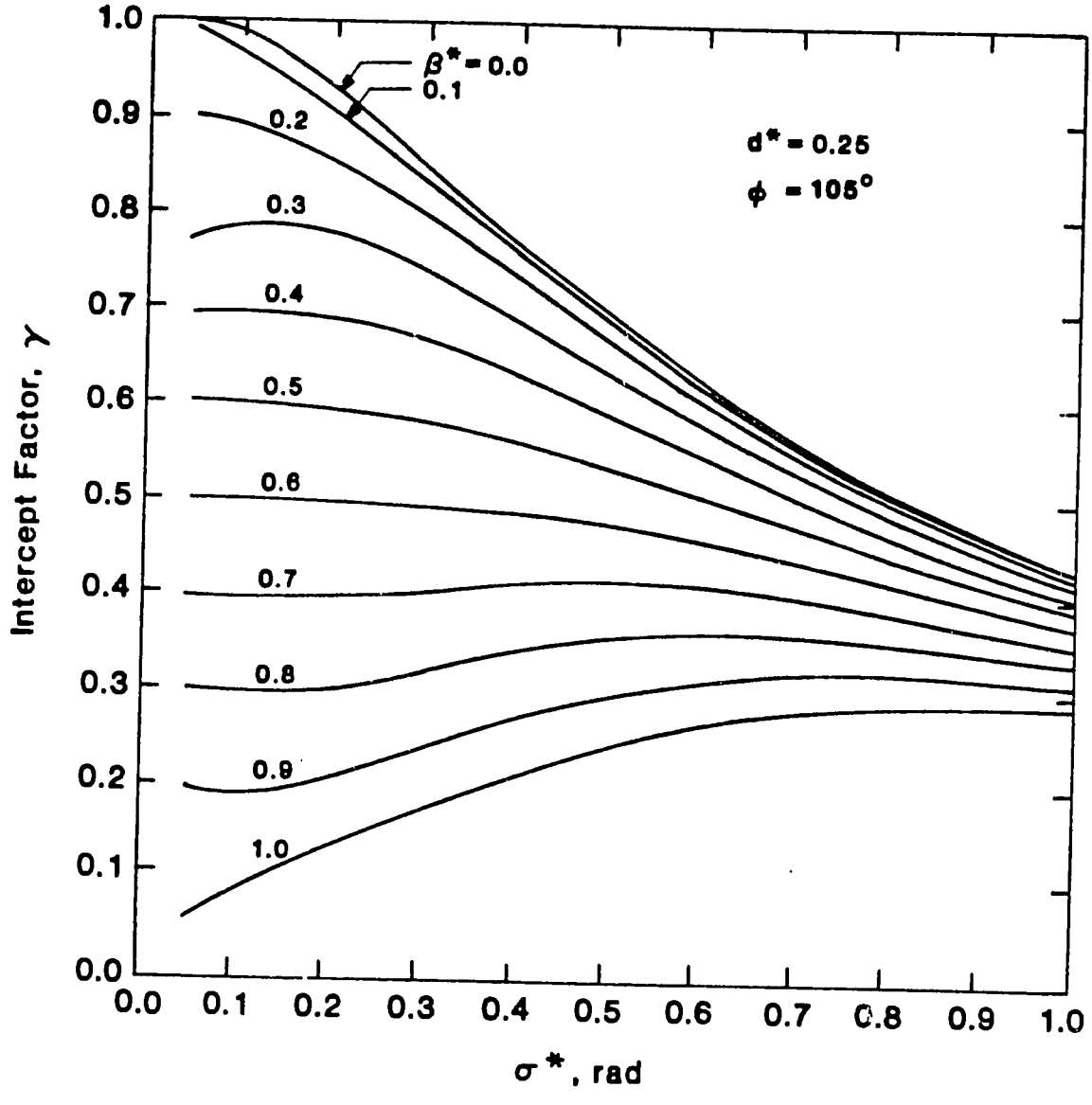


Figure 5.7 Intercept factor as a function of the universal random error parameter σ^* and the universal non-random error parameter β^* for $\phi = 105^\circ$ and for $d^* = 0.25$.

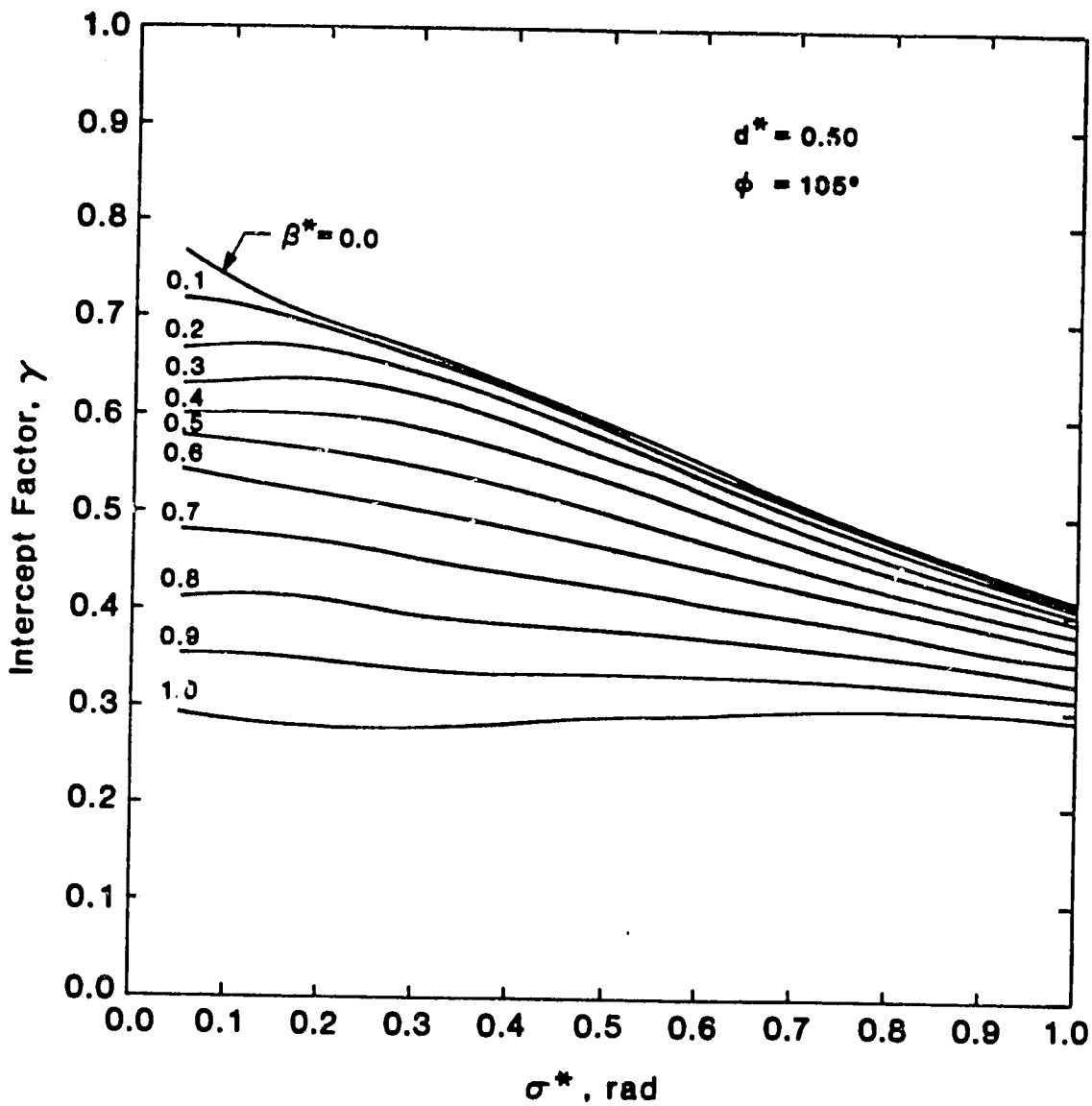


Figure 5.8 Intercept factor as a function of the universal random error parameter σ^* and the universal non-random error parameter β^* for $\phi = 105^\circ$ and for $d^* = 0.50$.

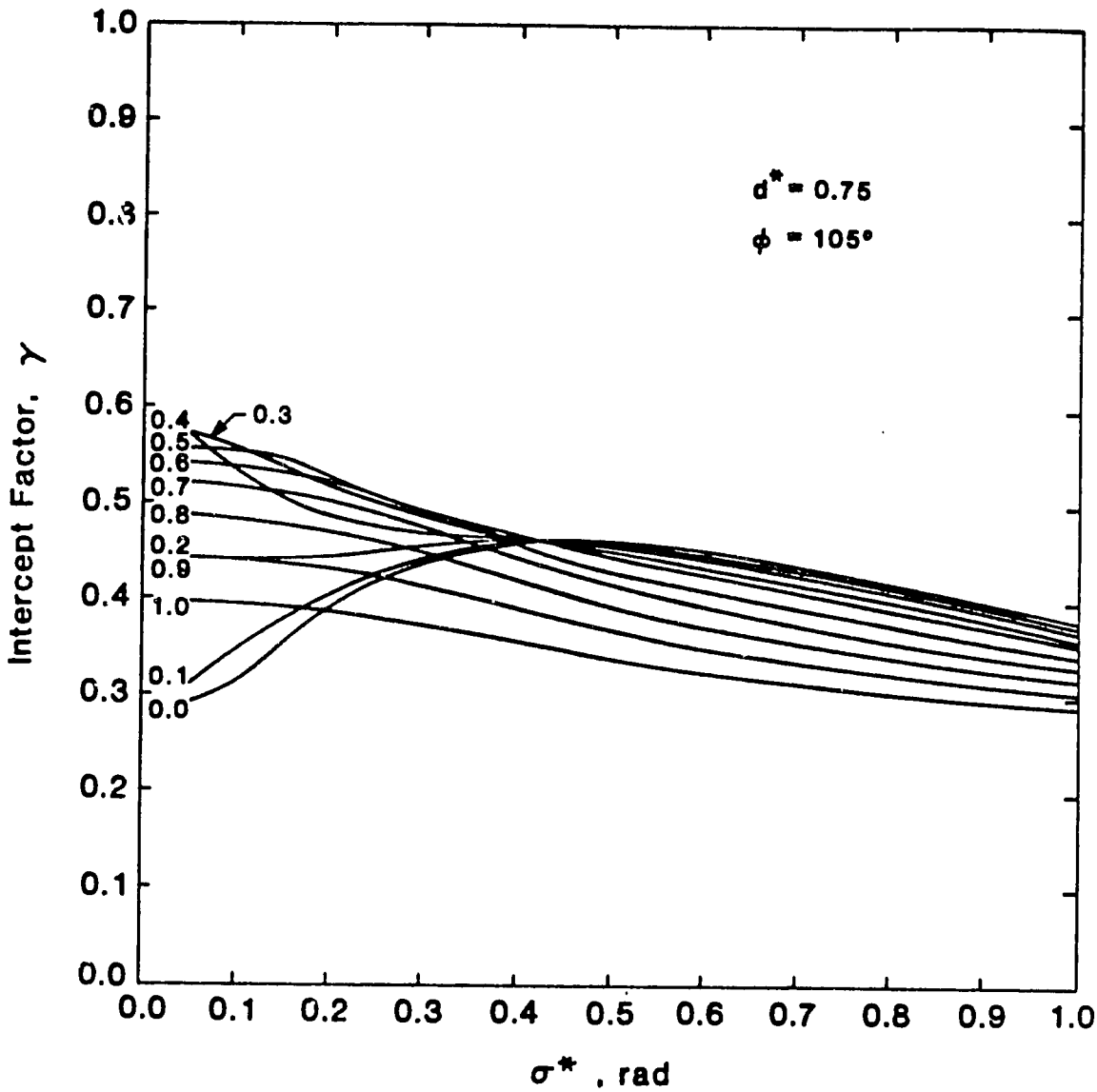


Figure 5.9 Intercept factor as a function of the universal random error parameter σ^* and the universal non-random error parameter β^* for $\phi = 105^\circ$ and for $d^* = 0.75$.

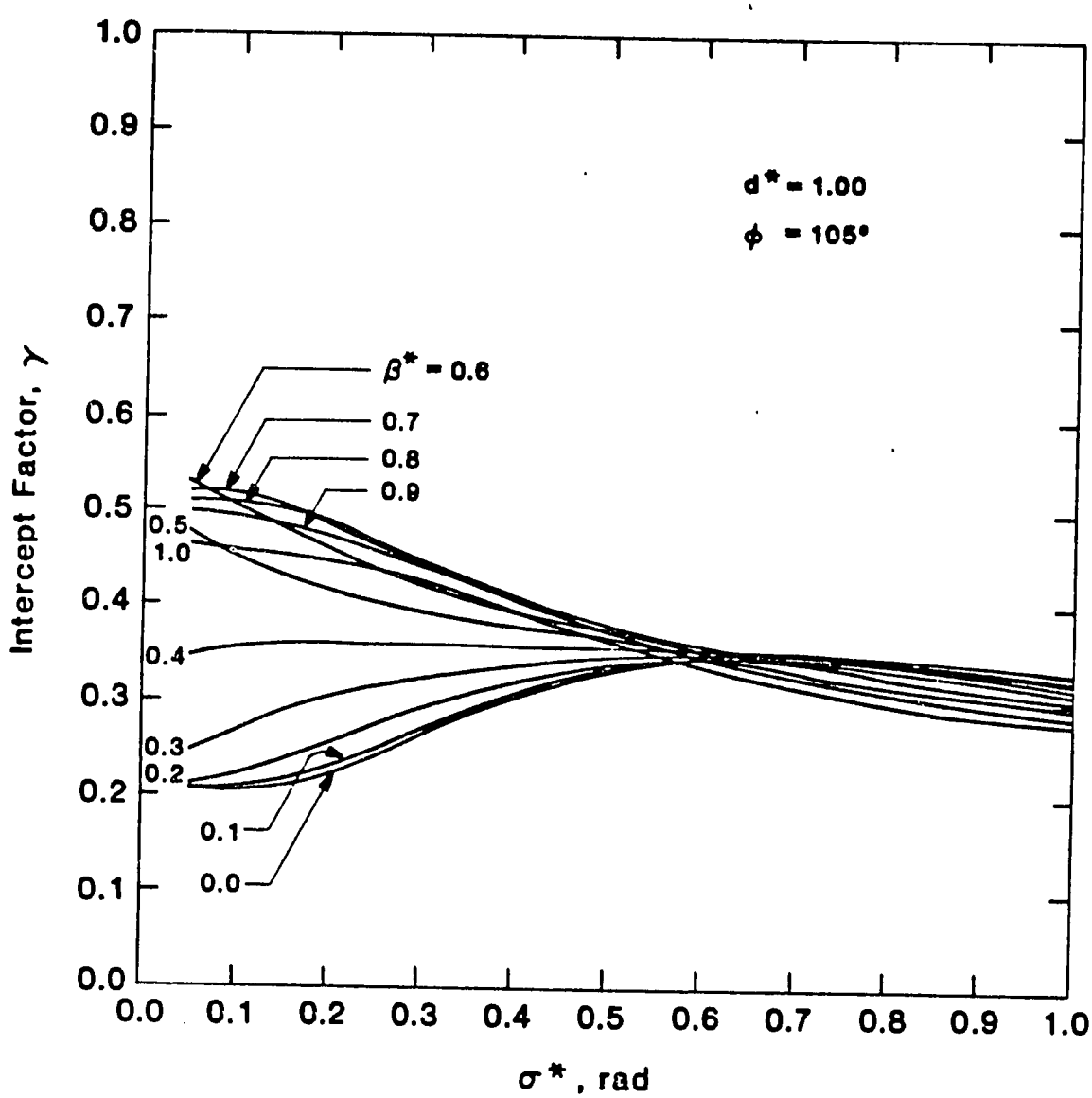


Figure 5.10 Intercept factor as a function of the universal random error parameter σ^* and the universal non-random error parameter β^* for ϕ = 105° and for d^* = 1.00 .

errors) and $d^* = 0.0$, 0.25, 0.5, 0.75, and 1.0. As discussed in Reference [1], an acceptable PTC design should have an intercept factor of 75% or better, i.e., $\gamma \geq 0.75$. Figure 5.11 shows constant intercept factor lines as a function of d^* and σ^* and for zero β^*. Using Figures 5.6 to 5.11, the bounds for the universal error parameters, for all practical applications, can be set as:

$$0.05 \leq \sigma^* \leq 0.5 \text{ rad}$$

$$0.0 \leq \beta^* \leq 0.5 \text{ rad}$$

$$0.0 \leq d^* \leq 0.5$$

In these intervals, curves shown in Figures 5.6, 5.7 and 5.8 are well-behaving polynomials and they can be appoximated using a two-dimensional least-squares curve fit method. Then, for a given d^* value $\frac{\partial\gamma}{\partial\sigma^*}$ and $\frac{\partial\gamma}{\partial\beta^*}$ are obtained from the curve-fit equation.

Once the derivatives are determined, Eqs.(5.7) and (5.8) can be solved using the Newton-Raphson method to get the optimum values of σ^* and β^* from which the optimum concentration ratio C_o, is calculated.

In this optimization process, the designer is required to determine the (optimum) value of d^* (= $(d_r)_y/D$) first, i.e., independent of the rest of the optimization process. Nonetheless this requirement is in harmony with the optimization philosophy described in the preceding section where the dimensions of the receiver were to be chosen first (independent of the dimension of the reflector). Therefore, the

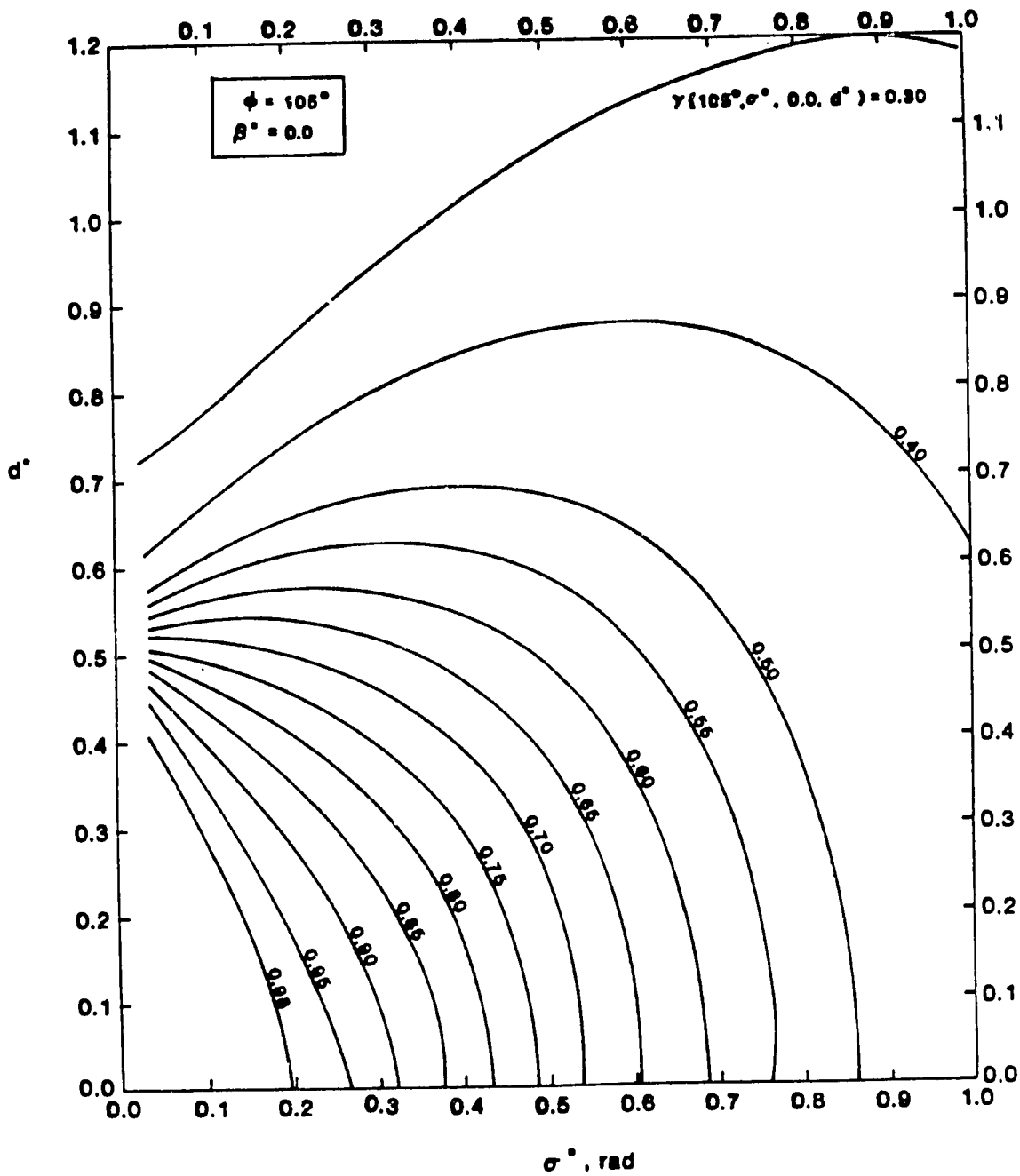


Figure 5.11 Constant intercept factor lines as a function of σ^* and d^* and for $\beta^* = 0.0$ and $\phi = 105°$.

designer would be required to choose the dimensions of the receiver such as to optimize d^*. In other words, the selection of the absorber tube diameter should be based primarily on the anticipated value of the mislocation error, $(d_r)_y$, which is given by the macro-design. As shown in Figure 5.12, the optimum value of d^* is zero (as expected). Nonetheless, in the range of 0.0 to 0.25, the curves are very flat and the maximum penalty when $d^* = 0.25$ is a mere 4% reduction in the intercept factor. Therefore, the optimum d^* can be taken to be in the range of 0.0 to 0.25. Thus, for a given mislocation error tolerance, $(d_r)_y$, the designer should choose the tube diameter such as to achieve a small d^* value (as close to zero as possible). However, the diameter should not be made too large in order to achieve a very small d^* value as this would consequently increase

- the weight of the receiver assembly requiring supports at shorter intervals,
- the cost -- more selective coating, larger glass envolope, more receiver supports,etc.
- the size of the reflector ($W_o = \pi D C_o$).

After the determination of the optimum concentration ratio, collector operating efficiencies (all-day average and instantaneous solar noon) can be calculated. The all-day average collector efficiency, $< \eta_c >$, can be calculated from:

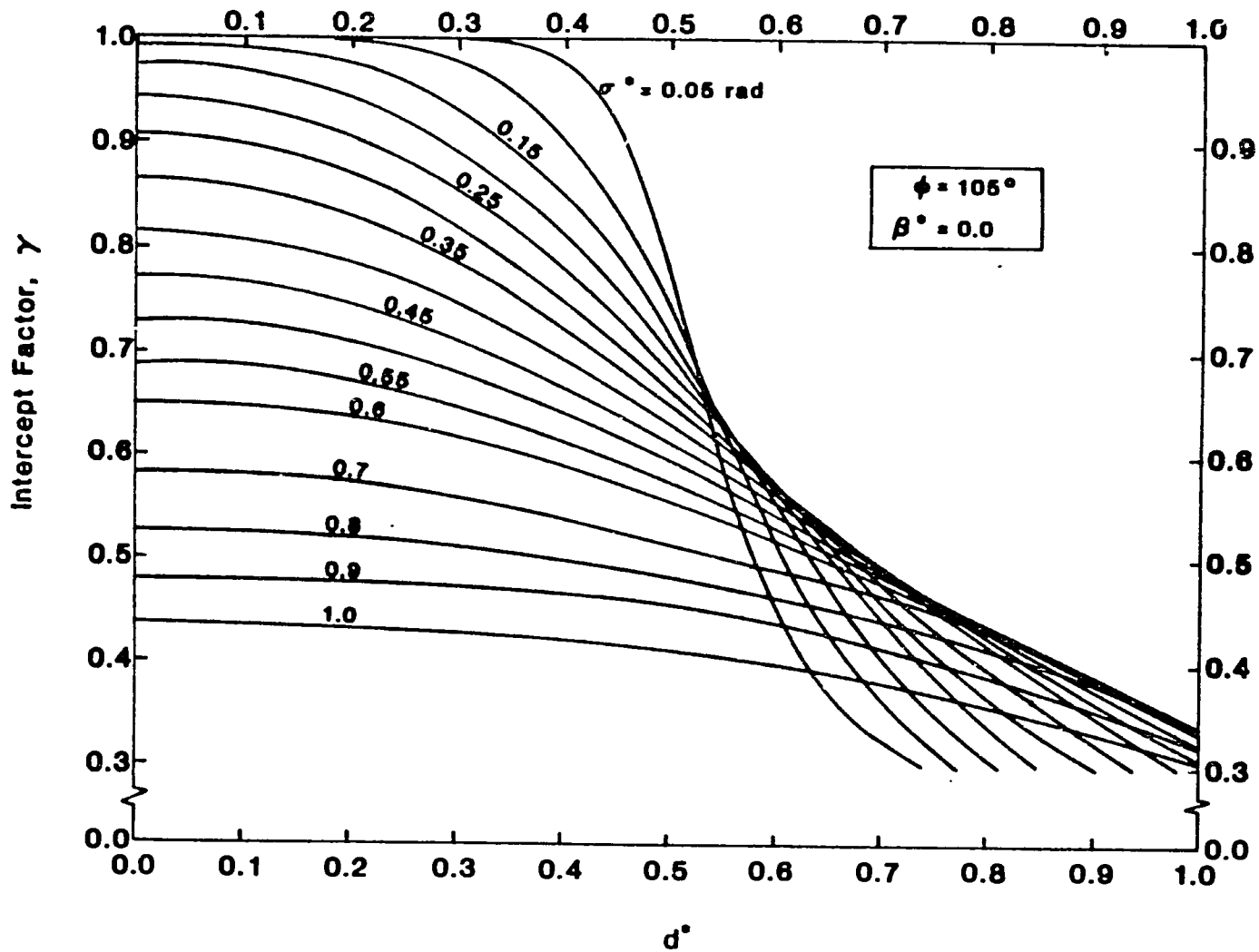


Figure 5.12 Intercept factor as a function of d^* and σ^* for $\beta^* = 0.0$ and $\phi = 105°$.

$$< q_{net} > = < I_b \cos\theta > < K(\theta) > [\rho(\tau\alpha)_n] \gamma_o - \frac{q_L}{C_o} \tag{5.11}$$

and

$$< \eta_c > = \frac{< q_{net} >}{< I_b >} \tag{5.12}$$

where

γ_o = Intercept factor at optimal concentration ratio,

$< q_{net} >$ = Net all-day average heat flux, $\frac{W}{m^2}$

$< I_b >$ = All-day average beam insolation, $\frac{W}{m^2}$

The instantaneous solar noon efficiency of the collector (optimized based on all-day average efficiency) can be calculated from

$$(q_{net})_{noon} = [I_b \cos\theta]_{noon} [K(\theta)]_{noon} [\rho(\tau\alpha)_n] \gamma_o - \frac{q_L}{C_o} \tag{5.13}$$

$$(\eta_c)_{noon} = \frac{(q_{net})_{noon}}{(I_b)_{noon}} \tag{5.14}$$

The steps for the concentration ratio optimization based on all-day average insolation can, therefore, be summarized as follows:

Given the macro level design, i.e., $[\rho(\tau\alpha)_n]$, σ, β, $(d_r)_y$ and tracking mode.

1. Calculate solar data for the application site for a clear equinox day, i.e., calculate $< I_b \cos\theta >$,

$\langle\cos\theta\rangle$, $\langle I_b \rangle$, $[I_b \cos\theta]_{noon}$, etc.

2. Calculate the all-day average incidence angle modifier for the chosen tracking mode, $\langle K(\theta) \rangle$, using data from existing collector designs,
3. Choose the rim angle from the optimum range of rim angles, 105° - 120°,
4. Choose the receiver assembly dimensions based on $(d_r)_y$ and other considerations (mentioned earlier) such as to optimize d^*. Subsequently, for the chosen receiver assembly dimensions and given temperature requirement, obtain the value of q_L from the thermal analysis (curves provided in [1]).
5. Calculate the right hand side of Eq.(5.7) and solve Equations (5.7) and (5.8) simultaneously to obtain the optimum concentration ratio C_o,
6. Calculate the all-day average and solar noon efficiencies of the collector using Equations (5.11)-(5.14),
7. Re-examine the optimum concentration ratio by studying the sensitivity of its value to changes in heat loss parameter (q_L), tracking mode, error tolerances, etc.

5.4 Summary

In this chapter, a rational approach for multi-objective design and optimization of PTC's was presented. A macro- and micro-level partitioning of the design problem is implemented. In this process, environmental goals, objectives and limitations were accounted for at the macro-level of design.

Subsystems and/or subsystem components were designed at the macro-level through a set of selection DSP's. In the selection DSP's, relative importances of attributes were used to account for the environmental goals, preferences and limitations, as well as, the application-specific goals or limitations. At the micro-level of design, subsystem designs were integrated such as to maximize the collector all-day thermal efficiency.

A seven-step procedure is developed to optimize the collector dimensions at the micro-level of design. In the following chapter the use of this method is demonstrated through illustrative examples for both the U.S. and the developing country applications.

Chapter Six

ILLUSTRATIVE EXAMPLES FOR PARABOLIC TROUGH SOLAR COLLECTOR DESIGNS FOR INDUSTRIALIZED AND DEVELOPING COUNTRIES

6.1 Introduction

In this chapter, the use of the PTC design method, presented in the preceding chapter, is demonstrated through illustrative examples. Illustrative examples for both industrialized and developing countries are presented.

Since most of the applications in developing countries are expected to be medium to low temperature applications, only one application is chosen which requires energy delivery at approximately 250°C at mid-latitudes (∿ 35°N) in the U.S. design environment and in a developing country design environment.

6.2 Assumptions and Design Data

The objective of these examples is to demonstrate the use of the optimization process at the micro-level of design, therefore, it will be assumed that the macro-level design of the subsystems (i.e., selection of the subsystem components and the subsystem designs) for the given design environment and application has been completed and the fabrication technique, the type of supporting structure, the tracker mechanism and the material properties, as well as the tracking mode have been chosen (based on environmental goals,

objectives, limitations, etc.) using the seven selection DSP's described in the preceding chapter in section 5.2.1. It is assumed that the design data for the chosen equipment and techniques (e.g., accuracy of the chosen tracker mechanism, slope errors associated with the chosen fabrication technique, projected errors for the chosen assembly method, etc.) are known. Note that these information are required for the completion of the macro-level design in any case, and therefore it is reasonable to assume that the aforementioned design data is available at the beginning of the micro-level design. Subsequently, the designer could determine the error tolerances (σ, β, $(d_r)_y$) for the given design environment using this design data and Table 5.5.

In the illustrative examples, in order to facilitate comparison between the designs and allow for meaningful interpretation of results, the same solar data, material properties, receiver dimensions, tracking mode and heat loss rate will be used. The changes in the design environment will be reflected in the values of the error parameters only. The solar data that will be used in these examples is given in Table 6.1. Derivation of this data is presented in Appendix C. The material properties that will be used in the illustrative examples are given Table 6.2.

TABLE 6.1 SOLAR DATA FOR THE EXAMPLE PROBLEMS[1]

Parameter	Tracking Mode			
	Two-axes	E-W	N-S	Polar
$\cos\theta_{noon}$	1.0	1.0	0.82	1.0
$[I_b\cos\theta]_{noon}$	865[2]	865	710	865
$\langle\cos\theta\rangle$	1.0	0.77[3]	0.88[3]	1.0
$\langle I_b\cos\theta\rangle$	791[3,2]	665[3]	670[3]	750[3]
$[K(\theta)]_{noon}$	1.0	1.0	0.95[4]	1.0
$\langle K(\theta)\rangle$	1.0	0.935[4]	0.99[4]	1.0

[1] This data is for a clear equinox day (K_h=0.75) at λ=35°N (see Appendix C),

[2] $[I_b]_{noon}$ = 865 W/m^2,

[3] All-day average based on 8h/day,

[4] These are averages from existing collector designs (see Appendix C).

TABLE 6.2 MATERIAL PROPERTIES FOR THE EXAMPLE PROBLEMS

Parameter	Value
Reflectance of mirror, ρ	0.85
Transmittance of glazing, τ	0.90
Absorptance of selective coating, α	0.95

The reflectance (ρ = 0.85) is typical of clean aluminum or dirty silver mirrors. The transmittance (τ = 0.9) and the absorptance (α = 0.95) are reasonable values for the state-of-the-art technology [18]. An east-west tracking mode (which is the tracking mode employed most often) is assumed, and as indicated earlier, optimization of the concentration ratio will be based on all-day average insolation and all-day average collector efficiency.

In the following two sections, optimization of the concentration ratio for the U.S. design environment and a developing country design environment are presented. A discussion and comparison of the results is given upon completion of the examples. In these sections, the seven steps given in the

preceding chapter are followed.

6.3 Example for U.S. Design Environment:

The values for the error parameters are listed in Table 6.3 . These represent typical values for state-of-the-art technology in the U.S. design environment. The entries are based on data reported by Sandia Laboratories for realistic materials and fabrication techniques [13, 18]. The values of the non-random error-tolerances, β and $(d_r)_y$, are obtained from the standard deviations reported in the literature.

The optimization of the concentration ratio using the steps given in the preceding chapter is as follows:

Step 1: The all-day average solar data for E-W tracking mode is given in Table 6.1.

Step 2: The all-day average incidence angle modifier for E-W tracking is given in Table 6.1.

Step 3: $\phi = 105°$ is chosen.

Step 4:
- An absorber tube of 2.54-cm outer diameter (D), surrounded by a glass tube of 5-cm outer diameter is chosen. With reasonable glass thickness (approximately 2mm) this leaves an air gap of 1.0 cm, approximately optimal in terms of heat transfer.
- With this absorber diameter, $d^* = \frac{0.31}{2.54} \cong 0.125$, which is in the optimal range.
- For operating temperature $(T_{abs}) \cong 250°C$
  Ambient Temperature $(T_a) = 10°C$
  $D = 2.54$ cm,

TABLE 6.3 ERROR TOLERANCES FOR THE U.S. DESIGN ENVIRONMENT

Parameter	Value	Remark
σ_{mirror}	0.25 mrad	
$2\sigma_{slope}$	5.39 mrad	
σ_{sun}	3.45 mrad	Average for a clear equinox day.
σ_{track}	2.00 mrad	This corresponds to approx. ±0.25°.
$\sigma_{displacement}$	2.00 mrad	This corresponds to approx. 3.1mm .
σ_{tot}	7.00 mrad	From Eq.(3.17).
Error Tolerances		
Random, σ	6.40 mrad	From Eq.(3.19).
Non-random, β	0.25°	
Non-random, $(d_r)_y$	3.1 mm	

. From Figure 6.1, $U_L \cong 8.4 \frac{W}{m^2}$

$$q_L = U_L(T_R - T_a)$$

$$= 8.4\ (250° - 10°) \cong 2000 \frac{W}{m^2}$$

Step 5: $$\frac{q_L}{\langle K(\theta)\rangle \langle I_b \cos\theta\rangle [\rho(\tau\alpha)_n]} = 4.426$$

Solving Equations (5.7) and (5.8) simultaneously gives:

$$\sigma^* = 181.75 \text{ mrad}$$

$$\beta^* = 123.90 \text{ mrad}$$

$$\gamma_o = 0.956 \quad (0.963)^*$$

From which $C_o = 28.4 \quad (32)^*$

This is also shown in Figure 6.3, where optimum concentration ratio is plotted as a function of σ and β for $d^* = 0.125$.

Then the reflector aperture width is:

$$W_o = \pi\ D\ C_o$$
$$= 226.6 \text{ cm}$$

Step 6: Using Equations (5.11) and (5.12):

$$\langle\eta_c\rangle = \frac{361.6}{791.0} = 0.457 \quad (0.471)^*$$

Solar noon efficiency is

$$(\eta_c)_{noon} = \frac{536.2}{865} = 0.62 \quad (0.63)^*$$

---

*Numbers in (...) designate the values that would have been obtained if all errors were treated as random (β=0.0, d^*=0.0 -- see Figure 6.2).

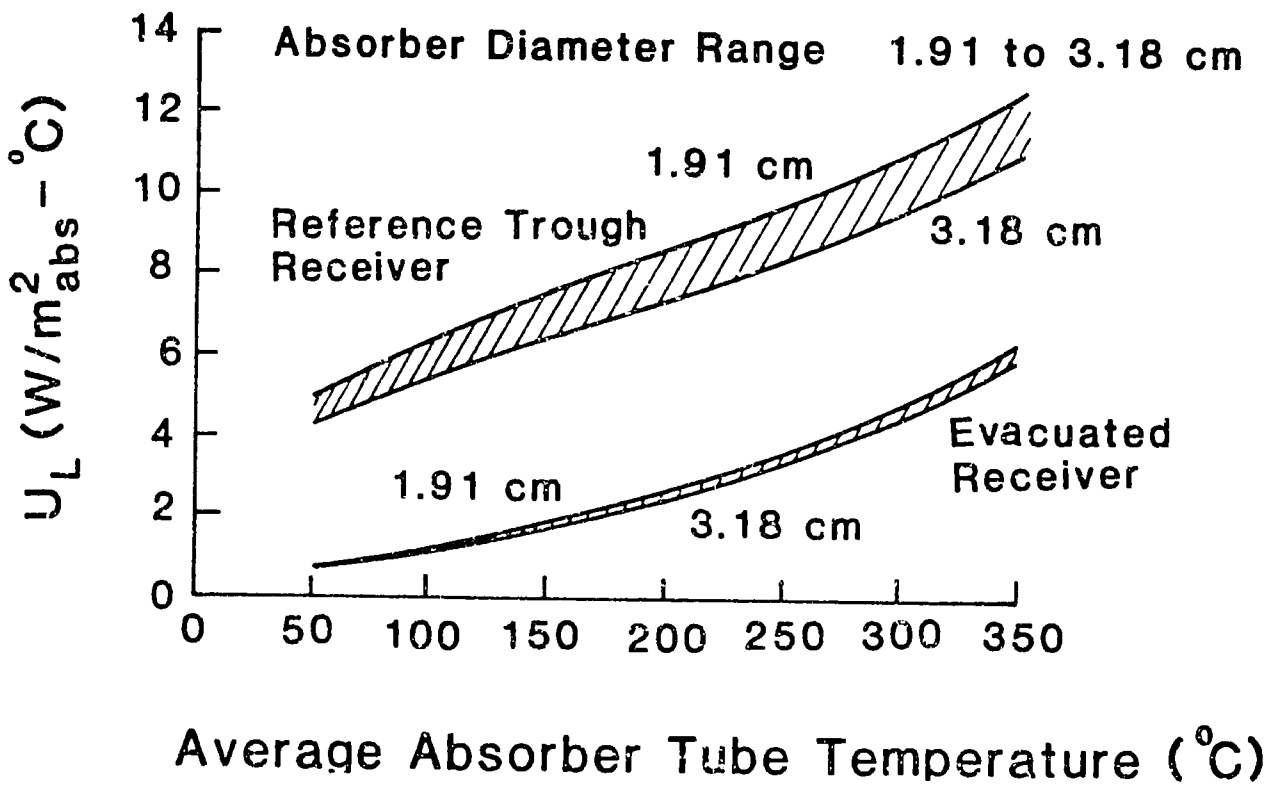


Figure 6.1 Heat-loss coefficient U_L as a function of average absorber tube temperature and absorber tube diameter (from [1]).

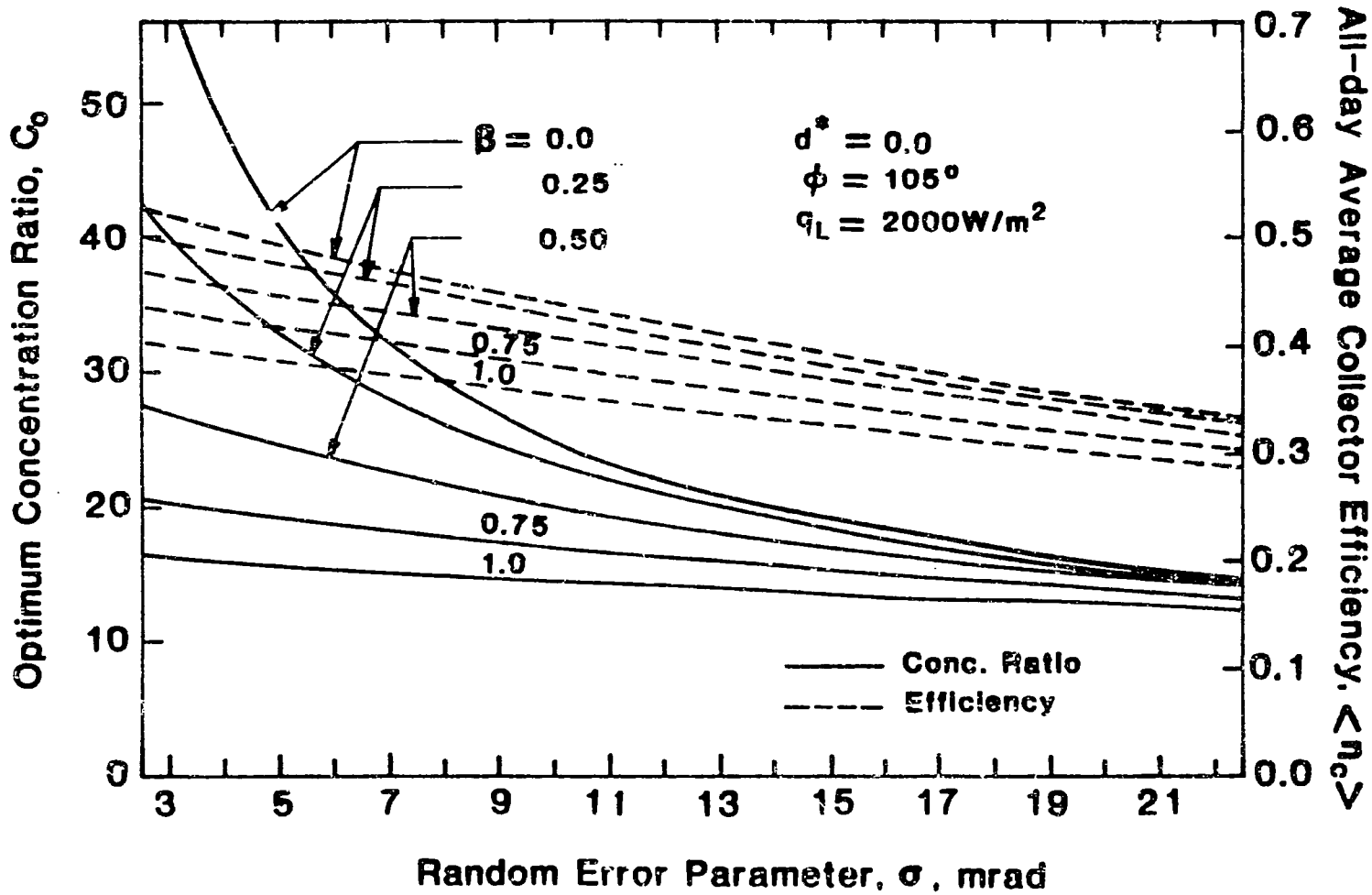


Figure 6.2 Example Problems -- Optimization of the concentration ratio (d^*= 0.0).

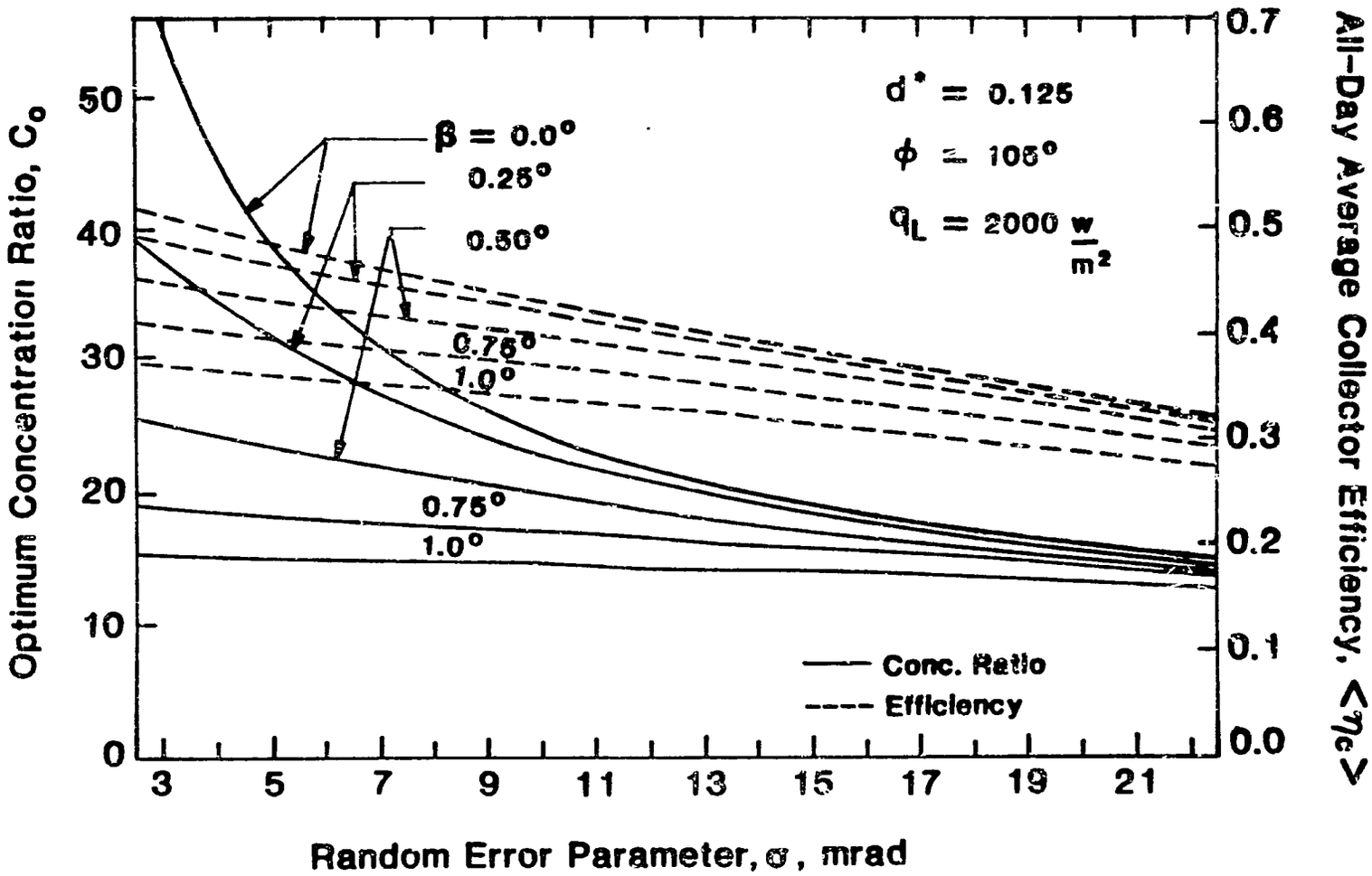


Figure 6.3 Example Problems -- Optimization of the concentration ratio ($d^* = 0.125$).

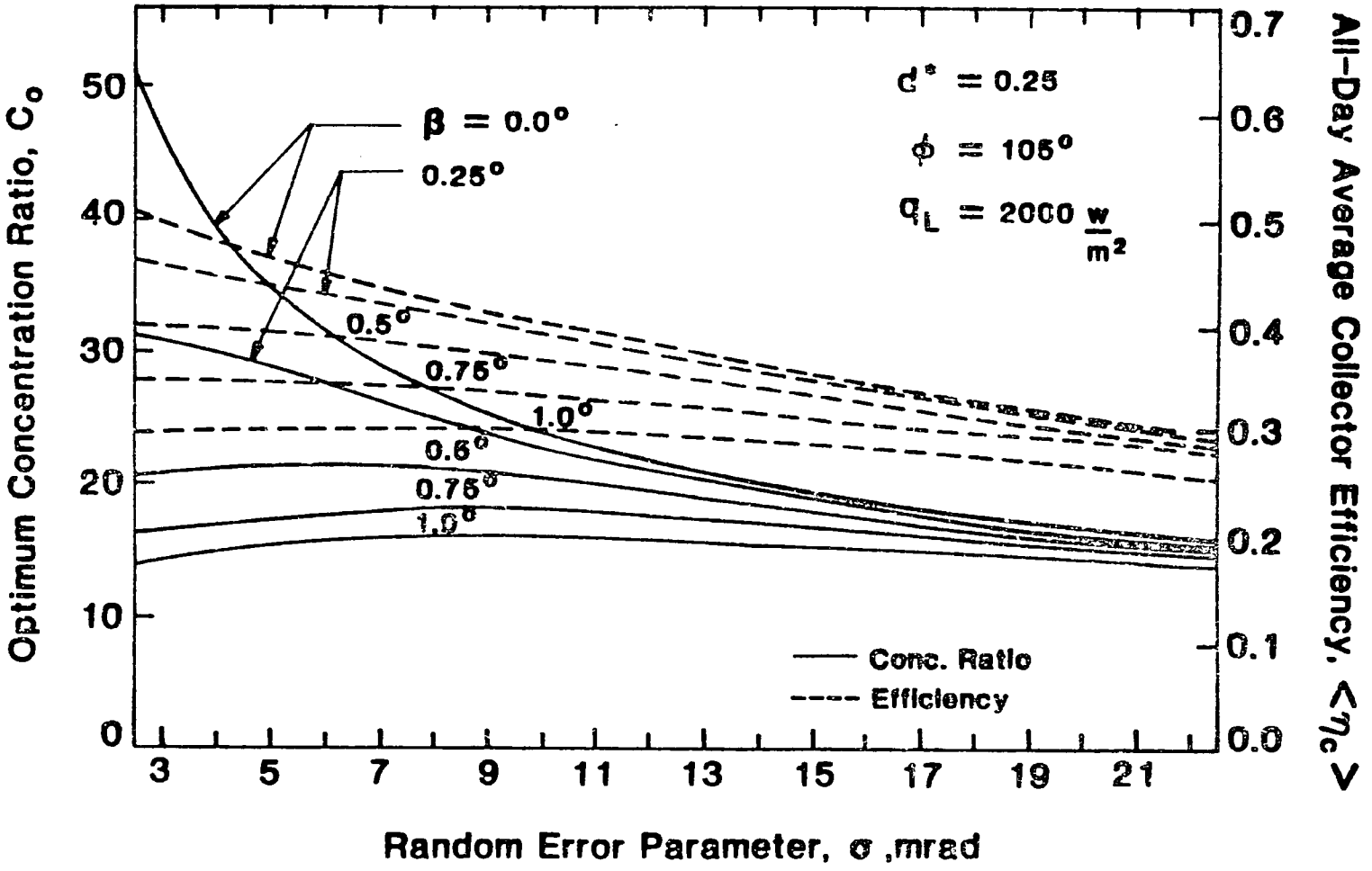


Figure 6.4 Example Problems -- Optimization of the concentration ratio ($d^* = 0.25$).

Step 7: a. <u>Sensitivity to heat loss parameter</u> q_L

$q_L = 1000 \frac{W}{m^2}$ ..... $\langle\eta_c\rangle$ $(C_o' = 23.6)^1 = 0.504$
$\langle\eta_c\rangle$ $(C_o = 28.4)^2 = 0.502$

$q_L = 2000 \frac{W}{m^2}$ ..... $\langle\eta_c\rangle$ $(C_o = 28.4) = 0.457$

$q_L = 3000 \frac{W}{m^2}$ ..... $\langle\eta_c\rangle$ $(C_o' = 33.3) = 0.415$
$\langle\eta_c\rangle$ $(C_o = 28.4) = 0.412$

b. <u>Sensitivity to changes in error tolerances</u>

- $\sigma = 6.4$ mrad, $\beta = 0.25°$

$(d_r)_y = 0.0$ ..... $\langle\eta_c\rangle$ $(C_o' = 29.6)^1 = 0.465$
$\langle\eta_c\rangle$ $(C_o = 28.4)^2 = 0.464$

$(d_r)_y = 3.1$ mm ..... $\langle\eta_c\rangle$ $(C_o = 28.4) = 0.457$

$(d_r)_y = 6.2$ mm ..... $\langle\eta_c\rangle$ $(C_o' = 27.6) = 0.425$
$\langle\eta_c\rangle$ $(C_o = 28.4) = 0.424$

- $\sigma = 6.4$ mrad, $(d_r)_y = 3.1$ mm

$\beta = 0.0°$ ..... $\langle\eta_c\rangle$ $(C_o' = 33.2) = 0.470$
$\langle\eta_c\rangle$ $(C_o = 28.4) = 0.465$

$\beta = 0.25°$ ..... $\langle\eta_c\rangle$ $(C_o = 28.4) = 0.457$

$\beta = 0.50°$ ..... $\langle\eta_c\rangle$ $(C_o' = 23.0) = 0.425$
$\langle\eta_c\rangle$ $(C_o = 28.4) = 0.414$

---

[1] $\langle\eta_c\rangle$ $(C_o' = \ldots) = \ldots$ designates the all day average efficiency of collector, optimized based on the new heat loss (or error) parameter. C_o' is the new optimum concentration ratio.

[2] $\langle\eta_c\rangle$ $(C_o = \ldots) = \ldots$ designates the all-day average efficiency of the collector under the new operating conditions.

- $\beta = 0.25°$, $(d_r)_y = 3.1$ mm

$\sigma = 4.4$ mrad ..... $\langle\eta_c\rangle$ $(C_o' = 33.0) = 0.475$
$\langle\eta_c\rangle$ $(C_o = 28.4) = 0.471$

$\sigma = 6.4$ mrad ..... $\langle\eta_c\rangle$ $(C_o = 28.4) = 0.457$

$\sigma = 8.4$ mrad ..... $\langle\eta_c\rangle$ $(C_o' = 25.0) = 0.435$
$\langle\eta_c\rangle$ $(C_o = 28.4) = 0.431$

c. <u>Sensitivity to tracking mode</u>

Two-axes	$C_o = 26.9$,	$\langle\eta_c\rangle = 0.604$
E-W	$C_o = 28.4$,	$\langle\eta_c\rangle = 0.457$
N-S	$C_o = 28.4$,	$\langle\eta_c\rangle = 0.492$
Polar	$C_o = 27.35$,	$\langle\eta_c\rangle = 0.568$

These results will be discussed in a later section after the completion of the example for the developing country design environments.

6.4 Example for Developing Country Design Environment

Since, at this time, realistic data for equipment, materials, fabrication techniques, etc., are not available for the developing country design environments, design data from the U.S. design environment are used as reference to project values for the error tolerances in the developing country design environments. As indicated earlier, other design parameters (material properties, receiver dimensions, heat loss rate and tracking mode) are assumed to be the same for both environments. The projected values for the error

TABLE 6.4 ERROR TOLERANCES FOR DEVELOPING COUNTRY DESIGN ENVIRONMENT

Error Tolerances	Value
Case (i)	
σ	8.7 mrad
β	0.5°
$(d_r)_y$	6.2 mm
Case (ii)	
σ	11.3 mrad
β	1.0°
$(d_r)_y$	6.2 mm

parameters are listed in Table 6.4. In this table, two sets of values for the error parameters are listed:

Case (i) 8 mrad slope errors

Twice the U.S. mislocation error, i.e., $(d_r)_y = 6.2\,\text{mm}$

Twice the U.S. tracking error, i.e., $\beta = 0.5°$

Case (ii) Twice the U.S. slope errors, i.e., $\sigma_{slope} = 10.8$ mrad

Twice the U.S. mislocation error, i.e., $(d_r)_y = 6.2\,\text{mm}$

Four times the U.S. tracking error, $\beta = 1.0°$

Steps 1-4 Same as those in section 6.3, except

$$d^* = \frac{0.62}{2.54} \cong 0.25$$

Step 5 The right-hand side of Eq.(5.7) is the same as before, 4.426. Solving Equations (5.7) and (5.8) using the error parameters listed in Table 6.4 (see Figure 6.4):

Case (i) $C_o = 21.0 \quad (24)^*$

$\gamma_0 = 0.87 \quad (0.944)^*$

Then $W_o = 167.5$ cm.

Case (ii) $C_o = 16.0 \quad (16.9)^*$

$\gamma_o = 0.798 \quad (0.91)^*$

Then $W_o = 127.7$ cm.

---

*Numbers in (...) designate the values that would have been obtained, if all errors were treated as random ($\beta = 0.0$, $d^* = 0.0$ -- see Figure 6.2).

Step 6:

Case (i) $\langle\eta_c\rangle = 0.377 \quad (0.434)^*$

$(\eta_c)_{noon} = 0.52 \quad (0.59)^*$

Case (ii) $\langle\eta_c\rangle = 0.298 \quad (0.39)^*$

$(\eta_c)_{noon} = 0.435 \quad (0.543)^*$

Step 7:

Case (i) a. <u>Sensitivity to heat loss parameter</u> q_L

$q_L = 1000 \frac{W}{m^2}$ ..... $\begin{cases} \langle\eta_c\rangle \ (C_o' = 14.9) = 0.448 \\ \langle\eta_c\rangle \ (C_o = 21.0) = 0.437 \end{cases}$

$q_L = 2000 \frac{W}{m^2}$ ..... $\langle\eta_c\rangle \ (C_o = 21.0) = 0.377$

$q_L = 3000 \frac{W}{m^2}$ ..... $\begin{cases} \langle\eta_c\rangle \ (C_o' = 26.1) = 0.323 \\ \langle\eta_c\rangle \ (C_o = 21.0) = 0.316 \end{cases}$

b. <u>Sensitivity to changes in error tolerances</u>

- $\sigma = 8.7$ mrad, $\beta = 0.5°$:

$(d_r)_y = 3.1$ mm ..... $\begin{cases} \langle\eta_c\rangle \ (C_o' = 24.8) = 0.41 \\ \langle\eta_c\rangle \ (C_o = 21.0) = 0.40 \end{cases}$

$(d_r)_y = 6.2$ mm ..... $\langle\eta_c\rangle \ (C_o = 21.0) = 0.377$

- $\sigma = 8.7$ mrad, $(d_r)_y = 6.2$ mm:

$\beta = 0.25°$ ..... $\begin{cases} \langle\eta_c\rangle \ (C_o' = 24.0) = 0.405 \\ \langle\eta_c\rangle \ (C_o = 21.0) = 0.40 \end{cases}$

$\beta = 0.5°$ ..... $\langle\eta_c\rangle \ (C_o = 21.0) = 0.377$

$\beta = 0.75°$ ..... $\left[\begin{array}{l}\langle\eta_c\rangle\ (C_o' = 18.4) = 0.340 \\ \langle\eta_c\rangle\ (C_o = 21.0) = 0.337\end{array}\right.$

- $\beta = 0.5°$, $(d_r)_y = 6.2$ mm:

$\sigma = 6.7$ mrad ..... $\left[\begin{array}{l}\langle\eta_c\rangle\ (C_o' = 21.6) = 0.385 \\ \langle\eta_c\rangle\ (C_o = 21.0) = 0.380\end{array}\right.$

$\sigma = 8.7$ mrad ..... $\langle\eta_c\rangle\ (C_o = 21.0) = 0.377$

$\sigma = 10.7$ mrad ..... $\left[\begin{array}{l}\langle\eta_c\rangle\ (C_o' = 20.0) = 0.365 \\ \langle\eta_c\rangle\ (C_o = 21.0) = 0.360\end{array}\right.$

c. <u>Sensitivity to tracking mode</u>

Two-axes	$C_o = 18.6$,	$\langle\eta_c\rangle = 0.541$
E-W	$C_o = 21.0$,	$\langle\eta_c\rangle = 0.377$
N-S	$C_o = 20.4$,	$\langle\eta_c\rangle = 0.41$
Polar	$C_o = 19.4$,	$\langle\eta_c\rangle = 0.481$

Step 7:

Case (ii) a. <u>Sensitivity to heat loss parameter</u> q_L

$q_L = 1000\ \frac{W}{m^2}$ ..... $\left[\begin{array}{l}\langle\eta_c\rangle\ (C_o = 10.9) = 0.3924 \\ \langle\eta_c\rangle\ (C_o = 16.0) = 0.3769\end{array}\right.$

$q_L = 2000\ \frac{W}{m^2}$ ..... $\langle\eta_c\rangle\ (C_o = 16.0) = 0.298$

$q_L = 3000\ \frac{W}{m^2}$ ..... $\left[\begin{array}{l}\langle\eta_c\rangle\ (C_o = 19.4) = 0.227 \\ \langle\eta\ \rangle\ (C_o = 16.0) = 0.219\end{array}\right.$

b. <u>Sensitivity to changes in error tolerances</u>

- σ = 11.3 mrad, β = 1.0°:

  $(d_r)_y$ = 3.1 mm ..... $\langle\eta_c\rangle$ (C_o' = 14.4) = 0.330
  $\langle\eta_c\rangle$ (C_o = 16.0) = 0.320

  $(d_r)_y$ = 6.2 mm ..... $\langle\eta_c\rangle$ (C_o = 16.0) = 0.298

- σ = 11.3 mrad, $(d_r)_y$ = 6.2 mm

  β = 0.75° ..... $\langle\eta_c\rangle$ (C_o' = 18.0) = 0.330
  $\langle\eta_c\rangle$ (C_o = 16.0) = 0.330

  β = 1.0° ..... $\langle\eta_c\rangle$ (C_o = 16.0) = 0.298

- β = 1.0°, $(d_r)_y$ = 6.2 mm

  σ = 9.3 mrad ..... $\langle\eta_c\rangle$ (C_o' = 16.0) = 0.298
  $\langle\eta_c\rangle$ (C_o = 16.0) = 0.298

  σ = 11.3 mrad ..... $\langle\eta_c\rangle$ (C_o = 16.0) = 0.298

  σ = 13.3 mrad ..... $\langle\eta_c\rangle$ (C_o' = 15.6) = 0.295
  $\langle\eta_c\rangle$ (C_o = 16.0) = 0.293

b. <u>Sensitivity to tracking mode</u>

Two-axes	C_o = 14.0,	$\langle\eta_c\rangle$ = 0.425
E-W	C_o = 16.0,	$\langle\eta_c\rangle$ = 0.298
N-S	C_o = 15.4,	$\langle\eta_c\rangle$ = 0.329
Polar	C_o = 14.42,	$\langle\eta_c\rangle$ = 0.394

In the following section, these results are discussed. Also, they are compared with those of the U.S. design environment.

6.5 Discussion of Results

In the preceding sections, it was shown that the optimization method developed in Chapter Five can be used to develop optimal PTC designs for different design environments. It was shown that the technological capabilities and the manufacture and assembly preferences of different design environments can be effectively incorporated into the optimization process through the use of error parameters. It was found that the optimum value of concentration ratio decreases as the values of the error parameters (i.e., error tolerances) increase, all other variables being constant. In other words, for fixed receiver dimensions, the optimum reflector dimension gets smaller as the error tolerances increase. For example, in the solved examples, for:

σ = 6.4 mrad, β = 0.25°, $(d_r)_y$ = 3.1 mm, W_o = 226.6 cm,

σ = 8.7 mrad, β = 0.5° , $(d_r)_y$ = 6.2 mm, W_o = 167.5 cm,

σ =11.3 mrad, β = 1.0° , $(d_r)_y$ = 6.2 mm, W_o = 127.7 cm.

As expected, however, the performance of the collector degrades with increasing error-tolerances. A designer who recognizes this and knows the optimum concentration ratio (for given error tolerances) can associate the cost of fabricating and installing the system with a performance level (efficiency). Subsequently, he can look at the sensitivity analyses to determine whether performance enhancement justifies the cost of incorporating more restrictive tolerances into the design, or of introducing different

materials and methods of construction. That is, using the results of the sensitivity analyses he can reexamine the macro-level design decisions and improve them (if necessary).

In the following sections interpretation of the sensitivity analyses of the example problems is presented. Sensitivity of the optimization to changes in the error parameters, heat loss parameter, and the tracking mode are discussed.

6.5.1 Sensitivity of Optimization to Change in Error Parameters

Tables 6.5 - 6.7 summarize the sensitivity of performance to changes in error parameters. As shown in the tables, if the collector (optimized for operation with certain error levels) operates with error levels higher or lower than the error tolerances, the operating efficiency will deviate from its optimum value. As expected the efficiency will be higher if operating error level is lower than the error tolerance value and vice versa. For example, for the U.S. example, the collector was optimized to tolerate a tracking error of 0.25°, however, if it operates without any tracking error ($\beta = 0°$, $\Delta\beta = -0.25°$), its efficiency will be 46.5% instead of 45.7%. If it was optimized for operation with zero tracking error, however, the optimum concentration ratio would have been 33.2 (instead of 28.4) and the efficiency would have been 47.0%, a gain of only half a percentage point. Therefore, it can be concluded that an optimum based on error tolerances is rather broad, and the collector does not suffer a significant performance degradation for operating at different error levels. The same is true

TABLE 6.5 CHANGE IN EFFICIENCY IF COLLECTOR OPERATES WITH ERROR LEVEL DIFFERENT THAN ERROR TOLERANCE (U.S. EXAMPLE*)

Difference between error tolerance and operating error level $\Delta x = x_{oper} - x_{tol}$		All-day efficiency of collector (optimized for x_{tol}) if operated with error level x_{oper}	All-day efficiency if collector optimized for operation at x_{oper}	Difference in Efficiency (%)
$\Delta\sigma$	- 2 mrad	47.1	47.5	0.4
	+ 2 mrad	43.1	43.5	0.4
$\Delta\beta$	- 0.25°	46.5	47.0	0.5
	+ 0.25°	41.4	42.5	1.1
$\Delta(d_r)_y$	- 3.1 mm	46.4	46.5	0.1
	+ 3.1 mm	42.4	42.5	0.1

*See Table 6.3 for error tolerances used in optimization. The optimum all-day efficiency is 45.7 %.

TABLE 6.6 CHANGE IN EFFICIENCY IF COLLECTOR OPERATES WITH ERROR LEVEL DIFFERENT THAN ERROR TOLERANCE (DEVELOPING COUNTRY EXAMPLE - CASE (i))

Difference between error tolerance and operating error level $\Delta x = x_{oper} - x_{tol}$		All-day efficiency of collector (optimized for x_{tol}) if operated with error level x_{oper}	All-day efficiency if collector optimized for operation at x_{oper}	Difference in Efficiency (%)
$\Delta\sigma$	- 2 mrad	38.1	38.5	0.4
	+ 2 mrad	36.1	36.5	0.4
$\Delta\beta$	- 0.25°	40.0	40.5	0.5
	+ 0.25°	33.7	34.0	0.3
$\Delta(d_r)_y$	- 3.1 mm	40.0	41.0	1.0
	+ 3.1 mm	-	-	-

* See Table 6.4 for error tolerances used in optimization. The optimum all-day efficiency is 37.7 %.

TABLE 6.7 CHANGE IN EFFICIENCY IF COLLECTOR OPERATES WITH ERROR LEVEL DIFFERENT THAN ERROR TOLERANCE (DEVELOPING COUNTRY EXAMPLE - CASE (ii))

Difference between error tolerance and operating error level $\Delta x = x_{oper} - x_{tol}$		All-day efficiency of collector (optimized for x_{tol}) if operated with error level x_{oper}	All-day efficiency if collector optimized for operation at x_{oper}	Difference in Efficiency (%)
$\Delta\sigma$	- 2 mrad	29.8	29.8	0.0
	+ 2 mrad	29.3	29.5	0.2
$\Delta\beta$	- 0.25°	33.0	33.0	0.0
	+ 0.25°	26.5	26.1	0.4
$\Delta(d_r)_y$	- 3.1 mm	32.0	33.0	1.0
	+ 3.1 mm	-	-	-

*See Table 6.4 for error tolerances used in optimization. The optimum all-day efficiency is 29.8 %.

for the developing country examples too (see Tables 6.6 and 6.7).

6.5.2 Sensitivity of Optimization to Change in Heat Loss Parameter

Once the collector has been optimized for operation at a certain temperature, the deviation from optimal performance at different temperatures can be calculated to study the efficiency of the collector at lower or higher temperatures. In the examples, optimization of the concentration ratio was determined for an assumed heat loss parameter, $q_L = 2000 \frac{W}{m^2}$, and the efficiency of this collector at lower or higher temperatures corresponding to $q_L = 1000 \frac{W}{m^2}$ and $q_L = 3000 \frac{W}{m^2}$ was then calculated. As shown in Table 6.8, at lower temperatures the collector will operate with higher efficiency and vice versa. Again the optimum is broad. If the collector were optimized for the new heat loss levels, the gain will be at the most 1.55 percent.

TABLE 6.8: SENSITIVITY OF OPTIMIZATION TO CHANGE IN HEAT LOSS PARAMETER q_L

HEAT LOSS PARAMETER ($\frac{W}{m^2}$)	ALL-DAY EFFICIENCY OF COLLECTOR (%) (optimized for q_L = 2000), if operated at different heat loss level (...) = Gain in Efficiency if collector is optimized for the new heat loss level		
	U.S. Example	Developing Country Example	
		case (i)	case (ii)
1000	50.2 (0.2)	43.7 (1.1)	37.7 (1.55)
2000	45.7	37.7	29.8
3000	41.2 (0.3)	31.6 (0.7)	21.9 (0.80)

6.5.3 Sensitivity to Tracking Mode:

Even though the tracking mode was selected at the macro-level of design, the designer can at this stage reexamine his decision by comparing the performance of the selected tracking mode to those of the alternatives. Table 6.9 summarizes such a comparison for the example problems.

TABLE 6.9 COMPARISON OF TRACKING MODES

Tracking Mode	All-day efficiency, (%)		
	U.S. Example	Developing Country Examples	
		case (i)	case (ii)
2- axes	60.4	54.1	42.5
E-W	45.7	37.7	29.8
N-S	49.2	41.0	32.9
Polar	56.3	48.1	39.4

As expected, all-day efficiency of 2-axes tracking mode is the highest and polar-axis tracking is the second best. As discussed earlier, however, the tracking mode selection will involve multiple objectives, therefore, these numbers can only be used for reexamining the decision on the tracking mode and changing the attribute ratings (if necessary). Nonetheless, it is important to note that, the optimum concentration ratios for N-S and E-W tracking modes are almost identical (see pages 109, 113, 114) in all three examples. Since,

N-S and E-W tracking modes are usually the only two serious competitors in the selection process, this finding is a good news. A collector optimized for operation with E-W axis tracking can also be operated with N-S axis tracking without any performance penalty. Therefore, the designer can delay his decision on the tracking mode until the actual installation of collectors and even use a mix of N-S and E-W oriented collectors (if necessary).

6.5.4 Comparison of Optimization Based on Random Errors Alone with Optimization Based on Random and Non-random Errors:

As discussed earlier, previous investigators have treated all errors as random and represented them as angular standard deviations and subsequently, summed them up in the single parameter σ. In the present work, errors are divided into two (random and non-random) groups and both are included in the optimization process.

Results from the present work agree very closely with those of the previous investigators when non-random errors are set equal to zero, as shown in Figure 6.5. However, results of concentration ratio optimization based on both random and non-random errors differ from those based on random errors alone. A comparison of these results for the example problems is presented in Table 6.10. As shown, when optimization is based on random errors alone, the optimum values of concentration ratio, intercept factor, all-day efficiency and solar noon efficiency are consistently

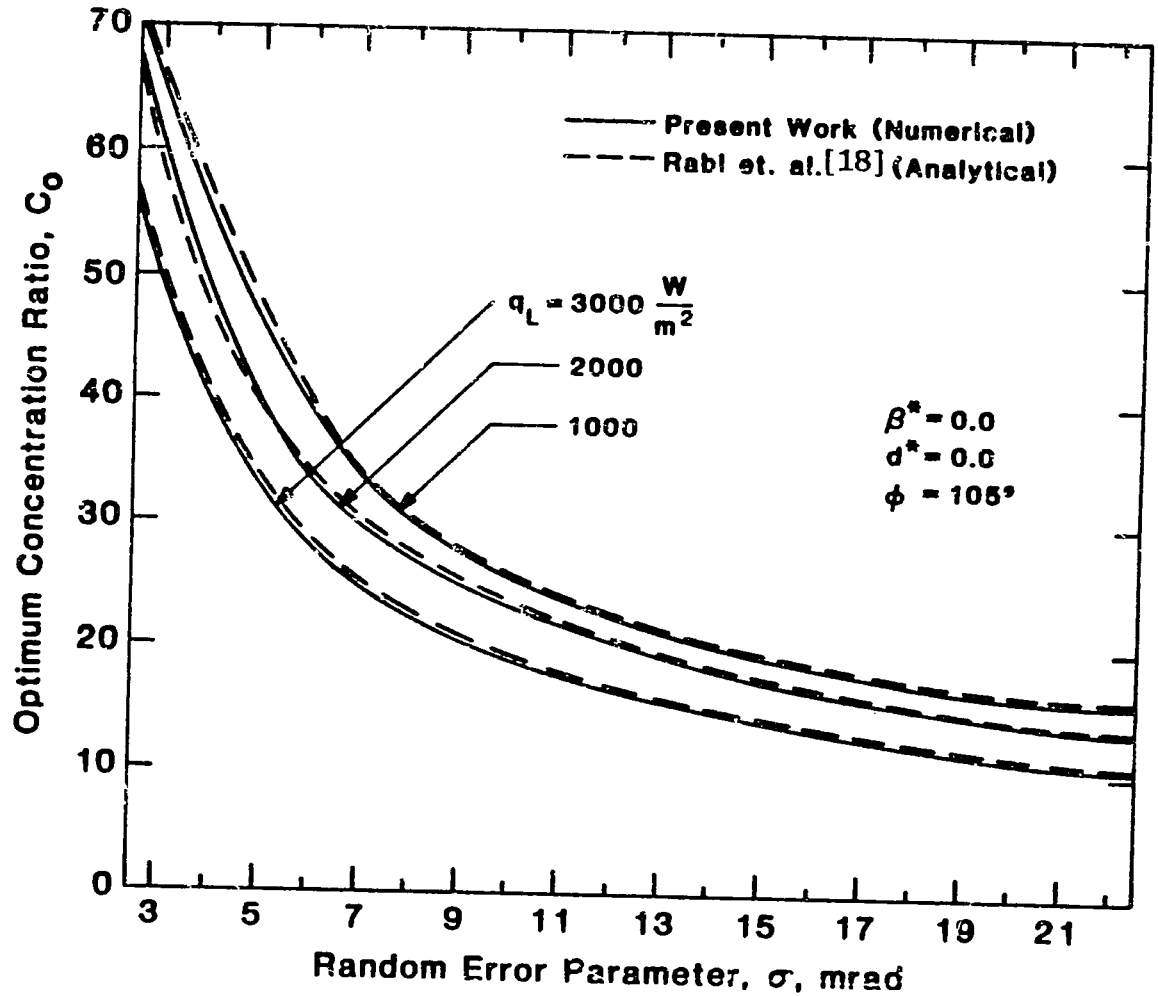


Figure 6.5 Comparison of the results of present work (with zero non-random errors) with the results of Rabl et. al.[18] .

TABLE 6.10 COMPARISON OF OPTIMIZATION BASED ON RANDOM ERRORS ALONE WITH OPTIMIZATION BASED ON RANDOM AND NON-RANDOM ERRORS

		PARAMETER	Optimization based on Random and Non-random errors	Optimization based on Random errors alone	% Error when optimization is based on Random errors alone
U.S. EXAMPLE		C_o	28.4	32.0	12.7
		γ_o	0.956	0.963	0.70
		$\langle\eta_c\rangle$	0.457	0.471	3.06
		$(\eta_c)_{noon}$	0.620	0.630	1.60
DEVELOPING COUNTRY EXAMPLES	CASE (i)	C_o	21.0	24.0	14.3
		γ_o	0.870	0.944	8.5
		$\langle\eta_c\rangle$	0.377	0.434	15.1
		$(\eta_c)_{noon}$	0.520	0.590	13.5
	CASE (ii)	C_o	16.0	16.9	5.6
		γ_o	0.798	0.910	14.0
		$\langle\eta_c\rangle$	0.298	0.390	30.9
		$(\eta_c)_{noon}$	0.435	0.543	24.8

higher. When non-random error tolerances are small (e.g., U.S. design environment), the differences between the results of the two optimizations are small. (The error in the optimum concentration ratio is 12.7%, however, as discussed earlier, the optimum concentration ratio is rather broad. So, this error in concentration ratio is tolerable.) When non-random error tolerances are large, however (e.g., developing country examples), the differences between the results of the two optimizations are significant. (Again, the error in the value of the optimum concentration ratio is tolerable; optimum is broad.) The optimization based on random errors alone overpredicts the optimum intercept factor. As a result, the optimum all-day and solar noon efficiencies are overpredicted (as much as 30%) and this would eventually lead to undersizing the collector array and mismatch between the energy requirement and the actual energy delivery of the collectors. This finding is an important one as it reinforces the need for inclusion of non-random errors into the optimization and performance prediction processes.

6.6 Summary

Illustrative examples for the U.S. design environment and a developing country design environment were presented. It was demonstrated that the developed design and optimization method could be used to develop PTC designs for different design environments. The results of the examples were discussed and it was concluded that the optimum concentration ratio was broad.

Therefore, if the collector was operated at a heat-loss level or error level different than the one it was optimized for, it would not suffer a significant performance degradation. Furthermore, it was found that a collector optimized for east-west operation could be used for north-south operation. Finally, it was shown that optimization based on random errors alone resulted in significant overprediction of the collector efficiency. Therefore, it was concluded that optimization based on both random and non-random errors was needed, particularly, for developing country applications.

Chapter Seven

CLOSURE

7.1 Conclusions

In this report a comprehensive and general-purpose design and optimization method for parabolic trough solar collectors is presented.

The design method developed here can be used for the design of PTC's for different design environments (economic, technical and geographic) with different constraints and set of objectives. It is demonstrated that this design approach can be used to dimension and optimize the PTC's efficiently. Moreover, it is shown through illustrative examples that it can be used to develop efficient 'error-tolerant' trough designs in any design environment for any given set of constraints and design requirements. This method will especially prove useful for developing PTC designs for developing countries.

Since the design approach and the basic principles are more-or-less the same for all solar energy systems, the computer-based design method presented in this report can be used (with minor additions or modifications) for the design of other solar energy systems besides parabolic troughs.

7.2 Discussions and Recommendations

In this study, emphasis was placed on the development of the design method rather than its immediate utilization. Therefore,

even though every effort has been made to explain the design steps and to demonstrate the use of the method by illustrative examples, the authors feel that a "user's guide" or a similar document explaining the design steps without the technical details will be extremely useful and will help enhance the impact of the present work. Moreover, a handbook which includes tables of results may prove very helpful to designers in developing counries.

As another option, once data for selection DSP's become available, the design method can be made computer-based (as it should be) and be implemented for interactive use on a computer. Then, the designer will answer a series of questions only, during an interactive session with the computer and develop an optimal design efficiently (without the need for a handbook). At the present, some of the analysis and synthesis softwares are on the computer, but lack of data for selection DSP's, among other things, prevent making the process completely computer-based.

After cost data for materials, subsystem components, labor, alternative fabrication techniques, etc., become available, the designer will be required to reexamine the design (at the detailed design stage) and carry-out cost-to-performance trade-offs. These trade-offs would again be based on various design requirements, environmental goals, objectives and limitations, as well as their relationships to costs of various materials, structural methods, etc.

If the complete design process is made computer-based as suggested in this study, then all the cost data can be entered into the data-base and cost-to-performance trade-off studies can be carried out on the computer at the detailed stage of design too. A sample cost-to-performance trade-off study is presented in Appendix B. Therefore, it is recommended that a data-base for PTC's be developed so that the computer-based design method proposed in this report can be implemented.

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Appendix A

MODELS FOR SELECTION DECISION SUPPORT PROBLEM

A.1 Introduction

Selecting the best system design or the optimal subsystem designs or the optimal components for a subsystem based on multiple objectives is usually a difficult task. The presence of multiple (and sometimes contradictory) objectives tend to confuse and frustrate the designer and usually leads to the choice of a candidate which 'works' rather than a candidate which is best suited for the job and satisfies all the criteria and constraints, i.e., the 'optimal' candidate. The problem is compounded by the qualitative nature of some of the information required for the selection. Therefore, it is highly desirable that the designer have a formal and structured model in which

- all the design cirteria can be considered,
- qualitative information can be processed, and
- design alternatives (candidates) can be compared and evaluataed rationally.

The use of a structured selection process is of great importance in the PTC design method described in Chapter Five where the successful design and the dimensionining of the trough depends on selecting the 'best' subsystem designs and the 'best' subsystem components for a given design environment, at the Micro-Level design.

Several methods for solving selection type DSPs have been proposed, e.g., Ostrofsky [37], Ganesan [33], Pugh [38], Hill et. al. [39]. Although these methods are named differently, all of them follow the same basic scheme as shown in Figure A.1.

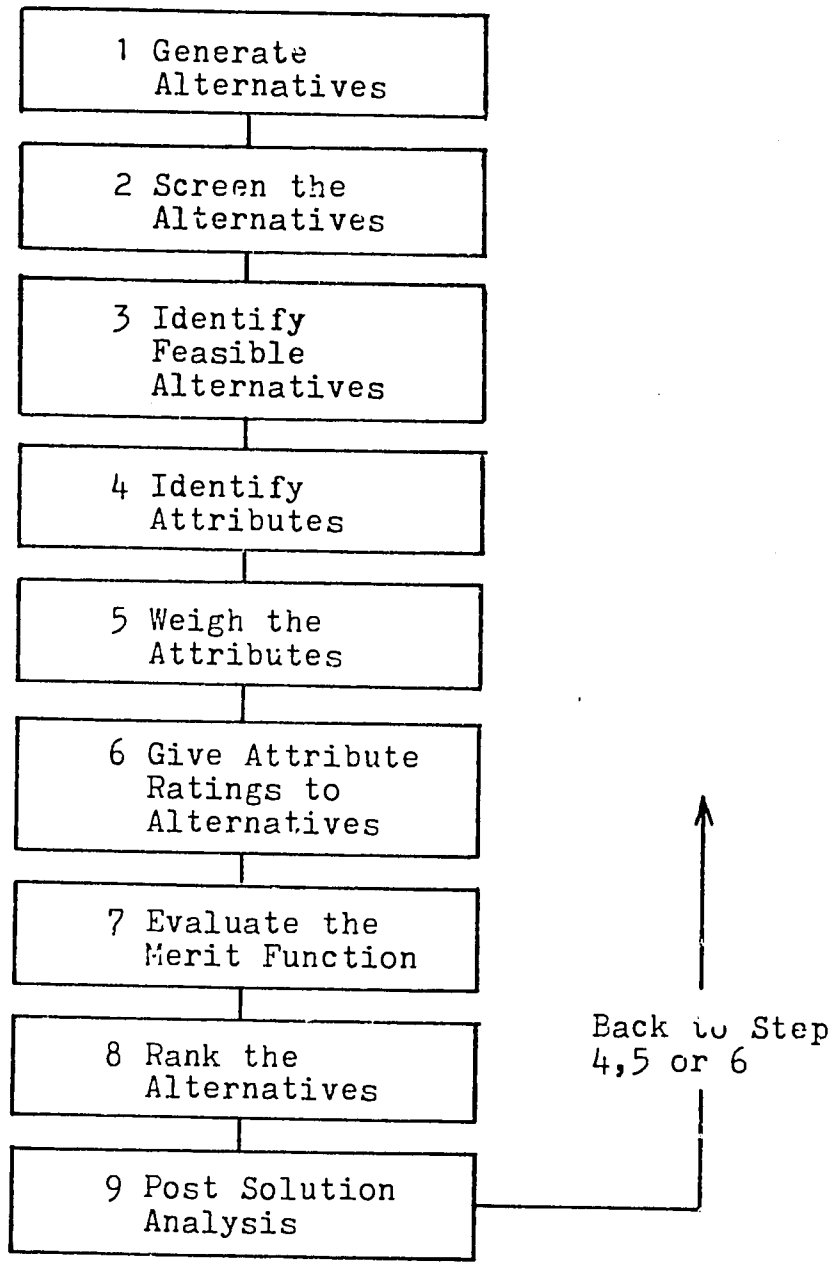


Figure A.1 Schematic diagram for solving a Selection DSP (from [28]).

In the following sections, a rational approach for developing mathematical models for selection DSP's is presented. An illustrative example is also given; the selection of the tracking mode for a typical application in a developing country design environment is presented.

A.2 Steps for Formulating a Selection DSP

A.2.1 Generating Alternatives

As shown in Figure A.1, the first step in the selection process is to generate a set of system alternatives or candidate designs. A number of methods are available in the literature to assist the designer in generating alternatives (e.g., morphological chart, checklisting, brainstorming [25,40]).

A.2.2 Screening of Design Alternatives

Of the many alternatives generated in step 1, however, not all of them are feasible. This is because not all the alternatives in all subsystems (or elements) are compatible. For this reason the design alternatives which are clearly infeasible should be ignored so that no further effort is spent on evaluating the infeasible alternatives (Step 2 Figure A.1). It is however, very important that no feasible alternatives are eliminated. Should any doubt occur whether an alternative is feasible or not, it should be kept in.

A.2.3 Identification of Alternatives

After the process of generating and screening the alternatives, a number of feasible design alternatives are identified (Step 3, Figure A.1). In order that the evaluation of alternatives can be done in the next step, useful information and specifications must be furnished with all the alternatives.

It is extremely important that the alternatives are described in sufficient detail in order to facilitate rating each of the feasible alternatives on the basis of the specified attributes.

A.2.4 Identification of Attributes

The next step in solving selection DSPs is to identify attributes on which the alternatives are to be rated (Step 4, Figure A.1). These attributes may vary enormously from one problem to another depending on the needs of each problem. The attributes usually emerge from the needs defined in the problem statements. Usually an attribute represents a component of the desired solution which must be quantifiable. The relative importance of attributes are not considered in this step. What the engineer should be careful about is that no relevant attribute is ignored regardless of its importance compared to other attributes. An attribute which is not taken into consideration in this step will not affect the selection process and the selection process could yield an optimal alternative which will perform well in all aspects except that of the ignored attribute. Therefore, the set of attributes defined must be comprehensive, understandable, unambiguous and well-serve the needs of the design.

A.2.5 Relative Importance of Attributes

When more than one attribute exists, relative importance or relative weights must be assigned to the attributes because not all the attributes are equally important (Step 5, Figure A.1). This process is generally subjective and requires very careful consideration. Several methods may be used in assigning the relative importance. Two of the methods that may be used are presented here.

Ranking Method

In this method, the attributes are ranked in order of importance. The least important attribute gets the lowest rank and the lowest assigned weight. The second least important attribute gets the second lowest rank and the second lowest assigned weight, and so on. Then the weights are normalized. See Table A.1 for illustration. In Table A.1, attribute C is the least important with respect to the other criteria, hence it is assigned the highest rank.

The advantage of this method is that it is easy to apply and very suitable when the number of attributes is not too large. Also, when the available information is not adequate but some decisions have to be made this method is very useful. The disadvantage of this method however, is that when number of attributes defined is large, ranking of attributes becomes rather cumbersome. Another disadvantage of this method is that difference between every successive pair of attributes is the same, which is not necessarily true. As shown in Table A.1, in this method it is important that the reasons supporting the ranking be given. Further, it is important to justify the rank ascribed to a particular attribute. This may be done on the table or in the text asociated with the table.

Comparison Method

In this method, the preference between each pair of attributes is compared, and a viewpoint is established. Assume that there is a selection problem with six attributes identified, A, B, C, D, E and O (a dummy attribute, discussed later). For this problem, there will be 15 decisions to be made. The viewpoint represents these 15 decisions qualitatively (Table A.2a). This qualitative viewpoint is changed to a quantitative one in Table A.2b. For each comparison, the preferred attribute (between the two) is

Attribute	Rank*	Remark	Weight**	Normalized Weight I_i
A	3	(Reasons supporting the ranking, Viewpoints, etc.)	3	0.200
B	1		5	0.333
C	5		1	0.067
D	4		2	0.133
E	2		4	0.267
		Sum	15	1.000

* Lower number indicates preferences

** Higher number indicates preferences

Table A.1 Relative importance of Attributes (Ranking method) (from [28]).

Attribute	Decision	Comments
A / B	B ≻ A	
A / C	A ≻ C	
A / D	A ≻ D	(Reasons supporting
A / E	E ≻ A	each decision)
A / O	A ≻ O	
B / C	B ≻ C	
B / D	B ≻ D	
B / E	B ≻ E	
B / O	B ≻ O	
C / D	D ≻ C	
C / E	E ≻ C	
C / O	C ≻ O	
D / E	E ≻ D	
D / O	D ≻ O	
E / O	E ≻ O	

Table A.2a Establishing a viewpoint (from [28]).

assigned one point and the other attribute is assigned a zero. In the case when the two attributes are equally important, both attributes are assigned 1/2 point each (should be avoided if possible). The allocation of points is done pairwise for all the attributes. Then, the points obtained by each attribute are added up. The attribute which gets the highest score is the most important attribute. The scores are, then, normalized as in the ranking method. See Tables A.2 and A.3 for illustrations.

The advantage of this method over the ranking method is that comparing two attributes at a time is easier than ranking all the attributes at once. This method, however, sometimes results in cycling (i.e. attribute A > attribute B > attribute C > attribute A). Cycling can be avoided by adding a new relevant attribute or refining the definition of attributes and/or avoiding equal preferences.

In Table A.2, a dummy attribute is introduced so that the least important attribute retains some effect on the evaluation of alternatives. Without the dummy attribute, it may happen that the least important attribute is assigned no score at all which is the same as not taking that attribute into consideration. Nevertheless, a dummy attribute is not needed when the number of attributes is large. In this case, the attribute which receives no score at all may be considered unimportant, hence, may be eliminated. The number of comparisons need to be made in this comparison method depends on the number of attributes used. For a problem with n attributes, number of comparisons is $(n-1) + (n-2) + (n-3) + \ldots + 1 = n(n-1)/2$. Finally, it needs to be emphasized again that without the viewpoint, Table A.2 has no meaning.

Attribute	A	B	C	D	E	O	Score
A	-	0	1	1	0	1	3
B	1	-	1	1	1	1	5
C	0	0	-	0	0	1	1
D	0	0	1	-	0	1	2
E	1	0	1	1	-	1	4
O	0	0	0	0	0	-	0
						Sum	15

Table A.2b Attribute Weights:
Assignment by comparison method (from [28]).

Attribute	Score	I_j
A	3	0.200
B	5	0.333
C	1	0.067
D	2	0.133
E	4	0.267
	Sum	1.000

Table A.3 Normalized weights (from [28]).

A.2.6 Attribute Rating

The next step in the process is the assignment of the rating values to each alternative with respect to each attribute (Step 6, Figure A.1). These ratings (A_{ij}s) may be derived using different types of scales, viz. ratio, interval and ordinal scale, [41].

Ratio Scale

A ratio scale is a scale which has an absolute zero point. It is a direct measure of properties such as length, weight, mass, volume, etc. The information given based on this scale is generally "hard". It is quantified by the properties of the alternatives. This type of scale has a universal absolute zero point regardless of unit system used. Attributes measured on this scale should not be converted to any other scale. A case can be made for converting cost or profit, which are direct measures of economic efficiency (indirect measures of technical efficiency), to an interval scale.

Interval Scale

An interval scale is similar to the ratio scale in that it is a direct measure of physical properties or performance of the alternatives. It does not, however, have a universal absolute zero point. A good example of this type of scale is the temperature scale which has different absolute zero points (e.g. zero degrees Farhenheit is different from zero degrees celcius). While the zero point in the ratio scale has the same meaning for everyone, the zero point in the interal scale can convey different meanings depending on the unit system being used. Ratings in this scale are considered "hard" if they are obtained directly from the physical properties or specifications of alternative, however, they are "soft" if they are converted from the ordinal scale.

Ordinal Scale

Some attributes such as reliability, appearance, visibility, etc. are qualitative properties and are not rated quantitatively. In order to combine attributes such as these with others, some numerical scale must be created. This can be done by converting an ordinal scale to an interval scale using a numerical scale associated with qualitative ratings. An example is shown in Table A.4 where qualitative ratings are assigned with numberical values. Another method that may be used (for converting the scale) is using the method presented for creating relative weights for attributes in Section A.2.5.

When the process of rating the alternatives based on the attributes is finished, the next step is to normalize these ratings in order that the ratings of all attributes are of the same magnitude (R_{ij}). One of the methods that may be used is to define a normalized rating for alternative i attribute j as:

$$R_{ij} = \frac{A_{ij} - A_j^{min}}{A_j^{max} - A_j^{min}} \tag{A.1}$$

This formulation is for the case when the larger value of an attribute rating represents preference. When the smaller value of an attribute rating represents preference, the normalized rating R_{ij} is defined as

$$R_{ij} = 1 - \frac{A_{ij} - A_j^{min}}{A_j^{max} - A_j^{min}} \tag{A.2}$$

A_j^{min} and A_j^{max} in both formulae represent the lowest and highest possible values of the attribute rating A_{ij}. By using the method just outlined, an attribute rating on an ordinal scale is converted to a rating on an interval scale for use in solving selection DSPs.

Description of Performance	Rating	
	Qualitative	Quantitative
(Physical description of qualitative ratings, specific details, etc.)	Excellent Very Good Good Acceptable Poor	5 4 3 2 1

Table A.4 Ordinal scale ratings (from [28]).

In some cases, such as in a design which involves many subsystems, the rating A_{ij} may not be expressed as a constant value but as a function of variables of the system being considered. In such cases, the rating A_{ij} is defined as

$$A_{ij} = A_{ij}\ (\underline{x})$$

where x is a vector of the variables in the system. We can write

$$R_{ij} = R_{ij}\ (\underline{x})$$

A.2.7 Merit Function

The next step in solving selection DSP is to define and evaluate the merit function (Step 7, Figure A.1) for each alternative. A merit function combines all the individual ratings of attributes together using proper weights or importances defined earlier. There are several methods in modeling the merit function (see Table A.5).

The most frequently used model, however, is the linear model

$$MF_i = \sum_{j=1}^{n} I_j R_{ij} \qquad i = 1, \ldots, m$$

where

m	=	number of alternatives
n	=	number of attributes
Ij	=	relative importance of jth attribute
R_{ij}	=	rating for alternative i attribute j
MF_i	=	value of merit function for alternative i

The reasons why the linear model is considered sufficient in most cases are as follows [42].

1.	Linear Additive $MF_i = \sum_j I_j R_{ij}$
2.	Higher Order Additive $MF_i = \sum_j I_j \log R_{ij}$
3.	Multiplicative $MF_i = \prod_j (R_{ij})^{I_j}$

Table A.5 Models for merit function (from [37]).

1. The linear model turns out to be an excellent model for actual decisions in various applications.
2. With some minor exceptions, none of the other models has been found to be significantly better than the linear model in supporting the decision.

These observations suggest that, in most applications, it would make considerable sense to at least start with a linear model. When the cost and time spent in developing and implementing more complex methods are taken into account, it is unlikely that the greater sophistication will be justified. For most practical purposes, the linear model is likely to be sufficient, [42].

In cases where the attribute ratings are functions of variables in the subsystems or other interacted systems, the merit function is

$$MF_i = \sum_{j=1} I_j R_{ij}(\underline{x}) \tag{A.3}$$

The alternatives, after the merit functions are evaluated, can be ranked from the one with the highest value to the lowest (Step 8, Figure A.1). The alternative with the highest rank is the most favorable alternative with respect to given ratings and relative weight of the attributes.

A.2.8 Post Solution Analysis

Post solution anlaysis of the selection process consists of two types of activities, validation and sensitivity analysis which includes both sensitivity of the solution to changes in the attribute weights and sensitivity of the solution to change in the attribute ratings. These activities are very important because of the nature and quality (hard or soft) of the information being used.

i) Validation

Having ranked all the alternatives in order of decreasing merit function values, the engineer is able to identify the best and some of the better alternatives. In general when the number of alternatives is fairly large (greater than 6, say) the ranking will naturally divide alternatives into several groups for which the merit function values are very close. For example, a ranking of 7 alternatives may be as shown in Table A.6. In this case these alternatives may be grouped into three groups as shown. The first group represents the three best alternatives; the second group represents the two second best alternatives and so on. Alternatives in the same group usually have some characteristics in common. These characteristics should be examined and, if they are desirable, should be included as additional attributes for the selection. This is to ensure that no important attributes were left out and, because of that, a number of alternatives were ranked lower than what they should have been. Also, reexamination of the relative weights, attribute ratings and numerical calculation is needed to ensure that no biased judgments or numerical errors have occurred at any step. Validation of the solution is very important especially when the highest ranked alternatives is an unexpected one.

ii) Sensitivity Analysis

In applications where the number of alternatives is not small, it is very likely that the values of the merit functions of the top two or three alternatives are very close. If this occurs, it is necessary that a sensitivity analysis is performed. Sensitivity anlaysis is expecially important because the relative weights and ratings derived from "soft" informatioon are of subjective nature. Therefore, the sensitivity analysis consists of deter-

Alternative	Merit Function	Rank
1	0.80	3
2	0.63	5
3	0.68	4
4	0.87	1
5	0.85	2
6	0.37	7
7	0.42	6

1st group

2nd group

3rd group

Table A.6 Ranking of alternatives (from [28]).

mining the effect in the solution of small changes in the relative weights of attributes and also to small changes in the attributes ratings.

a) Sensitivity to Changes in the Attribute Weights

During the selection process, the weights of attributes are derived using judgment which totally depends on the experience, knowledge and preference of each individual. For this reason, the sensitivity to the change in the weights of attributes needs to be performed. This can be done by re-examining and changing the ranking of the attributes in Table A.1 or changing the preference between a comparison and determining the effect of the change on the merit function. A stable solution or the top ranked alternative which is not affected by small changes in the weights of attributes is the best alternative and should be selected. When the ranking is altered by the changes in the weights of attributes, a decision may be made to perform the sensitivity analysis of the attribute ratings or the engineer may consider adding other attributes and then resolve the selection DSP.

b) Sensitivity to the Changes in the Attribute Ratings

As stated before, the ratings may be derived directly from the available quantitative information or subjectively. In the latter case, it is very often that errors in ratings occur. Hence, the sensitivity of the solution to changes in attribute ratings need to be performed. This can be done by studying the change in the merit function value to the changes in the attribute ratings (e.g. ± 5%).

Consider a change of $\pm \delta$ in the rating R_{ij} in attribute j of alternative i. The change in the merit function of that alternative will be

$$\Delta M_i = \pm \delta I_j$$

The new merit function will be

$$M_i^{new} = M_i^{old} + \Delta M_i$$

The alternatives are then ranked again and if the top ranked alternative remains unchanged, the solution is considered stable. If the top ranked alternative is changed, sensitivity of the merit function to other ratings needs to be evaluated further. In some cases, addition or redefinition of attributes may be necessary.

A.3 Sample Selection DSP:

In this section, the selection of the tracking mode for a typical application for a developing country design environmental is presented to illustrate the use of the selection process [36].

The alternative tracking modes for PTC's were shown in Figure 2.5. The tracking mode to be employed with a certain collector design will be closely related to the type and size of the application in mind. For example, a polar axis mount is generally believed to be impractical for large installations because of problems with wind loading and plumbing. A polar mount may, however, be desirable for small installations with relatively short collector modules, for example, for home heating. However, in addition to the type and size of application, the characteristics of the design environment (e.g., availability of different tracker mechanisms, technology and maintenance requirements, power failure etc.) will also play some role in the selection of the tracking mode. Consequently, the designer will need information about the application type (small or large-scale installation, urban or rural application, land availability, etc.), as well as the design environment for the tracking mode selection.

Using these information and the characteristics of the different tracking modes, the designer will be required to consider several criteria and use the steps given in the preceeding section to create a mathematical model for the selection of tracking mode.

A.3.1 Alternatives

Alternatives for the tracking mode were shown in Figure 2.5. A brief description of each tracking mode together with the incidence factor (angle of incidence of the solar beam radiation, incident on the reflecting surface of the PTC) are presented in Table A.7. Some background on the alternative tracking modes are presented below in order to support the ratings that will be assigned to the attributes in section A.3.3.

1. Two-axis tracking:
   - Computer controlled tracker system is required for computing the tracking angles,
   - Wind loading will create problems and plumbing and coupling will be difficult.
2. E-W horizantal axis-continuous tracking;
   - Sunset and sunrise tracking angle of the collector will be the same,
   - In case of a pump and tracker failure damage to components can be considerable,
   - Annual energy delivery will be 32.8% less than 2-axis tracking [18, pp.55] (for λ = 35°N)
   - Tracker system can be either a simple feedback type or micro computer controlled type.
3. N-S horizontal axis-continuous tracking:

TABLE A.7 INCIDENCE FACTORS FOR THE VARIOUS TRACKING ALTERNATIVES

ALT. NO.	DESCRIPTION	INCIDENCE FACTOR *	COMMENTS **
1	Rotation about two perpendicular axes with continuous adjustment to allow the surface normal to coincide with the solar beam at all times.	1	No hourly or seasonal variations in output because sun is fully tracked***
2	Orientation along east-west axis and rotation about E-W axis with continuous adjustment to obtain maximum energy incidence	$(1-\cos^2\delta\sin^2\omega)^{1/2}$	No appreciable variation in seasonal output but considerable variation in hourly output
3	Orientation along north-south axis and rotation about N-S axis with continuous adjustment to obtain maximum energy incidence	$[(\sin\lambda\sin\delta + \cos\lambda\cos\delta\cos\omega)^2 + \cos^2\delta\sin^2\omega]^{1/2}$	No appreciable variation in hourly output, but considerable variation in seasonal output
4	Orientation along polar axis and rotation about this axis with continuous adjustment to obtain maximum energy incidence	$\cos\delta$	No appreciable variation in hourly variation, but some variation in seasonal output depending on the latitute of the location

δ = Declination (i.e., the angular position of the sun at solar noon with respect to the plane of the equator)

ω = Hour angle, solar noon being zero and each hour equalling 15° of longitude with mornings positives and afternoon's negatives.

λ = Latitute

* Incidence Factor = $\cos\theta$, where θ = incidence angle

** Further comments about the alternative tracking modes can be found in Section A.3.1 .

*** Atmospheric attenuation is not considered since it will be the same for each alternative.

- Requires large angular excursion everyday to track the sun, therefore, tracking cost will be higher,
- Have to make a full excrusion from sunset to sunrise position,
- Annual energy delivery will be 22.7% less than 2 axis tracking, and 15% better than E-W horizontal axis [18]. (for λ=35°).

4. N-S polar axis-continuous tracking
   - Polar axis tracking approaches within 4% the radiation availability of a 2-axis tracker, surpassing the horizontal E-W axis by about 30% [18] (for λ = 35°),
   - Wind loading will create problems because the collector is tilted up at an angle equal to the local latitute (i.e., parallel to earth's axis),
   - Hourly excursion of the sun is tracked, therefore, a full excursion from sunset to sunrise position is required.

A.3.2 Attributes

Proper identification of all the attributes characterizing these alternative tracking modes is the next step in establishing the mathematical model.

The attributes for the tracking mode selection are obtained from an extensive literature survey. As summarized in Table 5.2, four major areas of attributes are identified, each one having one or more items with which alternative tracking modes can be characterizecd. They are as follows:

A. Resources
   - Annual energy output
   - Seasonal variation in output
   - Hourly variations in output

B. Relative cost with respect to alternatives

- Field cost (shading cost, etc.)
- Tracking cost (Equipment, maintenance, etc.)
- Structure and foundation cost (wind loading etc.)
- Plumbing cost (connections, coupling, etc.)

C. Relative sophistication of tracker and technology requirements

D. Consequences of Failure

- Reliability for continued output
- Design safety

These attributes are described below:

i) Annual Energy

Total energy output from a given PTC orientation. The amount of solar energy available for each tracking mode is different and hence the total annual energy delivered will be different.

ii) Seasonal Variations in Output:

Due to the declination excursion of the sun (± 23°/year) energy delivered (output) will vary from season-to-season. Declination excursion and output will be related to the tracking mode.

iii) Hourly Variations in Output:

Due to the hourly excrusion of the sun (15°/hr) from E to W, energy delivered by the collector will depend on the tracking mode employed.

iv) Relative Field Cost:

For large installations one may need to have an array of collectors. In such instances shading of reflectors by adjacent collectors may be a problem. In order to avoid shading, one may have to leave more space between adjacent collectors-- a field cost is involved, beyond the minimum required.

v) Relative Tracking Cost:

The initial cost of the tracking equipment, the amount of energy consumed while tracking the sun and maintainance cost over the years.

vi) Relative Structure and Foundation Cost:

The size of the foundation and associated structures for support are to be designed to withstand the worst wind loadings. Wind loading on the collectors depend on the tracking mode.

vii) Relative Plumbing Cost:

The tracking mode employed dictates: The amount of tubing to be used, together with the associated insulation to be put on the tubes. Also for large installations, the ease of tube connections becomes major concern.

viii) Relative Sophistication of Tracker and Technology Requirements:

The level of technology required for tracking depends on the tracking mode employed. For example, two-axis tracking will probably require a sophisticated tracker equipment.

ix) Reliability for Continued Output:

If the tracking equipment fails or tracking is impossible for some reason for a period of time, what will happen? One may still get some energy out of the collector with a somewhat reduced efficiency depending on the tracking mode employed.

x) Safety of Design:

If the pump fails, then the stagnation temperatures at the receiver surface may damage the selective coating. Also, damage to other system components may result due to thermal stresses: e.g., most working fluids used in such systems degrade around 340°C. Of course,

during such times the reflector can be turned to face away from the sun, but in cases of power failure, which can handicap both the pump and the tracker, the stagnation temperature will depend on the tracking mode employed.

A.3.3 Attribute Ratings

Two kinds of scales (ordinal and ratio) will be used for quantifying the attributes of the alternatives. An ordinal scale will be used for attributes which are qualitatiave in nature and can only be expressed in words (e.g., reliability and safety). A ratio scale will be used for attributes which can be expressed with numbers (Ref. 41), e.g., annual energy output in Btu's. In the presentation here, emphasis is placed on the method rather than the technical details affecting the selection. Therefore, rating scales for only four representative attributes are detailed below to demonstrate the approach:

Annual energy output: (Ratio scale-Btu/ft^2)

A reference output of 100 Btu/ft^2 is assigned to the tracking mode with maximum annual energy output (2-axes tracking). Annual output from other tracking modes are accordingly determined using Ref. 18.

Relative plumbing cost: (Ordinal scale-no units)

Very High (10): Excessive plumbing job required. Connection of rows and/or columns (coupling of arrays) are very difficult. Many extra connections required with flexible hoses and extra insulation.

High (9): Same as above except less flexible hoses are required.

Normal (5): Easy connection of arrays. Smooth and stable pipe layout.

Relative sophistication of tracker and technology requirements: (Ordinal scale-no units)

High (10): Computerized tracking equipment with sophisticated flux detectors and feedback control.

Medium (7): Not very complicated tracking equipment (e.g., clock device and solar cells).

Low (2): Low sophistication in tracking equipment (e.g., manual tracking).

Design Safety: (Ordinal scale-no units)

The following ratings are set-up for the worst possible breakdown scenario where there is a 24-hour power and/or pump failure on a sunny day. What is the damage to the system components, if any?

High (10): Stagnation temperatures on the receiver surface reached beyond the degrading point of the selective coating and also beyond the degrading point of the working fluid. Thermal stresses caused permanent deformation of the receiver tube.

Medium (7): Stagnation temperatures almost reached the degrading point of selective coating and working fluid. Some damage is possible.

Nil (0): No damage whatsoever.

The attribute ratings assigned to different alternatives are tabulated in Table A.8. These ratings are normalized using equation (A.1) when a higher rating number represents preference (e.g., annual energy output). When a lower number represents preference (e.g., field cost, plumbing cost, etc.), equation (A.2) is used. In Table A.8 the circled numbers indicate the preferences (Note that there are equally preferred alternatives for some of the attributes). The normalized ratings are presented in Table A.9.

TABLE A.8 ATTRIBUTE RATINGS (A_{ij}) FOR THE ALTERNATIVE TRACKING MODES

	ATTRIBUTES (j)									
A_{ij} ALTER(i)	ANNUAL ENERGY DELIV. Btu/ft^2	SEASON. VAR. (See Table 1)	HOURLY VAR. (See Table 1)	FIELD COST	TRACK. COST	STRUCT. & FOUND COST	PLUMB. COST	COMPLEX & TECHN. REQNS.	RELIABI. FOR CONTD. OUTPUT	SAFETY OF DESIGN
ALT 1 (2-axis)	100	1	10	1	10	8	10	10	0	0
ALT 2 (E-W)	67.2	1	5	0	2	2	5	5	1	10
ALT 3 (N-S)	77.3	0.52	10	1	7	2	5	5	0	0
ALT 4 (POLAR)	96	0.92	10	1	7	10	9	5	0	4

TABLE A.9 NORMALIZED ATTRIBUTE RATINGS (R_{ij})

ALT(i)	NORMALIZED ATTRIBUTE RATINGS (R_{ij})									
	1	2	3	4	5	6	7	8	9	10
	ANN ENER.	SEASON VAR.	HOURLY VAR.	FIELD COST	TRACK COST	STRUCT. & FOUN. COST	PLUMB. COST	COMPLX. & TECH.	RELIAB. FOR CON. OUTPUT	SAFETY OF DESIGN
ALT 1	1	1	1	0	0	0.25	0	0	0	1
ALT 2	0.0	1	0.0	1	1	1	1	1	1	0
ALT 3	0.31	0	1	0	0.375	1	1	1	0	1
ALT 4	0.88	0.83	1	0	0.375	0	0.2	1	0	0.33
I_j Values	0.182	0.0727	0.0364	0.0182	0.1273	0.109	0.091	0.145	0.0545	0.164

(see Table A.10)

A.3.4 Attribute Importances

In the preceding three sections, the alternatives, the attributes and the attribute importances were generated without regard to any specific design environment or application. The values to be assigned for the importance of attributes, however, will no longer be application or design environment independent. At this stage, the designer will assign importances (weights) to the attributes based on:

- design goals and objectives and liminations of the design environment,
- application-specific requirements (e.g., annual (or seasonal or daily) energy delivery requirement) and limitations (e.g., land availability, site (latitute) of application, urban-rural application, etc.),
- size of application (large or small application),
- previous design experiences and intiution of the designer.

Therefore, information about the application and design environment will be incorporated at this stage of design.

In order to complete the demonstration of the selection process, here, a scenario for application and design environment is defined:

Select the tracking mode to be employed with PTC's to be designed for a small farm in a developing country. Collectors will be used for pumping irrigation water. Labor oriented, low technology tracker systems are preferred. A vast installation field is available and farm is locataed in mid-latitudes (λ= 35°N).

With the help of the above application scenario, importance values can be assigned to attributes. This has been done using the ranking method presented in Section A.2.5. The I_j values for the farm application are listed in Table A.10.

TABLE A.10 NORMALIZED ATTRIBUTE IMPORTANCES (I_j)

ATTRIBUTE	RANK	NORMALIZED IMPORTANCE	I_j
Field Cost	1	1/55 = 0.0182	I_4
Hourly Variations	2	2/55 = 0.0364	I_3
Reliability for Contd. Output	3	3/55 = 0.0545	I_9
Seasonal Variation	4	0.0727	I_2
Plumbing Cost	5	0.091	I_7
Structure and Foundation Cost	6	0.109	I_6
Tracking Cost	7	0.1273	I_5
Complexity & Rel. Sophistication of Tracking Equip.	8	0.145	I_8
Safety of Design	9	0.164	I_{10}
Annual Energy Delivery	10	0.182	I_1
TOTAL	55		

TABLE A.11 MERIT VALUES FOR TRACKING MODES BASED ON ATTRIBUTE IMPORTANCES GIVEN BY TABLE A.10

ALTERNATIVE	MERIT	RANK	DIFFERENCE (%)
ALT 1: 2 - Axis	0.482	4	28.8
ALT 2: E-W Axis	0.618	2	8.7
ALT 3: N-S Axis	0.677	1	0
ALT 4: Polar Axis	0.523	3	22.75

A.3.5 Evaluation

The final evaluation of all the preceding data (Tables A.8, A.9, and A.10) are summarized in a merit function. According to the merit function, Eqn. (A.3), the higher the value, the higher the preference. The merit values for the alternatives are presented in Table A.11.

By analyzing Table A.11, ALT 3 is preferred over ALT 2 by 8.7%, over ALT 4 by 22.8% and over ALT 1 by 22.8%. According to the preceding process, ALT 3, N-S axis tracking mode, is the preferred tracking mode for the small farm application.

APPENDIX B MODELS FOR COMPROMISE DECISION SUPPORT PROBLEM

B.1. INTRODUCTION

Compromise decision support problems are commonplace in the design of any engineering system [25,43]. An engineering system can be decomposed into subsystems. Each of these subsystems is characterized by independent variables (system descriptors that characterize the state of a system). Compromise DSPSs are formulataed and solved to determine the values of these variables and tc strike a balance between demands on, and teh capability of the system in the best possible manner.

A superior design can be obtained in one of the following two ways:

i) Iterate so as to:

- find the values of variables sequentially,
- check whether the design satisfied the expectations, and
- iterate until an adequate design has been obtained.

ii) Solve a compromsie DSP so as to:

- find the values of the variables that simultaneously satisfy the requirements and try to achieve the goals -- optimally.

The former represents optimization through iteration. It is akin to performing a fine-tuning on the design. The values of the variables are changed and verified sequentially. The decision as to what variable to change or how to change it reflects the experience-based insight of the designer. Except for samll textbook-like problems, a designer is unable to take into account the interaction between variables and the requirements despite the fact that solutions to similarly structured problems may be available. As a result the designer has to resort to iteration to come up with an acceptable design; but there is no guarantee that this is necessarily the best

solution. The latter represents an "optimization" problem: The values of the variables obtained and are "optimal." Iteration is necessary only if the problem specifications are changed. Due to the nature of real-world problems where the available information is constantly changing or being updated, iteration is usually encountered in the latter. This iteration, however, is used only to find a new set of optimal values corresponding to the change in the system environment. In the following section, methods for creating mathematical models for compromise DSP are presented togehter with a solved sample compromise DSP as applied to PTC's.

B.2. NOMENCLATURE FOR COMPROMISE D.S.P.

$\underline{A}$	the achievement of design goals
$\underline{C}$	capability of the system
$\underline{d}^-$	overachievement deviation variables
$\underline{d}^+$	underachievement deviation variables
$\underline{D}$	demands placed on the system
$\underline{G}$	goals or aspiration levels
k	number of system constraints
$\underline{L}$	lower bounds on system varialbes
m	total number of constraints
n	number of system variables
$\underline{P}$	priorities of ghe goals
$\underline{U}$	upper bounds on system variables
$\underline{W}$	relative weights for the variables
$\underline{X}$	system variables
>>	preference (rank order) symbol

B.3. COMPONENTS OF A COMPROMISE PROBLEM [25]

A compromise DSP can be stated in terms of the system descriptors which are:

- Variables - system variables
  - deviation variables
- Constraints - system constraints
  - goal constraints
- Bounds - on system variables
  - on deviation variables
- Objective - in terms of deviation variables

The formulation in words was presented in Section 4.4. In the following section an indepth review of the features of compromise DSP is presented.

B.4. IN-DEPTH REVIEW OF THE FEATURES OF A COMPROMISE DSP [25]

The generic word problem for Compromise DSP is explained with reference to Figure B.1.

B.4.1 System Variables and System Constraints

System variables $\underline{X} = (X_1, X_2, \ldots, X_n)$

System constraints $D_i(\underline{X}) \leq C_i$ and $D_i(\underline{X}) \leq C_i(\underline{X})$

System descriptors are either fixed by the specifications provided or variable as per the need of the design. The descriptors, as the name implies, describe the state of a system completely. Since some of the descriptors are fixed parameters and do to change during the course of the design, the state of the system is dependent entirely upon a set of variable descriptors termed

as system variables. Most engineering problems have at least two system variables. In general, a set of "n" design varialbes is represented by $\underline{X}$. These variables may be continuous, Boolean (1 for TRUE, 0 for FALSE) or a combination of the two. System variables are, by their nature, independent of the other descriptors and can be changed as required by the designer to alter the state of a system. In Figure B.1 the design variables X_1 and X_2, being the independent variables, are represented by the abscissa and ordinatae, respectively. In general, each member of the set X represents an axis of an n-dimensional space.

A system constraint is a constraint placed on the design that has to be satisfied for feasibility of the design. Mathematically, system constraints are functions of the system variables only. They are rigid and no violations are allowed. They relate the demands placed on the system $D(\underline{X})$ to the capability of the system C (or $C(\underline{X})$) to meet the demand.

System constraints may be all linear, nonlinear or a mixture of linear and nonlinear constraints. In engineering problems the system constraints invariably are inequalities. A graphical representation of system constraints is shown in Figure B.1. All the system constraints are inequalities in this particular illustration.

B.4.2 Deviation Variables and Goal Constraints

Deviation variables d_i^- -- underachievement of the ith goal.

d_i^+ -- overachievement of the ith goal.

Goal constraints $A_i(\underline{X})/G_i + d_i^- - d_i^+ = 1 \quad i = 1, 2, \ldots (m-k)$

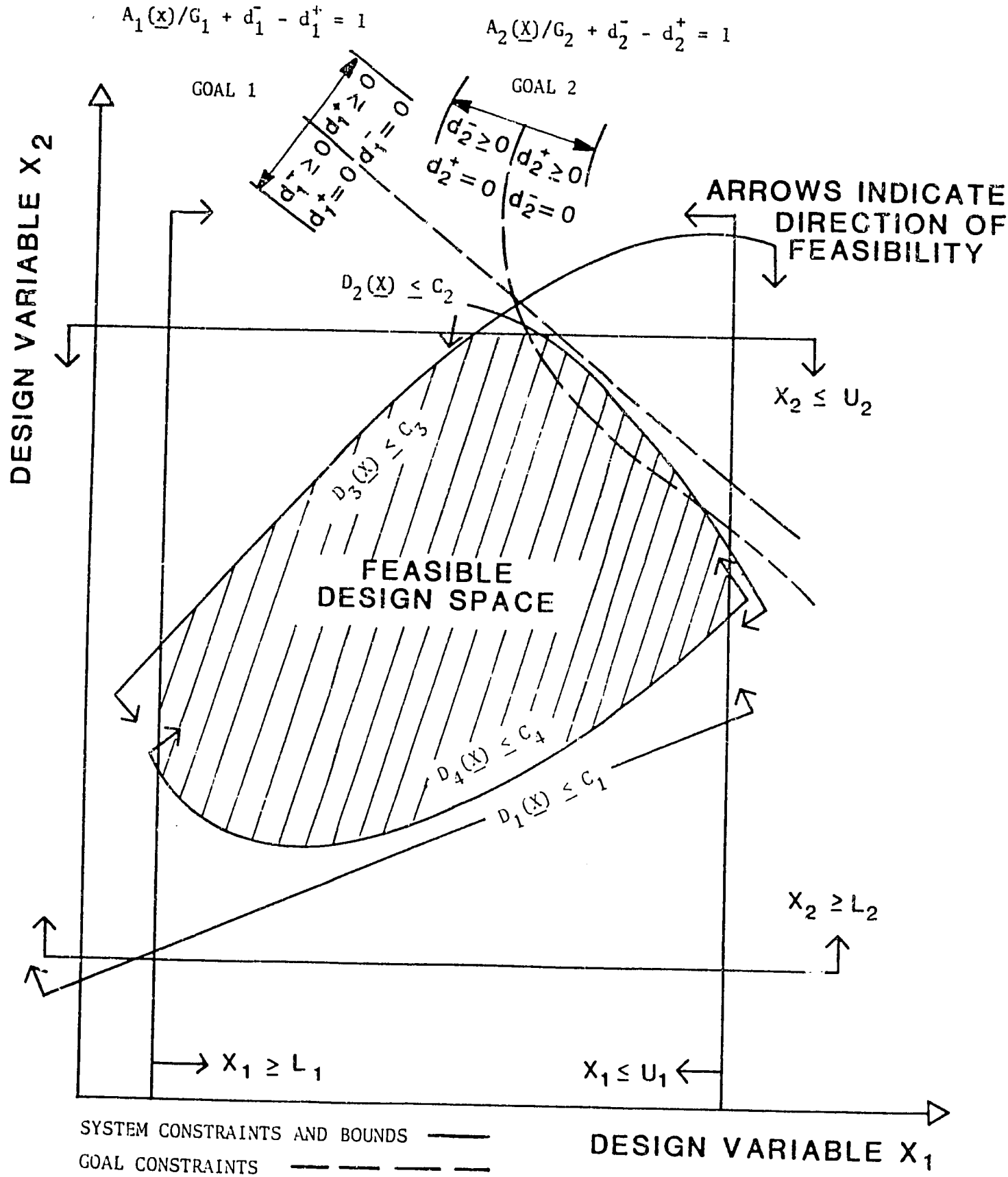


Figure B.1 Typical design space for a 2-variable (X_1, X_2) Compromise DSP (from [25]).

Goal constraints represent the aspiration levels of a desingner for the design. They are always expressed as equalities and relate the goals $\underline{G}$ of the designer (or aspiration levels) to the actual achievement of the design $\underline{A}$. It is possible that the designer's aspiration levels are inordinately high or the system constraints are much too restrictive to attain the aspired levels of achievement. The deviation variables d_i^+ and d_i^- are used to allow the designer a certain degree of lattitude in making decisions. A particular goal may either be overachieved ($d_i^+ > 0$, $d_i^- = 0$) or underachieved ($d_i^- > 0$, $d_i^+ = 0$). Two deviation variables therefore relate the actual performance of the design to the aspired level of performance. These variables serve to "anchor" the aspiration levels to realistic achievement levels. The difference between a system variable and a deviation variable is that the former represents a distance in teh i^{th} dimension from the Cartesian origin of the design space, whereas the latter has as its origin the surface of the goal constraint. This is illustrated in Figures B.1 and B.2. The value of the ith deviation variable is determined by the m agnitude of achievement of the ith goal, i.e.

$$A_i\ (\underline{X})/G_i + d_i^- - d_i^+ = 1$$

where

$A_i\ (\underline{X})$ is the achievement

G_i is the goal

and the following holds true

if $A_i > G_i$ (overachievement) then $d_i^- = 0$ and $d_i^+ > 0$

if $A_i = G_i$ (exact achievement) then $d_i^- = 0$ and $d_i^+ = 0$

if $A_i < G_i$ (underachievement) then $d_i^- > 0$ and $d_i^+ = 0$

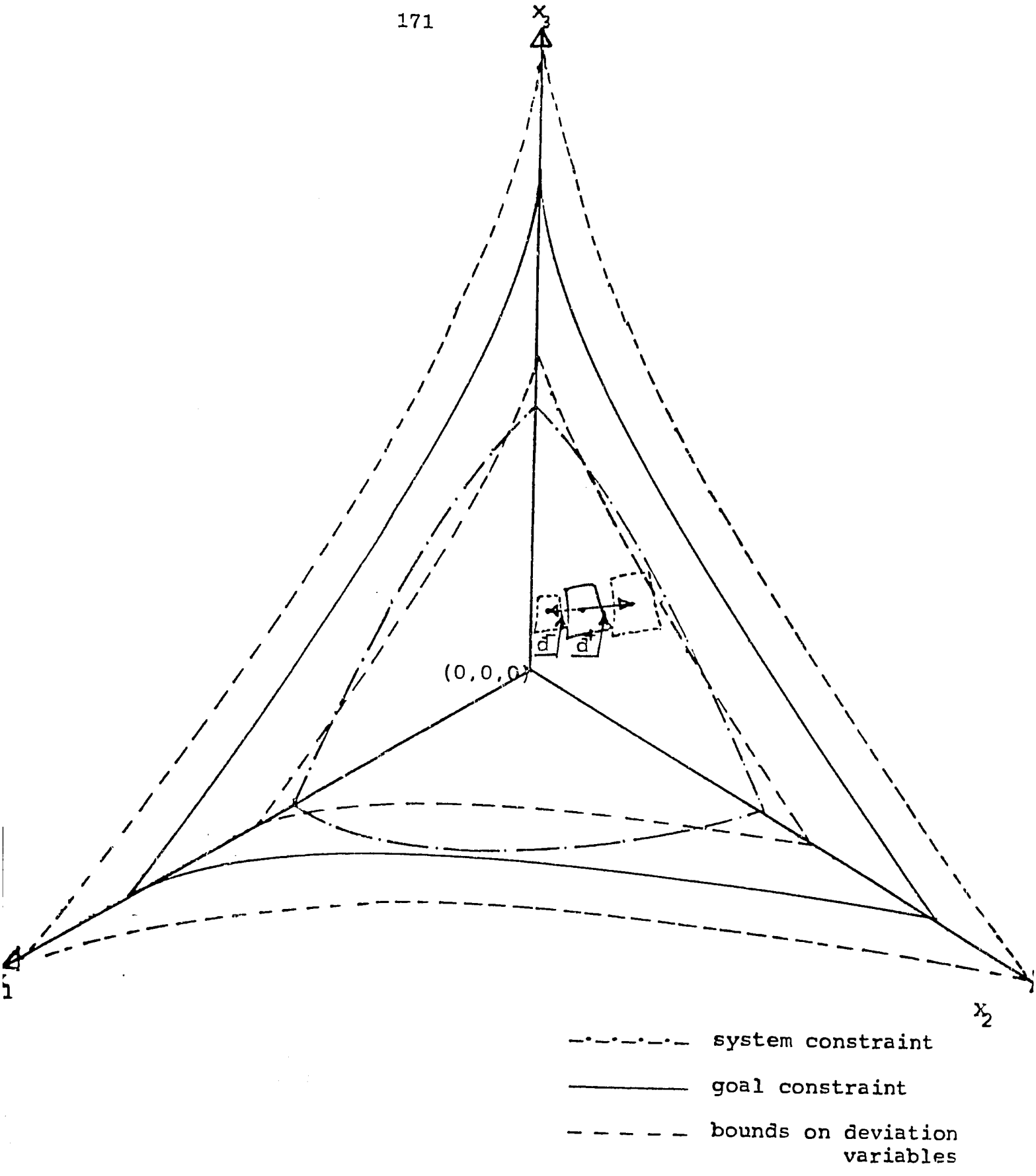


Figure B.2 Graphical representation of a goal constraint and the deviation variables in a 3-variable compromise problem (from [25]).

The value of the ith deviation variable is dependent upon the value of $A_i(\underline{X})$ alone (since G_i is fixed by the designer) which in turn is dependent upon the system variables $\underline{X}$. Further, at a point in the design space, only one of the deviation variables associated with a goal is greater than zero. Deviation variables can be continuous, Boolean or a mixture of the two. Obviously the deviation variables associated with a particular goal constraint are of the same type. If more than one goal exists, they are nondimensionalized such that the deviation variables vary between the same range (e.g. 0 to 1). In Figure B.1, 5 is a linear goal constraint and 6 is a nonlinear goal constraint.

B.4.3 Bounds

$\underline{L} \leq X \leq \underline{U}$

$0 \leq d_i^- \leq 1$ for i goal constraints

$0 \leq d_i^+ \leq 1$ for i goal constraints

These are specific limits placed on the magnitude of each of the variable. Each variable is associated with a lower and upper bound as a result of the limited capability of the system or based on the designer's judgement. If there are two or more goal constratins, it is imperative that all the deviation variables are dimensionless (or are of the same dimension) and it is desirable that they vary between a fixed range (e.g. 0 to 1). The bounds demarcate teh region in which a search; is to be made for a feasible solution.

B.4.4 Objective

Min $P(\underline{d}^-, \underline{d}^+)$

The designer sets an aspiration level for each of the goals. It may be impossible to obtain a design that is up to the standards aspired. Hence, a compromise solution has to be accepted by the designer. It is desirable, however, to obtain a design whose performance matches the aspirations as closely as possible. This, in essence, is the objective of a compromise solution. The difference between the goals and achievement is expressed by a combination of the appropriate deviation variables, $P(\underline{d}^-, \underline{d}^+)$. The function $P(\underline{d}^-, \underline{d}^+)$ is also termed an "achievement function" [44]. The magnitude of $P(\underline{d}^-, \underline{d}^+)$ is an indication of the extent to which specific goals are achieved. Hence, the name "achievement function." All the goals may not be equally important to the designer. Goal programming formulations are predominantly classified either as Archemedian or Preemptive based on the manner in which importance is asigned to the deviation variables. The achievement function in Archemedian goal programming is

$$P(\underline{d}^-, \underline{d}^+) = W_1 d_1^- + W_2 d_1^+ + \ldots + W_{2(m-k)-1} d_{m-k}^+ + W_{2(m-k)} d_{m-k}^-$$

where the weights $W_1, W_2, \ldots, W_{2m}$ reflect the desire to achieve one goal more than the others. In Archemedian goal programming the weights W_i are such that

$$\sum_{i=1}^{2(m-k)} W_i = 1$$

The values of these weights are often based on estimates and designer preferences. It may be difficult to come up with truly credible weights that attach more importance to one goal than the other. A systematic procedrue to

come up with reasonable preferences is to use an ordinal or an interval scaling scheme [41, p. f128]. In Preemptive goal programming, this uncertainty is circumvented by rank ordering the goals and this is more easily possible in an industrial environment. Goals are ranked lexicographically and a more important goal is attempted to be satisfied as much as possible before other goals are considered. The achievement function, for instance, may look like

$$P(\underline{d}^- , \underline{d}^+) = P_1(d_1^- + d_1^+ + d_2^-) + P_2(d_2^+ + d_3^- + d_3^+) + P_3(d_8^- + d_9^+), \text{ etc.},$$

where P_1 is much larger than P_2 which is much larger than P_3 and so on. The deviation variables d_1^-, d_1^+, d_2^- have to be minimized preemptively before the variables d_2^+, d_3^- and d_3^+ are considered and so on. The priorities represent rank, i.e., by how much one goal is preferred to another. No conclusions can be drawn with respect to the amount by which one goal is preferred or is more important than another. This approach is more suitable when there is less information available.

An objective may also be to minimize or maximize a function of system variables alone, in which case the goal programing formulation yields a regular "optimization" problem. The difference between the "achievement function" approach and an "optimization" approach is that, while the former can deal with multiple goals, the latter can deal with only one objective.

B.5 MODELS FOR A COMPROMISE DECISION SUPPORT PROBLEM [25]

B.5.7 Formulation of a compromise DSP

As indicatd earlier a designer modeling an engineering system often encounters multiple and conflicting objectives. Some information may be "soft" and some "hard." Some of the aspects of a system are summarized in Table B.1. These characteristics are well represented by a compromise formulation as explained in Section B.3. A goal programming approach is recommended to formulate the compromise problem due to the broad scope of this model. A general form of the compromise problem is presented in Section B.3. The mathematical form of this generalized formulation is presented in Section B.5.2. The general goal programming model is classified as either Archemedian (weighted) or Preemptive goal programming model based on the manner in which the goals are quantified. The Archemddian and Preemptive models differ only b;y the way in which the objective function is evaluated as shown in the word problems. In the Preemptive goal programming, $P_i >> P_j$ signifies that P_i is ranked higher than P_j. Numerical solution of this ranking model is possible only if P_i is several magnitudes larger than P_j.

The Compromise DSP is also able to handle Boolelan and real variables simultaneously. The evaluation of the Boolean variables (of type 1 or 0) is made possible b;y the introduction of additional system constraints such as

$$\sum_{i=1}^{n} X_i = 1 \text{ and}$$

$$\sum_{\substack{i=1 \\ i \neq j}}^{n} X_i X_i = 0$$

VARIABLE	Continuous	Discrete	Boolean	Mixed
VARIABLE	System		Deviation	
CONSTRAINT	System		Goal	
CONSTRAINT	All linear		All nonlinear	Mixed
CONSTRAINT	Deterministic		Probabilistic	
BOUNDS	System Variables		Deviation Variables	
OBJECTIVE	Linear		Nonlinear	Mixed
OBJECTIVE	Deterministic		Probabilistic	
OBJECTIVE	System Variables		Deviation Variables	
OBJECTIVE	Single		Multiple	

Table B.1 Characteristics of components of decision support problems (from [25]).

were n is the number of Boolean system variables X_i. A practical application of such a formulation is in the selection of the tracking mode for PTC.s. For a detailed review of the methodology refer to Ittimakin [29].

B.5.2 General Formulation of the Compromise Decision Support Problem

Given

- The demands on and the capability of the system
- The goals of the designer
- The design variables

Find

- $\underline{X} = (X_1, X_2, \ldots, X_n)$
- $\underline{d}^- = (d_1^-, d_2^-, \ldots, d_{m-k}^-)$
- $\underline{d}^+ = (d_1^+, d_2^+, \ldots, d_{m-k}^+)$

Satisfy

- System constraints

  $D_i\ (\underline{X}) \leq C_i \quad i = 1, \ldots, k$

- Goal constraints

  $A_j(\underline{X})/G_j + d_j^- - d_j^+ = 1 \quad j = (k+1), \ldots, m$

- Bounds: System variables

  $\underline{X} \geq \underline{L},\ \underline{X} \leq \underline{U}$

- Bounds: Deviation variables

  $d_j^-, d_j^+ \geq 0 \quad j = (k+1), \ldots, m$

  $d_j^-, d_j^+ \leq 1 \quad j = (k+1), \ldots, m$

Minimize

$$P(\underline{d}) = P_1 d_1^- + P_2 d_1^+ + P_3 d_2^- + \ldots + P_{2(m-k)-1} d_{(m-k)}^- + P_{2(m-k)} d_{(m-k)}^+$$

Either

$$\sum_{i=1}^{2(m-k)} P_i = 1 \qquad \text{Archemedian Goal Programming}$$

or

$$P_i >> P_j >> P_k \qquad \text{Preemptive Goal Programming}$$

$$i \neq j \neq k$$

B.6 Sample Compromise Decision Support Problem [36]

In this section, a sample Compromise decision support problem for designing a parabolic trough collector is presented. Once cost data for different materials, fabrication techniques, etc., become available, Compromise DSP can be used for trade-off studies to compromise between cost and performance. In the example presented in this section, compromise between quality of reflecting surface (mirror) and collector size (aperture width) is considered by using a fictitious cost function and a fictitious cost constraint.

Similar to the sample problem in Appendix A, first, a scenario for application is defined. (The example of Appendix A, the small farm irrigation project, is used here too.) Then, the problem is expressed in words; a word problem is set-up. Finally, the math formulation of the word problem is given.

It should be noted that the example given in this is included for the sole purpose of demonstrating the implementation of Compromise DSP (set-up and solution) techniques to the PTC design. The chosen example is not intended to be comprehensive and/or realistic.

B.6.1 Set-up of the Problem

Problem Statement

It is required to choose the size and reflectivity of the concentrator for the PTC's to be designed for use in the small farm irrigation project (in a developing country) introduced in the example in Appendix A. Utilization of locally available materials is necessary. Reflectors available in the local market are in the form of 200-cm square sheets and their specular reflectivities vary between 70-93%. Cost of the reflectors ($\$/m^2$) are proportional to their reflectivity; according to the cost function (Table B.2), the higher the reflectivity, the higher the cost. Concentrator reflective surface is preferred to be made from a "one-piece" reflector, without any "gluing together", since rainwater entering through cracks may speed-up the deterioration of the reflective coating. Cost considerations indicate that, money spent on collector reflective material cannot exceed $70.00 per meter of collector length. Heat delivery requirements dictate a minimum thermal efficiency requirement of 40% (instantaneous efficiency at solar noon). Designing the collectors such as to achieve the highest possible efficiencies will, however, be one of the goals (as it is the case in any solar thermal collector design). Additional design data is presented in Table B.2. Below, a rank ordered list of all the design goals in this example is given:

1. Minimize the underachievement of the efficiency of 40%

GROUP	PARAMETER VALUE	REMARK
RECEIVER	$q_L = 2000 \frac{W}{(m^2)\text{absor.}}$	Cylindrical receiver with selective coating and a glass envelope around it, as appropriate for operation in the 150°C - 250°C range
	$(\tau\alpha)_{eff} = 0.83$	$\tau = 0.88$ (average) $\alpha = 0.94$ (average)
	$D_{glass\ envelope} = 5cm$	Diameter of the glass envelope
	$D = 2.5cm$	Diameter of the absorber tube.
	$\gamma = 0.9$	The fraction of the reflected radiation from the concentrator that is intercepted by receiver
CONCENTRATOR	$\phi = 90^\circ$	RIM ANGLE. This value for rim angle is chosen arbitrarily.
REFLECTOR MATERIAL	$\text{COST}\ (\frac{\$}{m^2}) \propto \frac{10}{1 - \rho^2}$	This is an assumption made, such as to relate cost of the reflector material to its reflective power, which is expressed as its reflectivity (ρ).
SOURCE	$I_b = 900\ W/(m^2)\text{apert.}$ $\theta = 0^\circ$	Design values for instantaneous beam radiation and incident angle on concentrator aperture

Table B.2 Design data for the sample compromise DSP.

2. Avoid concentrator arclengths greater than 200 cm.
3. Avoid expenditures of more than $70.00 (per meter length of collector) for reflective material.
4. Maximize the thermal efficiency of the collectors.

A systematic approach is used to solve the above problem statement. First, the problem is rewritten with keywords: Given, Find, Satisfy and Optimize. This helps to identify the independent variables, constraints and goals, clearly. Second, a mathematical form of the word problem is developed. A one-to-one correspondence must exist between the word problem and mathematical formulation. The same keywords (Given, Find, etc.) are used in the mathematical form of the problem in order to ensure this one-to-one correspondence. Finally, the mathematical form of the problem is solved using a graphical technique.

Word Problem: At this stage, the reader is referred to sections B.6.4 and B.6.5 for the details of the formulation.

Given: The design data in Table and dimensions of the reflector materials available.

Find : The geometric concentration ratio, C

The reflectivity of the reflector surface, ρ

Deviation from desired goals (d_1^-, d_1^+, d_2^-, d_2^+, d_3^-, d_3^+, d_4^-, d_4^+)

Satisfy:

1. Collector thermal efficiency as close to 40% as possible.

2. Concentration ratio as close to 22.2 as possible

3. Cost of reflector material per concentrator length as close to 70$/m as possible

4. Collector thermal efficiency goal = 50%

Bounds on variables

5. Reflectivity $\geq$ 0.7

6. Reflectivity $\leq$ 0.93

7. Concentration ratio 10

8. Bounds on deviation variables

Minimize:

1. The underachievement of collector thermal efficiency of 40%

2. The overachievement of the concentrator arc-length of 200 cm

3. The overachievement of 70$/m for cost of reflector material used per concentrator length

4. Maximize the thermal efficiency of the collectors

Note that goal number 4 will be converted from maximization to minimization in order to make it compatible with the first three goals, so that they can all be put into one objective function. Hence, goal number 4 is rearranged as minimization of the underachievement of an arbitrary high (in this case 50%) thermal efficiency. Bounds for the deviation variables are obtained by substituting the bounds of system variables into the constraints.

Mathematical Formulation

Find: $C, \rho, d_1^-, d_1^+, d_2^-, d_2^+, d_3^-, d_3^+, d_4^-, d_4^+$

Satisfy:

$$\left.\begin{array}{ll} 1. & \rho - \frac{3}{C} + d_1^- - d_1^+ = 0.571 \\ 2. & C + d_2^- - d_2^+ = 22.2 \\ 3. & \frac{C}{(1 - \rho^2)} + d_3^- - d_3^+ = 77.62 \\ 4. & \rho - \frac{3}{C} + d_4^- - d_4^+ = 0.714 \end{array}\right\} \text{Goal Constraints}$$

$$\left.\begin{array}{ll} 5. & \rho \geq 0.7 \\ 6. & \rho \leq 0.93 \\ 7. & C \geq 10 \end{array}\right\} \text{Bounds on Variables}$$

$$\left.\begin{array}{ll} 8. & d_1^-, d_1^+, d_2^-, d_2^+, d_3^-, d_3^+, d_4^-, d_4^+ \geq 0 \\ & d_1^+ \leq 0.2238 \\ & d_1^- \leq 0.171 \\ & d_2^+ \leq 1 \\ & d_2^- \leq 12.2 \\ & d_3^+ \leq 86.7 \\ & d_3^- \leq 58.01 \\ & d_4^+ \leq 0.081 \\ & d_4^- \leq 0.314 \end{array}\right\} \text{Bounds on Deviation Variables}$$

Minimize:

$$Z = P_1 d_1^- + P_2 d_2^+ + P_3 d_3^+ + P_4 d_4^-$$

where

d_i^+ = Amount by which constraint i has exceeded goal (overachievement)

d_i^- = Amount by which constraint i is short of goal (underachievement)

$P_1, \ldots, P_4$ = Priorities, their subscripts serve to identify priority level for the goal.

B.6.2 Graphical Solution

The graphical solution to the above mathematical formulation is presented in Figure B.3. A cartesian coordinate system having two axes, C and ρ, is drawn. The bounds and constraints given in the mathematical formulation are plotted and labelled.

Since this is a goal programming problem, the feasible design space should be obtained with the help of the objective function. First, the area representing underachievement of 40% efficiency (area below 40% - efficiency curve) is excluded. This was the goal of greatest importance. The second and third goals are accounted for by setting d_2^+ and d_3^+ equal to zero. The set of points which satisfies system constraints (curves 5, 6 & 7) and represents fulfillment of the first 3 goals is represented by the shaded area (ABCD). The final goal is to maximize the efficiency (or to minimize the underachievement of the 50%-efficiency goal). As shown in the Figure, 50% eff-curve lies outside the area

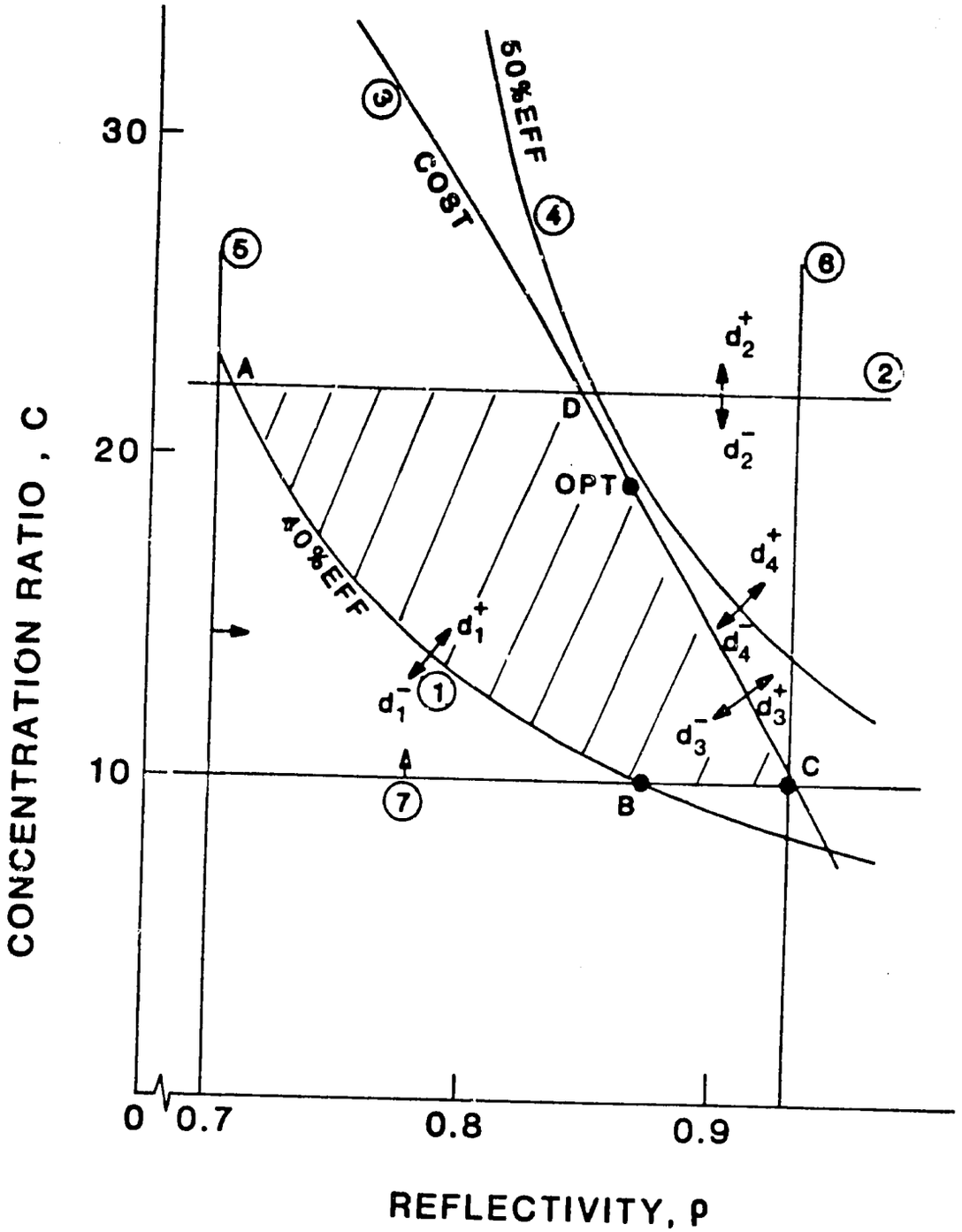


Figure B.3 Graphical solution of the sample Comprise DSP.

ABCD, therefore, the optimal solution will have to occur on line CD, which forms the rightmost boundary of the feasible design space, so that the underachievement of the 50% efficiency goal, d_4^-, is minimized (hence efficinecy maximized). The optimal solution will be at the precise location where the distance between cost and 50% - eff curve, is the shortest. This will ensure the minimization of d_4^- as best as possible. This optimal point is found by equating the derivatives of the cost and 50% - eff curves (see section B.6.6 for details).

C = concentration ratio = 19.6

ρ = reflectivity = 0.865

d_4^- = 0.002 (i.e., goal No.4 is underachieved. The thermal efficiency of the design will be 49.8% instead of 50%)

The only active constraint in the problem is the cost constraint.

B.6.3 Post-Solution Analysis:

Although 86.5% and 19.6 are found to be the optimum values for the concentrator reflectivity and concentration ratio, respectively, it turns out that the choice of any other point on the line CD would not drastically reduce the efficiency (at point C thermal efficiency is 45.1%). Furthermore, achievement of a 50% thermal efficiency goal was a fictitious one anyway. Therefore, the designer may exercise flexibility while designing the concentrator. In fact, he can take into account additional less important goals in his design. For example, he may choose to move to point C and

have smaller collectors with 4% less efficiency. In return, smaller collectors may require less foundation cost due to reduced wind loading.

Additional arguments and conclusions, like the one above, can be obtained by studying the figure further and performing a complete sensitivity analysis. However, since the main objective of this example has been the demonstration of the method, further discussion and the sensitivity analysis of this example is omitted.

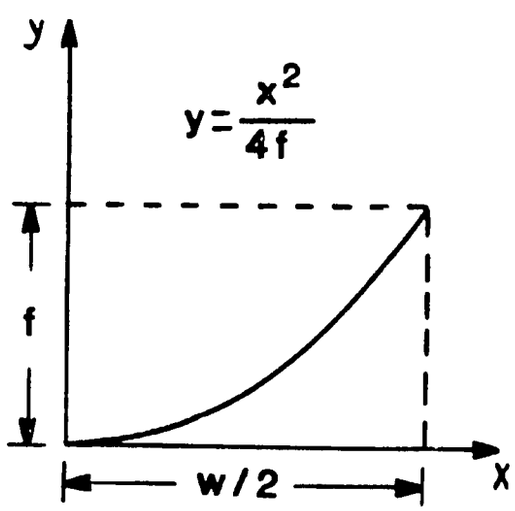
B.6.4 Arclength of a PTC

For a 90° rim angle PTC, the focal length is:

$$f = \frac{W}{4}$$

Arclength, L, is given by the formula:

$$L = 2 \int_0^{w/2} (1 + (dy/dx)^2)^{1/2} dx$$



For a PTC:

$$\frac{dy}{dx} = \frac{2x}{4f} = \frac{x}{2f}$$

Therefore,

$$L = 2 \int_0^{w/2} (1 + \frac{x^2}{4f^2})^{1/2} \, dx$$

Using substitution method, above integral can be solved to give:

$$L = 1.148 \ w \qquad \text{(B.1)}$$

B.6.5 <u>Formulation of the constraints and bounds for the compromise problem</u>:

In the problem statement, the independent variables were identified as the 'size' and reflectivity of the concentrator. Usually what is meant by the 'size' is the aperture width, w. However, it is more meaningful to talk in terms of geometric concentration ratio since the absorber area is already known. Geometric concentration ratio can be expressed in terms of w only, after substitution of the absorber diameter (Table B.2):

$$C = \frac{w}{\pi D} = 12.73 \ w \qquad \text{(w in m)} \qquad \text{(B.2)}$$

The upper bound for C can be calculated with the help of equation (B.1) and (B.2)

$$C_{max} = (12.73) \frac{L_{max}}{1.148}$$

Maximum concentrator arclength, (L_{max}) = 2m. Therefore,

$C_{max} = 22.2$; $C \leq 22.2$, and consequently the goal constraint number two can be written as:

$$C + d_2^- - d_2^+ = 22.2 \qquad (B.3)$$

Using the thermal efficiency equation in Appendix C and substituting the design data in Table B.2:

$$\eta = 0.7\,\rho - \frac{2.1}{C} \qquad (B.4)$$

Now, using (B.4) goal constraint number 1 can be formulated as

$$0.7\,\rho - \frac{2.1}{C} \geq 0.4$$

or

$$\rho - \frac{3}{C} + d_1^- - d_1^+ = 0.571 \qquad (B.5)$$

Similarly, goal constraint number 4 can be written as

$$0.7 \quad - \frac{2.1}{C} \quad 0.5$$

or

$$- \frac{3}{C} + d_4^- - d_4^+ = 0.714 \qquad (B.6)$$

Finally, goal constraint number 3 can be formulated as follows:

Total area of reflective material per unit concentrator length	$= L.1 \quad (m^2)$
Cost per unit concentrator length	$= L\ (m^2)\ .\ (\frac{cost}{m^2})$

Using the cost function in Table B.2 and Equations (B.1) and (B.2):

$$1.148 \left(\frac{C}{12.73}\right) \cdot \left(\frac{10}{1 - \rho^2}\right) \left(\frac{\$}{m}\right) \leq 70 \frac{\$}{m}$$

Rearranging and putting in the deviation variables yields:

$$\frac{C}{1 - \rho^2} - d_3^- - d_3^+ = 77.62 \qquad \text{(B.7)}$$

Finally, in order to have a design, the collector must have a finite size, i.e., concentration ratio,C, must have a finite lower bound. A reasonable lower bound for C is 10 (from experience), therefore:

$$C \geq 10 \qquad \text{(B.8)}$$

B.6.6 Calculations for Optimal Solution

The precise location on the cost curve, where d_4^- is minimized as best as possible, can be found by finding the shortest distance between the cost and 50%-eff curves. At this location, the slopes of the two curves should be equal to each other. Rearranging Equations (B.6) and (B.7) and differentiating them with respect to ρ will give

$$\frac{\partial C}{\partial \rho} = \frac{-3}{(\rho - 0.714)^2} \qquad \text{(B.6)'}$$

$$\frac{\partial C}{\partial \rho} = - 155.24\ \rho \qquad \text{(B.7)'}$$

Equating the two and solving for the roots will yield the optimal reflectivity, $\rho = 0.865$.

Appendix C

DERIVATION OF COLLECTOR EFFICIENCY AND SOLAR DATA

C.1 Collector Efficiency

The instantaneous thermal efficiency of a PTC can be obtained from a heat balance on the receiver tube:

$$\dot{Q}_{net} = \dot{Q}_{in} - \dot{Q}_{loss} \tag{C.1}$$

Rewriting Eq. (C.1) in terms of heat fluxes gives:

$$q_{net} A_a = q_{in} A_a - q_{loss} A_r \tag{C.2}$$

where subscript 'a' and 'r' stand for aperture and receiver, respectively.

If Eq. (C.2) is divided by A_a, the net heat flux, q_{net}, is obtained as:

$$q_{net} = q_{in} - \frac{q_L}{C} \tag{C.3}$$

where

q_L = heat loss from receiver surface per unit receiver length; $\frac{W}{m^2}$

C = Geometric concentration ratio

$$= \frac{\text{Area of aperture } (A_a = WL)}{\text{Area of receiver } (A_r = \pi DL)}$$

$$= \frac{W}{\pi D} \tag{C.4}$$

The total flux intercept by the receiver, q_{in}, is:

$$q_{in} = I_b \cos\theta \ \eta_o \tag{C.5}$$

where

I_b = Instantaneous total beam isolation, $\frac{W}{m^2}$

θ = Incidence angle on the aperture

η_o = Optical efficiency

Therefore

$$q_{net} = I_b \cos\theta \ K(\theta) \ [\rho(\tau\alpha)_n]\gamma - \frac{q_L}{C} \tag{C.6}$$

Then the instantaneous thermal efficiency, η_c, of PTC can be obtained from:

$$\eta_c = \frac{q_{net}}{I_b} \tag{C.7}$$

C.2 Solar Data

The solar data given in Table 5.6 is obtained using Reference 18. The incidence factors, $\cos\theta_{noon}$, are calculated using Table A.1 and

$\omega = 0°$ (solar noon)

$\delta = 0.1°$ (equirox, March 21st)

$\lambda = 35°N$ (latitute)

The beam irradiance at normal incidence, I_b, can be expressed as [18]:

$$I_b = (0.6598 + 0.4226\cos\omega - \frac{H_d}{H_h}).K_h I_o \tag{C.8}$$

where

ω = Hour angle,

$\frac{H_d}{H_h}$ = Ratio of diffuse over hemispherical irradiation,

K_h = Clearness index,

I_o = Solar constant = 1353 $\frac{W}{m^2}$

Since PTC will operate only during periods of fairly high insolation, it is appropriate to take K_h=0.75, corresponding to clear days. The associated ratio of diffuse to hemispherical irradiation (H_d/H_h) is 0.23 [18]. Therefore, Eq. (C.5) can be rewritten as:

$$I_b = 436.14 + 428.83\cos\omega \qquad [\frac{W}{m^2}] \tag{C.9}$$

At solar noon, ω=0.0°, therefore,

$$[I_b]_{noon} = \underline{\underline{865\ W/m^2}} \tag{C.10}$$

The all-day average beam insolation, $\langle I_b \rangle$, can be obtained from integration of Eq. (C.9):

$$\langle I_b \rangle = \frac{1}{\omega_c} \int_0^{\omega_c} I_b(\omega)\, d\omega$$

$$\langle I_b \rangle = 436.14 + 428.83 \frac{\sin\omega_c}{\omega_c} \tag{C.11}$$

where ω_c is the cut-off angle. For all-day average based on 8h/day, ω_c= 4h.(15°/h), therefore,

$$\langle I_b \rangle = \underline{\underline{791\ W/m^2}} \tag{C.12}$$

The all-day average incidence factors, $\langle\cos\theta\rangle$, are obtained from integration of incidence factors given in

Table A.7 :

$$\langle\cos\theta\rangle = \frac{1}{\omega_c} \int_0^{\omega_c} \cos\theta \, d\omega \tag{C.13}$$

Similarly,

$$\langle I_b\cos\theta\rangle = \frac{1}{\omega_c} \int_0^{\omega_c} I_b(\omega)\cos\theta \, d\omega \tag{C.14}$$

Incidence-Angle Modifiers

The values for the incidence-angle modifiers are obtained from experimental data reported in Reference 19 for PTC's manufactured by various U.S. companies like Acurex, Solar Kinetics, Hexel (SERI), Hexel (Sandia) and Del. The incidence-angle modifier at solar noon is given by:

$$[K(\theta)]_{noon} = K(\theta)\big|_{\theta=\theta_{noon}} \tag{C.15}$$

For two-axes, polar and E-W tracking modes $\theta_{noon} = 0.0$. For N-S tracking mode $\theta_{noon} = 35.0°$ because $\lambda = 35°N$. The value for $[K(\theta)]_{noon}$ for N-S tracking mode is the average of the five sets of experimental data reported for the five PTC designs:

$$[K(\theta)]_{noon,N-S} = \frac{1}{5}(0.9858 + 0.968 + 0.95 + 0.934 + 0.919)$$

$$= \underline{\underline{0.9515}}$$

The all-day average incidence-angle modifiers are obtained by integrating the curve-fit equations [19]:

$$\langle K(\theta)\rangle = \frac{1}{(\theta_c - \theta_{noon})} \int_{\theta_{noon}}^{\theta_c} K(\theta)\, d\theta \qquad (C.16)$$

where θ_c is the cut-off incidence angle on the collector aperture and depends on the tracking mode. The values given in Table 6.1 are the averages for the five collector designs.