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A User's Manual for DELSOL3: A Computer Code for Calculating the Optical Performance and Optimal System Design for Solar Thermal Central Receiver Plants



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**A USER'S MANUAL FOR DELSOL3: A COMPUTER CODE FOR
CALCULATING THE OPTICAL PERFORMANCE AND OPTIMAL SYSTEM
DESIGN FOR SOLAR THERMAL CENTRAL RECEIVER PLANTS**

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ABSTRACT

DELSOL3 is a revised and updated version of the DELSOL2 computer program (SAND81-8237) for calculating collector field performance and layout and optimal system design for solar thermal central receiver plants. The code consists of a detailed model of the optical performance, a simpler model of the non-optical performance, an algorithm for field layout, and a searching algorithm to find the best system design based on energy cost. The latter two features are coupled to a cost model of central receiver components and an economic model for calculating energy costs. The code can handle flat, focused and/or canted heliostats, and external cylindrical, multi-aperture cavity, and flat plate receivers. The program optimizes the tower height, receiver size, field layout, heliostat spacings, and tower position at user specified power levels subject to flux limits on the receiver and land constraints for field layout. DELSOL3 maintains the advantages of speed and accuracy which are characteristics of DELSOL2.

1. The first part of the document discusses the importance of maintaining accurate records of all transactions and activities. It emphasizes that this is crucial for ensuring transparency and accountability in the organization's operations.

2. The second part of the document outlines the various methods and tools used to collect and analyze data. It highlights the need for consistent and reliable data collection processes to support effective decision-making.

3. The third part of the document focuses on the role of technology in data management and analysis. It discusses how modern software solutions can streamline data collection, storage, and reporting, thereby improving efficiency and accuracy.

4. The fourth part of the document addresses the challenges associated with data management, such as data quality, security, and integration. It provides strategies to overcome these challenges and ensure the integrity and availability of data.

5. The fifth part of the document discusses the importance of data governance and compliance. It outlines the necessary policies and procedures to ensure that data is handled in a responsible and lawful manner, in accordance with applicable regulations.

6. The sixth part of the document explores the future of data management and analysis. It discusses emerging trends and technologies, such as artificial intelligence and big data, and their potential impact on the field.

7. The seventh part of the document provides a summary of the key findings and conclusions. It emphasizes the need for a holistic approach to data management, one that integrates all aspects of the data lifecycle.

8. The eighth part of the document offers recommendations for further research and development. It suggests areas where additional data and analysis are needed to improve the effectiveness of data management practices.

9. The ninth part of the document discusses the importance of collaboration and communication in data management. It highlights the need for clear roles and responsibilities, as well as regular communication and reporting to ensure successful outcomes.

10. The tenth part of the document provides a final summary and conclusion. It reiterates the key points discussed throughout the document and emphasizes the importance of ongoing learning and improvement in the field of data management.

SOLAR THERMAL TECHNOLOGY FOREWORD

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

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

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

To be successful in contributing to an adequate national energy supply at reasonable cost, solar thermal energy must eventually be economically competitive with a variety of other energy sources. Components and system-level performance targets have been developed as quantitative program goals. The performance targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and making optimal component developments. These targets will be pursued vigorously to insure a successful program.

The computer code which this report describes was updated and used to perform studies comparing various solar central receiver systems for purposes of determining an optimum system design. This report describes the improvements which have been made in the code to more closely model a central receiver system, includes a description of the capabilities of the code, and provides a clearer description of how to use the computer code to determine an optimum system design.

ACKNOWLEDGEMENTS

This report was based on and includes significant portions of the DELSOL2 manual (SAND81-8237), which was authored by Theodore A. Dellin, Miriam E. John, and Christine L. Yang.

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A USER'S MANUAL FOR DELSOL: A COMPUTER CODE FOR CALCULATING THE OPTICAL PERFORMANCE AND OPTIMAL SYSTEM DESIGN FOR SOLAR THERMAL CENTRAL RECEIVER PLANTS

I. Introduction

In central receiver systems, a large number of individually tracking mirrors, called heliostats, are used to concentrate sunlight on a receiver at the top of a tower. These systems have the potential to deliver thermal energy over a wide range of power levels and temperatures. Applications include central station electric power generation, industrial process heat and production of fuels and chemicals. Analytical techniques for central receiver system design are required because it is impractical to investigate experimentally the wide ranges of design and application alternatives for central receivers. Furthermore, the analysis must be computer based because of: 1) the large number (i. e., thousands) of heliostats in many single system designs; 2) the strong time dependence of system performance due to the motion of the sun; and 3) the large number of options which have to be considered in optimal design. The DELSOL computer program was written to fill the need for an accurate, yet fast, easy to use and documented code for performance and design applications. Version I, which analyzed large power electric applications, was released in August 1978. Version II improved and extended the capabilities of Version I. Version II can handle both large and small power systems for electricity and process heat applications. The present Version III has been updated to incorporate more up-to-date cost defaults, new component cost and receiver loss relationships, more detailed parasitic loss calculations, and corrections to known errors in Version II. The code consists of a detailed model of the optical performance, a simpler model of the non-optical performance, an algorithm for field layout, and a searching algorithm to find the best system design. The latter two features are coupled to a cost model of central receiver components and an economic model for calculating energy costs.

Figure I-1 indicates schematically how the components of DELSOL are used in the two general classes of application. In (A), a complete system design (which may have been previously optimized by DELSOL) is specified by the user, and the code calculates its performance. Typical applications include design point evaluation and analysis of experiments at test facilities. In (B), the heliostat design, the range of system variables to be optimized, and the design constraints are specified by the user and the code calculates optimal designs for a range of power levels. Typical applications include system optimization and component design tradeoff studies.

As an optical performance tool, DELSOL simulates the effects of cosine, shad-

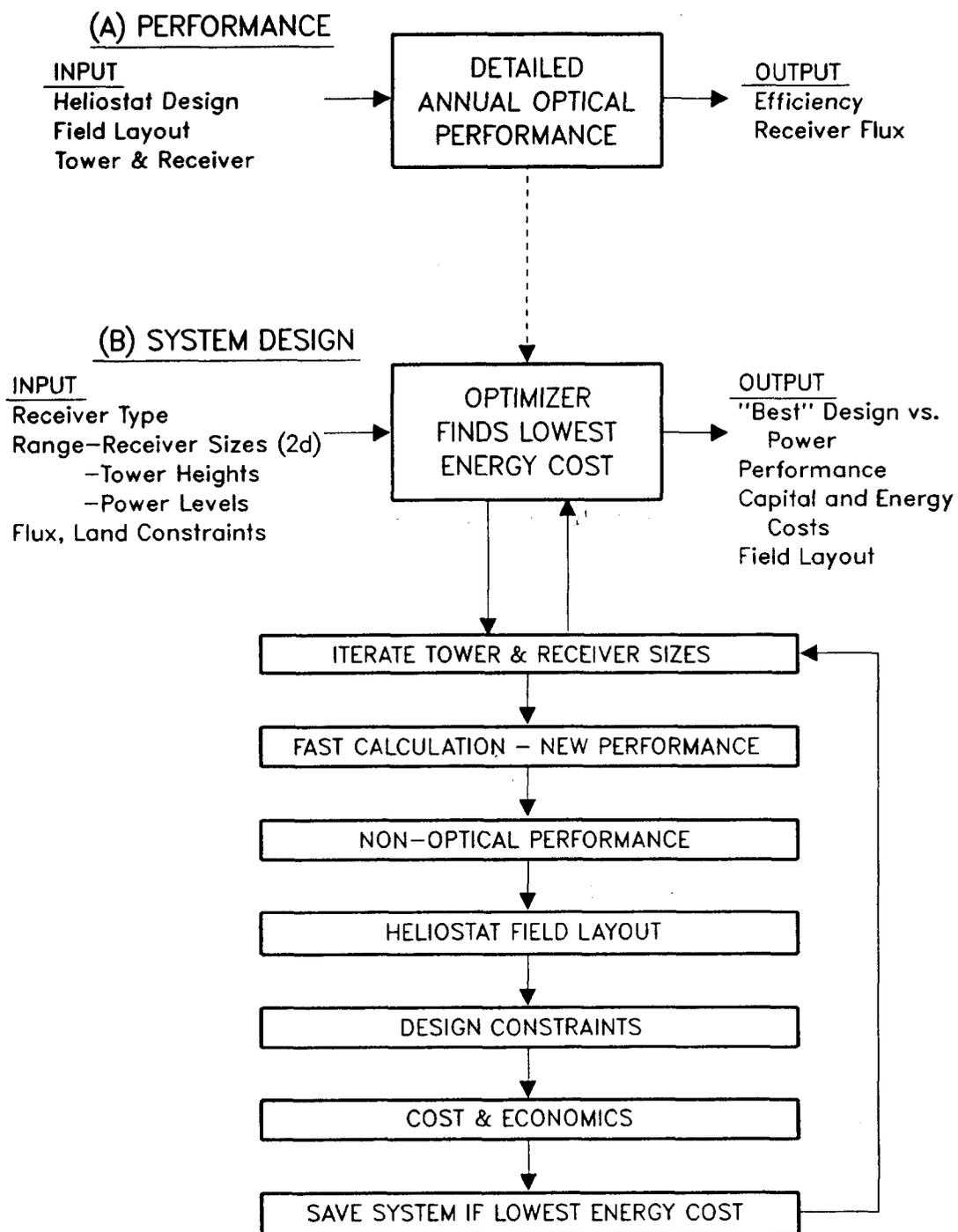


Figure I-1. Two General Types of Applications of DELSOL

owing, blocking, atmospheric attenuation, spillage, and flux profiles. The code has several special features. First, the running time for a single performance calculation is much less than for other codes, such as MIRVAL (Reference 1), but with the same accuracy for most problems. Second, because of the analytical form of the spillage and flux, one annual performance calculation determines the performance for any tower height or receiver size. Other codes must perform a new calculation each time the system is varied. DELSOL, therefore, has a very significant advantage in the execution time required for the large number of performance calculations necessary in design tradeoff and optimization studies. Third, DELSOL contains a detailed description of the types of errors that can degrade the performance of heliostats. Finally, DELSOL is relatively easy to use. With minimal input, DELSOL can analyze systems involving flat, focused, or canted heliostats with round or rectangular shapes; external, multiple aperture cavity, or multiple flat plate receivers; and variable aiming strategies.

As a system design tool, DELSOL determines the best combination of field layout, heliostat density, tower height, receiver size and tower position (land constrained system) based on the performance, total plant capital cost, and system energy cost. In this mode, the code can be used to define values of the key design parameters on which a detailed design can be based. The need for manually doing a succession of point designs in order to identify an optimum is eliminated. The optimal design is evaluated by searching over a range of tower heights and over two components of the receiver geometry (e. g., diameter and height of an external receiver) at the design point power level(s) to find the system with the minimum energy cost. The code is also capable of doing constrained optimizations in which the peak flux on the receiver is restricted below some maximum value and/or land availability is limited.

The development of DELSOL followed that of Sandia's other two central receiver performance codes, MIRVAL and HELIOS (References 1 and 2). The earlier codes have been used to validate the theory and programming in DELSOL. The agreement in performance predictions among the three codes is discussed in Chapter VII. While any one of the codes can, in principle, do the same kinds of problems, they were developed with different purposes in mind and thus do not greatly overlap in use. HELIOS is specially adapted for analyzing experiments at Sandia's Central Receiver Test Facility. MIRVAL employs a Monte Carlo ray trace technique, giving it the potential to analyze very complex systems that are well defined. DELSOL has been developed with speed in mind; hence it typically requires much less computer time for performance calculations, and it can also readily handle the multiple performance calculations required for system design and optimization.

DELSOL is based in part on the performance/design approaches developed at the University of Houston (References 3 and 4), but with many important additions. The mathematical basis is an analytical Hermite polynomial expansion/convolution of moments method for predicting the images from heliostats (Reference 3). The method has been extended at Sandia to allow a more general

representation of heliostat errors and to incorporate analytical scaling of the images as the tower height is varied (Reference 5). DELSOL also employs a method for optimizing heliostat densities similar to the Houston approach (Reference 4). The primary difference in the two codes is in their design/optimization capabilities. The Houston approach considers only one tower height and receiver size at a time. These variables must be optimized by manually rerunning the Houston codes until an optimum is located. In contrast, DELSOL automatically optimizes the tower height and receiver dimension(s), saving considerable user and computer time. (The user is cautioned, however, to provide his own values for the appropriate input variables if his system of interest differs significantly in size or cost/performance from the default system description in the code. See Appendix A.)

DELSOL is a FORTRAN IV code, developed on Sandia's CDC6600 and CDC7600, and adapted to execute on a CRAY-1. Typical execution times for performance calculations on the CRAY-1 are 45-60 seconds, while design and optimization calculations may take 5-300 seconds. Execution times on a VAX 11-780 will typically be about ten times as long as on the CRAY-1. This manual describes the status of DELSOL as of January 1986. The code is intended to evolve with the development of central receiver technology and revised versions of the code and manual will be released as needed.

I.A. Differences from Earlier Versions of DELSOL

Several corrections and additions have been made in DELSOL3 which distinguish it from its predecessors. Known errors which were fixed included correcting the logic for scaling flux point positions during the optimization of cavity receivers, correcting the flux calculation for cavity receivers and extending the calculation to allow general flux maps in front of the aperture, and correcting the logic when operating from storage and receiver power simultaneously. Also, the operating parasitic loss calculation was fixed and modified, and numerous typographical errors in the code and in the outputs were corrected.

At least four major enhancements were added to DELSOL3. First, receiver loss algorithms were modified based on References 6 and 7 to more closely model experimental and test facility data of receiver losses, including measured losses at the Solar One facility near Barstow, California. Next, algorithms for non-operating parasitic losses were added to the code, thus accounting for the energy which is consumed by a power plant at the times when power is not being produced. Third, the sizing algorithm for a cavity heat absorber area, which determines receiver cost, was modified so that the new area is based on aperture height rather than on minimum and maximum field dimensions. The previous algorithm resulted in an extremely large cavity which had very low incident flux levels on the upper portion of the heat absorber area. This modification assumes that some internal spillage is acceptable, and is intended to be an empirical model based on present and past detailed cavity designs.

The fourth major enhancement in DELSOL3 is the update of most of the default values in the code. As part of this update, new algorithms for calculating tower cost were included, a transition region was added between the tower and receiver, and the fixed cost algorithm was adjusted to reflect such things as structures, improvements, and miscellaneous equipment. Receiver, thermal storage, heat exchanger, and turbine-generator costs were adjusted based on the Saguaro molten salt cavity design (Reference 8). Heliostat, land, and wiring default cost values were modified. Also, the default heliostat was redefined to have about 100 square meters of reflective area, and the pointing errors of this heliostat were adjusted. Certain component efficiencies were modified, and the plant factor was changed from 1.0 to 0.9 to reflect the fact that some maintenance outages will be required in any realistic power plant. Lastly, default values used for economic assumptions were adjusted, such as the fixed charge rate and the rates of escalation and inflation. It is important that the user of this code verify that any default values which are used in DELSOL3 calculations are valid, since different economic scenarios could result in vastly different predicted energy cost values and since the relationship between component costs and efficiencies directly affects the optimum system which is chosen by DELSOL3.

Finally, several other minor enhancements were made in DELSOL3, including an optional weather factor algorithm based on latitude of the plant, an additional heliostat density optimization algorithm, a mixed mode smart aiming algorithm, optional interactive plotting of fluxes from a single zone or from the entire heliostat field, and addition of another heat exchanger for use between a receiver fluid and a different storage fluid. Also, the operating logic was adjusted so that receiver operation only occurred when net power was positive, and so that the turbine-generator only operated from storage instead of directly from the receiver.

I.B. Conventions in This Manual

In this description of DELSOL3, variables which are capitalized refer to namelist input variables. In some instances, different variable names will be used when describing the theory behind certain algorithms, in which case the variable names will not be capitalized, but these may be related to input variables by following the theory variable by the capitalized input variable in parenthesis. For instance, f_s (FSP) relates the input variable FSP to the theory variable f_s .

II. Problem Geometry

This section describes the field layout geometries and options, the various coordinate systems used in the DELSOL calculations, heliostat layout patterns, heliostat geometries and error sources, tower and receiver configurations, aiming strategies, and flux point positions and the usage of flux points.

II.A. Coordinate Systems and Angles

The geometry used in the calculations is shown in Figures II-1 and II-2. Polar (zenith) angles are measured from vertical. Azimuthal angles are measured clockwise from the south as shown in Figure II-2, although field azimuthal angles (Figure II-3) will be measured clockwise from the north. There are four basic vectors and coordinate system: \hat{s} , from the heliostat center to the center of the sun; \hat{n} , directed along the heliostat normal; \hat{t} , the reflected vector from the heliostat center to the aim point on the receiver; and \hat{r} , the outward surface normal of the receiver.

The orientation of the heliostats is determined by Snell's law: the angle of incidence equals the angle of reflection, i.e.,

$$\hat{n} \cdot \hat{s} = \hat{n} \cdot \hat{t}$$

Solving for \hat{n} and \hat{t} gives

$$\hat{n} = (\hat{s} + \hat{t}) / (|\hat{s} + \hat{t}|)$$

$$\hat{t} = 2(\hat{n} \cdot \hat{s})\hat{n} - \hat{s}$$

The five cartesian coordinate systems are listed in Table II-I. The (\hat{i}_t, \hat{j}_t) plane of the reflection normal system is given the special name "image plane".

II.B. Heliostat Zoning

In design optimization runs, DELSOL does not consider individually each of the thousands of heliostats required in large systems. Instead, the code calculates the performance at a set of field points. It is assumed that each field point represents the average performance in a surrounding zone of heliostats. For runs in which only the performance is calculated, the field can be described with the zoning approximation, or the coordinates of each individual heliostat can be defined. Zones are numbered radially outward and are numbered azimuthally starting with the north zone and proceeding clockwise, as shown in Figure II-4.

II.B-1. Zoning Options—There are two options for zoning: 1) zoning that completely surrounds the tower and that can be used with any receiver (INORTH=0); and 2) finer zoning of the area north of the tower which can be used only with a single north facing cavity or flat plate receiver (INORTH=1).

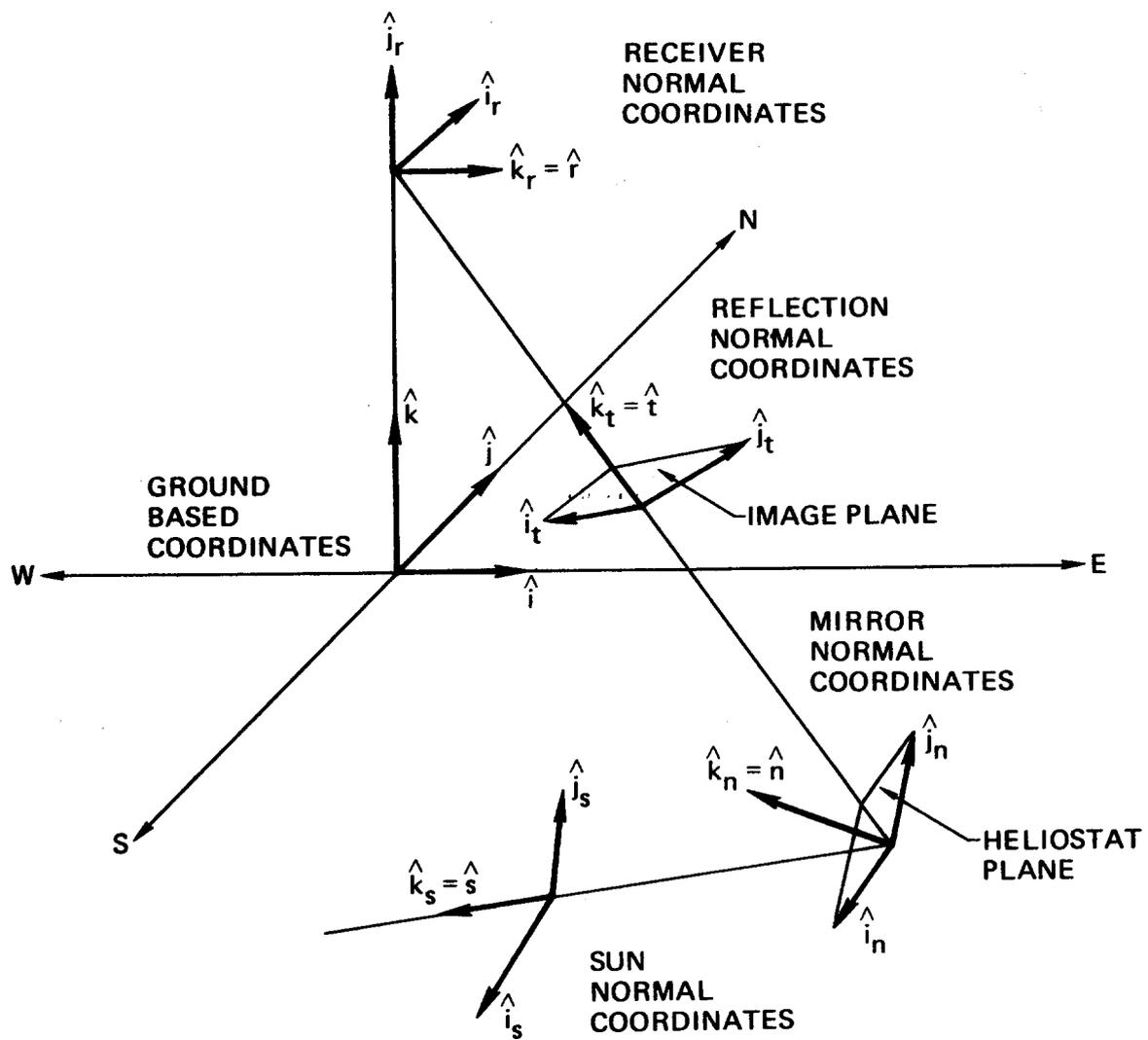


Figure II-1. Coordinate Systems for Field Performance Calculations

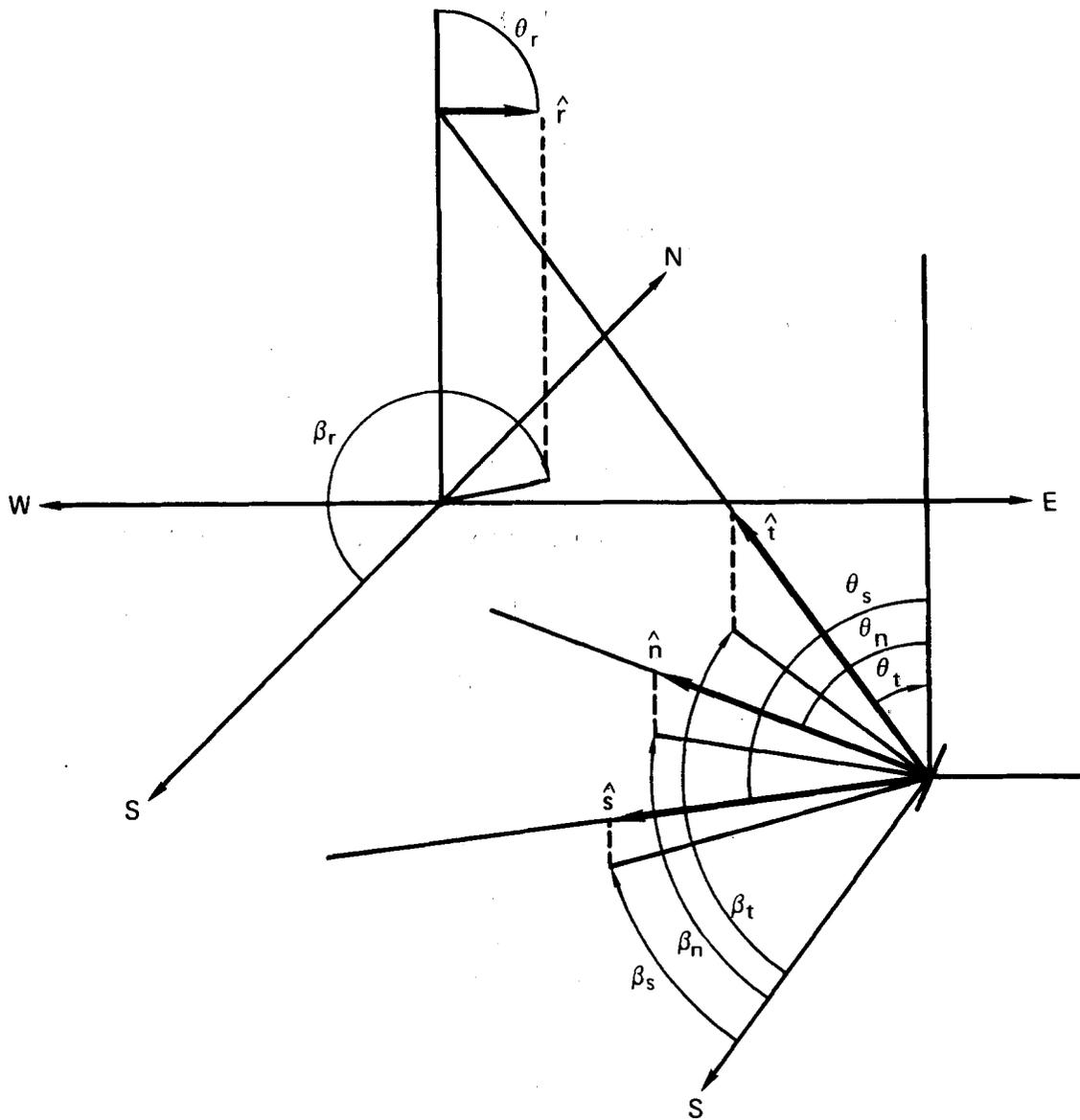


Figure II-2. Angles Associated with Sun, Mirror Normal, Reflection, and Receiver Normal Vectors

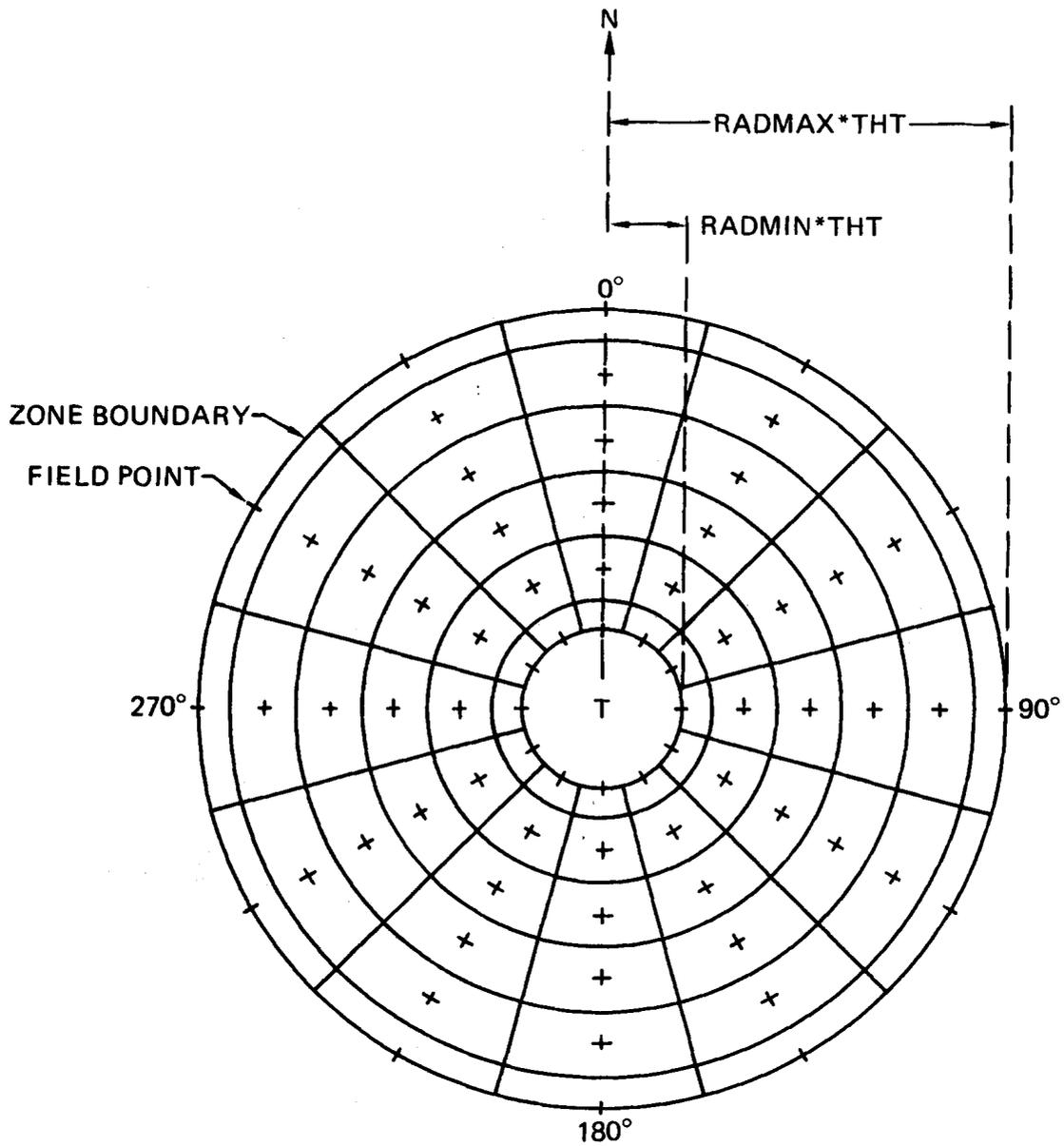


Figure II-3. Surround Field (INORTH=0). Field Point (x's) and Field Zone Boundaries (Solid Lines) for NRAD = 6, NAZM = 12. Field Azimuthal Angle Determined from Clockwise Rotation from North.

Table II-1
Coordinate Systems

Name	Unit Vector	Value	Definition of Orientation
Ground Based	\hat{i}	x_g	Due south
	\hat{j}	y_g	Due west
	\hat{k}	z_g	Vertical, upward
Mirror Normal	\hat{i}_n	x_n	Horizontal, in plane of mirror
	\hat{j}_n	y_n	Vertically upward when normal is horizontal, in plane of mirror
	$\hat{k}_n = \hat{n}$	z_n	Mirror normal
Sun Normal	\hat{i}_s	x_s	Horizontal
	\hat{j}_s	y_s	Vertical at sunset
	$\hat{k}_s = \hat{s}$	z_s	Towards sun
Reflection Normal	\hat{i}_t	x	Horizontal
	\hat{j}_t	y	Upward
	$\hat{k}_t = \hat{t}$	z	Towards tower
Receiver Normal	\hat{i}_r	x_r	Horizontal, tangent to receiver surface
	\hat{j}_r	y_r	Upward, tangent to receiver surface
	$\hat{k}_r = \hat{r}$	z_r	Outward normal of receiver surface

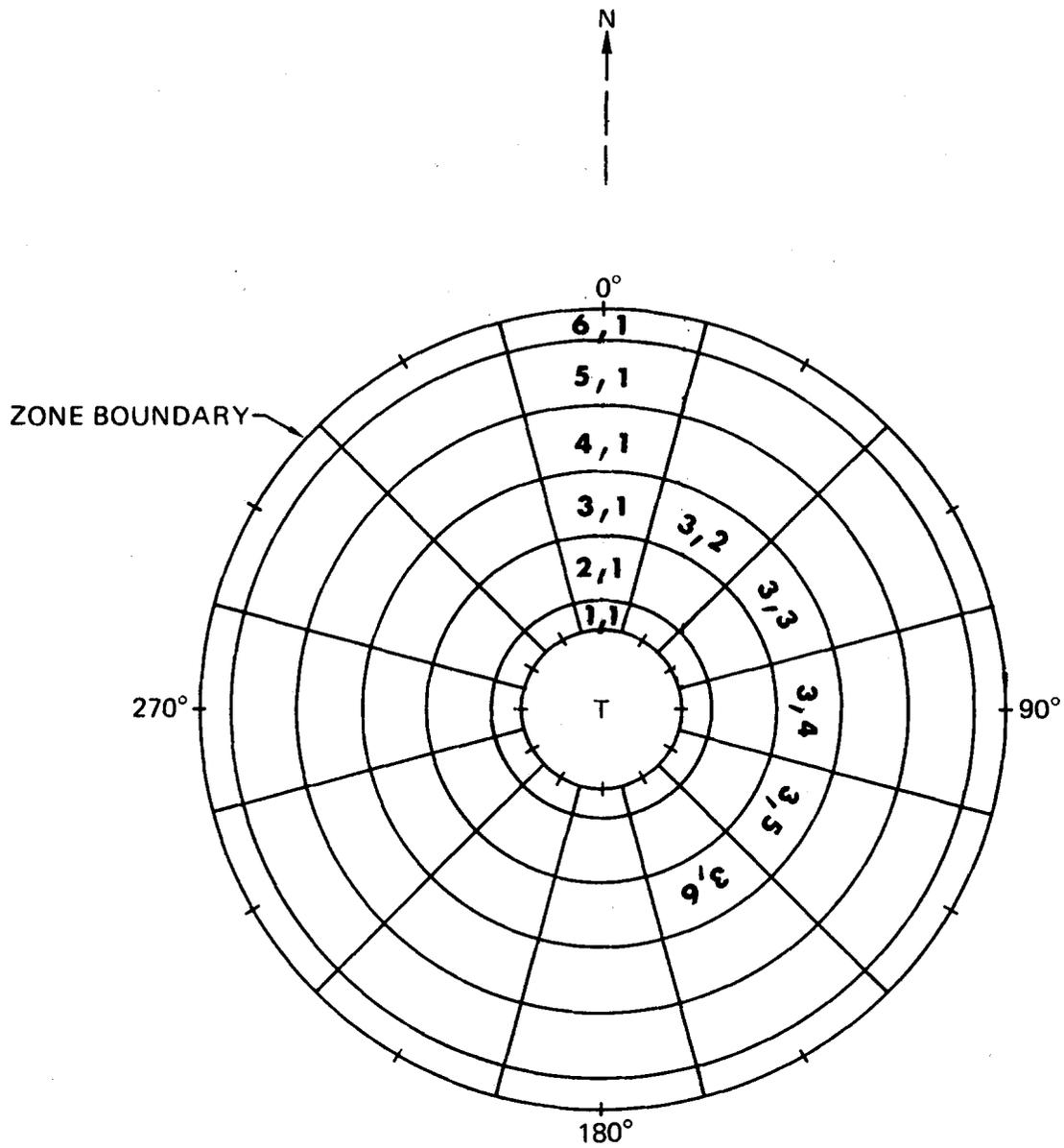


Figure II-4. Method of Zone Numbering Used by DELSOL

a) Surround Field (INORTH=0)

The field points are located on a regularly spaced radial-azimuthal grid surrounding the tower as shown in Figure II-3. There are NRAD values of the radius from a minimum of RADMIN to a maximum of RADMAX (RADMIN and RADMAX are in normalized units of tower height). There are NAZM values of the azimuthal angle with the first azimuthal value being due North. The total number of field points (and therefore zones) is NRAD \times NAZM. The field point is in the center of the zone except at the inner and outer radial boundaries where it is at the boundary.

Heliostats are located by specifying the value of the radius and the azimuthal angle of the tower vector \hat{t} . $\phi_t = 0$ corresponds to a heliostat due North of the tower whose \hat{t} points due South. Similarly,

<u>Angle ϕ_t</u>	<u>Location</u>
0	N
45	NE
90	E
135	SE
180	S
225	SW
270	W
315	NW

b) North Field (INORTH=1)

This option can be used only with a single north facing cavity or flat plate receiver. This is specified in namelist REC by setting IREC \geq 0, NUMCAV=1, and RAZM(1)=180.0. The field points are located on a regularly spaced radial-azimuthal grid located north of the tower, as illustrated in Figure II-5. In addition, a "dummy" set of zones with field points due south of the tower is carried along. These southerly zones do not affect the calculations because they are automatically assigned zero intercept with north-facing receivers. The radial zoning is the same as that for the surround field (INORTH=0). The azimuthal zones utilized are NAZM-1 in number and extend \pm AMAXN degrees about the N-S axis. The default values produce 11 azimuthal zones each spanning 15° in the north part of the field. This gives half of the default 30° segment obtained when INORTH=0. Default values are:

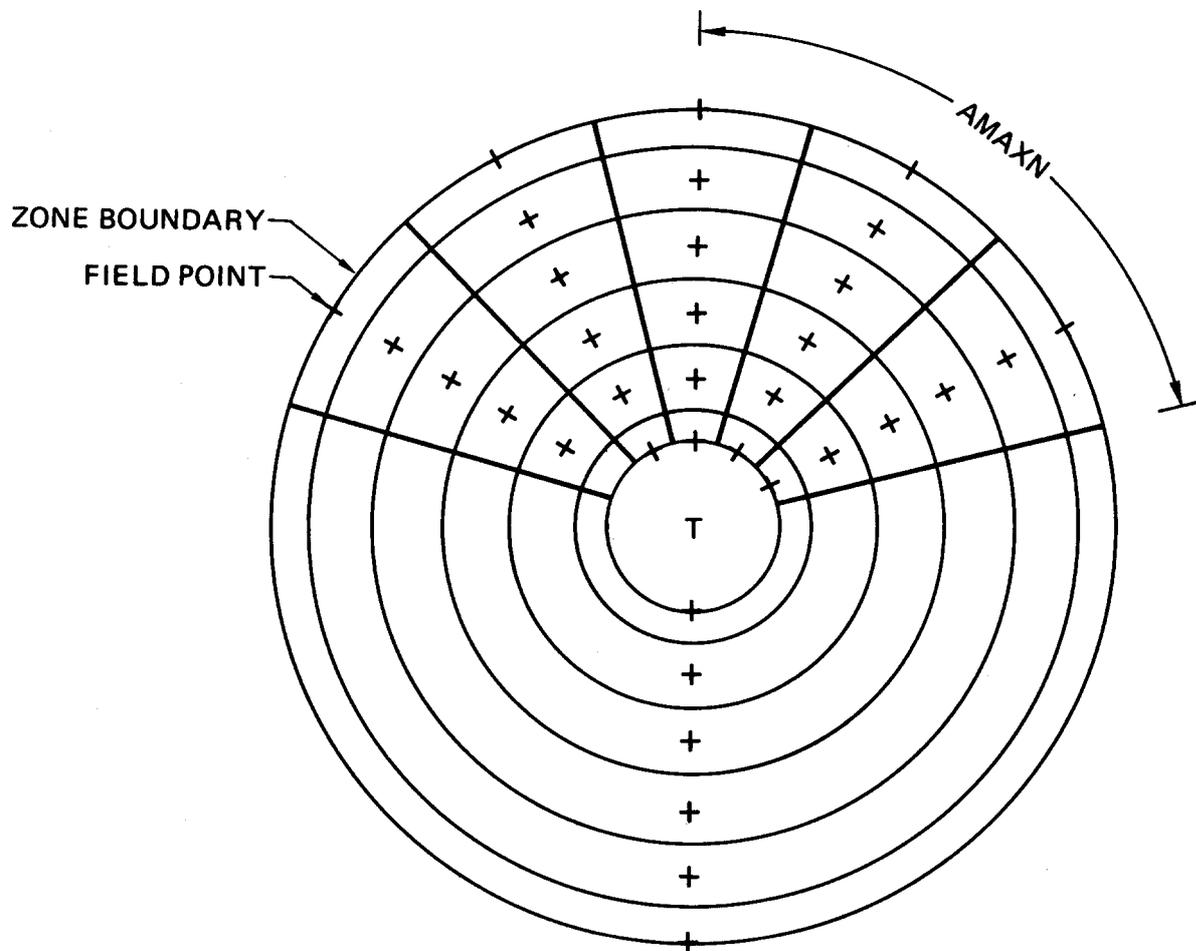


Figure II-5. North-only Field (INORTH=1). Field Points (x's) and Field Zone Boundaries (Solid Lines) for NRAD=6, NAZM=6, AMAXN=75. In actual problems, a larger NAZM and NRAD would probably be used.

NAZM = 12

AMAXN = 82.5°

II.B-2 Field Options—The number of heliostat zones is based on the specifications of NRAD and NAZM. For design and optimization runs, a circular field of zones is required, although the field can be a surround (INORTH=0) or north (INORTH=1) field. In this case, NRAD remains constant around the circumference. For a performance run, it is possible to define a non-circular zonal configuration by specifying IUSERF=1.

Although a heliostat field must be contained within the heliostat zone configuration chosen, the field does not have to occupy every zone. The variable IUSERF (namelist FIELD) in general is used to determine the relationship between the heliostat zone pattern and the actual heliostat field layout that determines field performance, as follows:

a) *IUSERF=0*

The user specifies RADMIN, RADMAX, NRAD, NAZM, and INORTH. No field boundaries are provided with this option, so the field boundaries are assumed to be the zone configuration boundaries. The code calculates and reports only the zone by zone performance for the symmetric grid defined by the five input variables above. Average field performance is meaningless in this case and therefore is not calculated. This option must be used for any initial performance run which will be used later for a field buildup (optimization) run. The best guess receiver and tower dimensions should be specified in conjunction with using this option.

b) *IUSERF=1*

The code defined north biased surround field of Figure II-6 is used. User specifications of the field variables RADMIN, RADMAX, NRAD, NAZM, INORTH, NRADMN, and NRADMX are ignored. That is, the zonal configuration cannot be changed from that of Figure II-6. The layout is typical of fields required for larger industrial or electrical power plants (greater than about 250 MWth or 100 MWe, from Reference 9). Field averaged performance is calculated and reported. This option can only be used for an independent performance run in which the field is defined by the user with the variables DENSIT, AZMSEP, and FLAND. This option should not be used during a performance rerun of a system which has been previously optimized by DELSOL. The best guess receiver and tower dimensions should be specified in conjunction with using this option.

c) *IUSERF=2*

This option allows the user to define a field zone by zone. The field definition can be specified directly by the user in a performance calculation or can be obtained from the results of a DELSOL optimization during a performance rerun.

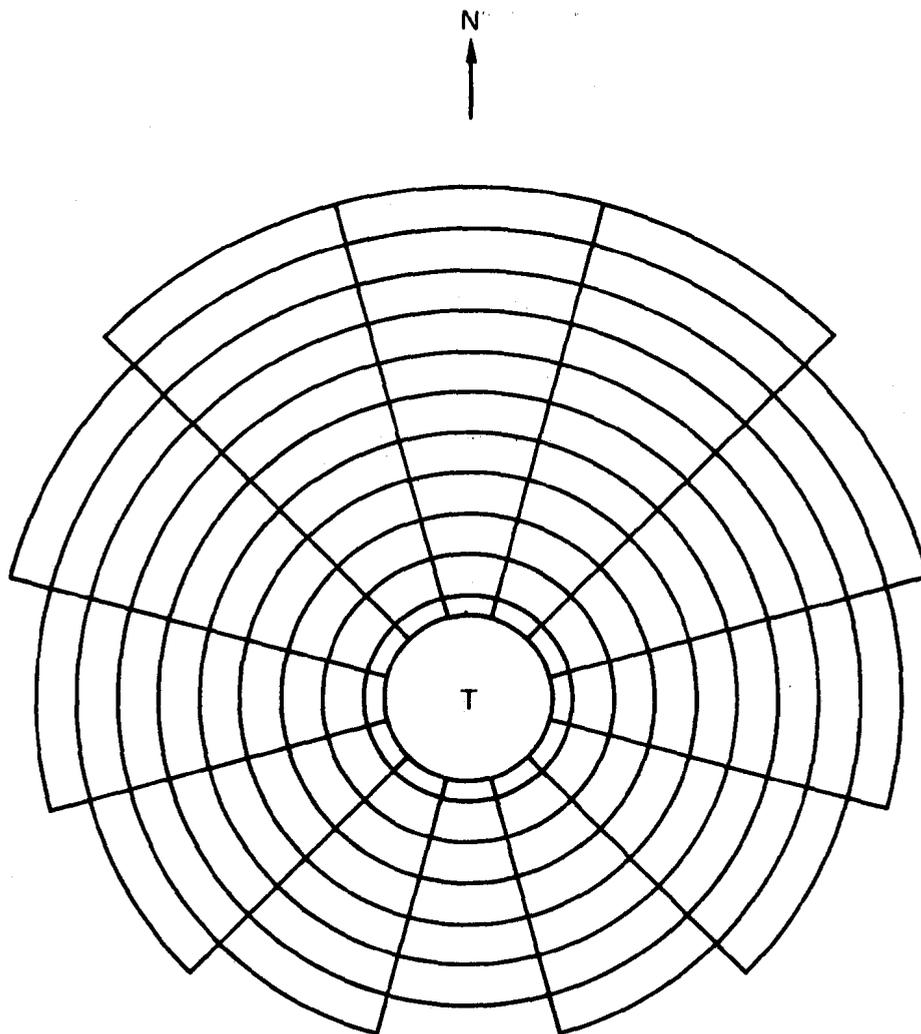


Figure II-6. Code Defined Field (IUSERF = 1). RADMIN = 0.80; RADMAX = 7.15; NAZM = 12; NRAD = 11. Letting I = 1, NAZM, boundaries are defined as follows:

<u>I</u>	<u>NRADMN(I)</u>	<u>NRADMX(I)</u>
1,2,12	1	11
3,11	1	10
4,10	1	9
5,9	1	8
6,8	1	7
7	1	6

To directly specify such a field, the following variables must be defined: (1) RADMIN, RADMAX, NRAD, NAZM, INORTH, and AMAXN, to set up the zoning; and (2) NRADMN, NRADMX, DENSIT, AZMSEP, and FLAND, to characterize the field zone by zone. In addition, for a performance calculation on a system optimized by DELSOL (where the results were saved on a file by specifying IO-TAPE=1 in namelist OPT), all of the above variables can be read from the file by specifying ITAPE=3. In this case, IUSERF=2 will be the code default, and should not be set by the user to any other value.

For the Lth azimuthal zone ($L=1$, NAZM) as numbered in Figure II-4, all radial zones are occupied from the minimum radial zone number, NRADMN(L), through the maximum radial zone number, NRADMX(L). If no zones are occupied in the Lth azimuthal zone, then NRADMN(L)=NRADMX(L)=0. The radial/azimuthal zone boundaries may not exactly match the boundaries of the user's field. The FLAND array can be used to trim the DELSOL zoning. If there is a land constraint, FLAND will be calculated automatically by DELSOL. In the absence of a land constraint, the user may specify FLAND. For the (K,L) zone, FLAND(K,L) is the fraction of the land area in the (K,L) zone that is occupied by the heliostat field. If the whole zone is occupied, FLAND(K,L)=1.0; if half the zone is occupied, FLAND(K,L)=0.5, etc. Field averaged performance is calculated and reported using this option. This option cannot be used for any initial performance run which will be used later for a field buildup (optimization) run.

d) IUSERF=3

This option allows the user to specify the x and y (east and north) coordinates of the base of every heliostat relative to the tower base. For the performance at a single time (IPROB=2, namelist BASIC), an asymmetrical heliostat field can be used. However, in order to calculate daily or annual performances the field must be symmetric about the N-S axis.

A special convention is used to group and number the heliostats. The heliostats are grouped into "rows" as illustrated in Figure II-7. In a field that surrounds the receiver the rows will usually be completely or partially filled circles. In a north-only field the rows will be arcs or lines. The rows do not intersect. The rows are numbered starting with the row nearest the tower and proceeding outward. Within each row the heliostats are numbered starting with the heliostat on the N/S line or just east of the N/S line. The numbering increases in a clockwise manner around the tower. Note that for a line or arc of heliostats (see row 4 in Figure II-7) the number starts in the middle, proceeds to the eastern edge, goes to the western edge and then heads to the middle again. The code considers the shading and blocking by only those heliostats within \pm two rows of the row in which the heliostat of interest is located.

For any of the options described above, the number of zones and hence the accuracy increases as NRAD and NAZM increase. The tradeoff is that computing time and cost will also increase. The variation in execution time is approximately linear with the number of zones, while the increase in accuracy with the number

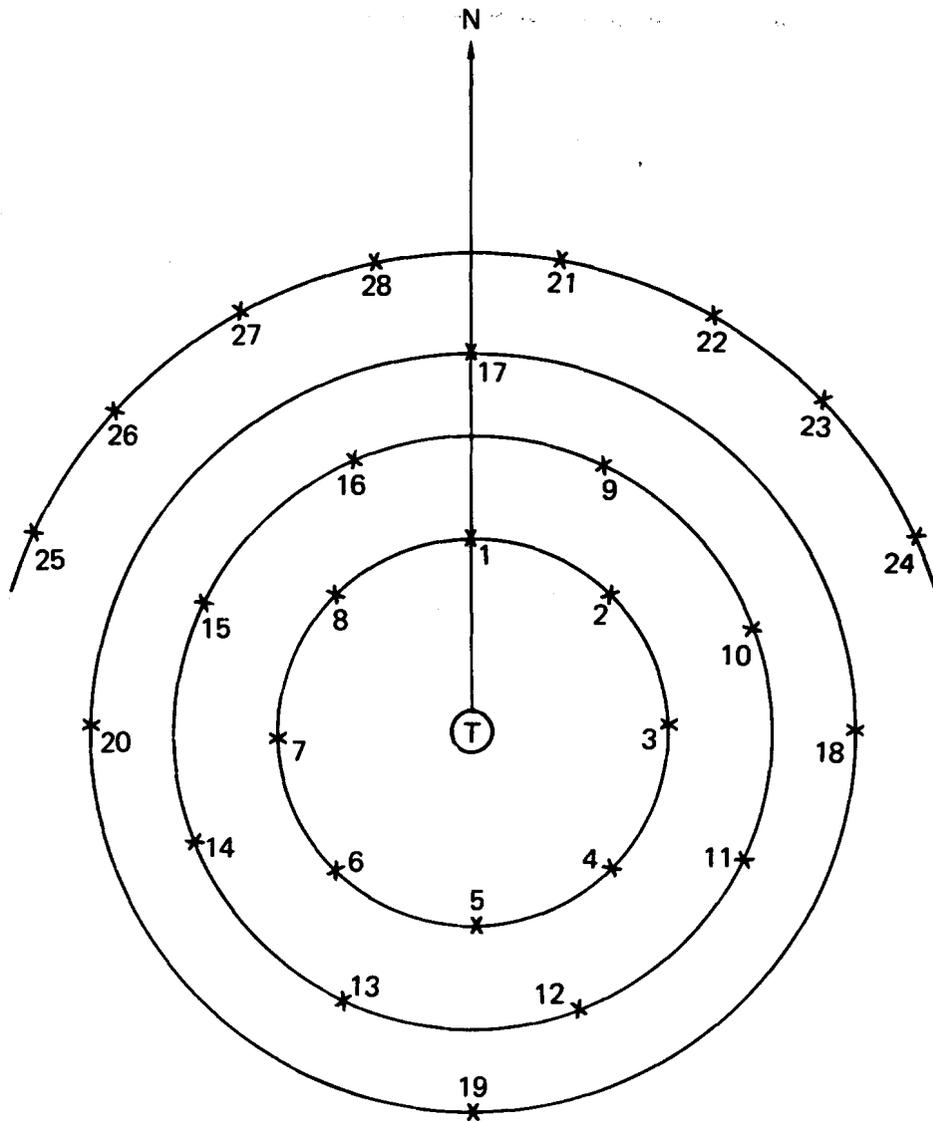


Figure II-7. Schematic Diagram of Heliostat Numbering and "Rows" in an Individual Heliostat Field (IUSERF=3, Namelist FIELD)

Row 1: Heliostats	1- 8
2	9-16
3	17-20
4	21-28

of zones follows a "law of diminishing returns." The default values offer a good compromise:

$$\text{NRAD} = 12$$

$$\text{INORTH} = 0$$

$$\text{NAZM} = 12$$

$$\text{AMAXN} = 82.5$$

The default field option is IUSERF=0 for an initial performance calculation and IUSERF=2 for a performance rerun where ITAPE=3. The default field limits encompass most designs:

$$\text{RADMIN} = 0.75$$

$$\text{RADMAX} = 7.5$$

II.B-3. Rotating Fields—DELSOL can analyze central receiver systems that rotate (IROTFL \neq 0). The rotation is synchronous with the azimuthal motion of the sun. An observer rotating with the field will only see the sun move vertically in one dimension. There is no apparent azimuthal motion of the sun. DELSOL also assumes that the receiver is in synchronous rotation. When using rotating fields, the azimuthal angle of the sun (when viewed from the field) always appears to be due south. (Note: In optimizing rotating field systems, DELSOL does not include the cost of the extra land required to allow the field to rotate.)

II.B-4. Land Constrained Heliostat Field—DELSOL allows the user to subject the heliostat field (not including the tower) to an existing land constraint. If NLAND \geq 0 (namelist FIELD for performance calculations; namelist OPT for design optimizations), then all heliostats must be within one of NLAND user defined rectangles. The rectangles can have arbitrary size, displacement, and orientation and may or may not overlap, as illustrated in Figure II-8. The center of the Ith rectangle is CLE(I) meters east and CLN(I) meters north of the first rectangle; therefore, CLE(1)=CLN(1)=0. ALP(I) is the angle, in degrees, that the sides of the Ith rectangle are rotated from the N-S and E-W axes. ALP(I) is positive for a clockwise rotation view from above. SLNS(I) and SLEW(I) are the length, in meters, of the sides of the Ith rectangle, which, prior to rotation by ALP(I), were parallel to the N-S and E-W axes, respectively.

In a land constrained field it is necessary to specify the location of the tower. In performance calculations a single tower position is considered. The center of the tower is YTOWER meters north and XTOWER meters east of the center of the first land constraint rectangle. In design optimization calculations DELSOL can search to find the optimum tower location. DELSOL considers NUMPOS equally spaced tower locations along a line from a first tower position of XTPST meters east, YTPST meters north to a final tower position XTPEND meters east, YTPEND meters north.

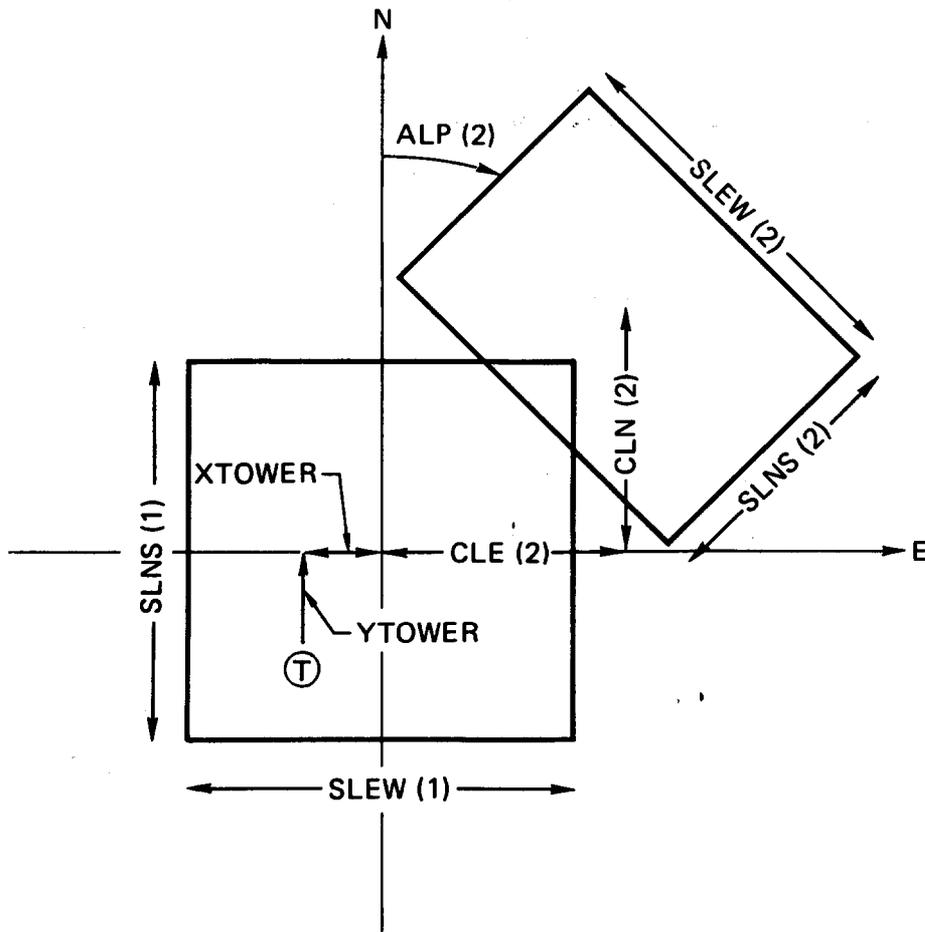


Figure II-8. Example of a Land Constraint with NLAND=2. T is the tower location. In a design optimization run, several T positions along a line can be searched to find the optimum position.

II.C. Heliostat Pattern and Density

It is assumed that the heliostats are arranged in the radial stagger pattern illustrated in Figure II-9. They lie on isoazimuthal and isoradial lines. The local heliostat density, ρ , (i.e., the ratio of mirror area to land area) is related to the local row spacing, ΔR , and azimuthal spacing, ΔAz , by the equation:

$$\rho = \text{DENSMR} \times \text{WM} \times \text{HM} \times \text{ROUND} / (\Delta R \Delta AZ / 2) \quad (\text{II.C} - 1)$$

where DENSMR = fraction of mirror area of a heliostat whose overall dimensions are WM \times HM

WM = heliostat width (meters)

HM = heliostat height (meters)

$$\text{ROUND} = \begin{cases} 1.0 & \text{rectangular heliostats} \\ \pi/4 & \text{circular heliostats} \end{cases}$$

ΔR = radial distance between heliostat centers (note that because of the stagger arrangement of heliostats, this distance is twice the distance between rows of heliostats) (meters)

ΔAz = azimuthal distance between heliostat centers at a given radial distance from the tower (meters)

The choice of heliostat density is indicated by the value of the variable IDENS. For IDENS = 1, 2, or 4, the values of ΔR and ΔAz are curve fits to optimized field layouts reported by the University of Houston (References 4, 9, 10, and 11), with a correction factor dependent on tower height for applications to small systems (IDENS = 1 or 2).

a) IDENS = 1 High reflectivity (~ 0.9), rectangular heliostats

$$\Delta R = (1.14424 \cot \theta_L - 1.0935 + 3.0684 \theta_L - 1.1256 \theta_L^2) \text{HM} \quad (\text{II.C} - 2)$$

$$\Delta Az = \left(1.7491 + 0.6396 \theta_L + \frac{0.02873}{\theta_L - 0.04902} \right) \text{WM} \frac{2 \times \text{RADIUS}}{2 \times \text{RADIUS} - \text{HM} \times \Delta R} \text{K(THT)} \quad (\text{II.C} - 3)$$

where $\text{K(THT)} = \left(1 - \frac{\text{HM} \times \Delta R}{2 \times \text{THT} \times \text{RADIUS}} \right)^{-1}$
and $\theta_L = \frac{\pi}{2} - \theta_t$ (see Figure II-2). RADIUS (in meters) is the radius from the tower base and HM is the height of the heliostat (in meters).

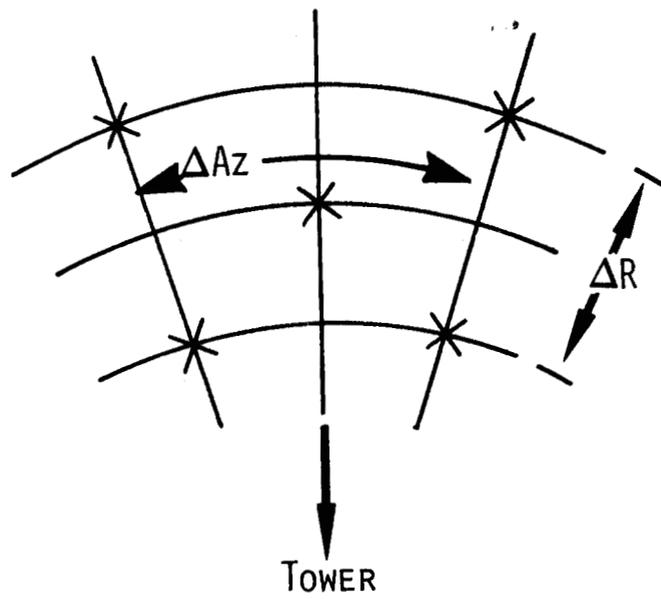


Figure II-9. Radial Stagger Arrangement of Heliostats. x's mark individual heliostat locations.

b) IDENS = 2 Low reflectivity (~ 0.6), round heliostats

ΔR same as in equation (II.C-2)

$$\Delta A_z = \left(1.6097 + 0.2966\theta_L + \frac{0.01914}{\theta_L - 0.01234} \right) WM \frac{2 \times \text{RADIUS}}{2 \times \text{RADIUS} - \text{HM} \times \Delta R} K(\text{THT}) \quad (\text{II.C} - 4)$$

c) IDENS = 3 User defined, zone by zone

ρ is specified by DENSIT(K,L), and $\Delta A_z/2$ by AZMSEP(K,L) in the namelist FIELD.

d) IDENS = 4 As defined in Reference 11, which uses 1984 cost values, this option is based on results using an updated parameterization of shading and blocking data. A distinction is made between north-facing cavities and external receivers.

For cavity receivers,

$$\begin{aligned} \Delta R/\text{HM} = & (62.324 + 0.63E + (3.151 + 0.65E)\cos\phi)\theta^{-1} \\ & - (0.5375 + 0.085E + (0.1984 + 0.065E)\cos\phi) \\ & + (2.253 + 0.21E + (0.842 + 0.16E)\cos\phi)\theta/100 \end{aligned} \quad (\text{II.C} - 5)$$

$$\begin{aligned} \Delta A_z/\text{WM} = & 2.16597 - 0.01E - 0.10273\cos\phi \\ & + (0.4965 + 3.3247\cos\phi)\theta/100 \\ & - (3.3815 + 11.1843\cos\phi)(\theta/100)^2 \end{aligned} \quad (\text{II.C} - 6)$$

For external receivers,

$$\begin{aligned} \Delta R/\text{HM} = & 63.0093 - 0.587313\theta + 0.018423909\theta^2 \\ & + \cos\phi(2.808733 - 0.1480498\theta + 0.001489201\theta^2) \end{aligned} \quad (\text{II.C} - 7)$$

$$\begin{aligned} \Delta A_z/\text{WM} = & 2.46812 - 0.0401054\theta + 0.000923594\theta^2 \\ & + \cos\phi(0.17344593 - 0.009112590\theta + 0.00012761\theta^2) \end{aligned} \quad (\text{II.C} - 8)$$

where $E = (\text{thermal design power in MW})/100$
 $\phi = \text{heliostat azimuth angle, } 0^\circ \text{ is south}$
 $\theta = \text{receiver elevation angle from heliostat in degrees}$

Note that when IDENS=1 or 2 the azimuthal spacing and, therefore, the density depend on the tower height, THT.

The ΔR and ΔAz spacings from the above equations are tested to insure that the mechanical limits on adjacent heliostats are not exceeded; i.e., that adjacent heliostats will not hit each other in any combination of orientations. If the mechanical limits are violated, the azimuthal spacing is adjusted to accommodate the full exclusion circle of the heliostat.

Sections IV.B-2 and IV.B-3 discuss in depth the process and result of optimizing heliostat densities using one of the above sets of relationships as a starting point. By specifying the variable IHOPT=1 (namelist OPT) and also specifying the variables DHOPT (namelist BASIC), heliostat density optimization for a constant annual energy can be requested. Essentially, the values of ΔR and ΔAz are varied within limits to determine if a better field density can be obtained, based on cost. Since this is an optimization for a constant annual energy, which varies from system to system and which is not directly related to the user-specified design point power, a system with an optimized heliostat density may have a higher levelized energy cost for a fixed design point power than a comparable system without optimized densities. This is discussed further in Section IV.B-3.

II.C-1. Slip Planes—The individual placement of heliostats in a radial layout pattern given only the zone average ΔR and ΔAz leads to a complication as one moves radially inward from the center of the zone. Heliostats on successive rows become more compressed until they incur an unacceptable increase in shading and blocking (or reach mechanical limits for the zones close to the tower). The problem can be alleviated by removing a fixed fraction ($1-1/FSLIP$) of the heliostats in the unacceptably compressed row and by restarting the layout pattern based on the new number of heliostats in the row. Figure II-10 illustrates this interruption in the layout pattern for the default slip ($FSLIP=1.33$); the circular row at which the adjustment is made is called the "slip plane" in analogy with discontinuities in crystal structures. The number of rows between slip planes increases as the radius increases and as the tower height increases. (See Reference 12 for additional discussion on slip planes.)

DELSOL calculates a zone by zone correction to account for the heliostat number change at a slip plane. The user specifies the slip ratio, FSLIP in namelist FIELD, to be the number of heliostats present on the slip plane row before any are removed divided by the number remaining after removal. The default value for FSLIP ($4/3$) is a satisfactory one for most intermediate to small systems. By choosing a value of $FSLIP=1$, the user effectively eliminates the slip plane correction in the code.

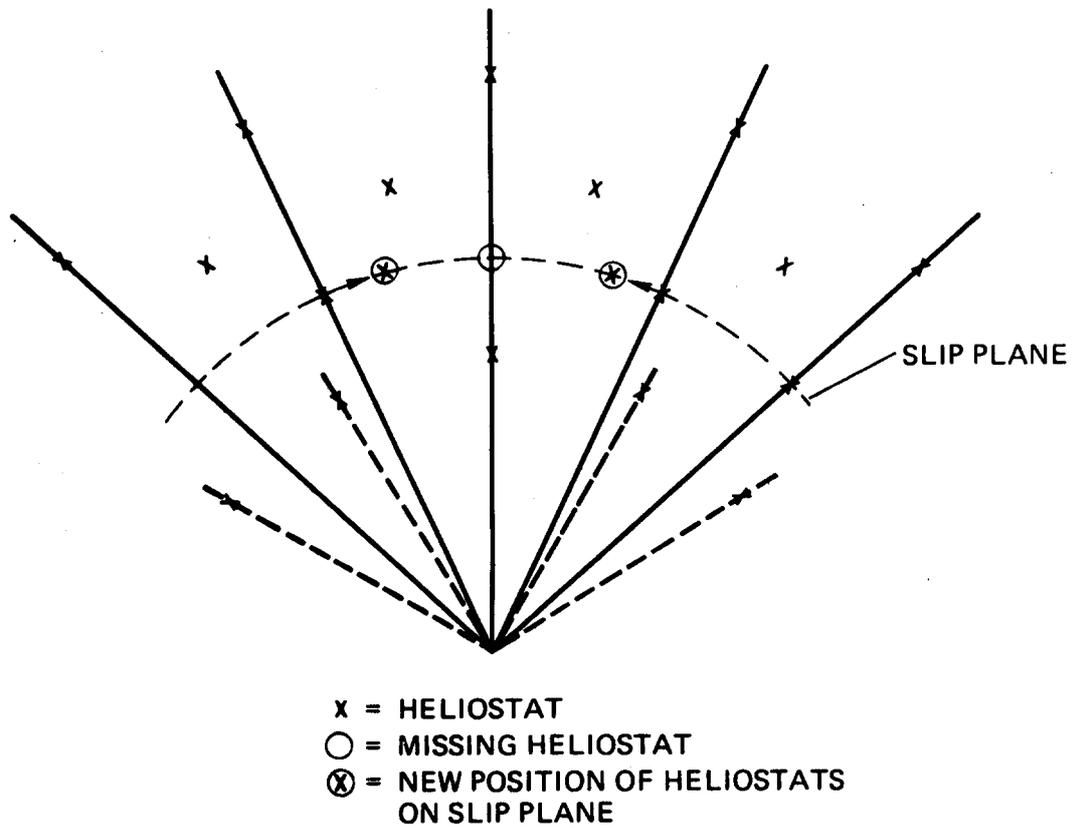


Figure II-10. Slip Planes in a Radial Stagger Layout (FSLIP=4/3)

II.D. Heliostats

Either rectangular (IROUND=0) or circular (IROUND=1) mirror shapes (Figure II-11(A) and (B)) can be accommodated by the code. The overall dimensions of the heliostat, WM and HM, enclose the mirrored surface, the edge supports, and cutouts or slots, if any. The fraction of the area defined by WM and HM which actually reflects sunlight is specified by the parameter DENSMR. The user has the option of generating more accurate images from canted heliostats by specifying the size and location of the cant panels (ICPANL=1, namelist HSTAT) rather than letting DELSOL specify based on NCANTX, NCANTY, HM, and WM. This option is highly recommended in small systems. The width and height of the reflective surface of each cant panel are WPANL and HPANL meters, respectively (Figure II-11(C)). The center of the Ith cant panel is displaced from the pivot point (center of the heliostat) by HXCANT(I) meters parallel to the horizontal edge of the heliostat and HYCANT(I) meters parallel to the vertical edge of the heliostat.

The reflectivity, given by the value of RMIRL, represents the time averaged value and not the value just after washing. RMIRL should also include transmission losses due to any enclosure surrounding the heliostat. (See also Section III.G-2.)

The heliostats are assumed to have altitude-azimuth drive systems pivoted at the center of the mirrored surface. Therefore, the geometrical center of a heliostat is also the center of rotation of the mirrored surface.

II.D-1. Heliostat Error Sources—The performance of heliostats is degraded by several error sources. Care must be taken with the input of these terms because different reports often use different descriptions for the same errors. Specifically, a distinction must be made between an error source (e.g., backlash in the azimuthal motor drive) and the effect of the error source (i.e., the magnitude of the displacement and/or distortion of the heliostat image on the receivers). The latter, the effect of the error source, depends on the geometry between the sun, heliostat, and receiver. Thus, a heliostat with a constant error source will provide variable effects on the image at different times of the year for the same field position, or at different field positions for the same time of the year, due to the changing relative positions of the sun and receiver.

Consider the example of the effect of a constant backlash error in the azimuthal drive in otherwise perfect heliostats. At noon on any given day of the year, a heliostat located due north of the tower will produce a larger displacement of the image on the receiver than its counterpart at the same distance due south. In fact, as heliostats in the south field approach a horizontal orientation (i.e., mirror normal \hat{n} vertical), errors in the azimuthal drive produce no displacement in the image on the receiver.

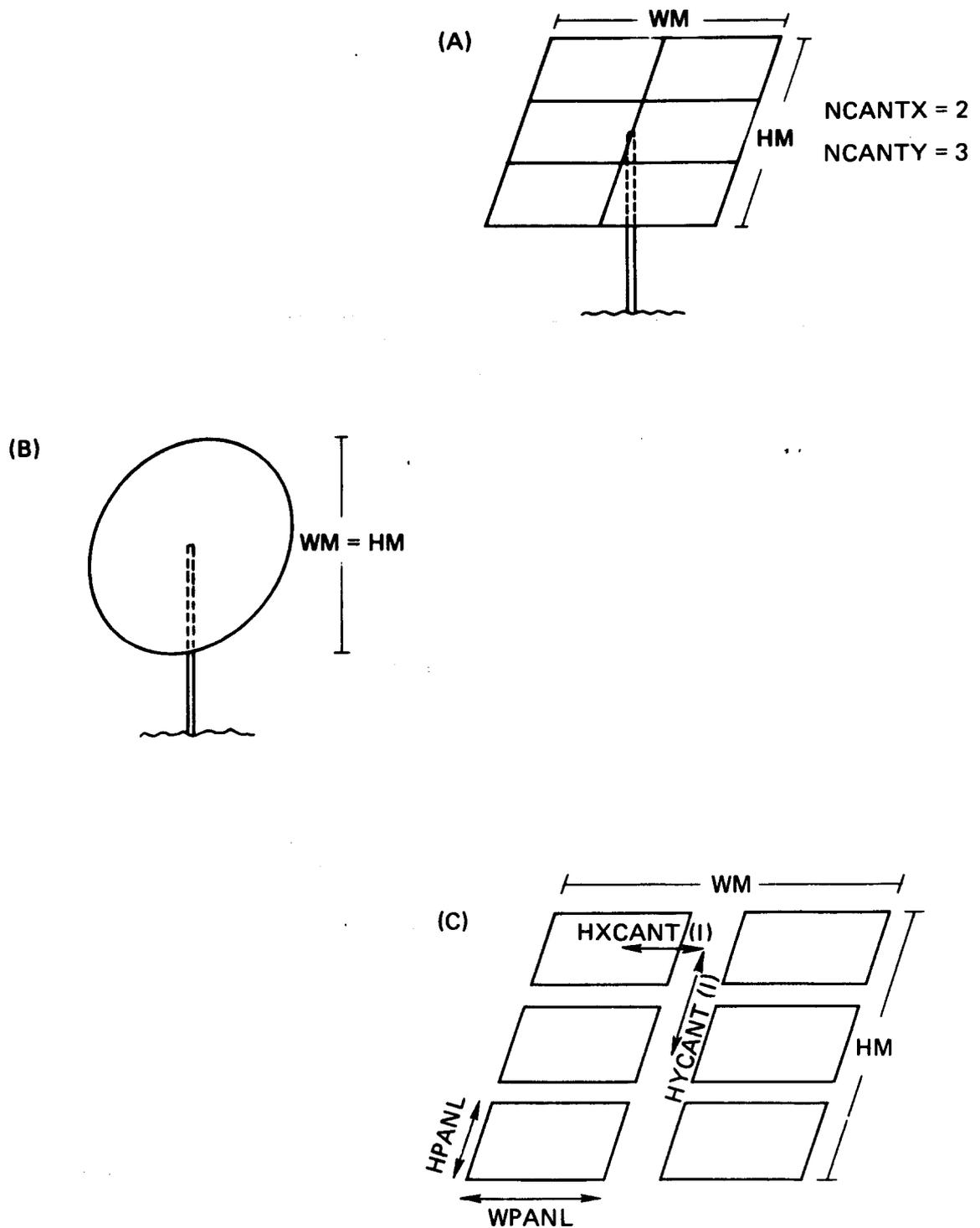


Figure II-11. Types of Heliostats. (A) Canted, rectangular heliostat with 2 cant divisions along the width and 3 along the height; (B) Circular heliostat with $WM=HM=diameter$; (C) Canted heliostat defined for more accurate image calculation ($ICPANL=1$)

Given that heliostats will be mass produced and assembled, it is assumed in DELSOL that the error sources are essentially the same for each heliostat regardless of field location. Hence, the user supplies as input the magnitude of the sources of error (e.g., motor inaccuracies, surface distortions), and the code calculates the time and field dependent effects of these sources. (This is identical to the approach in MIRVAL and HELIOS (References 1, 2, 5).)

The sources of heliostat errors can be grouped into three types according to the variable used to describe the error distribution. Each type produces different qualitative and quantitative effects on the position and profile of the heliostat image. The code assumes that the errors have normal probability distributions characterized by standard deviations in two perpendicular directions. The three error groups, typical sources, and the coordinate systems in which they are defined are listed in Table II-2. The default values are also included, and are consistent with a fairly accurate, high reflectivity mirror such as a Second Generation Heliostat (Reference 13).

II.D-2. Focusing and Canting—The finite size of the sun, the heliostat performance errors, and the size of the heliostat all determine the size of the image produced by a heliostat on the receiver, as illustrated in Figure II-12(A). Reducing the contribution of the heliostat size can lead to a smaller image size, and in turn, lower spillage, smaller receivers, and lower receiver radiation and convection losses. DELSOL simulates the two methods, focusing and canting, employed to reduce image size by decreasing the contribution from heliostat size.

In focusing, the mirror panels are concave in a manner so that rays from the center of the sun reflected from any point on the mirror panel hit the same point on the receiver, as shown in Figure II-12(B). A canted heliostat is divided into a number of submirrors. Each submirror is displaced relative to the others so that rays from the center of the sun reflected from analogous points of the submirrors all converge to the same point on the receiver, as indicated in Figure II-12(C). Thus, perfect focusing results in the minimum size image by eliminating the contribution of the heliostat size to the reflected image. Perfect canting approximates perfect focusing by reducing the total heliostat size to that of a single submirror. The greater the number of canted submirrors for a given size heliostat, the smaller the contribution of heliostat size to the image. In other words, canting is a Fresnel approximation to focusing. (Note also that the submirrors of a canted heliostat can each be focused in 0 to 2 dimensions.)

The curvature or displacement required for focusing or canting depends on the angles between the heliostat, sun, and receiver, and is therefore time dependent. For most heliostat designs the curvature cannot be varied, and the heliostat will be perfectly focused or canted for only the one or two times of the year when the sun is in the correct position. At all other times, the heliostat will produce "off-axis aberration" of the image; i.e., distortions of the ideal image due to operation when the sun is not in the correct position for the heliostat to be perfectly focused or canted.

TABLE II-2
HELIOSTAT ERROR SOURCES

Type	Error Distribution*	Typical Sources		Default Values (rad)
Heliostat angles	θ_n, β_n	Tracking errors in open-loop drive systems	σ_{θ_n}	(SIGEL) = 0.00075
		Foundation motion	σ_{β_n}	(SIGAZ) = 0.00000*
Surface normal	x_n, y_n	Mirror waviness	σ_{x_n}	(SIGSX) = 0.001
		Panel alignment errors	σ_{y_n}	(SIGSY) = 0.000*
Reflected vector	x, y	Tracking errors in closed-loop drive systems	σ_x	(SIGTX) = 0.000
		Atmospheric refraction	σ_y	(SIGTY) = 0.000
		Tower sway		

*Each distribution is of the form:

$$P(da, db) = (2\pi \sigma_a \sigma_b)^{-1} \exp \left(-\frac{1}{2} \left(\frac{da}{\sigma_a}\right)^2 - \frac{1}{2} \left(\frac{db}{\sigma_b}\right)^2 \right)$$

where a,b = variable pair defined above,

P = probability of displacements, da and db, from the nominal values of a and b.

*These values are the defaults in DELSOL3 and were used to generate the sample problems. However, a better choice of values would be SIGEL = SIGAZ = 0.00075 and SIGSX = SIGSY = 0.001. The user can either change these defaults in their version of DELSOL3 or input these values in the input for each run of DELSOL3.

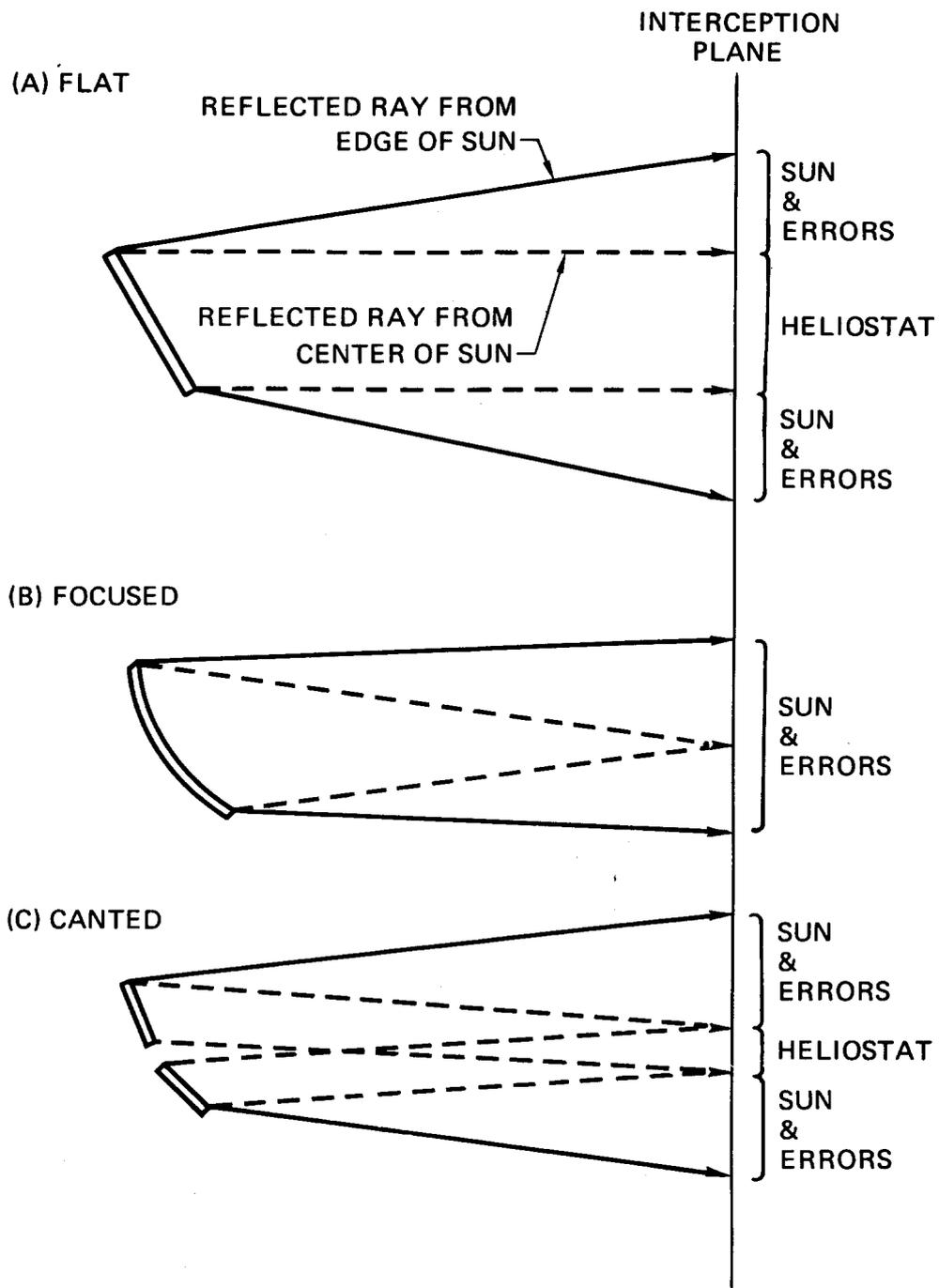


Figure II-12. Schematic of Images Formed by (A) Flat, (B) Focused, and (C) Canted Heliostats

The most common choice for the curvature of a rigid heliostat is a symmetrical "on-axis" focusing or cant. In this case, the heliostat is perfectly focused or canted at a point along the heliostat optical axis, \hat{n} , when the sun is positioned along \hat{n} , (i.e., $\hat{n} = \hat{s}$ in Figure II-1). When the sun is in other positions ($\hat{n} \neq \hat{s}$), there will be off-axis aberrations.

A second possibility is an asymmetric curvature such that the heliostat is perfectly focused or canted for a specific sun position (defined by the HCANT hour past noon on the DCANT day of the year). In this case the relative positions of the sun, heliostat, and receiver are important because, in general, the focal point will not lie along \hat{n} . This "off-axis" cant or focus results in off-axis aberrations when the sun position differs from that specified by (HCANT, DCANT).

On a yearly average, off-axis aberrations are less with an on-axis than off-axis cant or focus. Moreover, the symmetry of the on-axis cant or focus allows for a simpler manufacturing procedure. However, at the time specified by (HCANT, DCANT), an off-axis cant or focus produces a smaller image and higher flux density. This may be useful in test facilities where the number of heliostats is small, and periodic readjustment of their canting or focusing is possible. DELSOL allows both on-axis and off-axis canting but only on-axis focusing.

For canting, several options are available according to the choice of the parameters ICANT, NCANTX, and NCANTY. There are NCANTX \times NCANTY equally sized submirrors per heliostat with NCANTX (NCANTY) submirrors along the \hat{i}_n (\hat{j}_n) edge of the heliostat, as shown in Figure II-11(A). The larger NCANTX and NCANTY, the more closely a canted heliostat approximates a focused heliostat. Uncanted heliostats are specified by ICANT=0 and have only one sub-mirror equal to the heliostat itself; therefore, NCANTX=NCANTY=1. Fields in which each heliostat is individually canted off-axis on the HCANT hour past noon and the DCANT day of the year (default is solar noon, equinox, March 21) are specified by ICANT=3. A heliostat field in which every heliostat is focused "on-axis" with a focal length equal to its slant range is specified by the parameter ICANT=-1. Finally, fields in which heliostats have "on-axis" canting with user defined focal lengths (= RCANT(K) tower heights) are specified by ICANT=1. (This option can be used to produce a single cant for the whole field.)

Independent of canting, the mirror or submirrors can be focused in 0 to 2 dimensions. If the mirror is curved along the \hat{i}_n (\hat{j}_n) direction then the parameter XFOCUS=1.0 (YFOCUS=1.0). Thus, no focusing is specified by XFOCUS=0.0, YFOCUS=0.0. One dimensional focusing is specified by XFOCUS=1.0, YFOCUS=0.0, or XFOCUS=0.0, YFOCUS=1.0; 2-d focusing is specified by XFOCUS=1.0, YFOCUS=1.0. The parameter IFOCUS determines the specification of the focal lengths. DELSOL automatically sets the focal length equal to the slant range when IFOCUS=0. User defined focal lengths, XFOCAL and YFOCAL, can be specified when IFOCUS=1.

II.D-3. Default Heliostat—The default heliostat is a high reflectivity square advanced design with a single cant and focus, as defined below:

IROUND = 0	ICANT = 1
WM = 9.91 (m)	NCANTX = 2
HM = 9.93 (m)	NCANTY = 8
DENSMR = 0.970	RCANT = 12*6.00
RMIRL = 0.91	XFOCUS = YFOCUS = 1.0
SIGAZ = 0.0*	IFOCUS = 1
SIGEL = 0.00075	XFOCAL = YFOCAL = 12*6.00
SIGSX = 0.0010	
SIGSY = SIGTX = SIGTY = 0.0*	*See note on page 47.

II.E. Tower and Receiver

DELSOL considers three types of receivers as illustrated in Figure II-13: external cylinders, multiple aperture cavities, and multiple flat plates. Flat plate receivers are specified in the same manner as cavity receivers. The optical tower height, THT, is defined as the elevation of the middle of the external receiver, cavity aperture, or flat plate above the pivot point of the heliostat. To get the height above ground, the elevation above ground of the pivot point must be added to THT. The optical tower height is used in all DELSOL calculations except the tower capital cost calculation, which uses the height from the ground to the bottom of a transition region between the tower and the receiver. Component costing, including a description of the transition region, is discussed in Section V.A-4. All references in DELSOL outputs to tower height refer to the optical tower height, THT.

The size of external cylindrical receivers (IREC=0) is specified by the height, H, and width or diameter, W. The apertures on cavity receivers are specified by giving their dimensions, orientation, and displacement from the tower centerline. For rectangular apertures (IREC=2), the horizontal edge has a length RX and the perpendicular edge has a length RY. For elliptical apertures (IREC=1), one axis is horizontal with length RX and the other axis has a length RY. The orientation of the apertures is specified by the \hat{r} vector which is the outward surface normal at the center of a surface stretched across the aperture. It is assumed that all apertures are oriented so that an extension of the \hat{r} vectors will go through the tower centerline at the same point. (See Figure II-2.) θ_r (RELV) is the polar angle of \hat{r} ; it equals 90° if the cavity aperture is vertical and is greater than 90° if the cavity faces downward. β_r (RAZM) is the azimuthal angle; $\beta_r = 180^\circ$ if the aperture faces North. The width W of the cavity structure is taken as twice the horizontal distance from the center of the cavity aperture to the tower centerline.

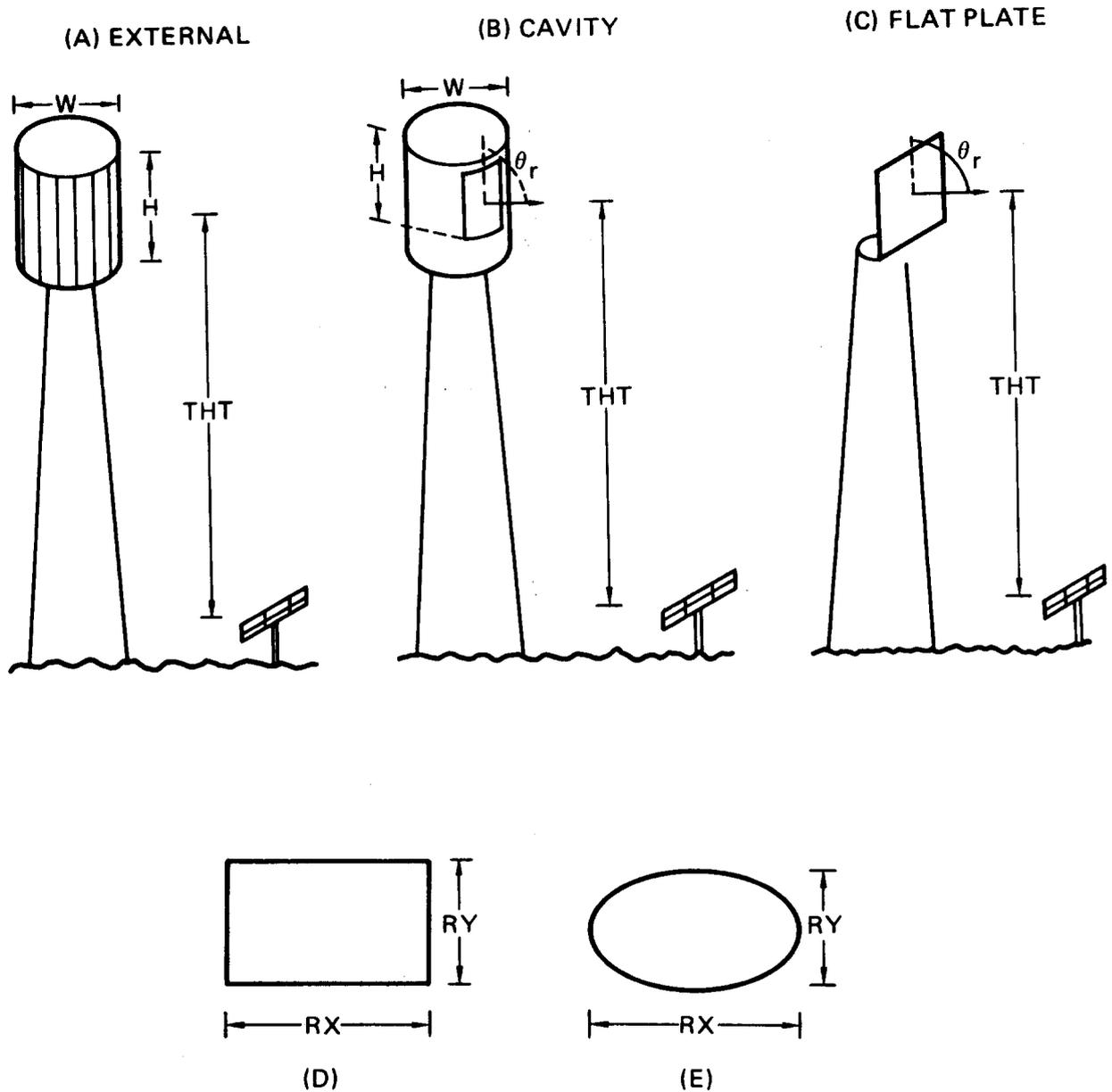


Figure II-13. Types of Receivers. (A) External Cylindrical; (B) Cavity with Single Aperture; (C) Single Flat Plate; (D) Rectangular Aperture or Flat Plate; (E) Elliptical Aperture or Flat Plate

That is, the aperture is always located at a distance of $W/2$ from the tower centerline, regardless of the actual depth of the cavity (defined by $RWCAV(I)$ as described below). In multiple aperture cavities, the same receiver width and tower height apply to all apertures (i.e., a horizontal circle can be passed through the aperture centers). The height H is the total vertical height of the heat absorbing unit in the cavity, as described below. A total of $NUMCAV (\leq 4)$ apertures can be specified. Single or multiple flat plate receivers with rectangular ($IREC=3$) or elliptical ($IREC=4$) shapes are specified in an identical manner to a single or multiple cavity receiver with rectangular or elliptical apertures, that is, using the variables RX and RY to define plate dimensions.

In designing cavity receivers it is necessary to describe the configuration within the cavity only in order to determine the cost, thermal losses, and flux profiles of the receiver. All other calculations are done at the aperture. DELSOL assumes the the inside of the cavity is a section of a vertical cylinder centered horizontally on the aperture as shown in Figure II-14. The relative depth $RWCAV(I)$ of the heat absorbing surface inside the I th aperture is specified as the ratio of the radius of the cavity to the receiver radius, $W/2$. The bottom of the cylindrical heat absorbing surface is chosen so as to intercept all possible images that pass through the aperture from the farthest heliostat in the field. The height of the heat absorbing surface is specified in one of three ways. If the default value of the variable H is used, the heat absorbing surface height will be specified as $1.1 \times RY$ (1.1 times the aperture height). If a different value H is specified, then that value is taken to be the actual height of the heat absorbing surface. However, the height will never be allowed to be larger than that height needed to intercept all of the image that passes through the aperture from the nearest heliostat. Thus, the limiting values of the top and bottom of the heat absorbing surface are a function of the minimum and maximum heliostat positions within the sector of the field seen by the cavity, the aperture height, the orientation of the aperture, the optical tower height, and the depth of the heat absorbing surface. The equations for these limiting conditions are detailed in Section V.A-5.

If a smaller cavity heat absorbing surface height is chosen than the limiting height, this will have three consequences. First, the receiver cost will be smaller, since cost is based on heat absorber area. Second, certain receiver losses are based on heat absorber area, and these losses will also decrease. Finally, although the performance of the receiver will remain constant other than receiver losses since performance is calculated at the aperture, some of the flux that passes through the aperture may now be incident on uncooled parts of the interior of the cavity (i.e., the roof). The designer should verify that this internal spillage does not cause any uncooled surfaces to fail.

II.F. Heliostat Aiming

DELSOL has several options for aiming the heliostats at different points on the receiver. The "smart" aiming options described below ($IAUTOP \neq 0$ or 5) are generally required when trying to design flux-limited receivers. The options are

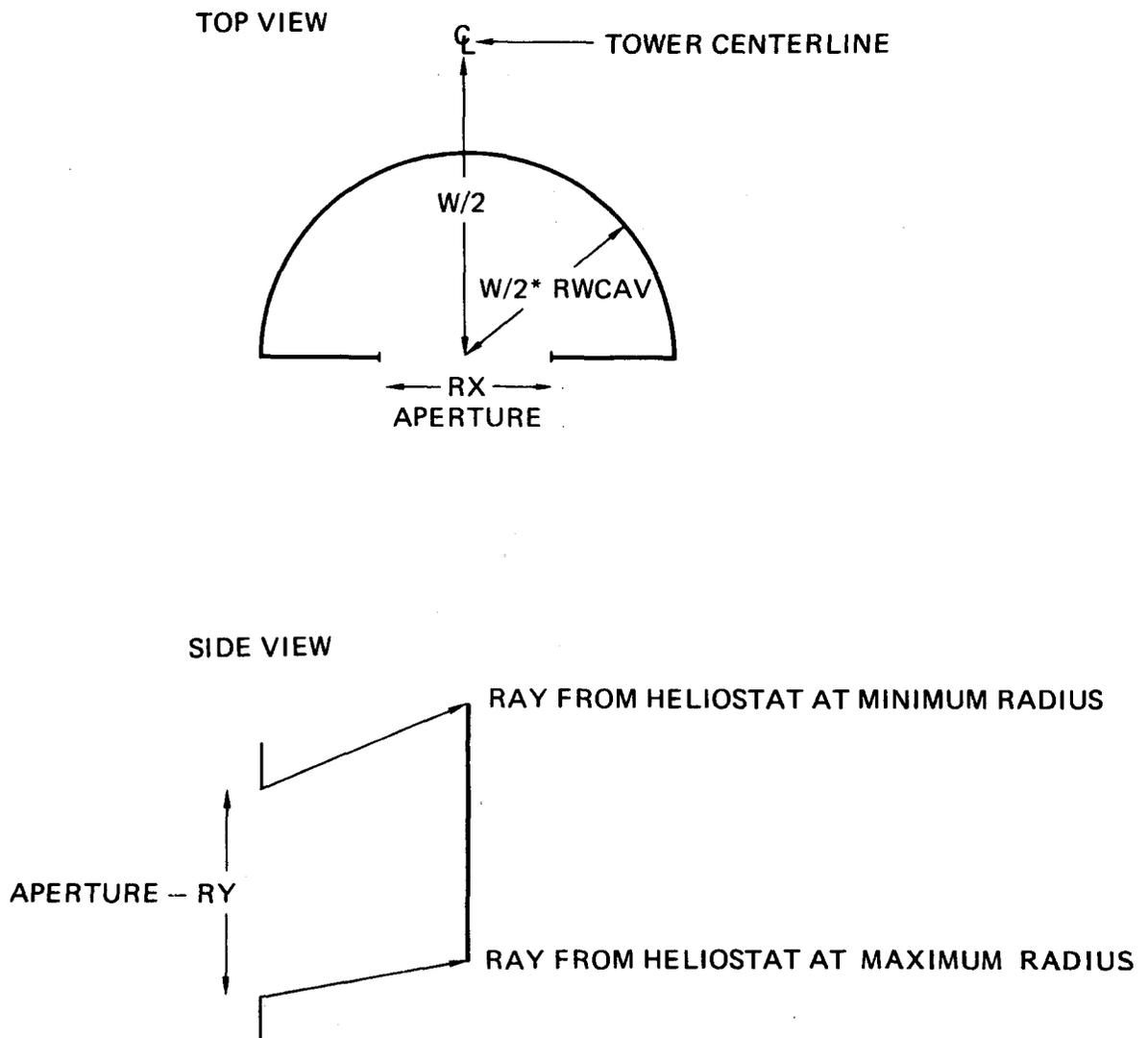


Figure II-14. Heat Absorbing Surface Within a Cavity. It is modeled as a segment of a right circular cylinder centered on the cavity aperture.

controlled by the IAUTOP parameter in namelist REC and are illustrated in Figure II-15. All "smart" aiming options are time dependent; i.e., the number of aim points can change over the year if the image changes.

II.F-1. Single Aim Point (IAUTOP=1)—This is the simplest of all aiming options. All heliostats are pointed at the center (when viewed from the heliostat surface) of the receiver (Figure II-15(A)). This option produces the maximum flux on the receiver.

II.F-2. One-Dimensional "Smart" Aiming (IAUTOP=1)—The heliostat images are spread out along the "height" of the receiver or aperture until the spillage starts to increase. As seen in Figure II-15(B), the smaller images of the inner (or best focused) heliostats can be spread out over more aim points than the larger images of the outer (or less well focused) heliostats. This option reduces both the peak flux and the flux gradients on the receiver. This is the "smart" aiming option to use with external receivers (IREC=0) and with cavity or flat plate receivers of elliptical shape (IREC=1 or 3). Since the size of the images from the heliostats can change with time, the one-dimensional smart aiming also changes with time, so that both the number and position of the aimpoints may change.

II.F-3. Two-Dimensional "Smart" Aiming (Rectangular Cavity Apertures or Flat Plates Only, IAUTOP=2)—This option is similar to IAUTOP=1 except that the images are spread out in two dimensions as shown in Figure II-15(C). This results in even smaller peak fluxes than IAUTOP=1. However, this option should only be used with rectangular cavity apertures (IREC=2) or rectangular flat plates (IREC=4). If used with elliptical receivers the spillage will increase. Furthermore, if used with external cylinders much of the flux will be incident on the receiver at grazing angles where the absorption is poor, and the flux normal to the receiver (as calculated by DELSOL) will not be representative of the actual peak flux that could be incident on a single tube of the receiver.

II.F-4. Single Aim Point at the Lower Part of the Receiver (IAUTOP=3)—The heliostats are aimed as close to the bottom of the receiver as is possible without increasing spillage significantly as shown in Figure II-15(d). The aimpoints will vary somewhat with time as the heliostat image sizes vary, so that spillage remains relatively constant. There are several reasons for considering this strategy. First, if the fluid enters from the bottom of the receiver the peak fluxes will occur near the colder (and presumably stronger) end of the piping. The penalty is increased radiation and convection losses in real life, since the average receiver temperature is increased. However, if the fluid enters from the top of the receiver the radiation and convection losses are minimized, but the peak flux occurs near the hot end of the tube. Typically, peak fluxes will be close to those levels resulting from the single aimpoint strategy (IAUTOP=1).

II.F-5. One-Dimensional Aiming at the Lower Part of the Receiver (IAUTOP=4)—Similar to IAUTOP=3 except that the images are spread out along the bottom of the receiver, as shown in Figure II-15(E). This option should

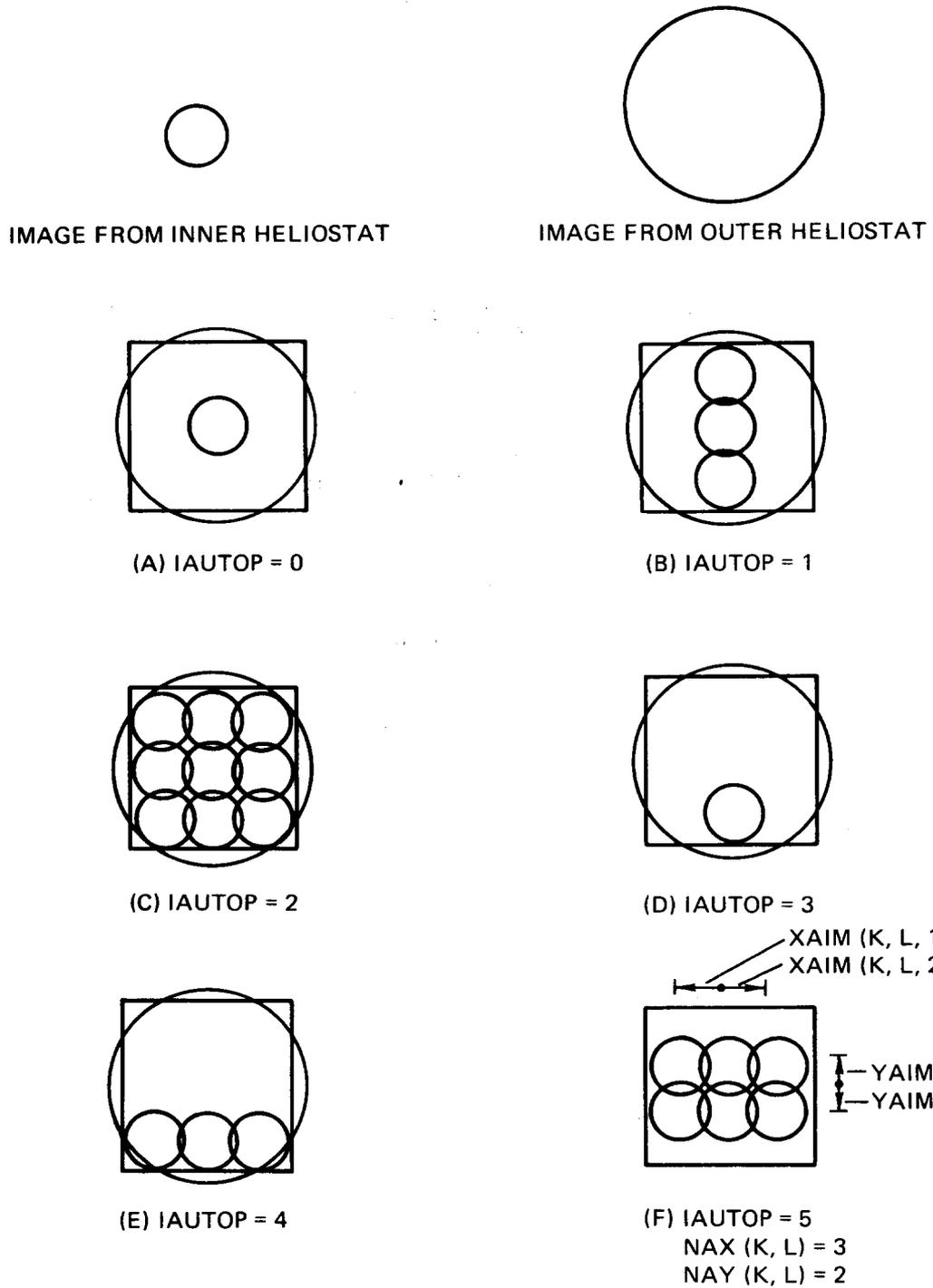


Figure II-15. Aiming Options.

only be used with rectangular cavity apertures (IREC=2) or rectangular flat plates (IREC=4), for the reasons described in Section II.F-3.

II.F-6. User Defined Aiming Strategy (IAUTOP=5)—A user defined aiming strategy can be defined for each zone through the variables NAY(K,L), NAX(K,L), YAIM(K,L,M), XAIM(K,L,M), and NUMPT(K,L) where K=1 to NRAD, L=1 to NAZM, and M=1 to 2. Each zone has a rectangular grid of NAX by NAY points with the grid limits set by XAIM and YAIM. The zone numbers (K,L) are shown in Figure II-4 in their relative field position. Figure II-15(F) gives an example of this case. This aiming strategy is not time dependent; that is, the aimpoints are the same no matter what time of day or year it is, even though image size and thus spillage might change with time.

A sub-option of this case is obtained when IFXOUT(I,J)=-2, where I=1, NYEAR and J=1, 16 to represent time of day (namelist NLFLUX). Only one value of the array IFXOUT should be nonzero. This sub-option allows interactive graphical feedback of the effect of user specified aimpoints for a single zone. For each zone, the code will allow the user to plot the flux map for that zone, plot the cumulative flux map from all zones up to and including that zone, or change the aimpoints of that zone and plot again. Although this sub-option quickly gives the user a feel for the effect of changing aimpoints, it should be used with care when using a large number of heliostat zones, since tedium could result. This sub-option can only be used if the code was loaded along with DISSPLA software (Reference 14), and is only set up to plot on a computer terminal which can emulate a Tektronics 4014 terminal.

II.F-7. Combination "Smart" Aiming (IAUTOP<0)—This option is a combination of the aiming strategies IAUTOP=2 and IAUTOP=4. For this aim strategy, inner heliostats will be aimed at the bottom of the aperture or billboard receiver. However, starting at zones as far out or farther out than -IAUTOP, aimpoints are spread out over the entire aperture or billboard. This option is one method of reducing the internal spillage (flux impinging on uncooled parts of the receiver, such as the roof) in a cavity receiver without exceeding flux limits at the bottom of the heat absorbing area.

II.G. Flux Density Distribution

DELSOL has the option of calculating the flux density on an arbitrary planar or vertical cylindrical surface, when IFLX is set to 1 (namelist NLFLUX). The flux on a complex receiver which is composed of several planar and/or cylindrical surfaces can be mapped by several final performance executions. The flux calculation is done independently from the receiver performance calculation, and only affects the system as a limitation on flux peaks is imposed. Therefore, the flux surface being examined does not have to be on the heat absorbing surface. This is more applicable for cavity receivers, because the heat absorbing surface configuration which is chosen by DELSOL for component costing purposes may not be a realistic configuration. For the same heat absorbing area, different cavity

configurations may give different flux profiles and peak fluxes, as well as different internal spillages.

For cavity receivers, DELSOL tests each flux point to insure that it can be seen through the aperture from the heliostat being calculated (i.e., that the flux point is not shadowed by the outside of the cavity). Flux maps at or in front of the aperture are assumed not to have any aperture shadowing. In addition, for multiple aperture cavities, DELSOL allows the user to specify the aperture(s) through which the reflected sunlight can reach the flux surface (ICAVF, namelist NLFUX). This latter feature can be used to account for the possibility that the flux surface may be blocked by the internal structure of the cavity.

The flux from a heliostat is found by projecting the flux point along the $-\hat{t}$ direction (i.e., back towards the heliostat) to the image plane whose origin is the aimpoint on the receiver. The Hermite series (Equation III.F-1) is evaluated and multiplied by $-\hat{f} \cdot \hat{t}$, where \hat{f} is the normal of the flux surface at the flux point. For multiple aimpoints this procedure is repeated for each aimpoint. **To represent accurately the flux from a zone of heliostats, the code uses the average flux from a number of heliostats spanning the zone, depending on image size, and not just a single heliostat located at the field point.** The flux from a field of heliostats is obtained by summing the flux from the zones within the field. The single time of the year at which the flux is calculated is determined by the user with the variable IFXOUT(I,J), where I=1, NYEAR and J=1, 16 to describe the time during the day. The appropriate values for I and J to correspond to a given day and time of year are shown in Table III-1. **Only one value in the IFXOUT array should be nonzero during any single DELSOL calculation.**

All flux density distributions for systems previously optimized by DELSOL are calculated using the value REFSOL as the insolation incident onto the heliostats. At times during the year when the insolation is not equal to REFSOL, the actual flux densities will be different from those values which are printed in the output by the ratio of the actual insolation to REFSOL. However, flux maps for systems which are input by the user will use the actual insolation for the requested time.

II.G-1. Specification of Flux Point Positions—The flux points are specified by giving their location in ground based coordinates relative to the receiver “center” and by defining the direction of the outward normal on the side of the surface upon which the flux is incident. The receiver center (XFC=YFC=ZFC=0, namelist NLFUX) is on the tower centerline a distance THT (namelist REC) above the plane of the heliostat pivots. This is at the same elevation as the middle of an external receiver or the middle of a cavity aperture or flat plate receiver. DELSOL provides four options for generating a 2-D grid of equally spaced flux points: (1) points on the outer surface of a vertical cylinder (IFLAUT=1); (2) points on the inner surface of a hollow vertical cylinder (IFLAUT=2); (3) points on one side of an arbitrarily oriented plane (IFLAUT=3); or (4) a code-generated

grid of points on the DELSOL assumed heat absorbing surface (IFLAUT=4). The grid of flux points for the first three options does not have to lie on the DELSOL assumed heat absorbing surface unless desired, and also does not have to correspond to the assumed height of the heat absorbing surface. Thus, the effect of different internal cavity configurations on flux distribution can be examined by specifying different flux surfaces, the noncooled surfaces of the interior of a cavity can be checked for internal spillage, or the flux distribution of small sections of a receiver can be examined in greater detail.

If IFLAUT=1, the points are generated on the outside of a cylinder with a diameter of DIAMF (meters). The center of the vertical cylinder is XFC meters to the east, YFC meters to the north, and ZFC meters up with respect to the receiver center. There are NXFLX flux points around the circumference from a minimum surface normal azimuth of FAZMIN degrees to a maximum of FAZMAX degrees (see Figure II-16). The north side of the cylinder has an azimuth angle of 180° , the east is at 270° , and so on. There are NYFLX flux points on the height of the flux surface from a minimum of FZMIN meters to a maximum of FZMAX meters, relative to ZFC. This option is most useful for studying cylindrical external receivers or for examining the flux distributions of individual tubes in a receiver.

If IFLAUT=2, the flux points are on the inside of a hollow vertical cylinder. All of the variables have the same meaning as above, except that since the surface normals are on the inside of the cylinder the azimuth on the north side is 0° (not 180°), and the east side azimuth is 90° (not 270°), etc., as shown in Figure II-16. This option is useful for generating flux maps for the interiors of cavity receivers. However, it must be remembered that the center of curvature of a cavity heat absorbing area, as defined by DELSOL, is at the aperture, so that the cylinder defining the flux surface should be centered using the appropriate values of XFC, YFC, and ZFC. Then, the diameter (DIAMF) of the cylinder defining the flux surface should be based on the actual depth of the cavity, which may be different from half of the width W of the cavity structure, depending on the choice of the parameter RWCAV(I).

If IFLAUT=3, the flux points are located on a plane. The outward surface normal \hat{f} on the side of the plane on which the flux is incident makes a polar angle of POLF degrees with the vertical and an azimuthal angle of AZMF degrees with respect to the south direction (these angles are defined in an analogous manner to the angles of the \hat{n} , \hat{s} , \hat{t} , and \hat{r} vectors in Figure II-2). A cartesian coordinate system (\hat{i}_f , \hat{j}_f , \hat{k}_f) is constructed with $\hat{k}_f = \hat{f}$, where \hat{i}_f is in the plane and horizontal and \hat{j}_f is in the plane and pointing up when \hat{k}_f is horizontal (Figure II-17). The origin of this coordinate system is XFC meters to the east, YFC meters to the north, and ZFC meters up with respect to the "center of the receiver" as described above. There are NXFLX equally spaced values of the flux points along the \hat{i}_f axis from a minimum of FAZMIN meters to a maximum of FAZMAX meters. Similarly, there are NYFLX equally spaced values of the flux points along

AZIMUTH ANGLES

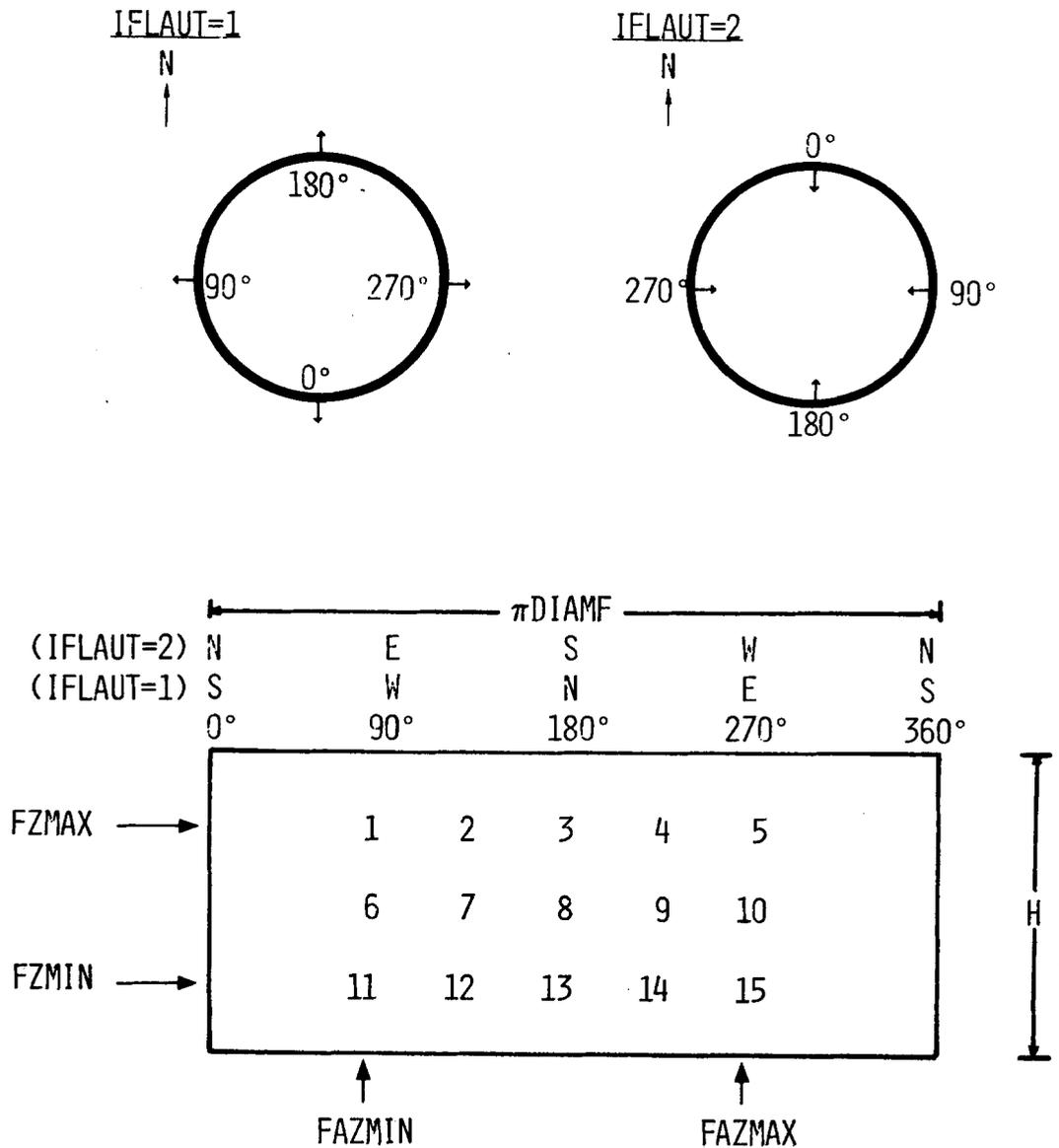


Figure II-16. Flux Points on a Cylinder. For IFLAUT=1 the points are on the outside of the cylinder, and for IFLAUT=2 the points are on the inside. In this Figure NXFLX = 5, NYFLX = 3. Point number $NMXFLX = M + (N-1) * NXFLX$, where $M=1$, NXFLX and $N=1$, NYFLX. For clarity, the receiver has been "unfolded" and laid flat.

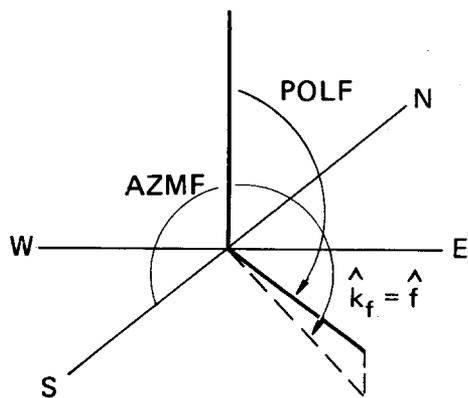
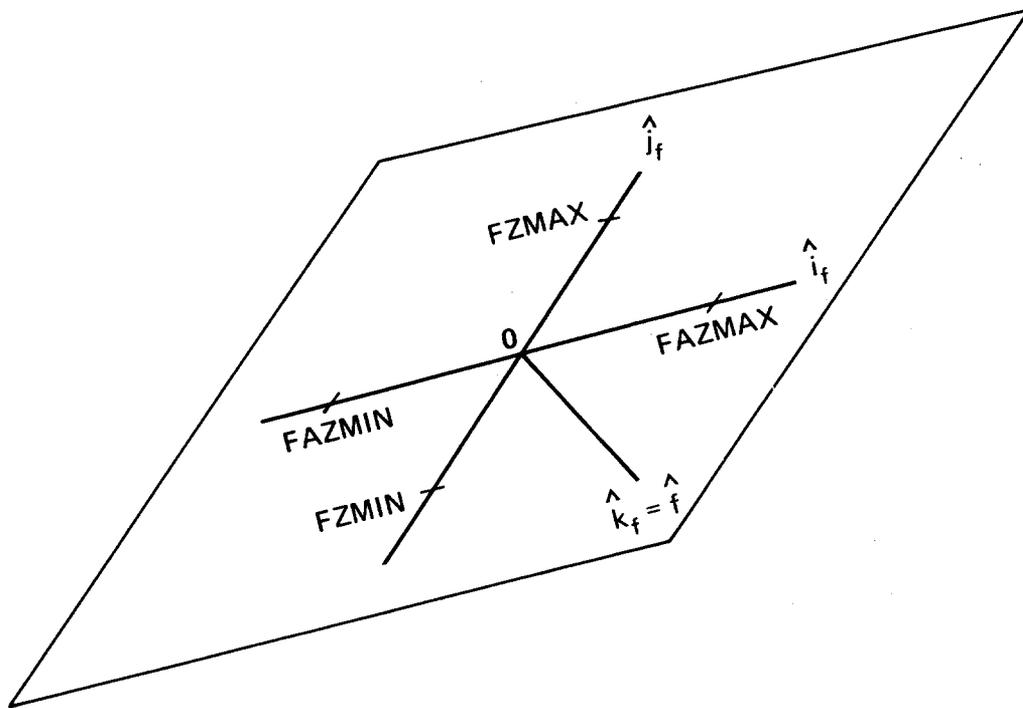


Figure II-17. Flux Points on a Plane. The origin O is displaced (X_{FC} , Y_{FC} , Z_{FC}) from the receiver surface and the normal f has a polar angle $POLF$ and an azimuthal angle $AZMF$. The i_f axis is in the plane and horizontal. The j_f axis is in the plane and pointing upward. The limits of the 2-D grid of equally spaced points are shown.

the \hat{j}_f axis from a minimum of FZMIN meters to a maximum of FZMAX meters, with respect to the point (XFC, YFC, ZFC).

If IFLAUT=4, the flux points will be automatically located by the code on the assumed heat absorbing surface of the receiver. For this calculation, the cavity heat absorber height will always be assumed to be that value specified by H (namelist REC). The default choices for NXFLX, FAZMIN, FAZMAX, NYFLX, FZMIN, and FZMAX will result in a single point on the center of the north facing heat absorbing surface. Essentially, for this option the code chooses the "correct" values of DIAMF, XFC, YFC, ZFC, POLF, and AZMF, and then selects the appropriate option (IFLAUT=1, 2, or 3) for an external, cavity, or flat plate receiver, respectively. For this case, as for the first three options, the desired values for NXFLX, FAZMIN, FAZMAX, NYFLX, FZMIN, and FZMAX should be specified. Also, if the surface to be examined for fluxes is not on the code-defined heat absorbing surface (e.g., examining flux at the aperture of a cavity receiver), then this option cannot be used, and one of the first three options should be used instead.

II.G-2. Flux Constrained System Designs—Many receiver designs have flux limitations imposed on the heat absorbing surface to meet lifetime requirements. DELSOL provides the option during the optimization procedure to design systems with a peak flux constraint. The flux at NFLXMX points, where $NFLXMX \leq 4$, is calculated at the design point for the reference insolation REF-SOL as the field is being built up. The NFLXMX points can be chosen from a larger grid of flux points, but during the optimization calculation fluxes will be calculated only for the NFLXMX points. If the flux limit (FLXLIM(I)) is exceeded at one of the NFLXMX points, no more zones are added to the field. The user must ensure that the flux points being checked lie on the heat absorbing surface, or a system with incorrect flux levels might be obtained. **In calculating the flux during optimization studies, DELSOL assumes that the relative shape of the flux profile at the design point is the same as the relative shape of the annual average flux profile as described by an initial performance calculation.** This assumption is more correct for surround fields than for north fields, but in any case depends on the design point which is chosen by the user. It is recommended that a more detailed flux map always be generated during a final performance calculation to verify that flux limits are not exceeded.

When the receiver size is iterated during an optimization calculation, the location of the flux points is scaled in such a way that they remain at the same relative position on the receiver. For external receivers, a width W and height H are specified on the REC namelist which occurs just before the OPT namelist in the optimization input group. Flux points on the heat absorbing surface would be specified by using IFLAUT=1 with XFC=YFC=ZFC=0 and DIAMF=W. Generally, the peak flux would occur at the middle of the north side of an external receiver (unless IAUTOP=3 is used), so that only one flux point needs to be tested (this is generated by using all of the default values in namelist NLFLUX). However, up to four flux points can be tested by specifying different input values. The

flux point grid defined during system optimization should be defined with respect to the initial values of receiver dimensions. Then, as the receiver size is varied the azimuthal location of the flux points for an external receiver remain unchanged. The height of the flux points is given by

$$\text{Height of flux point} = (\text{Initial location}) \frac{H_{it}}{H}$$

where H_{it} is the current iterated receiver height. For example, if a flux point is chosen as 3/4 of the way up the receiver on the NE side, it will remain in this relative position as W and/or H is varied.

For cavity receivers, the locations of flux points on the heat absorbing surface scale with W and the height of the heat absorbing surface based on $RADMIN$ and $RADMAX$ as

$$(x, y) = (x, y)_{\text{initial}} \frac{W_{it}}{W}$$

$$z = z_{\text{initial}} \frac{HCAV_{it}}{HCAV_{\text{initial}}}$$

where W_{it} is the current iterated width, and $HCAV_{it}$ is the height of the heat absorbing surface based on current values of THT , W , and RY . The surface normal at the flux point is held constant.

Choosing the correct location of flux points for a cavity heat absorbing surface is not straightforward because the vertical center of the receiver ($ZFC=0$) is the vertical center of the aperture but not the vertical center of the heat absorbing surface. The bottom of the heat absorbing surface is chosen by *DELSOL* to intercept all possible images that pass through the aperture from the farthest heliostat in the field, as described in Section V.A-5. The top of the heat absorbing surface is defined as described in Section II.E, depending on either the ratio of the value H to the aperture height RY or on the methods of Section V.A-5. For either case, the scaling methods described above work to keep the flux points in the same relative location on the heat absorbing surface.

For cavity receivers, the peak flux will usually occur along the back centerline, but not necessarily at the center of the height of the heat absorbing surface. The user should test several points along the centerline of the back wall in order to locate and properly design for the maximum flux.

For a single flat plate receiver, the flux points on the heat absorbing surface are specified using $IFLAUT=3$ with $POLF=RELV(1)$, $AZMF=RAZM(1)$, $ZFC=0$, $XFC=-W \times \sin(AZMF)$, and $YFC=-W \times \cos(AZMF)$, where W is the "diameter" defined in namelist *REC* (or use $IFLAUT=4$ option). The spacing

of the flux points along the \hat{i}_f axis scale with RX(1) and along the \hat{j}_f axis with RY(1) as

$$x_{fit} = x_f \frac{RX(1)_{it}}{RX(1)}$$

$$y_{fit} = y_f \frac{RY(1)_{it}}{RY(1)}$$

where RX(1) and RY(1) are the values of the receiver dimensions from namelist REC, $RX(1)_{it}$ and $RY(1)_{it}$ are the values used in the iteration, and x_f and y_f are the coordinates of the flux points generated by the values in namelist NLFLUX. Generally, the peak flux occurs in the center of a flat plate receiver, unless IAUTOP is set to 2 or 4 (aiming at the bottom of the receiver).

For flux-limited external or flat plate receivers the use of IAUTOP=1 and 2, respectively, is strongly suggested. If all of the heliostats are aimed at the center or bottom of the receiver, then a flux level at the peak flux point will be closely related to a power level, so that any higher power level would exceed that flux level. However, if the aimpoints are spread out over the receiver, then changing the receiver size will vary the flux levels at any specific point, so that for any chosen power level a specific flux limit can be reached by increasing the receiver size appropriately. This is not a concern for cavity receivers, since the aimpoints are always located at the aperture, so that the flux levels on the heat absorbing surface can be decreased by moving that surface farther away from the aperture.

It is suggested that fluxes should not be calculated during the initial performance run which precedes the optimization calculation. This omission will facilitate the process of designing a flux-limited system. Also, a single aimpoint (IAUTOP=0) can be used during the initial performance run to save time, since the flux profile does not affect the system design until the optimization calculation is done.

II.G-3. Oblique Flux Considerations—The flux which is calculated by DELSOL is assumed to be flux normal to the defined flux surface. If the flux surface truly is smooth or if the incident flux is normal to the surface then the flux calculation is correct. However, if the heat absorbing surface is composed of small diameter tubes and the flux plane is a plane through the centerline of those tubes, then the flux which is calculated by DELSOL will be the flux at the crown of the tube only. Thus, if the angle of incidence of the flux is such that the flux is normal to the tube at a location other than at the crown, this location on the tube may have a higher flux level than that recorded at the crown of the tube. This is one reason why the aim strategy IAUTOP=2 (aimpoints spread out horizontally and vertically) is not recommended for external cylindrical receivers. The problem is most likely to occur in cavity receivers in which the heat absorbing surface is other than a right circular cylinder centered on the aperture.

To see whether this problem is occurring, and to see if flux limits are being exceeded due to this oblique flux, the user can define a flux surface equivalent to a single tube at the critical location. Checking the calculated flux on this surface will give a worst case estimate (assuming no tube-to-tube shadowing) of the flux at locations on the tube other than at the crown.

III. Detailed Performance Calculation

In a performance calculation, the user specifies a complete system design and the code calculates the performance of the system. This calculation includes the effects of cosine losses, shadowing, blocking, atmospheric attenuation, and spillage of a field at a given time, at a given sun angle, over a specific day, or over an entire year. A detailed performance calculation gives the required results for use in optimization calculations, and a performance calculation can be done for a system which has been optimized by DELSOL. This latter calculation may also include an annual energy calculation as well as an annual field efficiency calculation.

III.A. Performance Calculation Options

DELSOL will calculate the performance of a central receiver system at a single time, over a single day, on a user defined matrix of sun positions, or over the year, depending on the chosen value of the variable IPROB (Namelist BASIC).

III.A-1 IPROB=0 or 4, Annual Performance—DELSOL calculates the performance at a finite number of times during the year and integrates to get daily and annual averages. The problem is simplified by the daily and seasonal symmetry of clear sky insolation, described in Section III.B. Only the half year between winter and summer solstice and the times between solar noon and sunset need to be sampled. NYEAR equally spaced days starting at December 21 (day 354.75) and ending on June 21 (day 172.25) are considered, as illustrated in Table III-1. At each of these days the time is varied from solar noon until sunset in steps of HRDEL hours, also shown in Table III-1. The last time step at each day is taken as the time when the sun angle, θ_s , is ASTART degrees from the vertical.

IPROB=4 is specified when the results of the performance calculation are needed in order to do an optimization calculation. For this option, annual field efficiencies are calculated. The performance should be saved by specifying ITAPE=1 (Namelist BASIC).

IPROB=0 is specified when a final detailed performance calculation is desired. This calculation can be done for a system which was previously optimized by DELSOL or for a user specified system. This option calculates annual field performance, and also calculates annual energy for the specified system. If the performance of a previously optimized DELSOL system is being requested, the user should specify ITAPE=3 to indicate that the system is to be obtained from the file which was written during the optimization procedure.

III.A-2. IPROB=1, Single Computational Day—DELSOL calculates the performance only on the UDAY (Namelist BASIC) day of the year. No annual average is calculated. The time steps are controlled by HRDEL as described for IPROB=0.

**Table III-1. Time Steps
Days of the Year Sampled**

<u>Calculational Day</u>	Day of the Year	
	<u>NYEAR = 3</u>	<u>NYEAR = 5</u>
1	354.75	354.75
2	81.0	35.375
3	172.25	81.0
4		126.625
5		172.25

NOTE: Day 354.75 is winter solstice
 " 81.0 is spring equinox
 " 172.25 is summer solstice

Hours after Solar NOON Sampled*

<u>Calculational Time Step</u>	HRDEL = 1.			HRDEL = 2.		
	<u>Day = 354.75</u>	<u>Day = 81.</u>	<u>Day = 172.25</u>	<u>Day = 354.75</u>	<u>Day = 81.</u>	<u>Day = 172.25</u>
1	0.	0.	0.	0.	0.	0.
2	1.	1.	1.	2.	2.	2.
3	2.	2.	2.	3.3	4.	4.
4	3.	3.	3.		4.8	5.8
5	3.3	4.	4.			
6		4.8	5.			
7			5.8			

*ASTART = 75°

III.A-3. IPROB=2, Single Computational Time—DELSOL calculates the performance only at UTIME hours past solar noon (UTIME is negative in the morning) on the UDAY day of the year (Namelist BASIC).

III.A-4. IPROB=3, Matrix of Sun Angles—Instead of calculating performances at certain specified times, this option allows the user to obtain the performance at certain specified sun angles. NUAZ values of the azimuthal angle, UAZ, and NUEL values of the zenith angle, UEL, are considered in all possible pairwise combinations.

III.A-5. Selection of NYEAR, HRDEL, and Reference Times—Both accuracy and calculational time of the performance calculation (but not the optimization calculational time) increase with the number of day and hourly time steps chosen. Fortunately, a relatively few days (3 to 5) and a reasonable time step (1 hour) appear to produce accuracies better than 1%. Generally, it is better to decrease HRDEL than to increase NYEAR when attempting to increase accuracy.

Two times of the year have special significance. First, REFTIM hours past noon on the REFDAY day of the year is called the reference time. This is the time of the year which is used to determine the design point power levels of the system, as described in Section IV.C-1. Second, HCANT hours past noon of the DCANT day is used to determine the off-axis canting of heliostats, if any, as described in Section II.D-2. **The reference time must correspond to one calculational time.** In addition, daily start-up and shutdown times are determined by the user-specified zenith angle, ASTART ($< 90^\circ$).

Default values are:

NYEAR = 5

HRDEL = 1.0

ASTART = 75.0°

REFTIM = 0.0 (solar noon)

REFDAY = 81.0 (equinox, March 21)

HCANT = 0.0

DCANT = 81.0

III.B. Seasonal and Daily Variation of Sun Positions and Sunshape

The performance of a system is dependent on the position of the sun, the actual insolation, the shape of the sun, and weather effects, all of which can vary with time.

III.B-1. Position of the Sun—The sun position vector \hat{s} is specified by (θ_s, β_s) as illustrated in Figure II-2. If refraction effects in the atmosphere are ignored, θ_s and β_s can be calculated by (References 15 and 16):

$$\cos\theta_s = \sin\lambda\sin\delta + \cos\lambda\cos\delta\cos\tau \quad (III.B - 1)$$

$$\sin\beta_s = \sin\tau\cos\delta/\sin\theta_s \quad (III.B - 2)$$

where

λ = latitude (> 0 in northern hemisphere),

τ = hour angle measured from noon (> 0 in afternoon; 15° per hour),

δ = declination.

δ is determined by:

$$\sin\delta = \sin(23.442274^\circ) \sin\phi \quad (III.B - 3)$$

where

$$\begin{aligned} \phi(\text{radians}) = & \phi_0 + 0.007133\sin\phi_0 \\ & + 0.032680\cos\phi_0 - 0.000318\sin 2\phi_0 \\ & + 0.000145\cos 2\phi_0 \quad (\text{Reference 17}) \end{aligned} \quad (III.B - 4)$$

and

$$\phi_0 = \frac{2\pi(\text{DAY} + 284.)}{365.24} \quad (III.B - 5)$$

The effect of atmospheric refraction is to make the sun's apparent zenith angle θ'_s (i.e., the zenith angle observed through the atmosphere) less than the true zenith angle θ_s . The correction is given by a numerical fit (Reference 18):

$$\begin{aligned} \Delta\theta_s(\text{radians}) = & \theta_s - \theta'_s \\ = & A (\theta_s/B)^{(C+D\theta_s)} - E \end{aligned} \quad (III.B - 6)$$

where

$$\begin{aligned}
A &= +0.004013327 \\
B &= +0.06476916 \\
C &= -0.66956539 \\
D &= +0.019276169 \\
E &= -0.00051297
\end{aligned}$$

$\Delta\theta_s$ is multiplied by the relative atmospheric pressure (PRES or DPRES, Namelist BASIC) to account for the effect of altitude. It is the apparent sun angle, not the actual sun angle, that is tracked by the heliostats.

The default latitude is that for Barstow, CA:

$$\lambda(\text{PLAT}) = 35.0^\circ.$$

III.B-2. Insolation—The extraterrestrial insolation of the sun, S_0 , including the effect of eccentricity of the earth's orbit, is given by (Reference 19):

$$S_0 \text{ (kw/m}^2\text{)} = 1.353 + 0.045 \cos \left(2\pi \frac{\text{DAY} + 10.0}{365.0} \right) \quad (\text{III.B} - 7)$$

where DAY = day of the year.

The position of the sun is symmetric about the summer and winter solstices. The code ignores the small change in declination during each day and assumes that sun position is symmetric about noon.

DELSOL assumes clear sky models to predict the direct normal insolation, S , at the earth's surface. The parameter INSOL controls the insolation model choice. Insolation is decreased by transmission through the atmosphere. Losses depend on such factors as the weather, air mass traversed, and altitude, which determine the extent of photon absorption and scattering. The result is that part of the direct insolation is converted to a diffuse form which cannot be concentrated by the heliostats. The annual energy predicted by the clear sky models is corrected for weather effects as described below.

These insolation models are analytical approximations to a widely varying actual insolation value. That is, measured data for a specific location and time may not agree with the results of any insolation model. For a performance calculation, the user should choose a model which, when incorporated with weather considerations, will predict the closest insolation to measured values. For optimization (design point) calculations and for flux map calculations on optimized systems, the value REFSOL (Namelist BASIC) is used as a fixed insolation value.

a) INSOL = 0, Meinel Model (Reference 20)

$$S = S_0 \{ (1.0 - 0.14\text{ALT}) \exp(-0.357(\sec\theta_s)^{0.678}) + 0.14\text{ALT} \} \quad (\text{III.B} - 8)$$

where S_0 is given by Equation (III.B-7) and ALT is the altitude in km.

- b) INSOL = 1, Hottel Model (Reference 21)

$$S = S_0 \{a + b \exp(-c \sec \theta_s)\} \quad (III.B - 9)$$

$$\begin{aligned} \text{where } a &= 0.4237 - 0.00821 (6.0 - \text{ALT})^2 \\ b &= 0.5055 + 0.00595 (6.5 - \text{ALT})^2 \\ c &= 0.2711 + 0.01858 (2.5 - \text{ALT})^2 \end{aligned}$$

- c) INSOL = 2, Constant Insolation

$$S = \text{SOLCON (constant specified in Namelist BASIC)} \quad (III.B - 10)$$

- d) INSOL = 3, Allen Model (Reference 22)

$$S = S_0 \left\{ 1.0 - 0.263 \left(\frac{\text{DH2O} + 2.72}{\text{DH2O} + 5.0} \right) (m \times \text{DPRES})^\gamma \right\} \quad (III.B - 11)$$

where

- m = air mass correction
- DH2O = precipitable water overhead (mm)
- DPRES = atmospheric pressure/sea level atmospheric pressure
- $\gamma = 0.367 \left(\frac{\text{DH2O} + 11.53}{\text{DH2O} + 7.88} \right)$

The air mass correction, m , depends on the zenith angle, θ_s , according to:

$$\begin{aligned} m &= \frac{1}{\cos \theta_s} & (\theta_s < 60^\circ) \\ m &= \frac{1}{\cos \theta_s} - 41.972213(90 - \theta_s)^\beta & (\theta_s \geq 60^\circ) \end{aligned} \quad (III.B - 12)$$

where

$$\begin{aligned} \beta &= -2.0936381 - 0.04117341(90 - \theta_s) \\ &+ 0.000849854(90 - \theta_s)^2 \quad (\text{Reference 23}) \end{aligned} \quad (III.B - 13)$$

Note that the altitude of the site affects the insolation via the relative pressure DPRES.

e) INSOL = 4, Moon Model (Reference 22)

$$S = S_0 \{0.183 \exp(-m \times \text{DPRES}/0.48) + 0.715 \exp(-m \times \text{DPRES}/4.15) + 0.102\} \quad (\text{III.B} - 14)$$

The above equations are plotted in Figure III-1 for ALT=0. The default values give yearly insolation predictions corresponding to a Barstow, CA, location (Reference 24):

$$\begin{array}{ll} \text{INSOL} = 0 & \text{DPRES} = \text{PRES} = 1.0 \\ \text{ALT} = 0.65 & \text{DH}_2\text{O(I)} = \text{H}_2\text{O} = 20.0 \end{array}$$

III.B-3. Time Dependent Weather Effects—DELSOL allows the user to define the weather characteristics of the site being analyzed. The weather factors can be defined separately for each of the NYEAR calculational days (IWEATH=1, Namelist BASIC) or can be held constant over the year (IWEATH=0, 2). The weather affects both performance and design calculations.

a) Cloudiness

The energy produced on the Ith calculational day is multiplied by DWEATH(I) (IWEATH=1) or WEATH (IWEATH=0, 2) to correct for the probability that some insolation will be lost due to cloudiness. If IWEATH=2, the variable WEATH is defined based on the reference latitude (PLAT in Namelist BASIC) as

$$\text{WEATH} = 2.16255 \exp(-0.02804 \times \text{PLAT})$$

The default values are set for a Barstow, CA location:

$$\text{IWEATH} = 0$$

$$\text{DWEATH(I)} = \text{WEATH} = 0.83$$

b) Atmospheric Pressure

The atmospheric pressure divided by sea level atmospheric pressure on the Ith calculational day is given by DPRES(I) (IWEATH=1) or PRES (IWEATH=0, 2). The relative atmospheric pressure affects the refraction of sunlight in the atmosphere, and its influence is accounted for in the Allen and Moon insolation models.

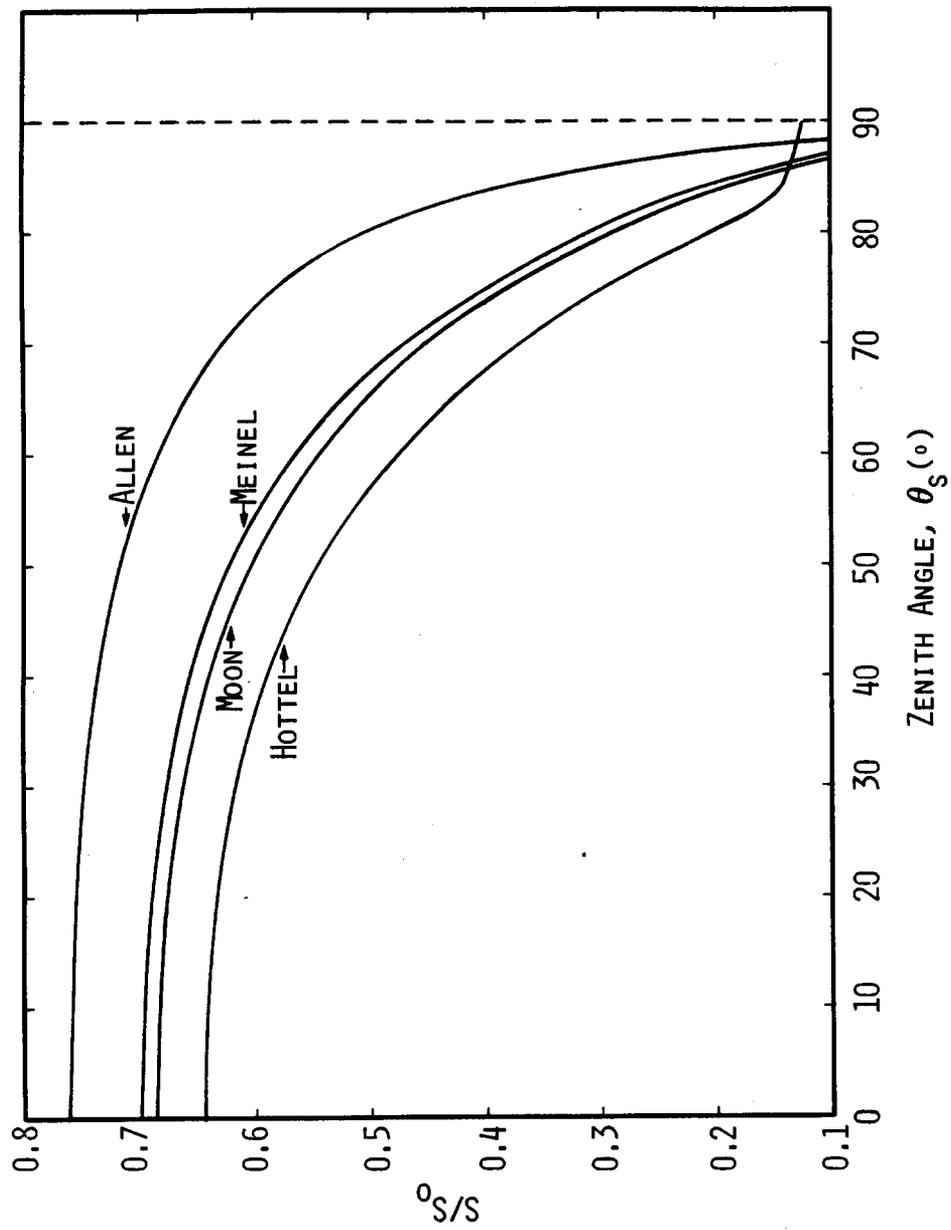


Figure III-1-1. Ratio of Incident to Extraterrestrial Insolation, S/S_0 , as a Function of Solar Zenith Angle (Sea Level)

c) Precipitable Water

The precipitable water overhead (in mm) on the Ith calculational day is given by DH2O(I) (IWEATH=1) or H2O (IWEATH=0, 2). This quantity is used only in the Allen insolation model (INSOL=3).

III.B-4. Sunshape—The image of the extraterrestrial sun is limb darkened; i.e., the insolation decreases toward the edge. The size and shape of the solar intensity is further modified by the very small angle scattering in the earth's atmosphere. In general, the size of the solar image increases as the total insolation decreases because of increased scattering. The shape of the solar image is important in its effects on the spillage and flux calculations. The sunshape models available in DELSOL are set by the choice of parameter NSUN (Namelist BASIC).

a) NSUN = 0, Point Sun

A point sun, while unrealistic, has been useful for debugging the field performance calculation and for studying the effects of heliostat size and errors on the images projected on the receiver.

b) NSUN = 1, Limb Darkened Sun

This is one of the simpler models for a limb darkened sun described by Reference 3:

$$S(r) = \begin{cases} S_0 (1.0 - 0.5138(r/R)^4) & (r \leq R) \\ 0.0 & (r > R) \end{cases} \quad (III.B - 15)$$

where r = angle subtended between the center of the sun to some point toward the edge ($<R$), in rad;

R = maximum angle subtended
= (4.65×10^{-3})

c) NSUN = 2, Square Wave Sun

The intensity is constant to $r = R$ ($=4.65$ mrad), and then drops to zero:

$$S(r) = \begin{cases} S_0 & (r \leq R) \\ 0.0 & (r > R) \end{cases} \quad (III.B - 16)$$

d) NSUN = 3, User Specified Sunshape

The user specifies the intensity vs. angle in a circularly symmetric sunshape. There are NSUNPT pairs of values of intensity, SUNI, vs. angle from the center of the sun, SUNR. The angles are in ascending order and the first angle **must** be zero (i.e., the center of the sun). $\pi r \times \text{SUNI}(r) dr$ gives the power from the sun within a differential circular ring from r to $r+dr$.

The default in the code is the limb darkened model (NSUN = 1).

III.C. Field Performance Calculation

DELSOL will compute field performance terms for specific times, sun angles, or for a yearly sampling of times, depending on the choice of IPROB. For IPROB=0 or 4, for instance, DELSOL will compute daily and annual averages of the total performance and the individual performance terms. These time averages are weighted according to the following table:

<u>Quantity</u>	<u>Weighting</u>
cosine	insolation
shadowing	insolation x cos
blocking	insolation x cos x shadowing
attenuation	insolation x cos x shadowing x blocking
spillage	insolation x cos x shadowing x blocking x attenuation

For example, the average blocking from time t1 to time t2 is:

$$\langle \text{blocking} \rangle = \frac{\int_{t_1}^{t_2} \text{block}(t) \text{shadow}(t) \text{cosine}(t) \text{insolation}(t) dt}{\int_{t_1}^{t_2} \text{shadow}(t) \text{cosine}(t) \text{insolation}(t) dt}$$

The same type of weighting is used in averaging the performance for a user defined field.

III.D. Cosine Effect

In general, heliostats are not perpendicular to the incident direct insolation. The total power reflected per unit area of heliostat is proportional to the cosine $\hat{n} \cdot \hat{s} = \hat{n} \cdot \hat{t}$. The code uses the analytical formulas for the heliostat orientation and the cosine derived in Reference 25. Therefore, the amount of energy reflected by a heliostat, S_r , is:

$$S_r = S \times (\hat{n} \cdot \hat{s}) \times \text{RMIRL} \quad (\text{III.D} - 1)$$

where

$$\hat{n} \cdot \hat{s} = \frac{1}{\sqrt{2}} \{1 + \cos\theta_s \cos\theta_t + \sin\theta_s \sin\theta_t \cos(\beta_t - \beta_s)\}^{1/2} \quad (\text{III.D} - 2)$$

The angles are defined in Figure II-2.

III.E. Shadowing and Blocking

Shadowing occurs when one heliostat is in the shadow of one or more neighbors. Blocking occurs when a part of the unshaded region of the heliostat cannot be seen from the receiver because of its neighbors. Shadowing and blocking are strongly time and position dependent.

Shadowing (blocking) is calculated by projecting the neighboring heliostats along the sun (tower) direction onto the plane of the heliostat being considered. The area that is shaded (blocked) is then calculated analytically. Twelve nearest neighbors are considered in the calculation.

Two options are provided for overlapping of shadowing and blocking on a heliostat. For ISB=0 (Namelist HSTAT) the shading and blocking are assumed to **never** overlap. This is generally the case except at low sun angles. This approximation is an upper bound on shading and blocking losses. For ISB=1 the shading and blocking are assumed to **always** overlap. This approximation is a lower bound on the losses. The default choice is the conservative one (ISB=0).

III.E-1. Effect of Slip Planes on Shadowing and Blocking—As explained in II.C-1, heliostats have to be removed from slip planes in radial stagger layout patterns. These missing heliostats will reduce the shadowing and blocking. DELSOL assumes that the shadowing and blocking losses are reduced by the ratio of the number of missing heliostats to the total number of heliostats in a zone. For example, if 5% of the heliostats are missing due to slip planes, a 10% shadowing loss would be reduced to 9.5%.

III.E-2. Tower Shadow—DELSOL calculates the effect of the shadow cast by the tower and receiver. The tower and receiver shadow is modeled as that cast by a vertical cylinder of height TOWL meters (above the plane of the heliostat pivots) and diameter of TOWD meters. Both values scale with THT during system optimization, so that the ratio of these values to the THT specified in an initial performance run remains constant as THT is varied during the optimization. For this reason, the values should be carefully and correctly specified during an initial performance run (IPROB=4) and **should not be input during the optimization process**. The default values are consistent with the default values of THT and W:

TOWL = 175.0 m
TOWD = 10.0 m

III.F. Flux Density and Spillage

The details of the theoretical method for calculating the flux in DELSOL is given in References 3 and 5. The flux distribution from a heliostat, normalized to unit power, is represented analytically by a truncated expansion in Hermite polynomials:

$$F(x, y) = (2\alpha_x\alpha_y)^{-1} \exp\left(-\frac{1}{2}\left(\frac{x}{\alpha_x}\right)^2 - \frac{1}{2}\left(\frac{y}{\alpha_y}\right)^2\right) \times \left(\sum_{i=0}^6 \sum_{j=0}^{6-i} A_{ij} H_i\left(\frac{x}{\alpha_x}\right) H_j\left(\frac{y}{\alpha_y}\right) / i!j!\right) \quad (III.F - 1)$$

where α_x , α_y , and A_{ij} are calculated from the projection of the heliostat on the receiver, the sunshape, and the heliostat performance error distribution, and where x and y are the coordinates in the plane of the reflected image (Table II-1). The H 's are Hermite polynomials, the first three of which are:

$$\begin{aligned} H_0(x) &= 1 \\ H_1(x) &= x \\ H_2(x) &= x^2 - 1 \end{aligned} \quad (III.F - 2)$$

Reference 5 shows that the A_{ij} and α 's have a simple power law dependence on the tower height THT. Therefore, once the flux is found for one tower height, it is straightforward to calculate the dependence for other tower heights. Furthermore, since Equation (III.F-1) describes the flux over the entire image plane, the flux can be projected onto any receiver as long as the receiver dimensions are small compared to the slant range.

The code assumes that total energy in the flux distribution is reduced by shadowing and blocking, but that the spatial distribution of the flux is taken as proportional to that of an unshaded and unblocked heliostat. This is generally justified because shadowing and blocking losses are usually small and the convolution of the mirror shape with the sunshape and errors reduces the effect of shadowing and blocking on the flux profile.

The ability to use one flux calculation to predict the flux from a given heliostat design on any tower or receiver is the main strength of DELSOL. With this ability, DELSOL can scale the results of one detailed initial performance run during system optimization calculations and quickly calculate performances for comparison between different systems. However, note that the performance which is scaled is an annual average performance (flux map). Thus, if the design point performance is different than the annual average then the predicted performance during the optimization (scaled performance) will not match

a final performance calculation on the optimized system. This difference will be most noticeable in flux profiles.

The speed of the Hermite method results from the fact that a severely truncated polynomial (6th order) expansion is an accurate approximation to the flux density. As discussed in Reference 5, the accuracy of the Hermite method increases as the error sources of heliostat performance and/or their effect on the flux profile become larger. Specifically, DELSOL becomes more accurate in predicting the flux and spillage when: (1) the errors increase; (2) the slant range increases; or (3) the size of the heliostat is reduced (either physically or effectively by focusing or canting).

To calculate the fraction of the flux intercepted by the receiver, Equation (III.F-1) must be integrated over the projection of the receiver on the image plane. The resulting two dimensional integral can be evaluated analytically in one dimension and numerically, using a 16 point Gaussian quadrature, in the other.

III.F-1. More Accurate Images from Canted Heliostats—The normal method used in DELSOL is to use a single Hermite series to represent the heliostat's image. When the heliostat to receiver distance is small this can result in a blurring of the sharp edges of the image. A slower running option which calculates a more accurate image is available for canted heliostats (INDC=1 in Namelist HSTAT). The location of the center of the image from each cant panel is calculated. Then a separate Hermite series is used to represent the image from each cant panel. **This option can only be used in performance calculations with a single aimpoint at the center of the receiver (IAUTOP=1, Namelist REC).** Its effect on an optimized system can be determined by rerunning a performance calculation on the optimized system with INDC=1.

III.F-2. When to do Flux Calculations—Flux calculations should be done either to design flux limited systems or to define a detailed flux map of a previously optimized system. Therefore, flux calculations should not be done (IFLX=0) during an initial performance calculation. It is recommended that, during system optimization, a grid of flux points be defined covering either the entire heat absorbing surface or a known area of concern, and that up to four points from that grid be checked during optimization to verify that flux limits are not exceeded. During the final performance calculation, fluxes should be calculated for points over the entire heat absorbing surface to verify that flux limits have not been exceeded at any other points than those checked during optimization.

III.G. Time Independent Losses

The hourly and seasonal variation of: a) atmospheric attenuation from the heliostat to the receiver, b) receiver radiation and convection losses, and c) piping insulation losses are assumed negligible. In addition, mirror and receiver reflectivity, the thermal to electric conversion efficiency, and parasitic loads are represented by constant time averaged values.

III.G-1. Atmospheric Attenuation: Heliostat to Receiver—The seasonal variation of atmospheric attenuation at ground level for the test locations of Barstow and Albuquerque (based on constant visibility) is reported to be small (Reference 26) and is ignored in DELSOL. However, the effects of local altitude and visibility are not ignored. DELSOL offers two options, identified by the user's choice of the parameter IATM in the Namelist BASIC:

1) IATM = 0 Clear day, Barstow (visibility = 23 km)

$$\text{Loss (\%)} = 0.6739 + 10.46 R - 1.70 R^2 + 0.2845 R^3 \quad (III.G - 1)$$

(Reference 21)

2) IATM = 1 Hazy day, Barstow (visibility = 5 km)

$$\text{Loss (\%)} = 1.293 + 27.48 R - 3.394 R^2 \quad (\text{Reference 21})(III.G - 2)$$

3) IATM = 2 User defined attenuation

$$\begin{aligned} \text{Loss (fraction)} = & \text{ATM1} + \text{ATM2} \times R \\ & + \text{ATM3} \times R^2 + \text{ATM4} \times R^3 \end{aligned} \quad (III.G - 3)$$

where R is the slant range (heliostat to receiver) in km. The first two equations are graphically presented in Figure III-2. Similar equations for Albuquerque are also given in Reference 26, but these are not currently available as an option in the code. The default choice is the clear day model:

$$\text{IATM} = 0$$

III.G-2. Mirror and Receiver Reflectivity—While it is known that mirror reflectivity can degrade between washings (Reference 27), it is assumed constant along with receiver re-reflectivity. Default values are (namelist variable name is in parentheses):

$$\text{Mirror reflectivity (RMIRL)} = 0.91 \text{ (glass, average between washings; Reference 28)}$$

$$\text{Receiver absorption (RRECL)} = 0.965 \text{ (=1.0 - receiver reflectivity; default value for external molten salt design)}$$

III.G-3. Radiation and Convection Losses from the Receiver—Two options for calculating receiver losses are available in DELSOL, depending on the choice of the variable IRADFL (Namelist NLEFF). In one case, losses are calculated directly dependent on a set of temperature and weather assumptions, while in the other case receiver efficiency is scaled with receiver area (external or billboard

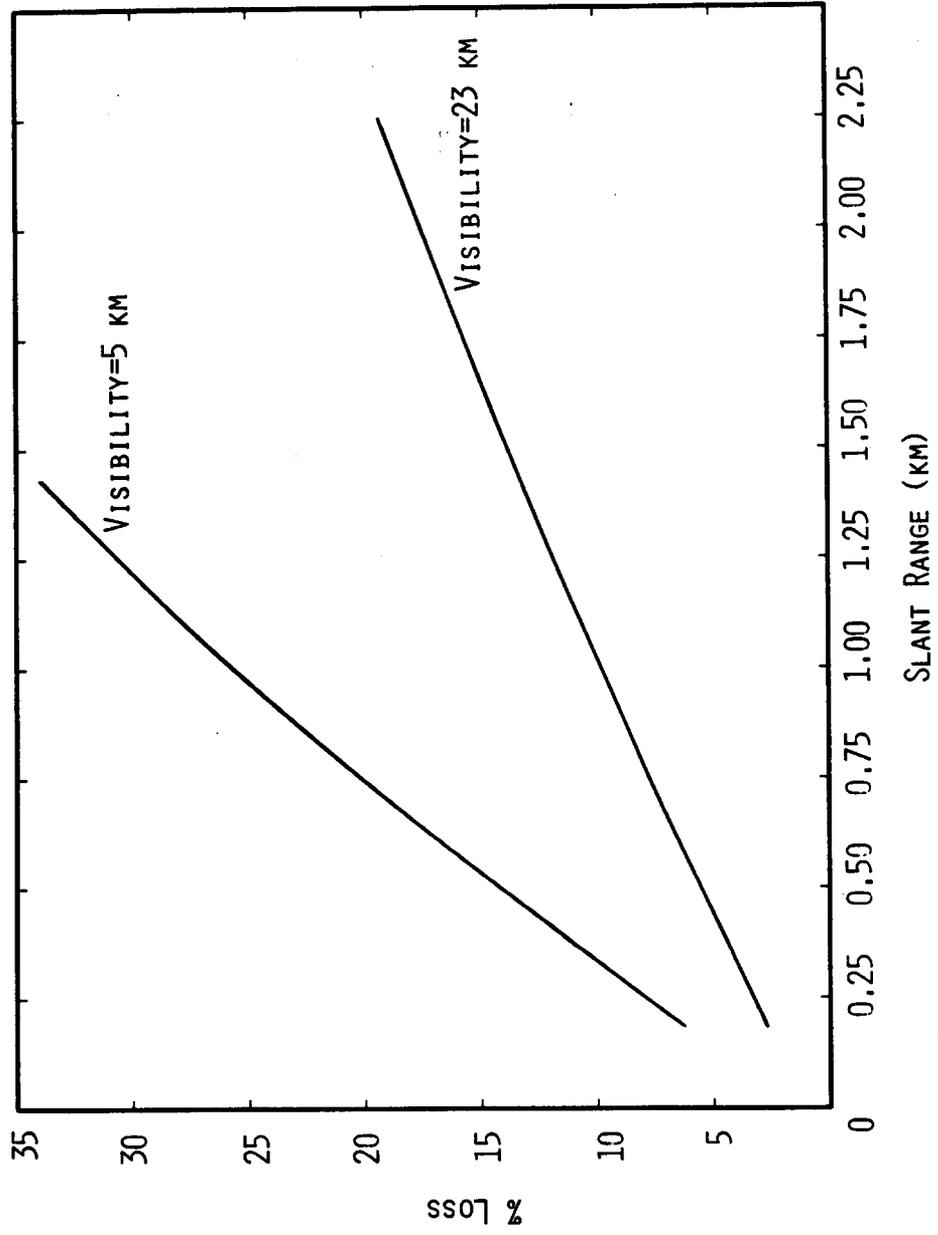


Figure III-2. Atmospheric Attenuation for Low and High Visibility, Barstow

receiver) or with aperture area (cavity receiver) from some reference system in which the losses are well characterized.

a) IRADFL = 0, Direct Calculation of Losses (References 6 and 7)

For this option, the individual losses for radiation and forced and natural convection are calculated separately and summed as

$$P_{\text{LOST,R}} = Q_{\text{rad}} + Q_{\text{conv}} \quad (\text{III.G} - 4)$$

In order to calculate the losses, the code assumes that the loss is not a function of time or method of operation of the receiver. This allows the approximation that the range of temperature operation gives an average wall temperature, T_{wall} , of 753 K (480°C). Further assumptions are that receiver emissivity $\epsilon = 0.90$, average wind speed $u_{\infty} = 7.2$ meters/second, and ambient air temperature $T_{\infty} = 20.0^{\circ}\text{C}$ (Reference 29).

The thermal radiation heat loss is expressed as a function of receiver area (external receivers) or aperture area (cavity receivers) in the following manner:

$$\begin{aligned} Q_{\text{rad}} &= \epsilon \sigma A T_{\text{wall}}^4 & (\text{III.G} - 5) \\ Q_{\text{rad}} &= (0.90)(5.669 \times 10^{-8} \text{W/m}^2\text{K}^4)(A)(753\text{K})^4 \\ Q_{\text{rad}} &= 16,403A \end{aligned}$$

where σ is the Stefan-Boltzmann constant and A is the receiver or aperture area.

The convection heat loss is calculated differently depending on whether the receiver is a cavity or a cylindrical external receiver. For an external receiver,

$$\begin{aligned} Q_{\text{conv}} &= h_{\text{mix}} A (T_{\text{wall}} - T_{\infty}) & (\text{III.G} - 6) \\ Q_{\text{conv}} &= 460 h_{\text{mix}} A \end{aligned}$$

The mixed convection coefficient for an external receiver is calculated according to Reference 29 as

$$h_{\text{mix}} = (h_{\text{forced}}^{3.2} + h_{\text{nat}}^{3.2})^{1/3.2} \quad (\text{III.G} - 7)$$

where $h_{\text{nat}} = 9.09$ ($\text{W/m}^2\text{C}$) based on the assumed temperatures and h_{forced} is separated into three cases depending on the receiver diameter (Reference 6).

In all cases, the Reynolds number is $\text{Re} = (1.751 \times 10^5)D$.

Case (1): $D \leq 4.0$ m

$$h_{\text{forced}} = \left(\frac{1}{D}\right)(0.3 + 0.488(\text{Re})^{0.5}(1.0 + \left(\frac{\text{Re}}{282,000}\right)^{0.625})^{0.80})(0.04199)$$

Case (2): $4.0 < D \leq 125.0$ m

$$h_{\text{forced}} = 14.0$$

Case (3): $D > 125.0$ m

$$h_{\text{forced}} = 33.75D^{-0.19}$$

For a cavity receiver, the convection heat loss is calculated as (Reference 7):

$$Q_{\text{conv}} = Q_{\text{forced}} + Q_{\text{nat}} \quad (\text{III.G} - 8)$$

$$Q_{\text{forced}} = 7,631 \frac{A}{W_{\text{ap}}^{0.2}}$$

$$Q_{\text{nat}} = 5,077 A_{\text{cav}}$$

where

A = aperture area

W_{ap} = aperture width

A_{cav} = approximation to total area inside of cavity

$$= \pi \frac{W}{2} \text{RWCAV} \times \text{HCAV}$$

$\frac{W}{2} \text{RWCAV}$ = cavity depth (radius)

HCAV = height of heat absorbing surface

b) IRADFL = 1, Scaled Approximation of Receiver Efficiency

Both the design point and a yearly average efficiency are calculated based on the assumption that the power loss due to radiation and convection is proportional to either: 1) the area of an external receiver, or 2) the total aperture area in a cavity design; i.e.,

$$P_{\text{LOST,R}} = \alpha_{\text{R}} A_{\text{R}} \quad (\text{III.G} - 9)$$

where A_{R} = external receiver, total aperture, or total flat plate area,
 α_{R} = proportionality factor.

In other words, $P_{LOST,R}$ is the same at any time of the day or year. Implicit in the assumption is that the same temperature profile is maintained on the receiver at all times and for any receiver size by adjusting the fluid flow rate, and that convective losses vary insignificantly with time.

Letting $\eta_{RC,R,DP}$ be the design point efficiency based on receiver radiation and convection losses, then:

$$\begin{aligned}\eta_{RC,R,DP} &= \frac{P_{th,R} - P_{LOST,R}}{P_{th,R}} \\ &= 1 - \frac{\alpha_R A_R}{P_{th,R}}\end{aligned}\quad (III.G - 10)$$

where $P_{th,R}$ = gross thermal power absorbed by the receiver at the design point.

Similarly, let $\eta_{RC,R,AVG}$ be the yearly average efficiency as calculated by:

$$\begin{aligned}\eta_{RC,R,AVG} &= \frac{E_{TOT,R} - (H_{OP} \times P_{LOST,R})}{E_{TOT,R}} \\ &= 1 - \frac{H_{OP} \times \alpha_R A_R}{E_{TOT,R}}\end{aligned}\quad (III.G - 11)$$

where $E_{TOT,R}$ = total gross energy absorbed by the receiver per year
 H_{OP} = total number of hours of receiver (not plant) operation.

α_R is determined from some reference design for which the radiation and convection losses have been calculated in more detail. Rearranging Equation (III.G-10),

$$\alpha_R = (1 - \eta_{RC,R}^{\circ}) \frac{P_{th,R}^{\circ}}{A_R^{\circ}}\quad (III.G - 12)$$

where the variables have the same meaning as above and the $^{\circ}$ superscript refers to the reference. Current default values depend on the type of receiver, but in all cases flow is from the bottom to the top of the receiver, molten salt flow is assumed, and $\eta_{RC,R}^{\circ}$ should be calculated based on the average ambient conditions (wind speed, temperature, etc.).

Defaults for an external receiver (cylindrical or flat plate) are

$$\eta_{RC,R}^{\circ} (\text{REFRC}) = 0.83$$

$$P_{th,R}^{\circ} (\text{REFTHP}) = 4.10 \times 10^8 \text{ watts}$$

$$A_R^\circ (\text{AREF}) = 2780.0 \text{ m}^2.$$

Defaults for a cavity receiver are

$$\eta_{RC,R}^\circ (\text{REFRC}) = 0.83$$

$$P_{th,R}^\circ (\text{REFTHP}) = 2.10 \times 10^8 \text{ watts}$$

$$A_R^\circ (\text{AREF}) = 761.0 \text{ m}^2.$$

III.G-4. Insulation Losses in Piping Runs—Only single module designs are considered, and the following two assumptions are made:

- 1) The hot piping run can be expressed as some constant, ℓ_{PH} , times the tower height, so that the total length is:

$$L_P = \ell_{PH} \times \text{THT} \quad (\text{III.G} - 13)$$

ℓ_{PH} should include the ground run to storage and the electric generating subsystem (EPGS) plus any necessary expansion allowances. The default value is based on an advanced salt design with storage and EPGS within one THT of the base of the tower plus a 30% increase for expansion:

$$\ell_{PH}(\text{FPLH}) = 2.6$$

- 2) The pipe diameter, D_P , scales directly with the square root of the flow rate, which is in turn directly proportional to the design thermal power delivered to the downcomer from the receiver. Referring to the previous Section for nomenclature:

$$D_P = \beta_P (\eta_{RC,R,DP} P_{th,R})^{0.5} \quad (\text{III.G} - 14)$$

where β_P = proportionality factor.

Piping losses are assumed to be proportional to the total pipe area. At the design point:

$$P_{\text{LOST},P} = \alpha_P L_P (\pi D_P) \quad (\text{III.G} - 15)$$

where α_P = proportionality factor. Combining Equations (III.G-13), (III.G-14), and (III.G-15) and defining $\alpha'_P = \pi \alpha_P \beta_P$,

$$P_{\text{LOST},P} = \alpha'_P \ell_{PH} \text{THT} (\eta_{RC,R,DP} P_{th,R})^{0.5} \quad (\text{III.G} - 16)$$

Following the approach in the previous Section for IRADFL=1, let $\eta_{P,DP}$ be the piping thermal efficiency at the design point, so that:

$$\begin{aligned}\eta_{P,DP} &= \frac{\eta_{RC,R,DP} P_{th,R} - P_{LOST,P}}{\eta_{RC,R,DP} P_{th,R}} \\ &= 1 - \alpha'_P \ell_{PH} THT (\eta_{RC,R,DP} P_{th,R})^{-0.5}\end{aligned}\quad (III.G - 17)$$

In analogous fashion, the yearly average piping efficiency, $\eta_{P,AVG}$ is calculated assuming that $P_{LOST,P}$ is constant through the year:

$$\begin{aligned}\eta_{P,AVG} &= \frac{E_{TOT,P} - H_{OP} \times P_{LOST,P}}{E_{TOT,P}} \\ &= 1 - \frac{H_{OP} \times \alpha'_P \ell_{PH} THT (\eta_{RC,R,DP} P_{th,R})^{0.5}}{E_{TOT,P}}\end{aligned}\quad (III.G - 18)$$

where $E_{TOT,P}$ = total energy delivered to piping per year ($=\eta_{RC,R,AVG} E_{TOT,R}$),
 H_{OP} = total number of hours of receiver (not plant operation).

As with finding α_R in the previous Section, α'_P is based on a reference design for which a detailed calculation is available. Rearranging Equation (III.G-17) and denoting the reference design values with a superscript $^{\circ}$ results in:

$$\alpha'_P = \frac{(1 - \eta_P^{\circ})(\eta'_{RC,R} P'_{th,R})^{0.5}}{L_P^{\circ}}\quad (III.G - 19)$$

Current default values are based on a salt design ($\eta_{RC,R}^{\circ}$ and $P_{th,R}^{\circ}$ given above):

$$\eta_P^{\circ} (\text{REFPIP}) = 0.990$$

$$L_P^{\circ} (\text{REFLP}) = 170.0 \text{ m}$$

III.G-5. Thermal/Electric Conversion Efficiency—There are two options for the design point thermal to electric conversion efficiency, $\eta_{TE,REF}$, identified by the user's choice of the parameter *ITHEL*:

- 1) *ITHEL* = 0 $\eta_{TE,REF}$ constant at all design point power levels;
value specified by the user
- 2) *ITHEL* \neq 0 $\eta_{TE,REF}$ varies with gross design point electrical output based on reported plant performance and designs (References 30-32)

The fit for option (2) is plotted in Figure III-3. For calculating total yearly electrical energy production for use in optimization, the yearly average thermal to electric conversion efficiency, $\eta_{TE,AVG}$, is assumed to be a constant fraction, f_{EFF} , of the design point value in order to account for off-design operation of the turbine plant:

$$\eta_{TE,AVG} = f_{EFF}\eta_{TE,REF} \quad (III.G - 20)$$

Note that during a final performance run (IPROB=0), the yearly average thermal to electric conversion efficiency is calculated as an average of the efficiencies at the time points throughout the year used to calculate annual energy (see Section III.H).

Default values are:

$$ITHEL = 0$$

$$\eta_{TE,REF} (ETAREF) = 0.42$$

$$f_{EFF} (FEFF) = 0.90$$

III.G-6. Process Heat Production—In design problems where only thermal energy is desired (i.e., no electrical production), the code can be flagged through variable IPH to automatically override the default electrical conversion calculation. A non-zero value of IPH in namelist NLEFF will set the following variables to the indicated values:

$$ETAREF = 1.0$$

$$FEFF = 1.0$$

$$CEPGS = 0.0$$

$$REFPRL = 0.0$$

$$FSP = 0.0$$

$$FEP = 0.0$$

$$ITHEL = 0$$

Output energy and energy cost labels as printed in both the optimization and final performance calculation sections will remain unchanged (MW_e and mills/KW-hr), but now the energy values will be in MW_{th} or KW_{th} .

III.G-7. Storage Efficiency—Round trip losses through storage are accounted for through variable EFFSTR, which is the net thermal efficiency, or (1.0 - round trip loss), of the energy sent through storage. Note that for molten salt or liquid

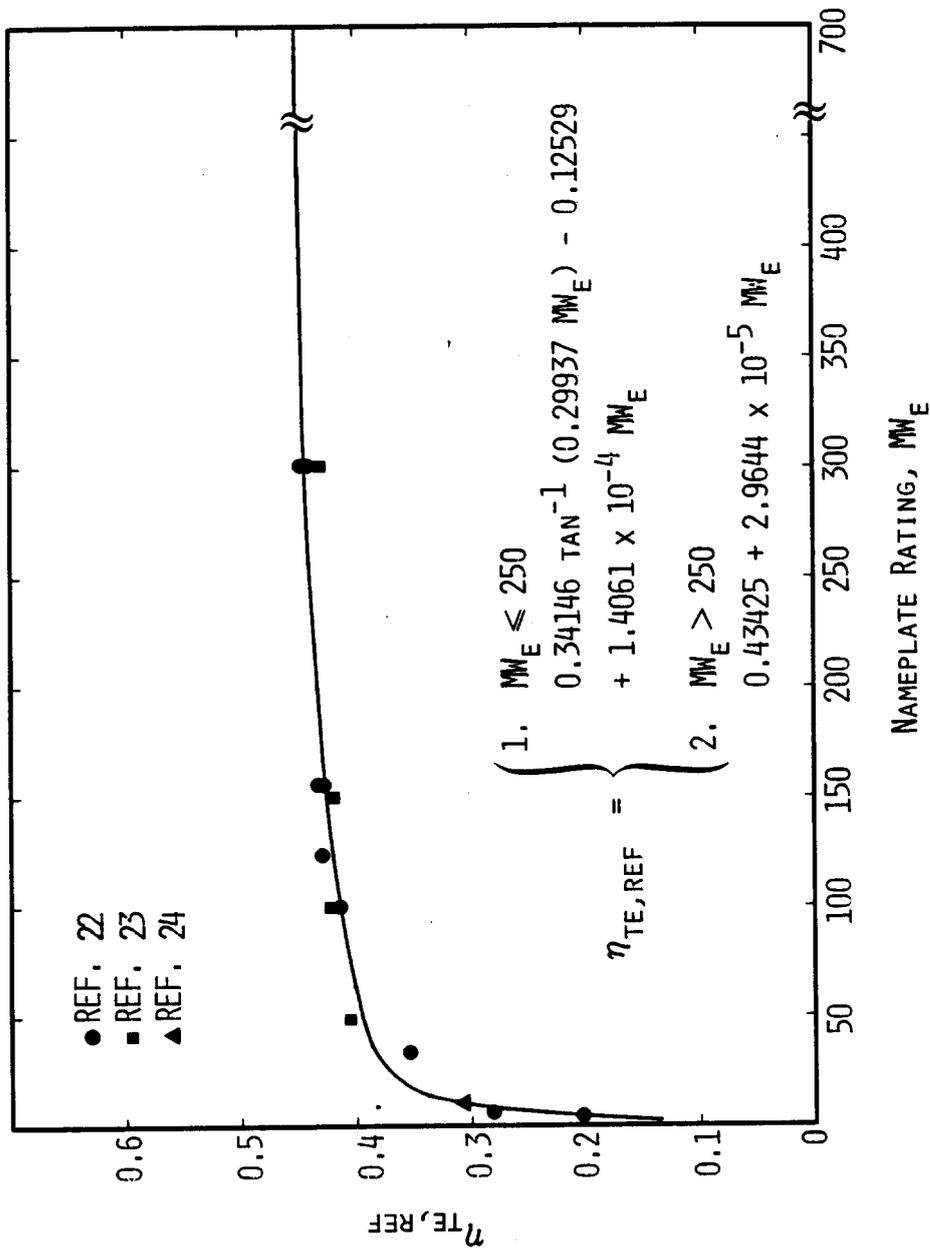


Figure III-3. Design Point Thermal to Electric Conversion Efficiency as Function of Turbine/Generator Nameplate Rating

sodium systems all energy from the receiver goes through storage before going to the electric generating equipment. The default value is consistent with a molten nitrate salt storage:

$$\text{EFFSTR} = 1.0$$

III.G-8. Parasitic Loads—The power rating and net yearly energy production of the plant include parasitic load factors (PL). At the design point:

$$\text{MW}_{\text{E,net}} = (1 - \text{PL}_{\text{REF}})\text{MW}_{\text{E,gross}} \quad (\text{III.G} - 21)$$

For system optimization purposes over the year:

$$\text{KW-HR}_{\text{net}} = (1 - \text{PL}_{\text{AVG}})\text{KW-HR}_{\text{gross}} \quad (\text{III.G} - 22)$$

where $\text{KW-HR}_{\text{gross}}$ includes an assumed weather outage.

This algorithm does not work well in calculating parasitic losses for systems with different solar multiples, since for that case the design point gross electric power and thus parasitic losses could be constant between different systems.

It is assumed that all energy from the receiver will be routed to storage, and that all energy to the turbine will come from storage. This means that the operating parasitic fraction REFPRL (Namelist NLEFF) should include parasitics associated with operating storage as well as operating the receiver and EPGS equipment. The only time at which REFPRL is not applicable is when, at the end of a day, the receiver shuts down and yet the turbine keeps operating from the energy remaining in storage. In this case, the parasitic fraction REFPRL is reduced to the fraction FSP, where FSP is the fraction of parasitic losses not attributable to field and receiver operation. This is the reason why PL_{REF} and PL_{AVG} differ from each other. Assuming that storage only operation requires this fraction f_s (FSP) of the design point parasitic load, then

$$\text{PL}_{\text{AVG}} = \frac{\text{Hr}_{\text{REC}}\text{PL}_{\text{REF}} + \text{Hr}_{\text{STOR}}f_s\text{PL}_{\text{REF}}}{\text{Hr}_{\text{REC}} + \text{Hr}_{\text{STOR}}} \quad (\text{III.G} - 23)$$

where $\text{Hr}_{\text{REC}} = \text{hrs/day of receiver operation}$
 $= \text{HROP}/365$
 $\text{Hr}_{\text{STOR}} = \text{hrs/day of storage operation (receiver shut down)}$
 $= \frac{\text{Energy stored}}{\text{MW}_{\text{e,gross}}/\eta_{\text{TE,REF}}}$

The amount of energy stored is dependent on the size of the storage tank(s). Section V.A-8 discusses in detail how storage is sized.

This approximate method of calculating PL_{AVG} is used during system optimization. However, during a final performance calculation (IPROB=0) the parasitic losses are calculated and averaged over the days and times for which energy calculation is accomplished, rather than depending on the approximation of hours of storage and hours of receiver operation.

The parasitic losses described above are only calculated when the plant (i.e., turbine) is generating energy. However, the total power plant also requires energy at other times, to run such mundane things as lighting and building heat, as well as to start and shut down equipment, such as unstowing the heliostat field or preheating the receiver. Reference 33 provides empirical relationships for non-operating parasitic losses as a function of rated gross electric power $P_{e,gross}$ for several different plant status conditions, such as at night, during maintenance outages, and during startup and shutdown of the plant. Specifically,

$$\begin{aligned}
 \text{startup/shutdown loss (MW}_e\text{)} &= PARL1 + PARL2 \times P_{e,gross} \\
 \text{prestartup/postshutdown loss (MW}_e\text{)} &= PARL3 + PARL4 \times P_{e,gross} \\
 \text{nighttime loss (MW}_e\text{)} &= PARL5 + PARL6 \times P_{e,gross} \\
 \text{weather loss (MW}_e\text{)} &= PARL7 + PARL8 \times P_{e,gross} \\
 \text{outage (PF) loss (MW}_e\text{)} &= PARL9 + PARL10 \times P_{e,gross}
 \end{aligned}
 \tag{III.G - 24}$$

All of the above parasitic losses need to be associated with some length of time in order to calculate the lost energy. It is assumed that the time of the PF outage (Namelist NLEFF) is $(1 - PF) \times 365 \times 24$ hours. Weather is assumed to be a fraction of all remaining time of the year as defined by $(1 - WEATH)$. Although in reality weather only affects daytime operations, this approximation is acceptable as long as the weather parasitic loss coefficients are not significantly different from night time loss coefficients. Times for startup/shutdown and prestartup/postshutdown operations are input by the user for the variables TSTRT and TPRES (Namelist BASIC) as the average time to perform one operation (either startup or shutdown, or either prestartup or postshutdown) for one day, in hours. Night time is defined to be the time left after all other times are accounted for, including startup/shutdown, prestartup/postshutdown, maintenance outages, weather outages, times when the receiver is operating (HROP), and times when the receiver is shut down but energy is being generated from storage. Note that startup and prestartup times do not reduce the hours of operation, since hours of operation of the receiver are fixed by the user's choice of the variable ASTART.

Defaults for all parasitic loss variables are as follows:

$$PL_{REF} (REFPRL) = 0.103$$

$$f_s (FSP) = 0.66$$

FEP = 0.0
TPRE = 1.0 hour
TSTRT = 1.0 hour
PARL1 = 0.5
PARL2 = 0.103
PARL3 = 0.5
PARL4 = 0.103
PARL5 = 0.5
PARL6 = 0.008
PARL7 = 0.5
PARL8 = 0.008
PARL9 = 0.18
PARL10 = 0.009

III.H. Energy Calculation During a Performance Run

A system is designed by DELSOL to have a certain power rating at a fixed point in time. Further, DELSOL calculates the field efficiencies at times throughout the year as defined by the variables NYEAR and HRDEL. However, the criterion by which DELSOL chooses an optimum system is that of lowest levelized energy cost, which is a function of equipment costs and of the net annual energy output of the plant. (Costs will be discussed in Chapter V.) Annual energy is calculated in two ways in DELSOL, once as an approximation for use in system optimization and once in detail vs. time in a final performance calculation (IPROB=0). A sample waterfall chart, without values, is shown in Figure III-4 to indicate the bookkeeping which DELSOL does to calculate annual energy.

For either an initial performance run for use in system optimization or a final performance run (IPROB=4 or 0) the code calculates the hours of receiver operation (HROP) and annual insolation based on the values of ASTART, WEATH, and INSOL. Next, field efficiencies are calculated for each time HRDEL over each day NYEAR. From this point on, annual energy is calculated during system optimization by using yearly insolation to calculate annual energy to the receiver and then using that value to subtract out receiver losses (Equation III.G-11) and piping losses (Equation III.G-18). Storage is assumed to be large enough to store any excess energy during optimization, so that none is discarded. Next, the turbine is assumed always to run at off-design conditions for optimization, having an average annual conversion efficiency of $ETAREF \times FEFF$. This is probably the

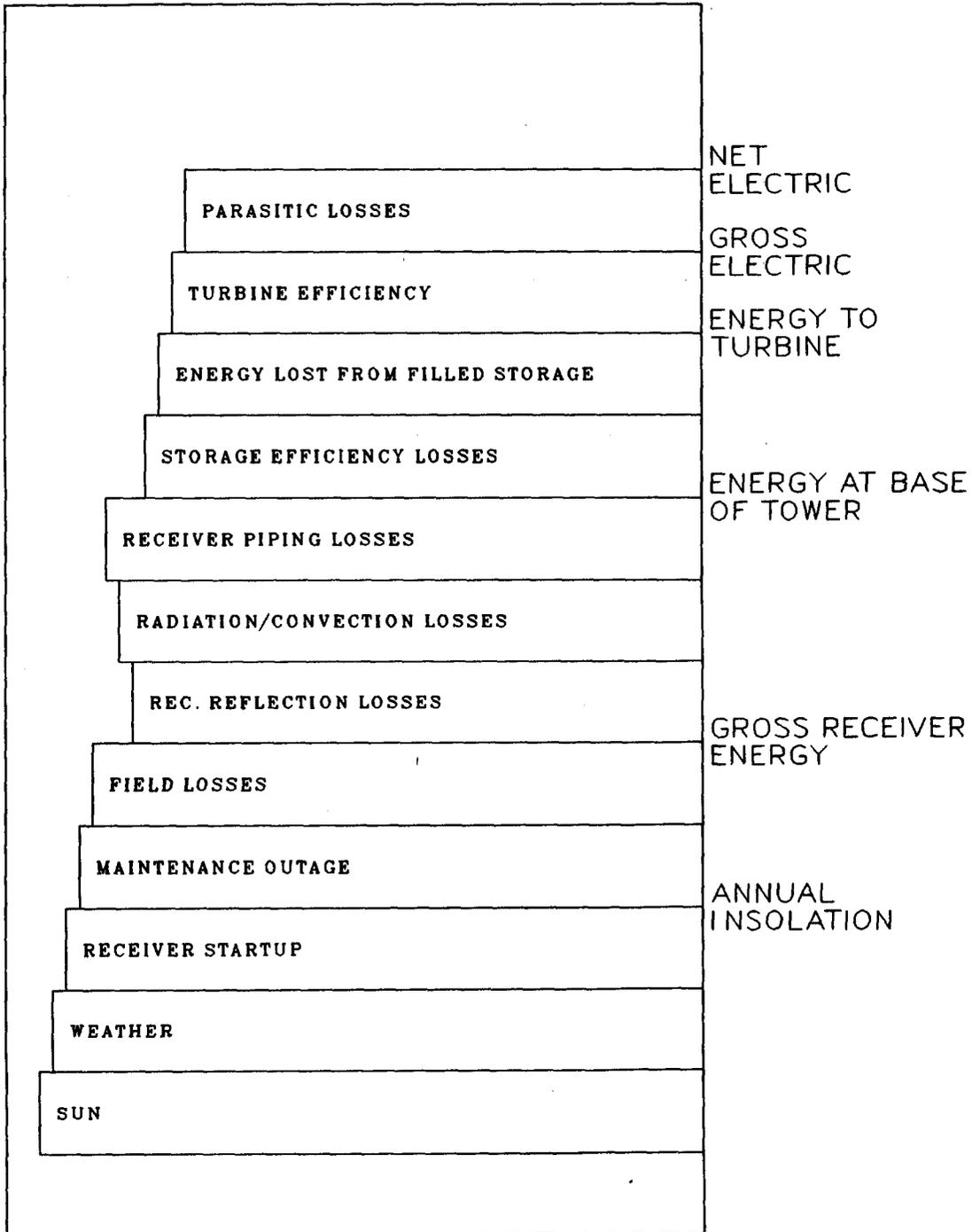


Figure III-4. DELSOL Energy Flow Diagram

least accurate assumption of optimization, since if storage is large, then the turbine will operate mostly at design point power conditions. Finally, parasitic losses are dependent on HRDP, the amount of storage, and other annual values such as annual weather or maintenance outages. Also, this final annual energy value will be reduced by the maintenance outage factor (PF).

For a final performance run (IPROB=0), energy is accounted for at NYEAR days and HRDEL time increments through the day. That is, power on the receiver at each point in time is reduced by receiver losses at that time, is routed to storage and discarded if storage is full, and is then routed to the turbine. If the power level is high enough to run the turbine at full power, then the conversion efficiency will be ETAREF, or else the conversion efficiency will be FEFF \times ETAREF. Operating parasitic losses will reduce the output from the turbine. This gross energy value will be reduced by the maintenance outage factor. The actual times of all operations are recorded and summed, and the total summations are used to calculate the level of non-operating parasitic energy losses.

Although the detailed performance energy summation is more detailed than that used during system optimization, at least three factors keep that calculation from matching well any known output from a solar power plant. First, the weather/insolation in actuality varies with time and may not equal the DELSOL assumed values during any specific time interval. This may affect how much energy is discarded because storage is full or how much energy is left in storage when the receiver shuts down, as well as just the energy produced during that time interval. Second, some additional amount of lost energy is going to be required over what DELSOL predicts in order to start up the turbine and heat exchanger equipment. It may take as much as an hour of feeding thermal energy to the turbine before any electricity is produced by the turbine. Finally, different operational tactics may produce different amounts of annual energy for the same system and set of conditions. DELSOL assumes that the turbine starts when the receiver starts and that storage is depleted every night. From an income standpoint, however, it may be wise to operate the turbine only during high energy demand times when the price paid for the energy will be highest, even if that means either throwing away energy at other times or having a larger storage tank than DELSOL designs in order to operate at certain times.

DELSOL annual energy results should be considered by the user to be approximate values. If more exact numbers are desired, a separate computer code should be used which incorporates actual weather and operating strategies in order to calculate annual energy. The field performance and cost information from DELSOL will be reasonably accurate, however, so that a final leveled energy cost could be calculated using DELSOL's cost/economic information and the annual energy from an independent calculation, where that independent calculation could use the field performance information from a DELSOL final performance calculation.

III.I. Relationship Between Performance and Optimization Calculations

In order to do a system optimization, the results of an initial performance calculation must be used. It is also suggested that a final performance run be done on any system which was optimized, in order to get a more accurate field performance calculation and in order to get a more accurate annual energy calculation for predicting levelized energy costs.

During optimization, DELSOL must recalculate the zone by zone annual average and design point optical performances at each new tower height and receiver size. The code does this by "scaling" the results of a detailed performance calculation. The results which are scaled are the descriptions of heliostat images on the receiver for each zone. That is, the initial performance run calculates heliostat images for each zone for each time step, and from that information calculates an annual average heliostat image for each zone. This annual average heliostat image is then scaled with tower height during system optimization and is combined with the design point and annual average field and system efficiencies to calculate design point power and annual energy.

The cosine, shadowing and blocking, and atmospheric attenuation losses used in the system optimization are described in Section IV.A, and all make a distinction between design point and annual average losses. However, the annual average heliostat image is used for both design point power and annual energy calculations during the optimization. This has two possible effects. First, if actual design point spillage is significantly different from the annual average spillage, then the optimization may over- or underpredict the design point receiver thermal power. This difference would become apparent if a final performance calculation were done on that optimized system, during which the correct design point spillage would be calculated and used. This difference is usually less than 1%. Second, the **shape** of the design point heliostat image may be different from the annual average. This would result in a different flux distribution being predicted during system optimization than during a final performance calculation. Thus, a design which was optimized to meet flux levels at certain locations on a receiver may actually exceed or fall short of those flux levels when a more accurate performance calculation is done on the system. This effect could be up to a 10% difference in predicted flux levels but is typically less than 5%.

Because the results of an initial performance run are used during system optimization, it is strongly recommended that the system for which the optimum performance is calculated be as close as possible to the final configuration chosen during system optimization. Specifically, a north facing cavity or flat plate should have the variables IREC and INORTH set consistently, in addition to having receiver and tower dimensions chosen as wisely as possible.

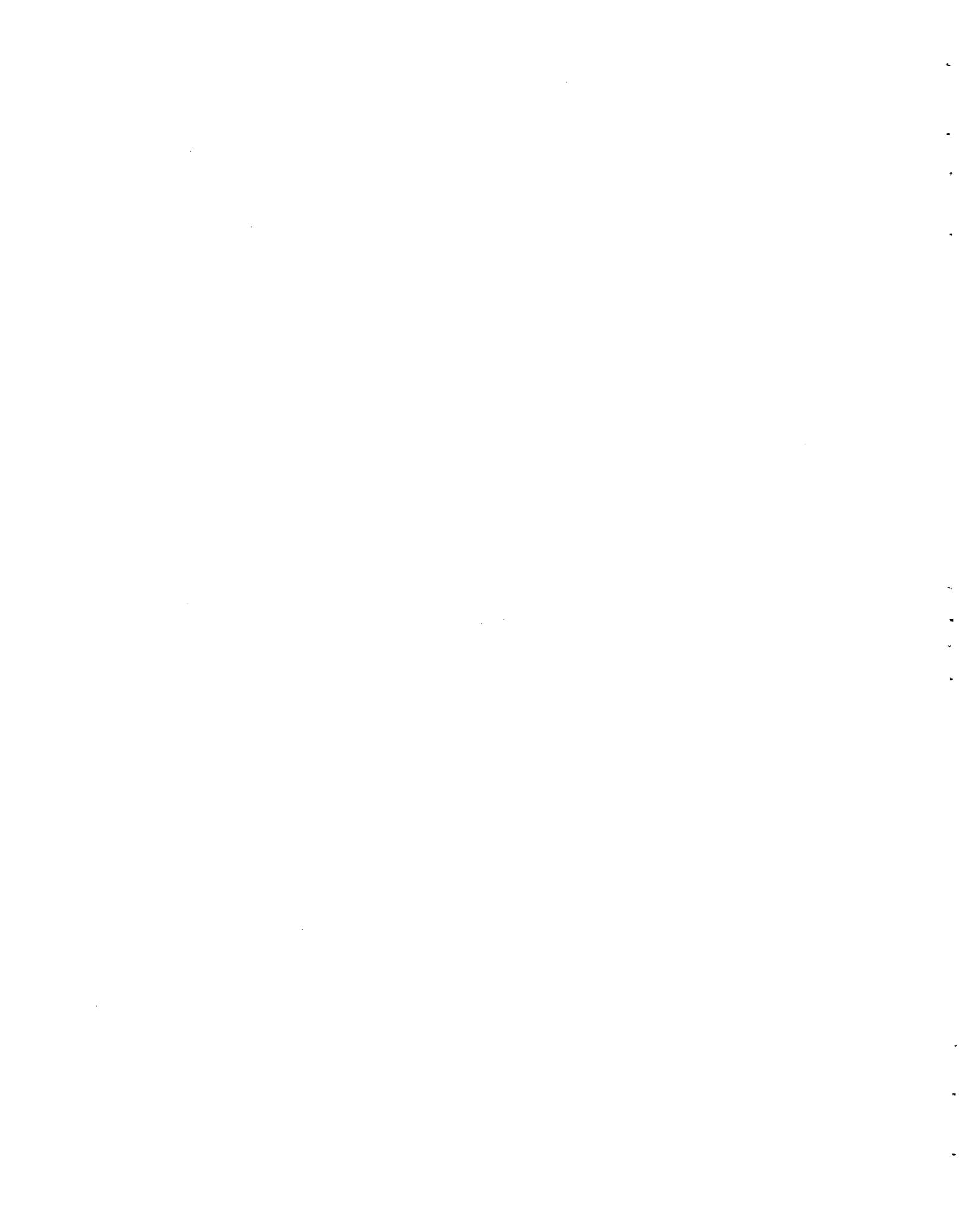
Similarly, the system configuration should not be changed in a final performance run if it is desired to determine the performance of a previously optimized system. Further, the capital costs of equipment are **only** calculated during the optimization process and are not modified in a final performance run. Thus, if

the receiver or tower dimensions or field configuration were changed, the costs and thus energy costs would no longer be correct for the modified system. (However, storage costs may be modified due to storage optimization which was requested during the optimization process but which is actually accomplished during a final performance run. See Section IV.C-5.) It is strongly suggested that only the input relating to flux calculations be varied during a final performance calculation of a previously optimized system using DELSOL.

III.J. Performance of Small Systems

DELSOL can be used to design systems having small power levels, if certain precautions are observed. The accuracy of Hermite polynomials, used to predict flux and spillages, becomes less when the slant range decreases with respect to heliostat and receiver sizes, or when receiver dimensions decrease for a constant heliostat size. Thus, for the most accurate results for small systems the use of a smaller heliostat might be required. Use of a smaller heliostat will also reduce the actual amount of spillage, especially when the image size is greater than the receiver size. One further advantage of using small heliostats is seen for DELSOL calculations on very small systems. DELSOL calculates heliostat images for each zone. However, if less than one heliostat is in each zone, then the DELSOL calculated image may be smaller than in actuality. By using more and smaller heliostats, the zonal approximation that DELSOL makes will not become invalid.

If different sized heliostats are used, it is necessary for the user to also vary the cost of heliostats (dollars/m²), since it is commonly accepted that smaller heliostats cost more per unit area. Also, turbine efficiencies and parasitic losses should be adjusted properly to account for the lower power levels and perhaps less efficient components that would be required.



IV. System Optimization Calculations

The purpose for which DELSOL was written was to allow quick and simple comparisons of different systems to determine which system produced the lowest energy cost. Specifically, systems with different receiver/tower dimensions, different power levels, heliostat spacings, and storage capacities can be compared without performing multiple executions of the code with different sets of input. Further, the different systems are compared during a single run by scaling system performances from an initial performance calculation, so that a time consuming performance calculation is not needed or used during system optimization, thus resulting in the other advantage of using DELSOL to compare different systems. Although both performance and energy values are used during optimization to compare different systems, it must be remembered that the optimization procedure is an approximation calculation. Thus, it is important that the user use DELSOL to do a final, more accurate, performance calculation on any system which is chosen to be best during system optimization based on levelized energy cost.

Because the optimization is based on the cost of energy, calculations are done during system optimization to determine the cost of individual system components and to determine the cost of certain economic assumptions. The methods in Chapter 5 for determining costs are used during system optimization.

During system optimization, DELSOL not only compares different systems, but also defines the heliostat field to meet the required power level. This is the only time when DELSOL changes the field dimensions and number of heliostats. In fact, that is an essential part of the optimization. The optimization compares systems of similar design point powers, but since field efficiencies can vary between systems, the number of heliostats must be varied during optimization to reflect that difference in efficiencies for the same power level.

IV.A. Optimization Methods for Calculating Performance and Energy

DELSOL must recalculate the zone by zone annual average and design point optical performances at each new tower height and receiver size, as shown in Figure IV-1, in order to design a system which produces the requested design point power and in order to do a comparison of energy cost. The code does this by "scaling" the results of a detailed initial performance calculation. The results which are scaled are the descriptions of heliostat images on the receiver for each zone. That is, the initial performance run calculates heliostat images for each zone for each time step, and from that information calculates an annual average heliostat image for each zone. This annual average heliostat image is then scaled with tower height during system optimization, and is combined with the design point and annual average field and system efficiencies to calculate design point

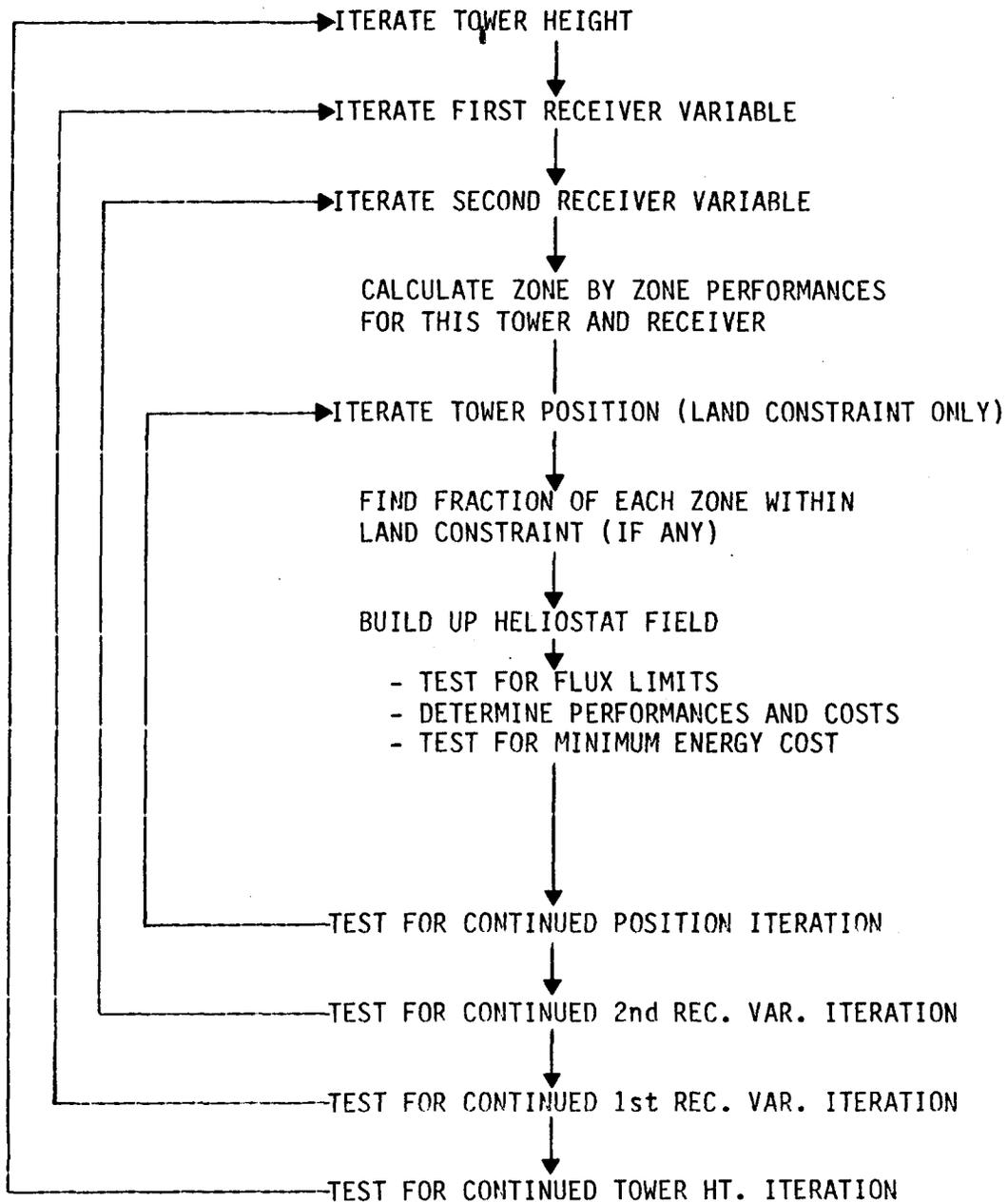


Figure IV-1. Schematic of Optimization Search

power and annual energy. Section III.I discusses the effect this approximation might have on calculating design point receiver thermal power during system optimization. Essentially, the approximation is good if design point spillage is close to annual average spillage. However, the shape of the image at design point may well be different from the annual average, so flux levels at a specific point may be up to 10% different than calculated during a final performance run.

The cosine, shadowing and blocking, and atmospheric attenuation losses used in system optimization are calculated using minor assumptions of the effect of scaling with tower height and receiver size, as discussed below. Unlike spillage and flux calculations, these losses are calculated separately for design point and for annual averages used during the optimization.

DELSOL designs a field for each system during optimization by using the insolation value REFSOL and the design point efficiencies as discussed below, and by adding zones or fractions of zones based on best cost/performance until the requested design power is reached. Note that total yearly insolation, which is used for calculating annual energy, is calculated during the initial performance run dependent on the insolation model chosen, and the design point insolation as predicted by that model may be different from REFSOL. For an actual plant, insolation at design point will vary due to weather conditions, but if design point insolation is reached (REFSOL) then design point performance predictions will be valid.

IV.A-1. Cosine—The field points remain at the same relative position in units of tower height as the tower height is varied. The angles between the sun, heliostat, and receiver (Section II.A) remain the same, and therefore the cosine is not a function of the tower height. The very small change in the cosine as the receiver width from the tower centerline is varied is ignored. Thus, only one design point and one annual average loss calculation is needed for examining a set of systems during optimization.

IV.A-2. Shadowing and Blocking—The actual shadow cast by a heliostat in the same relative field position is independent of the tower height. However, the displacement of heliostats relative to each other in radial layouts depends on the ratio of the heliostat dimension to the tower height. Hence, the shadowing and blocking has a small dependence on the tower height. The code, however, neglects this effect. For large systems, i.e., heliostat dimension/tower height $\ll 1$, this approximation is excellent. In smaller systems, the effect can be noticeable, but the generally small amount of shadowing and blocking even in these systems does not significantly affect overall system performance and energy costs. **In a small system design run, the user is advised to select a tower height (THT) for the initial performance run within the range to be searched in the optimization.** For example, if a small system is being optimized with tower heights of 30 to 50 meters, then the default value of 175 meters for THT should be replaced with 40 meters in the initial performance run.

Only one design point and one annual average loss calculation is done during system optimization, and the results are used for all systems examined.

IV.A-3. Atmospheric Attenuation—The atmospheric attenuation is exactly recalculated for every tower height and receiver examined during system optimization.

IV.A-4. Tower Shadow Scaling—DELSOL accounts for the tower shadow as described in Section III.E-2. The tower shadow as calculated or specified in an initial performance run is scaled with tower height during optimization. That is, the last specified tower shadow (TOWL, TOWD in Namelist REC) is scaled by the ratio of the current tower height to the tower height specified in the initial performance run. Thus, it is suggested that TOWL and TOWD be specified in the initial performance run to match the tower dimensions, and then that these variables not be changed during optimization input.

IV.A-5. Receiver Losses—Receiver design point losses are calculated using the algorithms described in Section III.G-3, depending on the receiver dimensions of each system examined during system optimization. It is assumed, as for a final performance calculation, that receiver losses represented as an efficiency do not vary with time of day or year, so annual receiver efficiencies are the same as design point efficiencies.

IV.A-6. Other Component Losses—Components downstream from the receiver have simple loss calculations, as described in Section III.G, and so these losses are calculated as described in that Section. These losses are assumed to be time independent, so annual efficiencies are the same as design point efficiencies. However, **the turbine annual efficiency is assumed to equal its off-design point efficiency**, as represented by the value ETAREF x FEFF (Namelist NLEFF). This worst case assumption is made because the code does not know during optimization the amount of time the turbine will actually have enough power to run at its rated capacity. The actual annual efficiency, and therefore the amount of annual energy, will always be higher than this assumption would indicate. This assumption could and usually does cause the largest difference in predicted annual energy (levelized energy cost) between an optimization calculation and the comparable final performance calculation on the same system. Since the final performance calculation is more exact, its annual energy prediction and levelized energy cost values should be used if a discrepancy exists with system optimization predictions.

The turbine annual efficiency assumption is not a very good assumption for systems which have reasonable quantities of storage to supplement power from the field, since for those cases storage will be used to operate the turbine at full power. The assumption was originally made based on water-steam systems. Although the assumption affects the actual energy and cost values calculated during optimization, the comparison determining which system is better should only be slightly affected, and so the assumption is acceptable for this purpose.

IV.A-7. Calculation of Annual Energy During System Optimization—In order to determine which system has the best levelized energy cost, an approximate calculation of annual energy is done during system optimization. This calculation makes several assumptions. First, the calculation uses the annual performance as described above. This annual performance is represented as a field efficiency multiplied by a balance of plant efficiency. Remember that the assumed annual turbine efficiency approximation causes the largest error in this calculation. The field area as described below is combined with the average annual insolation, as calculated in an initial performance run, and the plant efficiencies to calculate a gross annual energy. It is assumed during optimization that storage is large enough so that no energy is ever discarded (no heliostats ever deactivated due to excess power). Annual energy is calculated by subtracting operating and non-operating parasitic losses, based on hours of operation from the field and from storage only as calculated during the initial performance run. Finally, net annual energy is calculated by incorporating the maintenance outage factor into the predicted energy value. Note that, contrary to what is done in the performance calculations, time is not considered directly in calculating annual energy. Time is only considered indirectly as, during an initial performance calculation, it affected the calculated yearly insolation and hours of operation which are then used during optimization.

IV.B. Heliostat Field Buildup

During optimization, DELSOL works with the field defined by the minimum and maximum field dimensions and the heliostat densities in each zone, for which performances were calculated during an initial performance calculation. Each zone is rated by a performance/cost ratio, and zones are filled in with heliostats, starting with that zone having the best performance/cost ratio, until a requested power is reached. This field buildup is done for each system examined during optimization. Field costs associated with each field buildup are calculated and used to determine the optimum system. Once an optimum system is chosen, the heliostat field associated with that system remains constant during any future final performance calculations.

DELSOL allows the user to not only build up a heliostat field zone by zone during optimization, using default heliostat density relationships within each zone, but also to optimize the densities of heliostats within each zone. In this case, densities are varied around the default values, and a system is optimized to give best cost for a constant annual energy. This optimization is done in conjunction with the field buildup procedures, and thus the total system is still designed to a constant design point power, rather than energy. The ramifications of this will be described in Section IV.B-3.

IV.B-1. No Heliostat Density Optimization (IHOPT = 0)—In this case DELSOL does not try to vary the default or user defined heliostat field densities, as defined by the choice of IDENS (Namelist FIELD). A performance/cost ratio, PCR, is determined for each zone:

$$PCR_{k,l} = \frac{\eta_{F,k,l}}{C_{H,k,l}} \quad (IV.B - 1)$$

where k = radial zone index
 l = azimuthal zone index
 $\eta_{F,k,l}$ = yearly average field efficiency in zone (k, l)
 $C_{H,k,l}$ = cost of putting 1 m² of reflective surface in zone (k, l)
relative to the same cost for zone $(1,1)$.

In more detail,

$$\eta_{F,k,l} = \eta_{COS,k,l} \times \eta_{SHAD,k,l} \times \eta_{BLOCK,k,l} \times \eta_{ATM,k,l} \times \eta_{INT,k,l}$$

where η_{COS} = cosine efficiency = 1.0 - cosine loss
 η_{SHAD} = shadowing efficiency = 1.0 - shadowing loss
 η_{BLOCK} = blocking efficiency = 1.0 - blocking loss
 η_{ATM} = atmospheric transmittance = 1.0 - atmospheric attenuation
 η_{INT} = receiver intercept factor = 1.0 - spillage

The relative mirror cost is comprised of three parts:

$$C_{H,k,l} = \frac{C_{HEL,k,l} + C_{LAND,k,l} + C_{WIRE,k,l}}{C_{HEL,1,1} + C_{LAND,1,1} + C_{WIRE,1,1}} \quad (IV.B - 2)$$

where $C_{HEL} = \frac{\$}{\text{m}^2 \text{ mirror area}}$ for total heliostat structure,
equal for all heliostats in the field

$C_{LAND} = \frac{\$}{\text{m}^2 \text{ land}} \times \frac{1}{\text{mirror density per zone}}$; less dense zones
have greater associated land costs per heliostat

$C_{WIRE} = \frac{\$}{\text{heliostat}} \times \frac{1}{\text{glass area/heliostat}}$; the "\$/heliostat" varies
with local density (greater secondary wiring costs with lower
densities) and distance from the tower (greater primary wiring
costs as the field gets larger), as discussed in the wiring
cost model Section (V.A-3).

A $PCR_{k,l}$ is calculated for each zone, and the zones are ranked from best to worst PCR before optimization starts. To build up a field, the zones are added one at a time, starting with the most cost effective, i.e., the one with the highest PCR. As each zone is added, the design point thermal power to the receiver, the annual energy production from the field, and the total field costs (heliostats, land, and wiring) are updated. Also, the power dependent receiver and piping radiation and convection losses are recalculated to determine the net electrical power

production. When each design power of interest (as specified by POPTMN, POPTMX, and NUMOPT in Namelist OPT) is reached, the remaining plant capital costs and corresponding levelized energy cost (LEC) are calculated.

IV.B-2. Helioostat Density Optimization (IHOPT=1)—DELSOL has an option to optimize the helioostat separations within each zone at the same time that the field is being built up. In many problems the default densities are adequate. However, if the field costs or helioostat shape are very different from the DELSOL default values, then helioostat spacing optimization may be important. In all cases it is prudent to optimize helioostat separations periodically to see if this produces significant improvement in the energy cost, although Section IV.B-3 will explain why energy cost may not always be improved for a constant design point power.

The mathematical details of helioostat optimization are derived by Lipps (Reference 4). DELSOL bases its helioostat optimization on these equations and assumptions. A completely general optimization of the coordinates of every helioostat is not practical. Following the approach in Reference 4, the following assumptions are made in order to simplify the problem:

- 1) the helioostat layout pattern within any one zone is determined by two parameters: the "average" radial separation ΔR and the "average" azimuthal separation ΔAz ;
- 2) the shadowing and blocking in a zone are determined only by the layout parameters for that zone;
- 3) the optimum layout parameters to produce a given amount of annual energy will be determined. These may or may not be the optimum layout parameters to produce a given design power. This subtle point is discussed in more detail below; and
- 4) the maximum deviation of the optimized ΔR and ΔAz is constrained to be within a specified window around the initial ΔR and ΔAz defined for each zone in Namelist BASIC (IDENS). The size of the window of variation is controlled by DHOPT in Namelist BASIC.

Because the energy cost is not very sensitive to the helioostat spacings, the effect of the simplifying assumptions in most practical problem is minimal.

In order to optimize helioostat separations, DELSOL must generate considerable information about the shading and blocking as a function of helioostat position. When helioostat density optimization is requested, the code does 25 shadowing and blocking calculations for each zone during the initial performance calculation. The calculations are done on a 5×5 grid of helioostat separations. One side of the grid has constant density lines; the other side has constant aspect ratio lines ($= 0.5\Delta R^2 - 0.5\Delta Az^2$). The grid is used to interpolate the performances and performance derivatives with respect to separation required in helioostat spacing optimization. The grid is centered on the density and aspect ratio determined for each zone by the ΔR and ΔAz defined in Namelist FIELD. The size of the grid is

determined by DHOPT (Namelist BASIC). The larger DHOPT is, the farther the heliostat separations are allowed to vary from the initial values in searching for an optimum. However, the larger DHOPT becomes, the larger are the potential errors in interpolation and differentiation.

To prepare for field buildup, the code does four preliminary calculations for every zone. First, it finds the "best" aspect ratio at each density. If the land and wiring costs are negligible, the best aspect ratio at a given density would be the aspect ratio that gives the minimum shading and blocking. Second, the code finds the density that gives the maximum average performance/cost ratio (PCR) for that zone. When the zone is first added to the field, it will be at this density. Third, DELSOL finds the marginal value of increasing the density beyond the density that optimizes the average PCR. The marginal value is defined as the change in the busbar energy cost for adding or subtracting one heliostat from that zone. The marginal values decrease with density beyond the density that optimizes the average PCR. These marginal values determine how the density in the zone is increased during field buildup after the zone has been added to the field. Finally, when the first three calculations are completed for every zone, DELSOL ranks the zones accordingly from maximum to minimum average PCR. This ranking determines the order in which zones will be added to the field.

Field buildup proceeds as follows:

- 1) The zone with the best average PCR is used as the initial field zone; then,
- 2) The unused zone with the best average PCR is added to the field and the density of all zones already in the field is increased. The number of heliostats to be added to each zone already in the field is determined by requiring that the marginal value of adding one more heliostat to any zone is the same. (If the marginal values were unequal an optimum field would not exist since the energy cost could be lowered by moving a heliostat from a lower to a higher marginal value zone.);
- 3) Step (2) is repeated until: (a) all design powers are achieved; (b) a flux limit constraint is exceeded; or (c) all the zones have been added to the field.

IV.B-3. Effectiveness of Heliostat Density Optimization—DELSOL optimizes heliostat densities to produce a given amount of annual energy, E , at a minimum energy cost. However, in many cases the optimization results in a field layout having a lower annual efficiency/design efficiency ratio, thus producing less annual energy at a constant design point power. That is, although the annual efficiency after optimization will be higher (requiring fewer heliostats for a given amount of annual energy), the design point efficiency might be increasing even more rapidly. Since the heliostats are only added until the design point power is reached, fewer heliostats would be in the field than if the annual energy were kept constant, so the annual energy might not be as large as before. Thus, capital cost of heliostats and annual energy both might decrease. Then, if field cost is a

large enough fraction of total capital cost so that total capital cost decreases by a greater amount than annual decreases due to optimization, the levelized energy cost will decrease. However, for designs in which field costs are not as significant, the annual energy might decrease more than total capital cost (as a percentage), and thus LEC could increase due to heliostat density optimization at a constant design point power. In either case, if the user plots energy cost vs. annual energy, then improvement with heliostat spacing optimization can be seen.

In practice the difference in the energy costs between optimizing for a given annual energy vs. optimizing for a given design point are small ($< 1\%$). The difference disappears (i.e., optimizing for annual energy acts like optimizing for design point) if the non-field costs are relatively small or if the energy cost is not changing with annual energy. Why doesn't DELSOL offer the option of finding the system optimized to produce a given design point power? Because it is much more complicated and the small improvements are generally not significant.

The user should at least consider having the code do heliostat optimization. However, if after optimization levelized energy costs are higher than before, then density optimization will not help the user and should not be used for that problem.

IV.C. Variables With Which DELSOL Optimizes

DELSOL can vary certain design variables during optimization to perform a search for the combination of variables that minimizes the levelized energy cost (LEC). The design variables or parameters which can be varied during a single DELSOL run are listed in Table IV-1. The design parameters that are held constant during a single optimization search are listed in Table IV-2. This second set of variables can be "optimized" by performing several DELSOL optimization runs, each run having different values for these variables.

DELSOL can perform optimizations for systems with certain restraints. These restraints are a limitation on peak incident flux allowed on the receiver, and a restriction on the land available for the heliostat field. In this case, an optimum system design must have a combination of system design variables which produces the lowest LEC and which also meets the flux and/or land constraints.

Note that the computer time required for optimization will depend on the size of the matrix over which optimization is being performed. For instance, if the user allows a choice of 5 values each for tower height and receiver dimensions, then up to $5 \times 5 \times 5$ (125) calculations will be done during optimization; but if a choice of 10 values each is allowed, then up to $10 \times 10 \times 10$ (1000) calculations will be done. Thus the user is cautioned to choose the range of optimizations carefully so as to minimize computation time.

If the values of NUMTHT, NUMREC, or NUMHTW are set to 1 (allowing no variation in tower height or receiver dimensions), then the values which are used

Table IV-1.
Design Parameters Varied During Optimization

Note that some of the variables can have only discrete values (e.g., either 100 m or 120 m tower heights) while others are varied continuously.

-
- Design point power level (discrete values)
 - Tower height (discrete values)
 - Receiver dimensions (discrete values)
 - External cylinder
Height and diameter
 - Flat plate(s)
Height and width
 - Cavity(ies)
Height and width of aperture
-or-
Width of aperture and depth of cavity
 - Tower location for land constrained system (discrete values)
 - Field boundaries (continuous values)
 - Heliostat spacings (continuous values)
 - Storage capacity at a given solar multiple (discrete values)
-

Table IV-2.
Design Parameters Held Constant During A
Single Design Optimization Run

These parameters can be optimized only by doing several runs, each with a different value for the parameter of interest.

- Site
 - Latitude
 - Insolation
 - Weather
 - Atmospheric attenuation

 - Field
 - Type (surround or north-only zoning)
 - Heliostat layout pattern
 - Minimum and maximum radial boundaries

 - Heliostat
 - All design parameters

 - Receiver
 - Receiver type (external cylinder or flat plate or cavity)
 - Orientation of cavity aperture or flat plate
 - Ratio of dimensions of 2nd, 3rd, 4th apertures or flat plates (if any) to that of the 1st

 - Solar Multiple
-

for calculation are the values specified in the last REC Namelist, and any range of variables specified in the OPT Namelist are ignored.

IV.C-1. Design Point Power Level—DELSOL can simultaneously optimize systems at NUMOPT (≤ 20) equally spaced discrete design point power levels from a minimum value of POPTMN to a maximum value of POPTMX (watts). The design point occurs at REFTIM hours past noon on the REFDAY day of the year (Namelist BASIC). The insolation at the design point is assumed to be REFSOL kw/m^2 during optimization, despite the fact that during a performance calculation the calculated insolation from the chosen insolation model might have a different value. Thus, at the design point conditions the design point power level will be reached (as designed), but for different conditions the actual power level might vary. The requested power levels are reached by building up the heliostat field until that power is reached for a specific tower and receiver geometry.

IV.C-2. Tower Height—DELSOL can search over NUMTHT (≤ 20) equally spaced discrete values of the tower height from a minimum value of THTST meters to a maximum value of THTEND meters. The tower height to be specified is the optical tower height, or the elevation of the midpoint of the receiver above the plane of the heliostat pivot (see Figure II-13). The optical tower height is used in all DELSOL calculations except the tower capital cost calculation, which uses the height from the ground to the bottom of a transition region between the tower and the receiver. All references in job inputs and outputs to tower height refer to the optical tower height. If NUMTHT=1, the tower height will be fixed during optimization at the last defined value of THT (Namelist REC).

IV.C-3. Receiver Dimensions—DELSOL can search independently over two separate receiver dimension variables. Although the same names for the variables are used for all different receiver types, the meaning and definition of the variables depends on the type of receiver as specified by the value of IREC (Namelist REC):

- a) External Receiver Dimensions—The first receiver variable for an external receiver is the diameter W of the receiver. There are NUMREC (≤ 20) equally spaced discrete values of W from a minimum of WST meters to a maximum of WEND meters. The second variable which can be optimized is the ratio of the receiver height H to the receiver width W. There are NUMHTW (≤ 20) equally spaced discrete values of H/W from a minimum of HTWST to a maximum of HTWEND. If NUMREC or NUMHTW is set to 1, the value of the receiver variable will be fixed to be the last defined value of the appropriate variable (W or H) in Namelist REC.
- b) Flat Plate Receiver Dimensions—The first receiver variable for a flat plate receiver is the horizontal dimension of the first flat plate, RX(1). There are NUMREC (≤ 20) equally spaced discrete values of RX(1) from a minimum of WST meters to a maximum of WEND meters which are examined during optimization. The second receiver variable is the ratio of the first plate's vertical dimension to its horizontal dimension, RY(1)/RX(1).

DELSOL will examine NUMHTW (≤ 20) equally spaced discrete values of RY(1)/RX(1) from a minimum of HTWST to a maximum of HTWEND. If NUMREC or NUMHTW is set to 1, the value of the receiver variable will be fixed to be the last defined value of the appropriate variable (RX(1) or RY(1)) in Namelist REC.

In the case of multiple flat plate receivers, all receiver dimensions are assumed proportional to the first receiver's dimensions. RX2TRX, RX3TRX, and RX4TRX are the ratios of the second, third, and fourth plate's horizontal dimension to the first plate's horizontal dimension. The vertical/horizontal ratio, RYTRX, is assumed the same for all plates.

- c) Cavity Receiver Dimensions and Optimization—DELSOL assumes during optimization that a cavity receiver has an aperture which can be treated like a flat plate receiver as described above. It also assumes that the cavity is shaped as a semicircular right cylinder centered horizontally on the aperture, so that the heat absorbing surface depth needs to be determined. Further, the optimum height of the heat absorbing surface should be determined, in order to find an optimum system based on levelized energy cost (LEC). These are more design parameters than DELSOL can vary at one time, thus making cavity receivers more complicated to design than other receiver types. However, because varying some of these variables does not affect the optimum choice (based on LEC) of other of the variables, it is possible to run a series of optimization and performance runs that will lead to a "good" cavity design. This is especially true because almost all power calculations for cavities are done at the aperture (all except convective losses), so that power and energy are nearly independent of the configuration of the interior of the cavity. Thus, cavity depth and heat absorber height, which depend on flux levels and cost, can be optimized separately from aperture dimensions without affecting the optimum choice of those variables.

Different pairs of receiver variables are selected in sequence for optimization. First, the width of the aperture and depth of the cavity should be optimized by specifying IOPTUM=2. Second, the aspect ratio of the aperture can be optimized separately (IOPTUM=1). Finally, performance runs can be used to generate flux maps within the cavity so that the user can trim or adjust the shape of the heat absorbing surface, if desired or required.

The first step in optimizing a cavity is to determine the aperture width and cavity depth by specifying the variable IOPTUM=2. DELSOL searches NUMREC equally spaced discrete values of the width of the first (north) aperture, RX(1), from a minimum value of WST meters to a maximum value of WEND meters. The relative aperture height, RY(1), will remain fixed as specified by the value of RYTRX, and the dimensions of

other apertures (for a multiple cavity receiver) will be fixed by the values of RX2TRX, RX3TRX, and RX4TRX. The second receiver variable to be varied when IOPTUM=2 is the receiver diameter, W as defined in Section II.E. Since the depth of the Ith cavity is proportional to W (RWCAV(I), Namelist REC), the second receiver variable also varies the cavity depth. There are NUMHTW (≤ 20) discrete equally spaced values of the width, W, from a minimum of HTWST meters to a maximum value of HTWEND meters. W, and thus the cavity depths W x RWCAV(I), is determined almost entirely by receiver flux limits, if any. There is a slight performance disadvantage, due to receiver losses, of making the cavity deeper for a fixed aperture size. There is also a cost penalty for making the cavity deeper, since the size of the heat exchanger surface grows as discussed in Section V.A-5(b). Therefore, DELSOL will not increase the depth of the cavity above the minimum value allowed in the optimization search (HTWST x RWCAV(I)) unless it is forced to by a flux constraint on the heat absorbing surface. Note that the flux calculation is done separately from the power calculation and does not affect the power calculation in any way, since the power calculation is done at the aperture. Thus, other than a slight change in receiver losses, changing the cavity depth will not affect the receiver power, but it will directly affect the fluxes incident on the heat absorbing surface.

If NUMREC or NUMHTW is set to 1, then the appropriate value of RX(1) or W as defined in the previous REC Namelist will be used, rather than using the limits defined above.

The second step in optimizing a cavity is to fine tune the width and aspect ratio of the apertures by specifying IOPTUM=1. During this optimization step the user should set the parameter W in the Namelist REC to the optimum W found in the first step. With IOPTUM=1 the first receiver variable is again the width of the first aperture, RX(1). However, the second receiver variable is now the dimensionless aspect ratio of the aperture, RY(1)/RX(1). There are NUMHTW (≤ 20) equally spaced values of the aspect ratio from a minimum value of HTWST to a maximum value of HTWEND. As mentioned before, if NUMREC or NUMHTW is set to 1, then the appropriate value of RX(1) or RY(1) as defined in the previous namelist will be used, and the limits described here will be ignored.

Flux values should be checked during both steps of optimizing a cavity receiver as described above. In the first step, cavity depth directly affects flux, while having a different aperture in the second step could affect aim strategies and thus the flux incident on the absorber surface. This second effect should be minor, however, since the aperture area will probably stay nearly constant, although the aperture shape could change.

The final step of cavity receiver optimization is to fine tune the shape of the heat exchanger surface within the cavity. The heat absorbing surface of a cavity is modeled as a segment of a right circular cylinder centered horizontally on the cavity aperture, as described in Sections II.E and V.A-5(b). It is possible, based on the choice of the value H (Namelist REC), that after optimization the top portion of the heat absorbing surface may either have too low a flux or too high a flux. In the former case, the receiver may be oversized, and the user should rerun the second half of the optimization (IOPTUM=1) using a different value of H in Namelist REC to limit the heat absorbing surface height. In the latter case, the internal flux spillage onto uncooled surfaces such as the roof may cause design failures, and so the user should rerun the second half of the optimization using a larger heat absorber height. After the design has been finalized, the user should run a final performance calculation of the optimum system to generate detailed flux maps on the heat absorbing surface or other surfaces of concern. If necessary, the user can then manually trim the heat absorber to eliminate areas whose incident energy is low enough to not require active cooling. However, if manual trimming is done, the user will also have to recalculate by hand the cost of the receiver and any energy costs, since no capital cost calculations are done during a final performance calculation.

If the user allows the heat absorber height to be as large as possible during optimization, as defined by equations V.A-8 and V.A-9, it is possible that this calculated height will be very sensitive to the minimum radius (RADMIN, Namelist FIELD). While it may be desirable to use the high performance heliostats nearest to the tower, it may not be cost effective because of the increased receiver costs. The user may wish to repeat the cavity optimization procedure with a different value for RADMIN to investigate the sensitivity to this effect. However, it is likely that limiting the heat absorber height by specifying H (Namelist REC) will result in similar receiver cost reductions without requiring the elimination of heliostats, so that varying RADMIN should be done after trying all other optimization possibilities.

IV.C-4. Tower Position (Land Constrained Only)—In a system with a land constraint (NLAND>0, Namelist FIELD), DELSOL will search for the optimal position for the tower in the field. The tower does not have to be within the land constraint; only the heliostats must be within the constraint. The code considers NUMPOS (≤ 20) equally spaced discrete positions of the tower from (XTPST, YTPST) to (XTPEND, YTPEND). The units for these variables are meters east (for XTPST and XTPEND) or meters north (YTPST, YTPEND) of the center of the first land constraint rectangle. (Also see Sections II.B-4 and IV.D-2.)

IV.C-5. Storage Capacity—DELSOL sizes storage during system optimization based on the longest operating day. (See Section V.A-8 for how storage sizes are calculated.) The code assumes that by thus sizing storage no energy will be

thrown away due to storage being full at any time of the year, therefore avoiding the necessity of doing detailed energy flow accounting while optimizing other system design parameters. However, it is possible that for north biased heliostat fields some excess energy will be thrown away due to full storage at days other than the longest operating day, due to a combination of system efficiencies and insolation levels. Further, it is possible that choosing a smaller storage tank and discarding (not collecting) some energy may be more cost effective than never discarding energy. For an otherwise completely optimized system, DELSOL allows the user the option to determine the most cost effective storage size.

Storage optimization is requested during the optimization process in DELSOL (Namelist OPT) by specifying the variables ISTR and NSTR. ISTR, when nonzero, is the ratio of the maximum storage size to be examined to the storage size calculated by DELSOL at the longest day for the otherwise optimized system. NSTR is the number of equally spaced storage sized from zero to ISTR to be evaluated.

Although storage optimization is requested during system optimization, the storage optimization is actually performed during a final performance calculation on an otherwise optimized system (IPROB=1). Thus, the storage size and cost printed during system optimization will be the nonoptimized storage. During the final performance run, when energy accounting vs. time is occurring, the storage size will be varied, storage costs will be recalculated, and the actual amount of energy discarded for each different storage tank size will be calculated. The optimum storage size, along with annual energy data and adjusted capital and energy costs, will be printed out ahead of the annual power production detailed output.

The default values (ISTR=0, NSTR=1) allow no storage optimization. Re-running a specified optimum design for detailed performance for this case would give system performance for the maximum size storage capacity determined initially.

At this point a distinction should be made between physical storage size and the two values SMULT and capacity factor. SMULT, which is a user input (Namelists OPT and NLEFF), is the factor multiplying the minimum requirement for thermal power at the base of the tower to meet the specified power delivered to the process at the design point. Thus, SMULT, or the solar multiple, does not specify a storage size (cost) because it does not make a distinction between storing energy and discarding energy. The solar multiple is only used to size the field and receiver with respect to the defined plant rating. On the other hand, capacity factor (printed during system optimization) is a calculated value of the ratio of time operating during a year to total time in a year. Capacity factor is calculated in DELSOL by calculating the total amount of energy produced by the heliostat field during the year, reducing that value by annual average system efficiencies, and dividing that value by the total time in a year. Again, the assumption is made that no energy is discarded (rather than being stored), and

furthermore, that the assumed turbine efficiency is a worst case estimate (see Sections III.G-5 and IV.A-7). Thus, the capacity factor value calculated and displayed during a DELSOL optimization is only an estimate at best. By optimizing the physical storage size, the user will be changing the actual capacity factor, as well as storage and energy costs, because the amount of available stored energy will change without changing solar multiple. DELSOL will not recalculate the capacity factor.

IV.C-6. Heliostat Field Boundaries—The user has no control over this part of the system optimization. DELSOL will optimize the boundaries of the heliostat field as described in Section IV.B-1. The heliostat field is always constrained to lie within the zoning defined by the variables RADMIN and RADMAX, and may be further subjected to a land constraint as described in Section IV.D-2.

IV.C-7. Heliostat Spacings—DELSOL has an option for optimizing the spacing of heliostats within each zone (IHOPT=1 in Namelist OPT). The optimization has three constraints: (1) the layout pattern is always a radial stagger pattern; (2) the optimized densities and aspect ratios cannot be more than $\pm 20\%$ from the initial densities and aspect ratios defined in Namelist FIELD (the range is set by the variable DHOPT in Namelist BASIC); and (3) the tower height cannot be optimized simultaneously with optimizing heliostat spacings (see Chapter VI).

IV.D. Constraints on System Optimization/Design

During system optimization, DELSOL can design systems which meet flux limitations on the receiver or which have land availability constraints. In this case, no system will be accepted as an optimum unless the appropriate constraints are satisfied.

IV.D-1. Receiver Flux Constraint During Optimization—DELSOL has an option to calculate and monitor the flux at the design point at up to four points on the receiver surface ($NFLXMX \leq 4$). The maximum allowable values at these points are specified by FLXLIM(I) watts/m², where I=1, NFLXMX. If the flux limit at one of the points exceeds its limit, field buildup during optimization is halted for that combination of receiver and tower dimensions.

The flux values which are calculated during optimization are only approximations of actual peak flux levels, for at least three reasons. First, the design point insolation is assumed to be REFSOL (Namelist BASIC), which may not match either a measured insolation at a design point time or a calculated insolation using one of the insolation models available in DELSOL during a performance calculation. Second, in calculating the flux during optimization, DELSOL assumes that the relative shape of the flux profile at the design point is the same as the relative shape of the annual average flux profile as described by an initial performance calculation. This assumption is more correct for surround fields than for north biased fields, but in any case it depends on the choice of the design point by the user. This assumption usually causes the optimization calculation of flux to overpredict the actual flux level at a point on the receiver. Third, the peak flux on

the receiver may occur at a location other than those points being tested during optimization. In this case, a flux map generated during a final performance run using up to 169 points will indicate where the actual peak flux occurred.

Flux limits should be chosen based on one of two criteria: 1) to design to a given lifetime for a receiver, due to cyclic loads, and 2) to ensure that temperature limits are not exceeded. In the former case, the flux limit which is chosen should not be one which the user should never expect to exceed. In an actual receiver system, insolation levels will vary due to weather conditions and time of year/day, so that some cyclic loads will have lower flux levels and will have less effect on lifetime, while other cyclic loads will have higher flux levels than at design point and will have a greater effect on lifetime. It is the total effect of these different flux levels on lifetime that is important, and so the flux limit to be designed to at the design point should be some kind of an average limit. In the case of keeping temperature levels below certain limits, the user should again realize that actual insolation levels will vary and may at some point in time exceed the design point value REFSOL. Thus, either the system should be designed with a larger REFSOL, a lower flux limit, or during system operation the user should plan on reducing the number of heliostats focused on the receiver when actual insolation exceeds the design point value of REFSOL.

Flux point locations during optimization are initially defined relative to the receiver type and dimensions as described in the REC Namelist immediately preceding the OPT Namelist. The following steps should be used in setting up a flux limited design run:

- (1) Define the type and initial dimensions of the receiver desired on the REC Namelist preceding the OPT Namelist. This receiver should be consistent with the field and type of receiver used in the initial performance run whose results will be used during this optimization.
- (2) Set up a grid of flux points on the heat absorbing surface of this receiver, using the Namelist NLFLUX following the OPT Namelist. The user is cautioned to be certain that the user-specified flux surface does coincide with the DELSOL-defined heat absorbing surface, since during optimization the flux surface will be adjusted based on the changes being made to the heat absorbing surface. However, the flux surface does not have to be the same physical size as the heat absorbing surface. It can be larger, thus looking at the effects of spillage, or smaller, which might enable the user to examine a critical area in detail. It is suggested that the grid of flux points which is set up here be used during a final performance calculation also, so that the values of the points which are actually checked during optimization can be compared to the more accurately calculated values in the performance run to see the effects of the approximations used during system optimization.
- (3) Choose NFLXMX (≤ 4) points from the grid of flux points defined in step (2) at which the flux limits are to be tested. Specify the number of each

point in the NMXFLX(I) array (I=1, NFLXMX) in Namelist NLFLUX following Namelist OPT. During optimization, flux will be calculated only at these points, rather than at every point defined in step (2).

- (4) Specify the maximum value of the flux at each point defined in step (3) in units of watts/m² in the FLXLIM(I) array (I=1, NFLXMX) of Namelist NLFLUX. The peak flux limit may be different at different points to account for varying tube or metal temperatures or lifetime requirements.
- (5) For external or flat plate receivers select an appropriate automatic "smart" aiming option (Section II.F). That is, heliostat aimpoints should be spread out in some manner based on the dimensions of the receiver. Otherwise, a flux limit could be reached on a receiver no matter how large the receiver was, since flux and aimpoints would be localized and would not utilize the whole receiver. For cavity receivers, where the power of the receiver is calculated at the aperture but the flux is calculated on the cylindrical heat absorbing surface, the flux can be reduced without significantly affecting power by increasing the depth of the receiver. This effectively diffuses the flux. However, it is still recommended that a "smart" aiming (aimpoints spread out) be used for cavity receivers, since otherwise the depth of the cavity might need to be so large as to cause a large increase in receiver costs. For any receiver, the type of aim strategy which is used can affect the location at which peak flux occurs, and so should be considered by the user when choosing the points in step (3).
- (6) For external or flat plate receivers, optimize the height to width ratio, H/W, since changing the height will spread the flux differently and thus allow the flux limits to be met. For cavity receivers, in which the flux on the heat absorbing surface is nearly independent of the power calculated at the aperture, allow the diameter W (and hence the cavity depth RWCAV(I) x W) to vary. This is done using the option IOPTUM=2. A deeper cavity will have a lower peak flux level for the same power at the aperture.

As the receiver size is varied the flux points remain at the same relative position on the receiver surface, as illustrated in Figure IV-2. For external receivers, each flux point remains at the same azimuth angle, same fraction of the height, and on the cylinder surface, assuming it was initially on the cylinder surface. For flat plate receivers, the flux points remain at the same fraction of the height and same fraction of the width. For cavity receivers, the flux surface is taken as the inside of a vertical cylinder centered horizontally on the first aperture. The displacements of flux points relative to the center of the first aperture scale with the height of the heat absorbing surface. Locations and scaling of flux points for all receivers is discussed in detail in Section II.G-2.

The fluxes calculated during optimization at the NFLXMX receiver points may be less than the maximum values allowed (FLXLIM(I)). This may be due to one of two reasons. First, system energy costs may be lower for a lower peak

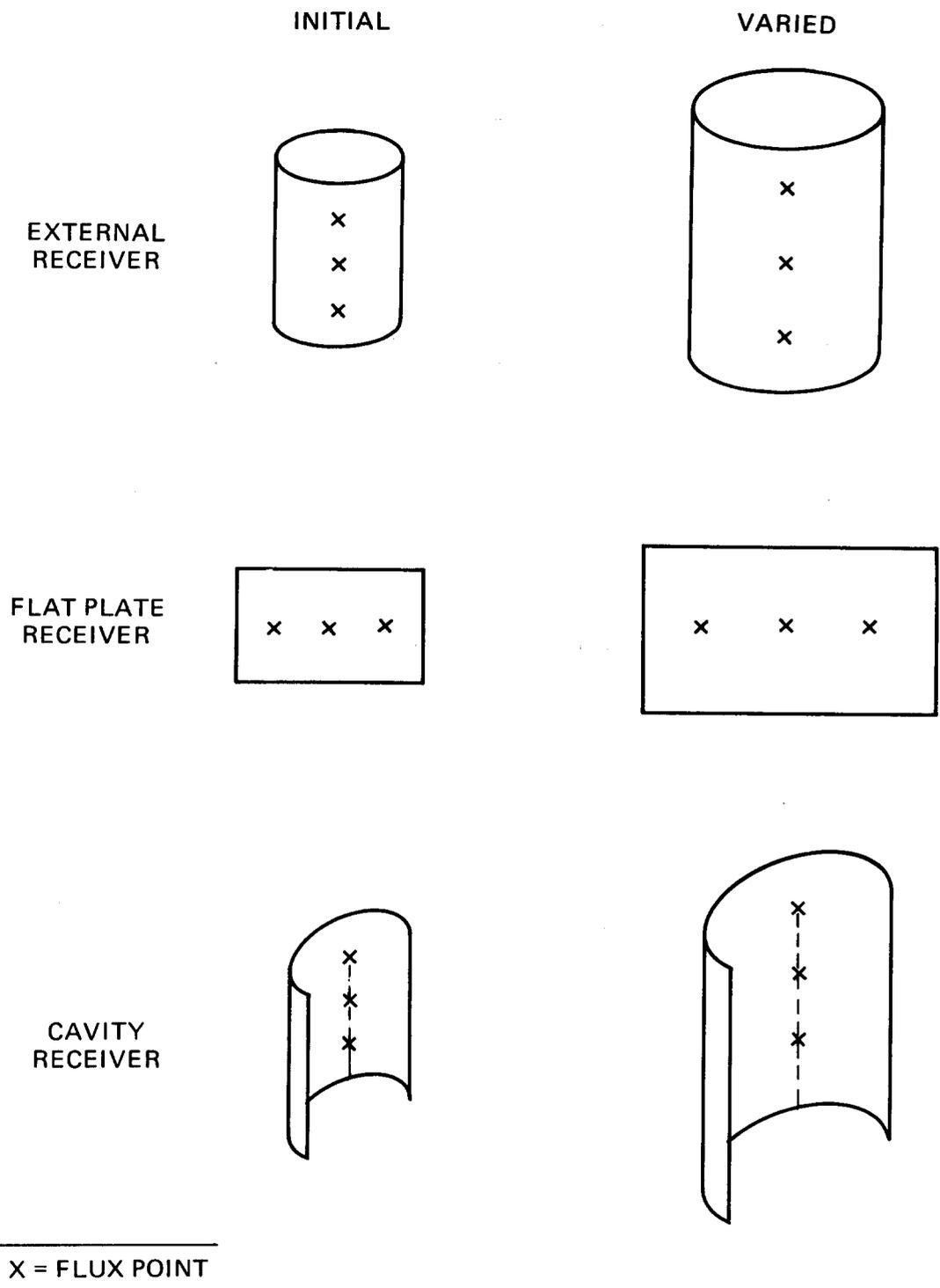


Figure IV-2. Location of Flux Points as Receiver Dimensions are Varied. Flux points remain at the same relative position as the receiver size is varied.

flux level. DELSOL determines the best combination of receiver size (with its associated cost, receiver losses, and spillage losses) and heliostat field size (with its associated cost and field losses). For a given set of component costs, as a receiver size decreases below its optimum, spillage increases and so field costs increase more than the decrease in receiver cost. If at that receiver size the allowable flux limit is not reached, then it is not cost effective to force the system to have a peak flux at the FLXLIM(I) limit.

The second reason why a peak flux limit may not be obtained during system optimization is that the receiver size is being varied in discrete steps, rather than continuously. In this case, the user can come closer to a given flux limit by using more closely spaced receiver sizes, or the flux limit can be set slightly higher than actually desired since the flux from the optimum will generally be below the limit. In any case, the user should request a more accurate detailed flux map during a final performance calculation to verify that flux limits are being met, if desired, but not exceeded.

IV.D-2. Heliostat Field Land Constraint—DELSOL allows the heliostat field to be constrained within a number of arbitrarily oriented rectangles. The input defining the land constraint is described in Section II.B-4. As mentioned in Section IV.C-4, with a land constraint it is necessary to search for the optimal location of the tower with respect to the constraint. Only the heliostat locations are constrained. The code does not require the tower to be in the land constraint. However, the user should make sure that land is available for the tower.

There is an additional complication in land constrained designs when the thermal energy is not used at the base of the tower. In repowering or process heat applications the thermal energy may have to be transported to a point near the edge of the land constraint. DELSOL does not consider the cost or losses in the piping run from the tower position to the use point. The user may want to fold in these effects manually. For example, consider a rectangular land constraint whose sides are parallel to the N/S and E/W directions. DELSOL will generally prefer to locate the tower south of the center of the land constraint. Suppose, however, that the thermal energy is required at the northern boundary of the field. It may then be cost effective to move the tower further north from the DELSOL optimum if the savings in the pipe run may more than offset the increased cost of thermal energy at the tower base.

IV.E. "Smart" Optimization Searching Algorithm

DELSOL has to consider $\text{NUMTHT} \times \text{NUMREC} \times \text{NUMHTW} \times \text{NUMPOS}$ combinations of tower height, receiver sizes, and tower positions in searching for the minimum energy cost system. Figure IV-1 shows a schematic of the optimization search. There are four nested iterations of the discrete system variables: tower height, first receiver variable, second receiver variable, and tower position. Since the zone by zone performances do not depend on the tower location, these performances are calculated outside of the tower position loop. For each set of

system variables, an optimal field is built up. At each design point power level attained in the field build-up, the levelized energy cost is tested to see if it is a new minimum. If it is a new minimum, the system design, performance, and costs are saved. When the iterations are complete, the lowest energy cost system from the allowed system variations is known at each power level.

Even if the user asks DELSOL to examine every system in the range of variables (IALL=1), not every system will be examined. DELSOL contains tests to avoid searching over systems that cannot meet the minimum power of interest. If a given tower height is too small to meet the minimum design power level for any receiver, DELSOL automatically skips to the next tower height without searching (in vain) for the optimum receiver size. Also, DELSOL checks to make sure that cavity receiver geometries are consistent. Requests to allow aperture widths which are wider than twice the depth of the cavity are ignored. This is due to the DELSOL assumption that cavity receivers are configured internally as right circular cylinders centered on the aperture, so that the interior of the cavity will never be greater than twice the depth of the cavity.

Other than for the above exceptions, DELSOL will examine every system requested in the range of variables when IALL=1. However, considering every possible combination of system variables is an inefficient way to find the optimum system(s). DELSOL, therefore, has an option to do a "smart" search over the receiver variables. This option (IALL=0) is the default option. Smart searching tries to consider the minimum set of system variables necessary to find the optimum system(s). The search algorithm attempts to start iterating a receiver variable at a value greater than its minimum allowed value and to stop iterating a variable before it reaches its maximum allowed value. The search strategy makes the following assumptions: (1) there is a single, well defined minima in each variable, which is not significantly dependent on the choice of the other receiver variable or the tower variables; and (2) the optimum tower height and receiver size increase when the power level increases.

The first assumption of smart optimization, that a single well defined minima in each receiver variable exists, allows DELSOL to find that minima for the second receiver variable using the first choice of the first receiver variable which results in the requested design point power level, and then to continue searching for the minima in the first receiver variable for values of the second receiver variable close to its minima. If increasing a receiver variable increases the energy cost of each system whose power level can be reached by changing that variable, DELSOL will stop the iteration and assume that a minima has been found for that variable. However, in actuality the minima values will move slightly as other receiver and tower dimensions are changed. Therefore, after DELSOL has found a minima for an inner variable and increases an outer variable to the next value, it starts the iteration on the inner variable at the discrete value which is one less than the minima found previously. For example, suppose the user has allowed receiver sizes of 10, 11, 12...20. At THT = 150 the minimum receiver size that is

optimum for any power level is 13. Then when doing the next tower height, which might be $THT = 160$, DELSOL will start to search at receivers of size 12.

The second assumption of smart optimization, that optimum tower height and receiver size increase with power level, allows DELSOL to use the minimum optimum receiver size at a lower power level as the starting point for the next power level. DELSOL also applies this to optimize a single power level in that once an optimum receiver is found, receivers with smaller areas are not examined, except that the optimization always starts with the next smaller area. This limitation on area is also not used on cavity receivers where the depth is being optimized, since the power is calculated at the aperture and remains constant as heat absorber area increases, or decreases slightly due to increased receiver losses.

DELSOL's "smart" optimization also includes several checks to try to ensure that the correct optimum system is chosen. One such check is that if a minima is found on the first try for a variable whose minima had previously been found to be one larger, the starting point for that iteration will be lowered and the iteration will be started again. This means that DELSOL may check the same system twice, once due to reducing the starting point here and again as it begins increasing the variable again until energy costs start increasing again. Despite this duplication, "smart" optimization will still examine many fewer systems than if every possible combination allowed is examined. Because of the assumptions made in "smart" optimization, it is possible that DELSOL will miss the best system. However, the difference in energy cost between the chosen system and the best system will be small, and the user can easily check for the better system by doing a more limited optimization with $IALL=1$ around the system which the "smart" optimization previously found to be optimum.

Flux limited receiver designs complicate the "smart" optimization search strategy. None of the methods for restricting the search can be applied until the flux constraint is satisfied. For example, DELSOL will increase the receiver size as long as a flux limit is exceeded even though energy costs may be increasing. In many respects, exceeding a flux limit is treated similarly to not reaching a design point power of interest. Thus, flux limited receiver optimizations have to search over more cases than the corresponding non-flux limited receiver "smart" optimizations. **It is very important when optimizing with a flux limit to use a two step coarse grid/fine grid strategy.** A search over a coarse grid of optimization variables locates an approximate optimum design rapidly. This is followed by a search over a fine grid of optimization variables centered on the coarse grid optimum. Thus a large range can be looked at without examining a large number of systems.

A detailed summary of the optimization search is provided as output. The user can follow the optimization strategy by analyzing this information. In addition, the information on the search can give a good indication of the sensitivity of the energy costs, performances, etc. to variation of the design parameters. For example, if a 150 meter tower is optimum but the user would like to know what

system costs would be at 160 meters, this information would be available in the output optimization summary. However, the energy costs associated with these systems in the optimization summary should not be viewed as real energy costs, due to the assumptions involved in calculating them, but may be viewed as relative comparative costs. A final performance calculation would still be needed to give DELSOL's most accurate prediction of energy costs.

IV.F. Sensitivity of Energy Costs to Variation of Design Parameters

Generally, the cost of energy is not very sensitive to modest variations of the design parameters away from the optimal values determined by DELSOL. It is important for the user to remember that the minima are shallow. First, the broad optimum means that a very fine (and time consuming) grid of variables is not needed. Second, the designer has the freedom to vary the system to maximize other considerations besides cost of energy. For example, DELSOL may select a large height to width ratio for a flux limited external receiver. However, a more modest aspect ratio may be desired for engineering or other reasons. The optimization can be repeated with smaller H/W ratios in order to see what the cost of energy penalty is. The energy cost differential may be so small that the other design considerations dominate and a smaller H/W ratio than the DELSOL minimum will be selected.

Small changes in the input generally produce small changes in the energy cost but can produce large changes in the optimum value of the design parameters. This is also a consequence of the shallow minima in the energy cost vs. design variables. This effect is often not understood by users. It seems counterintuitive that one can set out to design systems for the same application and yet produce significantly different designs just because of small difference in the input variables. If one were to compare energy costs, however, the different designs would probably be nearly identical on a cost basis.

V. System Costs and Economics

While DELSOL can be used to calculate field performance only, it also has capabilities for total system design. In DELSOL, an **optimized system design** is that combination of tower height, receiver size, and field layout which gives the lowest calculated system energy cost at a given design power level and solar multiple. In order to calculate the energy cost, both system performance and system capital and operating costs must be determined. The latter is only done during the optimization procedure; therefore, annual performance cannot be done on a system which is input by the user, since costs are unavailable. The subsystem cost models for estimating the total capital cost and the economic model for calculating the levelized energy cost are discussed below. **It is strongly suggested that the user carefully examine both the cost calculation procedures and the default values used in those calculations to verify that the resulting component costs will be appropriate for the system being examined.** Different systems and different technologies will almost certainly require modification of at least some of the reference system values discussed herein and used by DELSOL.

The units used in DELSOL input must be those specified for the individual variables, such as meters for all dimensions and dollars for all costs. The user should be aware that the output from DELSOL is not necessarily consistent in the units which are used. Specifically, land area might be in either m^2 or km^2 and annual energy might be in KWh_e or MWh_e , depending on the location in the output. Further, energy costs are quoted in mills/ KWh_e , **not** cents/ KWh_e . Although the values will be consistent with the labels, the user should be careful to note the correct specified units associated with any output value.

V.A. Total Cost Model

The total capital cost, CC_T , is calculated as the sum of the costs of several subsystems adjusted by a factor for uncertainties and miscellaneous expenses:

$$\begin{aligned} CC_T = & (CC_{HEL} + CC_{LAND} + CC_{WIRE} \\ & + CC_{TOW} + CC_{REC} \\ & + CC_{PUMP} + CC_{PIPE} + CC_{STORAGE} + CC_{HTXSTOR} + CC_{HTXCHG} + CC_{EPGS} \\ & + CC_{FIXED}) \\ & \times (1.0 + DI + CONT + SPTS) \end{aligned} \tag{V.A - 1}$$

As discussed in detail in Chapter 4, the optimization scheme considers one tower height/receiver size combination at a time and then builds up the heliostat field zone by zone until the desired power level(s) at the specified solar multiple is

achieved for that tower and receiver. Capital cost components can be grouped according to that point in the field buildup at which they are calculated. The line grouping of the costs in Equation (V.A-1) is to clarify those costs which are similarly calculated. The tower and receiver costs (CC_{TOW} , CC_{REC}) are fixed by the values of tower height and receiver dimensions for each pass through the field buildup subroutine MAX. Heliostat, land, and wiring costs (CC_{HEL} , CC_{LAND} , and CC_{WIRE}) are updated with each zone added in the field buildup. The power or system size related costs of piping, pumping, storage, heat exchangers, and EPGS (CC_{PIPE} , $CC_{STORAGE}$, $CC_{HTXSTOR}$, CC_{HTXCHG} , and CC_{EPGS} , respectively) are calculated as each design level is reached. It is assumed that certain fixed costs (CC_{FIXED} , e.g., master control, administration buildings, roads, etc., are common to all the systems. Factors for distributable and indirect costs (DI) to cover architectural and engineering services, contractor fees, and temporary facilities, for contingencies (CONT), and for spare parts (SPTS) are added to the basic capital cost of the major component subsystems. Values are expressed as a fraction of the total direct costs. Current default values are based on Nth plant design and construction:

$$DI (EXT) = 0.16$$

$$CONT (CONT) = 0.12$$

$$SPTS (SPTS) = 0.01$$

The individual capital cost models are described below. User supplied cost parameters should include materials, fabrication, and field installation, and subcontractor fees and contingencies, if any. The default values are consistent with the near-term 1984 five year plan cost goals or with 1984 current capabilities (References 34 and 35). Should the user desire to set any subsystem cost to zero to eliminate its contribution to the system design, then the input cost parameters, not the size or scaling parameters, should be set to zero.

V.A-1. Heliostats—Heliostat prices quoted by contractors usually include field wiring and installation. Therefore, the value CH input by the user should also include these costs. DELSOL will subtract the wiring costs as described in Section V.A-3 to determine the separate cost of heliostats:

$$\begin{aligned} CC_{HEL} &= C_H \left(\frac{\$}{\text{m}^2 \text{ mirror area}} \right) \times \text{total mirror area} + \$1E6 - C_{WIRE} \\ &= C_H \left(\sum^{\text{zones}} \text{zone mirror area} \right) + \$1E6 - C_{WIRE} \end{aligned} \quad (V.A - 2)$$

Zone mirror area is determined from the zone density and land area. The constant million dollar addition is to account for a beam characterization system and

for meteorological equipment. The default value is $C_H = \$120.0/\text{m}^2$ of heliostat area, which applies to a high reflectivity glass-metal heliostat. This value is consistent with stated near-term cost goals of the 1984 five year plan.

V.A-2. Land—The cost of land should be the cost of unimproved land. The area of land needed includes all of the land in each zone, increased by 30% to account for roads and additional land around the field, and increased by a fixed amount to account for the core area of the plant.

$$\begin{aligned} CC_{\text{LAND}} &= C_L \left(\frac{\$}{\text{m}^2 \text{land}} \right) \times \text{total land area} \\ &= C_L \left\{ \left(\sum^{\text{zones}} \text{zone land area} \right) \times 1.3 + 0.18\text{E}6\text{m}^2 \right\} \end{aligned} \quad (\text{V.A} - 3)$$

The default value is $C_L (CL) = \$0.62/\text{m}^2$ of land area.

V.A-3. Wiring—The calculated wiring costs are assumed to be included in the input heliostat cost, and are calculated and separated from heliostat costs by DELSOL according to the following:

$$\begin{aligned} C_{\text{WIRE}} &= \sum_i^{\text{zones}} (C_{W,R}R_i + C_{W,\Delta R}\Delta R_i + C_{W,\Delta Az}\Delta Az_i) \\ &\quad \times \text{number of heliostats in zone } i \end{aligned} \quad (\text{V.A} - 4)$$

where R_i = radial distance from the tower base to zone i
 ΔR_i = average row spacing in zone i
 ΔAz_i = average spacing between heliostats on the same row in zone i .

This model was supplied with the field performance results from Reference 9. It is designed to penalize heliostats placed farther out due to requirements of larger (or more) primary cables as the field grows radially from the tower, and longer plowed-in secondary line runs as the mirror density decreases with distance from the tower. From the defined zoning and density option in namelists FIELD and OPT, R_i , ΔR_i , and ΔAz_i are known. Default values for the wiring cost parameters, given for a single heliostat and as provided in Reference 35, are:

$$C_{W,R}(CWR) = \$0.03077/\text{m}$$

$$C_{W,\Delta R}(CWDR) = \$15.00/\text{m}$$

$$C_{W,\Delta Az}(CWDA) = \$9.00/\text{m}$$

V.A-4. *Tower*—The optical tower height THT is used for all performance calculations. The physical tower height THT_B, which is the actual tower height from the ground to the bottom of the receiver, is related to THT by

$$\text{THT}_B = \text{THT} + \text{HM}/2 - \text{H}/2 - \text{W} \quad (\text{V.A} - 5)$$

where HM = height of a heliostat

H = height of the receiver

W = height of a transition region from the tower to receiver;
this height is assumed to be the same as the receiver diameter W.
The cost of this transition region is assumed to be part of
the cost of the receiver.

The cost of the actual tower is calculated as

$$\begin{aligned} \text{CC}_{\text{TOW}} &= \text{C}_{\text{TOW1}} \times e^{\text{C}_{\text{TOW2}} \text{THT}_B} & \text{THT}_B \geq 120 \text{ m} \\ \text{CC}_{\text{TOW}} &= \text{C}_{\text{TOW3}} \times e^{\text{X}_{\text{TOW}} \text{THT}_B} & \text{THT}_B < 120 \text{ m} \end{aligned} \quad (\text{V.A} - 6)$$

It is assumed that towers shorter than 120 m in height are steel towers, while towers of 120 m or more are concrete towers, where the difference is shown only in the cost coefficients for the above equations. The user has two options for calculating the cost of the tower:

- a) ITHT = 0; cost based on Sandia studies (Reference 36) and repowering designs (Reference 35):

$$\text{C}_{\text{TOW1}} = \$0.78232\text{E}6$$

$$\text{C}_{\text{TOW2}} = 0.01130$$

$$\text{C}_{\text{TOW3}} = \$1.09025\text{E}6$$

$$\text{X}_{\text{TOW}} = 0.00879$$

- b) ITHT = 1; cost based on user supplied values of C_{TOW1} and C_{TOW2} in Namelist NLCOST, where these values are used for all THT_B values.

The tower cost for option a) is plotted in Figure V-1. The default choice of tower cost is ITHT = 0.

V.A-5. *Receiver*—The equation in DELSOL for costing receivers is of a form commonly used in the chemical process industries (References 37 and 38). This equation form, in which cost scales with receiver area, results from the fact that the receiver is a specially designed heat exchanger. The equation is

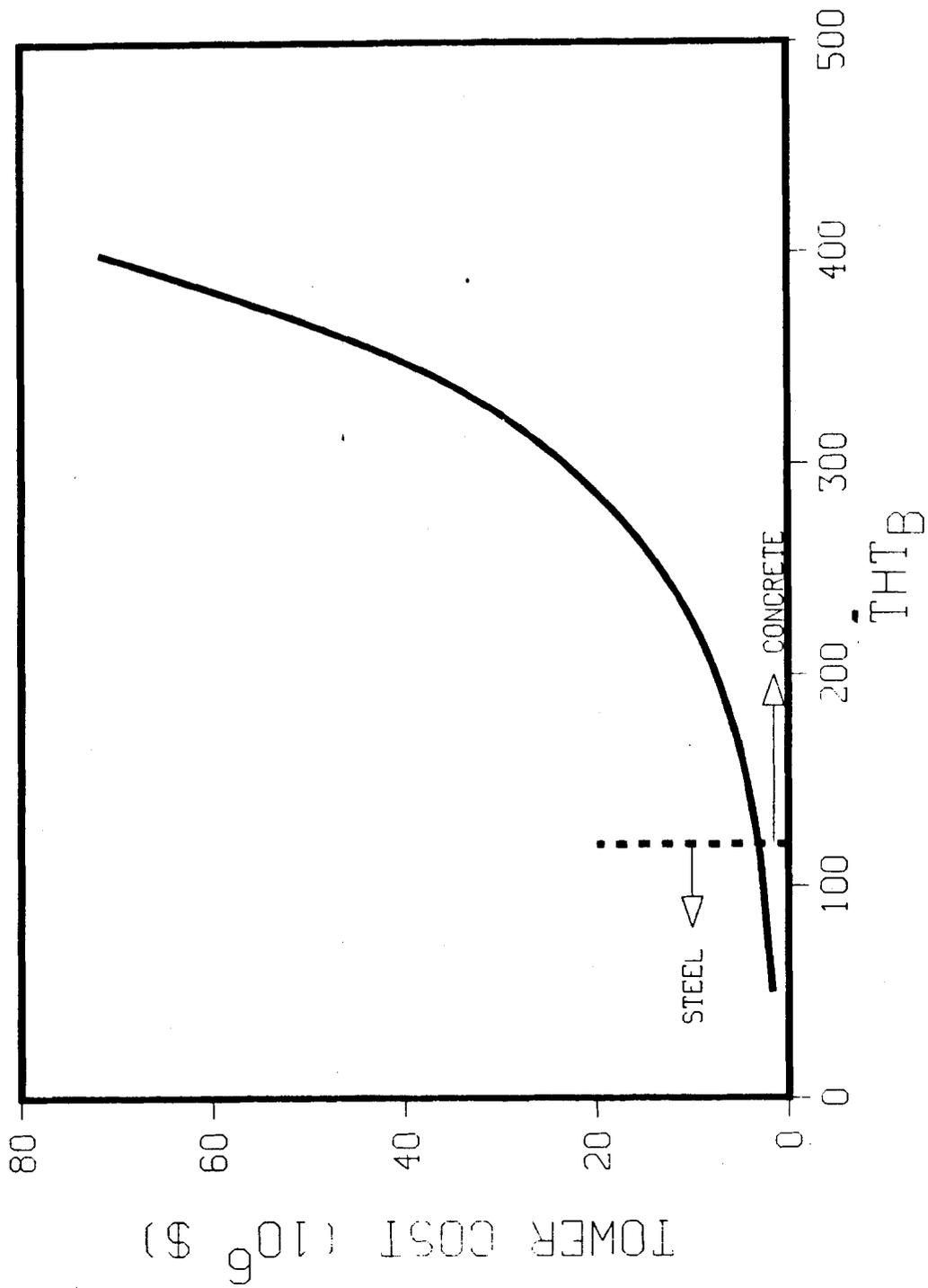


Figure V-1. Tower Cost Predicted for $ITHT = 0$

$$CC_{REC} = C_{REC,REF} \left(\frac{A_{REC}}{A_{REC,REF}} \right)^{X_{REC}} \quad (V.A - 7)$$

where $C_{REC,REF}$ = cost of a reference design (dollars)

$A_{REC,REF}$ = heat transfer area of the reference design

A_{REC} = heat transfer area of the receiver being evaluated

X_{REC} = scaling exponent for receivers, ≤ 1.0

Default values are based on the scaling exponent commonly used for heat exchangers and on a cavity salt receiver design (Reference 8):

$$C_{REC,REF} (CREC1) = \$23.0 \times 10^6$$

$$A_{REC,REF} (ARECRF) = 758.0 \text{ m}^2$$

$$X_{REC} (XREC) = 0.8$$

- a) External and Flat Plate Receivers—The area A_{REC} is simply the product of π times the diameter (W) times the height (H) for an external receiver. For a flat plate receiver the area is $RX \times RY$.
- b) Cavity Receivers—The bottom of the heat absorbing surface is calculated by DELSOL (for costing purposes) so that at the given cavity depth, $W/2 \times RWCAV$, a ray entering the bottom of the aperture from the farthest heliostat will strike the heat absorbing surface.

$$HBOT = (THT - RY/2 \times \sin(180 - RELV)) \times \left(\frac{RMAX - W/2 + W/2 \times RWCAV}{RMAX - W/2 + RY/2 \times \cos(180 - RELV)} \right) \quad (V.A - 8)$$

where $RMIN$ and $RMAX$ are the local minimum and maximum radii for the optimized heliostat field.

The height of the heat absorbing surface is specified in one of three ways. If the default value of the variable H is used, the heat absorbing surface height will be specified as $1.1 \times RY$ (1.1 times the aperture height). If a different value H is specified, then that value is taken to be the actual height of the heat absorbing surface. However, the height will never be allowed to be larger than that height needed to intercept a ray from the nearest heliostat entering the top of the aperture, as shown in Figure V-2a and described as

$$HTOP = (THT + RY/2 \times \sin(180 - RELV)) \times \left(\frac{RMIN - W/2 + W/2 \times RWCAV}{RMIN - W/2 + RY/2 \times \cos(180 - RELV)} \right) \quad (V.A - 9)$$

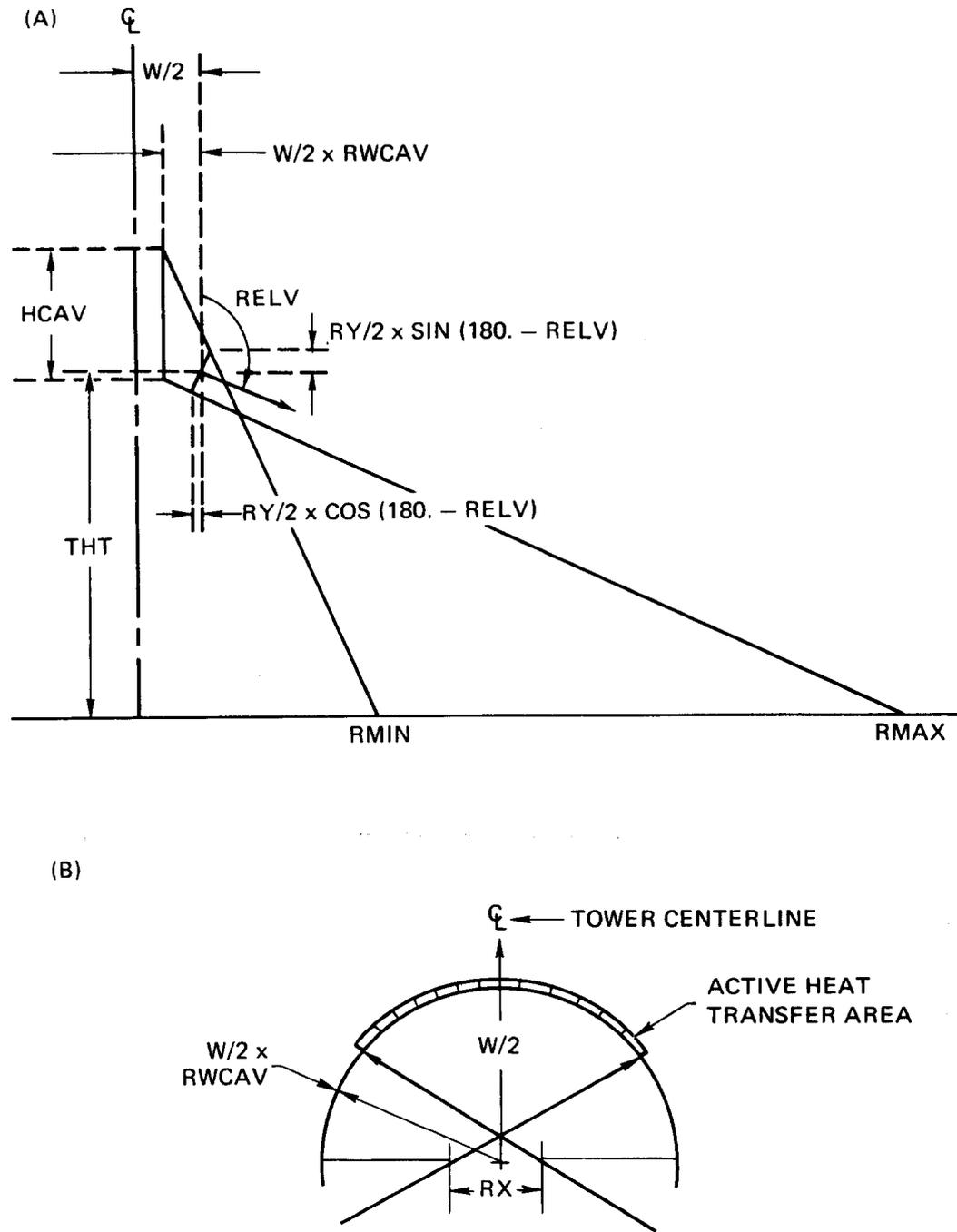


Figure V-2. a) Schematic illustrating the relationship of the height of the back wall of a cavity to other system dimensions; b) Assumed shape of the heat transfer surface in a cavity

In this case, the height of the heat absorbing surface is

$$HCAV = H_{TOP} - H_{BOT}$$

The circumferential width of the heat absorbing surface used in costing a cavity receiver is that portion of the cylindrical surface which can be seen through the aperture by the section of the field active for the cavity. Rays from the nearest heliostats on the boundaries of this sector are used to calculate the fraction of the surface seen (Figure V-2b). Note that if Equation (V-A-9) is used to determine the height of the heat absorbing surface, this height may be extremely sensitive to the choice of the variable RADMIN. In this case the user may find it desirable to rerun the code with values of RADMIN larger than the default in order to obtain a reasonable value for HCAV.

V.A-6. *Pumps*—The pump cost is assumed to be

$$CC_{PUMP} = C_{RP} + C_{SP} \quad (V.A - 10)$$

where C_{RP} = receiver/tower pump cost
 C_{SP} = storage pump cost

These costs are assumed to scale from the costs for a known reference design. The scaling parameter for pump costs is the product of the head times the capacity (Reference 37). For the receiver pump, the head is proportional to the tower height, and the flow rate is the total fluid flow, i.e., EPGS and storage requirement. Thus, the fluid flow is proportional to the solar multiple times the thermal power transferred in the heat exchangers. For the storage pump, the head is assumed to change negligibly from the reference design, and the flow rate is proportional to the thermal power alone (EPGS only). These assumptions lead to the following equations for the pumping costs:

$$C_{RP} = C_{RP,REF} \left(\frac{THT \times SM \times P_{th}}{THT_{RP,REF} \times SM_{RP,REF} \times P_{th,RP,REF}} \right)^{x_{RP}} \quad (V.A - 11)$$

$$C_{SP} = C_{SP,REF} \left(\frac{P_{th}}{P_{th,SP,REF}} \right)^{x_{SP}} \quad (V.A - 12)$$

where $C_{RP,REF}$ = cost of reference receiver/tower pump (\$)
THT = tower height (m)
SM = solar multiple
 P_{th} = thermal power to EPGS (watts)
 $THT_{RP,REF}$ = tower height for reference receiver pump design (m)

$SM_{RP,REF}$ = solar multiple for reference receiver pump design
 $P_{th,RP,REF}$ = thermal power to EPGS in reference receiver pump system (watts)
 x_{RP} = scaling exponent for receiver pump
 $C_{SP,REF}$ = cost of reference storage pump (\$)
 $P_{th,SP,REF}$ = thermal power to EPGS in reference storage pump system (watts)
 x_{SP} = scaling exponent for storage pump.

Default values are as follows:

$$C_{RP,REF} (CRPREF) = \$2.1 \times 10^6$$

$$THT_{RP,REF} (TRPREF) = 170.0 \text{ m}$$

$$SM_{RP,REF} (SMRP) = 1.5$$

$$P_{th,RP,REF} (PRPREF) = 2.6 \times 10^8 \text{ watts}$$

$$x_{RP} (XRP) = 0.85$$

$$C_{SP,REF} (CSPREF) = \$4.70 \times 10^5$$

$$P_{th,SP,REF} (PSPREF) = 3.0 \times 10^8 \text{ watts}$$

$$x_{SP} (XSP) = 0.15$$

V.A-7. Piping—Piping costs are assumed to scale with tower height and with pipe diameter in relation to a reference system (Reference 39).

$$CC_{PIPE} = THT(\ell_{PH}C_{HOT,REF} + \ell_{PC}C_{COLD,REF})\left(\frac{D}{D_{REF}}\right)^{x_{PIPE}} \quad (V.A - 13)$$

where ℓ_{PH} = multiplier on THT to give total hot piping run as described in Section III.G-4
 $C_{HOT,REF}$ = reference hot pipe cost, including pipe, insulation, fittings, hangers, supports, installation (\$/m)
 ℓ_{PC} = multiplier on THT to give total cold piping run (can be different from ℓ_{PH} if expansion allowance is less)
 $C_{COLD,REF}$ = reference cold pipe cost, as above (\$/m)
 D = pipe diameter (m)
 D_{REF} = reference pipe diameter (m)
 x_{PIPE} = scaling exponent for piping.

The pipe diameter is assumed to scale with the square root of the flow rate, which is in turn proportional to the product of the solar multiple times the design point thermal power delivered to the process:

$$\frac{D}{D_{REF}} = \left(\frac{SM \times P_{th}}{SM_{PIPE,REF} \times P_{th,PIPE,REF}} \right)^{0.5} \quad (V.A - 14)$$

Default values are based on a molten salt design in which hot and cold runs are the same length (allowing the total reference cost to be put in either $C_{HOT,REF}$ or $C_{COLD,REF}$):

$$\ell_{PH} \text{ (FPLH)} = 2.6$$

$$\ell_{PC} \text{ (FPLC)} = 2.6$$

$$C_{HOT,REF} \text{ (CHPREF)} = \$2.84 \times 10^4$$

$$C_{COLD,REF} \text{ (CCPREF)} = \$0.0/\text{m}$$

$$SM_{PIPE,REF} \text{ (SMPI)} = 1.5$$

$$P_{th,PIPE,REF} \text{ (PPIREF)} = 2.6 \times 10^8 \text{ watts}$$

$$x_{PIPE} \text{ (XPI)} = 1.06 \text{ (Reference 31)}$$

V.A-8. Storage—In DELSOL the cost of storage is based on a reference containment cost and size, and if the storage size exceeds a tank size limit then two smaller tanks of equal size are used instead. The equation for storage cost is

$$CC_{STORAGE} = n_{STOR} (C_{TK,REF} \left(1 + \frac{n_{EMPTY}}{n_{STOR}} \right) \left(\frac{V'_{TK}}{V_{TK,REF}} \right)^{x_{ST}} + C_{MED,REF} \frac{V'_{TK}}{V_{TK,REF}}) \quad (V.A - 15)$$

where n_{STOR} = number of storage tanks, or hot/cold pairs
 n_{EMPTY} = number of spare tanks (for drainage or backup)
 $C_{TK,REF}$ = reference storage media containment cost (including hot and cold tank pair, if so designed, insulation, foundation, valving, etc.) (\$)
 $C_{MED,REF}$ = reference storage media cost (\$)
 V'_{TK} = tank volume (m^3)
 $V_{TK,REF}$ = reference tank volume (m^3)
 x_{ST} = scaling exponent for tanks.

n_{STOR} is determined from an assumed maximum volume per tank:

$$n_{\text{STOR}} = \frac{V_{\text{STOR}}}{V_{\text{TK,MAX}}}$$

where V_{STOR} = total volume required for storage (m^3)
 $V_{\text{TK,MAX}}$ = maximum tank volume (m^3)

For non-integer values, n_{STOR} is rounded to the next highest integer. The total storage volume is related directly to the energy in storage:

$$V_{\text{STOR}} = V_{\text{TK,REF}} \left(\frac{E_{\text{STOR}}}{E_{\text{STOR,REF}}} \right) \quad (\text{V.A} - 16)$$

where E_{STOR} is the energy in storage. The individual tank volume is:

$$V'_{\text{TK}} = \frac{V_{\text{STOR}}}{n_{\text{STOR}}} \quad (\text{V.A} - 17)$$

assuming that multiple tanks will be constructed of equal volume. If only a single tank design is desired, the user can choose an appropriately large value for $V_{\text{TK,MAX}}$.

In DELSOL, storage is initially sized for the excess energy production on the longest day, June 21st. This storage size is always calculated and used in the system optimization process. The calculation of E_{STOR} is illustrated in Figure V-3. Its value is determined by a numerical integration to give the shaded area in the figure. The nominal number of hours of storage is simply E_{STOR} divided by P_{DES} . The assumption is made that this day will require the largest storage tank, so that no energy is thrown away at any time during the year. However, for north biased fields this assumption is not necessarily valid, since due to higher field efficiencies at other days of the year the integrated value mentioned above could be higher at another day than June 21, thus leading to discarded energy when the storage tank is sized for June 21. On the other hand, it is possible that having a smaller storage tank and discarding energy may be more cost effective than never discarding energy. The user is therefore given the option of optimizing the storage size to balance the cost of the storage tank against the cost of discarding energy. This option, which is specified using the variables ISTR and NSTR (Section IV.C-5), is requested as part of system optimization, but the storage optimization and final storage tank cost calculation is done during a final performance calculation. This is the only component cost which may be recalculated during a final performance calculation.

Default values for calculating storage costs are based on a hot tank/cold tank design:

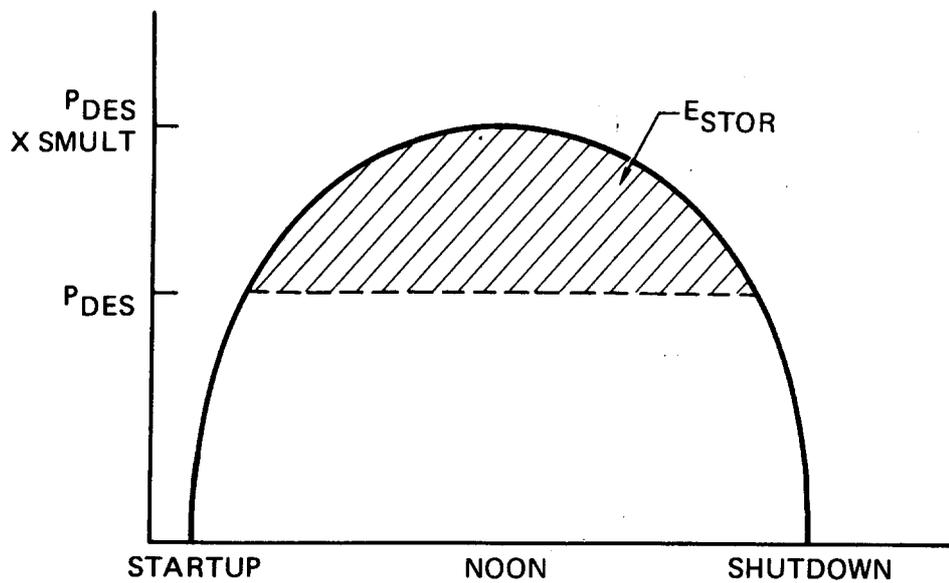


Figure V-3. Energy to storage is the excess energy produced above the design point requirement; it is given by the hatched area. The reference time in this example is noon.

$$n_{\text{EMPTY}} (\text{EMPTY}) = 0.0$$

$$C_{\text{TK,REF}} (\text{CSTREF}) = \$9.70 \times 10^6$$

$$C_{\text{MED,REF}} (\text{CSTRMD}) = \$6.80 \times 10^6$$

$$V_{\text{TK,REF}} (\text{VSTREF}) = 3740 \text{ m}^3$$

$$x_{\text{ST}} (\text{XST}) = 0.6 \text{ (Reference 31)}$$

$$V_{\text{TK,MAX}} (\text{VMAX}) = 1.23 \times 10^4 \text{ m}^3$$

$$E_{\text{STOR,REF}} (\text{ESTREF}) = 6.88 \times 10^8 \text{ watt-hrs}$$

V.A-9. Heat Exchanger Between the Receiver Fluid and the Storage Fluid—For current technology systems it may be desirable to have different types of fluids for the receiver and for storage, since fluids which store energy well (e.g., molten nitrate salt) may not absorb energy in a receiver as well as other fluids (e.g., liquid sodium). In this case, a separate heat exchanger is required as an interface between the two fluids. The cost of that heat exchanger scales with thermal power at the base of the tower:

$$C_{\text{CHTXSTOR}} = C_{\text{KN,REF}} \left(\frac{P_{\text{th}}}{P_{\text{th,KN,REF}}} \right)^{x_{\text{KN,P}}} \quad (\text{V.A} - 18)$$

where $C_{\text{KN,REF}}$ = Cost of receiver fluid-to-storage fluid heat exchanger for the reference thermal power (\$)

P_{th} = Actual thermal power at the base of the tower

$P_{\text{th,KN,REF}}$ = Reference thermal power at the base of the tower for the receiver fluid-to-storage fluid heat exchanger (watts)

$x_{\text{KN,P}}$ = Scaling exponent

The cost of this heat exchanger is only included if the variable $\text{ICKN} = 1$ (Namelist NLCOST). The default values are based on the cost of sodium steam generator heat exchangers:

$$\text{ICKN} = 0$$

$$C_{\text{KN,REF}} (\text{CKNREF}) = \$9.0 \times 10^6$$

$$P_{\text{th,KN,REF}} (\text{PKNREF}) = 320.0 \times 10^6 \text{ watts}$$

$$x_{\text{KN,P}} (\text{XKN}) = 0.8$$

V.A-10. *Heat Exchangers Related to Generating Electricity*—There are two options for calculating heat exchanger component costs, the first of which scales the cost of a reference system based on thermal power into the heat exchangers (out of storage), and the second of which scales the cost of a reference system based on individual heat exchanger areas.

- a) ICHE = 0 (default)—cost scales with thermal power into the heat exchangers based on a reference system:

$$CC_{HTXCHG} = C_{HE,REF} \left(\frac{P_{th}}{P_{th,HE,REF}} \right)^{x_{HE,P}} \quad (V.A - 19)$$

where $C_{HE,REF}$ = reference heat exchanger subsystem cost (\$)
 P_{th} = actual thermal power into the heat exchangers
 $P_{th,HE,REF}$ = reference design thermal power into the heat exchangers (out of storage) (watts)
 $x_{HE,P}$ = scaling exponent

Default values are based on proposed molten salt designs, and the total subsystem cost includes an evaporator, superheater, and reheater:

$$C_{HE,REF} (C_{HEREF}) = \$15.2 \times 10^6$$

$$P_{th,HE,REF} (P_{HEREF}) = 3.0 \times 10^8 \text{ watts}$$

$$x_{HE,P} (X_{HEP}) = 0.8$$

- b) ICHE ≠ 0—cost scales with individual heat exchanger areas based on a reference system:

$$CC_{HTXCHG} = n_{PH} C_{PH,REF} \left(\frac{A'_{PH}}{A_{PH,REF}} \right)^{x_{HE,A}} + n_{EV} C_{EV,REF} \left(\frac{A'_{EV}}{A_{EV,REF}} \right)^{x_{HE,A}} \\ + n_{SH} C_{SH,REF} \left(\frac{A'_{SH}}{A_{SH,REF}} \right)^{x_{HE,A}} + n_{RH} C_{RH,REF} \left(\frac{A'_{RH}}{A_{RH,REF}} \right)^{x_{HE,A}} \quad (V.A - 20)$$

where subscripts PH, EV, SH, and RH refer to the preheater, evaporator, superheater, and reheater, respectively, and:

n_i = number of type i heat exchangers
 $C_{i,REF}$ = reference cost of single type i heat exchanger (\$)
 A_i = area of heat exchanger i (m²)
 $A_{i,REF}$ = area of reference type i heat exchanger (m²)

$x_{HE,A}$ = scaling exponent.

n_i is calculated from a specified maximum area $A_{i,MAX}$ for a type i heat exchanger:

$$n_i = \frac{A_i}{A_{i,MAX}} \quad (V.A - 21)$$

where

$$A_i = A_{i,REF} \left(\frac{P_{th}}{P_{th,i,REF}} \right) \quad (V.A - 22)$$

and

$$A'_i = \frac{A_i}{n_i} \quad (V.A - 23)$$

For non-integer values of n_i in Equation (V.A-21), it is rounded to the next highest integer. Default values are based on sodium hockey stick designs (Reference 40), and no preheater is included. (Salt heat exchangers have not yet been studied in detail by the authors for costing according to this option.) Also, $A_{i,MAX}$ is set sufficiently large so that only single units will be built.

$$C_{PH,REF} (CPHREF) = \$0.0$$

$$A_{PH,REF} (APHREF) = 1.0 \text{ m}^2$$

$$A_{PH,MAX} (APHMAX) = 10^{10} \text{ m}^2$$

$$P_{th,PH,REF} (PPHREF) = 1.0 \text{ watt}$$

$$C_{EV,REF} (CEVREF) = \$3.77 \times 10^6$$

$$A_{EV,REF} (AEVREF) = 1300.0 \text{ m}^2$$

$$A_{EV,MAX} (AEVMAX) = 10^{10} \text{ m}^2$$

$$P_{th,EV,REF} (PEVREF) = 2.6 \times 10^8 \text{ watts}$$

$$C_{SH,REF} (CSHREF) = \$1.24 \times 10^6$$

$$A_{SH,REF} (ASHREF) = 400.0 \text{ m}^2$$

$$A_{SH,MAX} (ASHMAX) = 10^{10} \text{ m}^2$$

$$P_{th,SH,REF} (PSHREF) = 2.6 \times 10^8 \text{ watts}$$

$$C_{RH,REF} (CRHREF) = \$1.38 \times 10^6$$

$$A_{RH,REF} (ARHREF) = 310.0 \text{ m}^2$$

$$A_{RH,MAX} (ARHMAX) = 10^{10} \text{ m}^2$$

$$P_{th,RH,REF} (PRHREF) = 2.6 \times 10^8 \text{ watts}$$

$$x_{HE,A} (XHEA) = 0.6$$

V.A-11. *Electric Power Generating Subsystem (EPGS)*—This cost, which includes the cost of the turbine plant and electric plant, is scaled from a reference system cost:

$$CC_{EPGS} = C_{EPGS,REF} \left(\frac{\eta_{TE,REF} P_{th}}{P_{EPGS,REF}} \right)^{x_{EPGS}} \quad (V.A - 24)$$

where $C_{EPGS,REF}$ = cost of reference EPGS subsystem (turbine plant and electric plant) (\$)

$P_{EPGS,REF}$ = gross power rating of reference subsystem (watts)

$\eta_{TE,REF}$ = design point thermal to electric conversion efficiency (see section III.G-5).

Default values assume a 112 MW_{E,gross} output and constant $\eta_{TE,REF}$ for all power levels.

$$C_{EPGS,REF} (CEGREF) = \$37.5 \times 10^6$$

$$P_{EPGS,REF} (PEGREF) = 1.12 \times 10^8$$

$$\eta_{TE,REF} (ETAREF) = 0.42$$

$$x_{EPGS} (XEPGS) = 0.8$$

Note: This cost is automatically set to zero for a user specified industrial process heat design (IPH \neq 0 in Namelist NLEFF).

V.A-12. *Fixed Costs*—It is assumed that, regardless of plant size, all plants have some common field costs (e.g., buildings and roads, master control, etc.). The structures and improvements, as well as miscellaneous equipment, are somewhat related to the electric power output of the plant, while some other costs are related to the size and amount of other equipment (capital costs). The fixed cost algorithm is based on Reference 35, and can only be partly changed by the user:

$$CC_{\text{FIXED}} = 2.0E6 + 0.14 \times \text{DCC} + 0.093 \times P_e + C_{\text{FIXED}} \quad (\text{V.A} - 25)$$

where DCC = all other direct capital costs
 P_e = design point turbine electric power (watts)
 C_{FIXED} = any other additional fixed costs

The user only has control over C_{FIXED} , which has a default of:

$$C_{\text{FIXED}} (\text{CFIXED}) = \$0.0$$

V.B. Calculation of Levelized Energy Cost

Based on the total capital cost CC_T defined in Equation (V.A-1) using the component cost models discussed in the previous section, a levelized (or discounted average) cost of energy over the lifetime of the plant is calculated as follows (References 41 and 42):

- 1) The total investment at operation startup, $CC_{\text{ST-UP,T}}$, will be the current capital cost estimate, CC_T , escalated over the time period from the time of the cost estimate to the first year of construction (NYTCON), plus the interest on the borrowed investment during the construction period, i_{DC} . Note that the length of the construction period is not explicitly stated, but that time period would be factored into the value of i_{DC} .

$$CC_{\text{ST-UP,T}} = CC_T \times (1.0 + i_{\text{DC}})(1.0 + \text{ESC})^{\text{NYTCON}} \quad (\text{V.B} - 1)$$

In current, supposedly more valuable dollars,

$$CC_{\text{ST-UP,cur\$}} = \frac{CC_{\text{ST-UP,T}}}{(1.0 + r_{\text{inf}})^{\text{NYTCON}}} \quad (\text{V.B} - 2)$$

where r_{inf} is the general rate of inflation, which is not necessarily equal to the capital escalation rate ESC.

- 2) The levelized energy cost includes both capital recovery and operating and maintenance (O&M) charges. The O&M charges are calculated as a levelized percentage of the capital cost. DELSOL splits O&M charges into heliostat and non-heliostat rates:

$$\text{LEC} = \frac{(\text{FCR} \times CC_{\text{ST-UP,T}}) + (\text{O\&M}_{\text{H.LEV}} \times CC_{\text{ST-UP,H}}) + (\text{O\&M}_{\text{BAL.LEV}} \times CC_{\text{ST-UP,BAL}})}{\text{Annual Energy}} \quad (\text{V.B} - 3)$$

where Annual Energy = Net electric annual energy as described in Section III.H

FCR = fixed charge rate, i.e., annual charge against the capital investment to account for returns to shareholders, taxes and insurance, depreciation, debt cost, and discount rate

O&M_{H,LEV} = levelized heliostat O&M rate

CC_{ST-UP,H} = heliostat subsystem capital investment at startup (includes land and wiring)

O&M_{BAL,LEV} = levelized balance of plant O&M rate

CC_{ST-UP,BAL} = balance of plant capital investment at startup

V.B-1. Fixed Charge Rate—The user is allowed one of two options for determining the fixed charge rate, FCR:

- a) IFCR = 0—user specified value of FCR. In this case, the values of DISRT, RINF, and NYOP still need to be specified correctly for use in calculating O&M rates.
- b) IFCR ≠ 0—FCR is calculated by DELSOL based on user supplied values of economic parameters.

$$FCR = PTI + \frac{(1.0 - ITC) - (ITR \times DEP)}{(1.0 - ITR)f_{DIS}} \quad (V.B - 4)$$

where PTI = annual property tax and insurance rate

ITC = investment tax credit

ITR = income tax rate

DEP = depreciation allowance, discussed below

f_{DIS} = discount factor, discussed below.

With option b) above (IFCR≠0), the user is allowed one of two choices for calculating the depreciation allowance:

- 1) IDEP = 1—straight line schedule:

$$DEP = \sum_{y=1}^{Y_{DEP}} \frac{(1.0/Y_{DEP})}{(1.0 + r_{DIS})^y} \quad (V.B - 5)$$

where Y_{DEP} = depreciation life of the solar plant (years)

r_{DIS} = discount rate, discussed below.

- 2) IDEP = 2—sum-of-years digits schedule:

$$DEP = \sum_{y=1}^{Y_{DEP}} \frac{2(Y_{dEP} - y + 1)}{Y_{DEP}(Y_{DEP} + 1)(1 + r_{DIS})^y} \quad (V.B - 6)$$

The discount rate r_{DIS} is the effective cost of money to the owner and includes both debt cost and return on equity requirements according to:

$$r_{DIS} = [(1.0 - ITR) \times f_D \times i_D] + (1.0 - f_D) \times ROE \quad (V.B - 7)$$

where f_D = debt fraction
 i_D = debt cost (interest rate on borrowed capital)
 ROE = before tax return on equity.

(Note that $r_{DIS} = ROE$ for $f_D = 0$; i.e., 100% equity financed projects.)

The discount factor is:

$$f_{DIS} = \sum_{y=1}^{Y_{OP}} \frac{1.0}{(1.0 + r_{DIS})^y} \quad (V.B - 8)$$

where Y_{OP} = economic operating life of the plant (years).

V.B-2. Levelized O&M Rates—The levelized O&M rates are determined from the initial rate, $O\&M_i$; the yearly inflation and discount rates, r_{inf} and r_{DIS} , respectively; and the plant operating life, Y_{OP} :

$$\begin{aligned} O\&M_{LEV} &= \frac{\sum_{y=1}^{Y_{OP}} \frac{O\&M_y}{(1+r_{DIS})^y}}{\sum_{y=1}^{Y_{OP}} \frac{1}{(1+r_{DIS})^y}} \\ &= \frac{O\&M_i \sum_{y=1}^{Y_{OP}} \frac{(1+r_{inf})^y}{(1+r_{DIS})^y}}{\sum_{y=1}^{Y_{OP}} \frac{1}{(1+r_{DIS})^y}} \end{aligned} \quad (V.B - 9)$$

Default values are based mostly on 1984 5-year plan economics:

$$i_{DC} \text{ (AFDC)} = 0.0318 \text{ (assumes a 3-year construction period)}$$

$$ESC \text{ (ESC)} = 0.00$$

$$NYTCON \text{ (NYTCON)} = 0 \text{ (assumes plant construction begins now)}$$

$$r_{inf} \text{ (RINF)} = 0.00$$

$$\text{IFCR (IFCR)} = 0$$

$$\text{FCR (FCR)} = 0.0615$$

$$\text{O\&M}_{h,i} \text{ (RHOM)} = 0.015$$

$$\text{O\&M}_{\text{BAL},i} \text{ (RNHOM)} = 0.015$$

$$\text{PF (PF)} = 0.9$$

$$r_{\text{DIS}} \text{ (DISRT)} = 0.0315$$

$$\text{PTI (PTI)} = 0.01$$

$$\text{ITC (TC)} = 0.10$$

$$\text{ITR (TR)} = 0.48$$

$$f_{\text{D}} \text{ (FDEBT)} = 0.5431$$

$$i_{\text{D}} \text{ (RDEBT)} = 0.11$$

$$\text{ROE (ROE)} = 0.15$$

$$\text{IDEP (IDEP)} = 2$$

$$Y_{\text{DEP}} \text{ (NDEP)} = 24 \text{ years}$$

$$Y_{\text{OP}} \text{ (NYOP)} = 30 \text{ years}$$

VI. Program Flow

DELSOL can be used in two ways: to do a detailed performance calculation for a system which is completely defined by the user, or to define by optimization a system having a lowest energy cost and then do a detailed performance calculation on that system. For the first case, no optimization, annual energy calculation, or system cost calculations are done. Heliostat field zoning and zone heliostat densities must be specified, along with desired receiver and tower dimensions. In fact, every default variable in the BASIC, FIELD, HSTAT, REC, and NLEFF Namelists should be examined to verify that the proper system is being examined. Even then, no energy calculations will be done, and no costs will be assigned to the system, but only field efficiencies and flux densities will be calculated. A user defined system should be examined by specifying $I\text{PROB} \neq 4$ (Namelist BASIC) and $I\text{USERF} = 2$ or 3 (Namelist FIELD).

The most useful function of DELSOL, that of finding an optimum system design, has three calculational steps and several minor steps. The main steps are to do an initial performance calculation, to optimize several variables using the results from the initial performance calculation, and to do a final performance calculation on the optimum system. These steps fit into the list of actions suggested for optimization in Table VI-1.

Before any calculations are done, the user must still take the time and effort to see that the DELSOL defaults describe the proper system. Specification of the site, field boundaries, heliostat design, and receiver type are generally straightforward. However, determining receiver thermal losses and system costs can be much more involved. The radiation and convection losses depend on receiver geometry, receiver material, temperature, and ambient conditions. The system costs depend on the technology and applications. Detailed cost estimation may be required to generate the input to DELSOL. In addition to the direct capital costs, operating and maintenance costs must be estimated. Finally, the economic parameters suitable for the intended application of the system have to be specified.

The initial performance calculation is required as a first step for optimizing a system design, since the results will be scaled to give the performance of the different systems in searching for the optimum design. The specifications of receiver type (IREC) and field type (INORTH) should be consistent with each other and with the system to be designed. Annual field performance will be calculated at this time for every zone in the heliostat zonal pattern. This involves finding the image shapes for heliostats from every zone. However, no power limitation is yet imposed on the system, so heliostat aiming strategies will not affect the results, except that using multiple aimpoints will increase the computational time directly. Thus, during the initial performance run, a single aimpoint strategy should be used. Also, because the heliostat field has not yet been optimized

Table VI-1
Steps in Designing a System

- I. Define System**
 - Heliostat type; receiver type; flux limits; field boundaries
 - Non-optical performance parameters: receiver losses; EPGS
 - Costs appropriate to technology and application
- II. Initial performance calculation**
 - Use a guess for optimum tower height
 - Save results for other optimizations using this heliostat, site, tower height
- III. Coarse optimization (can be done at same time as II)**
 - Limited number of widely spaced optimization variables
 - If optimum value(s) of a design variable(s) is at the minimum or maximum value allowed in search for optimum, increase the range of values searched and do another coarse optimization
- IV. Fine optimization**
 - Use a finer grid of optimization variables centered on results of III
 - Reuse initial performance results from II unless tower height is very different
- V. Heliostat density optimization**
 - A. New initial performance calculation**
 - Use optimum tower height from IV
 - Use default densities or optimized densities from similar system optimization
 - B. Optimization (can be done at same time as VA)**
 - Do not vary tower height
 - Choose a fine grid of receiver sizes
 - C. Converge density optimization**
 - If optimum heliostat layout is very different from initial layout used in VA, repeat VA and VB using the optimum densities from VB as the input densities for VA
- VI. Detailed performance calculation of optimum system**
 - Do a user defined field performance calculation of optimum system
 - Optimize storage capacity if desired
- VII. Investigate other design concepts (optional)**
 - Repeat I-VI with different heliostat or receiver type, different working fluid
- VIII. Non-energy cost design considerations**
 - Energy cost is generally insensitive to small perturbations from optimal system
 - If other considerations suggest deviating from DELSOL optimal design, run DELSOL to calculate energy cost of modified system

to reach a certain design power, calculation of flux on the receiver is meaningless and should not be done. The initial performance calculation fixes the values of the constant design parameters listed in Table IV-2. Although it is possible to change some of the receiver variables in later steps such as optimization, it **should not be done**. The variables specified in that table should only be specified during an initial performance run.

After the initial performance calculation, it is possible to save the results on a computer file. Thus, the initial performance can be calculated as a separate computer run from optimization if this file is requested and saved as discussed in Section VI.A-4. Similarly, it is possible to save the results of an optimization calculation on a computer file for future use. Thus, it is possible to do the three calculational steps as three distinct and sequential computer jobs, or it is possible to combine the steps into a continuous computer job by specifying the right flags. This discussion, however, will treat the three calculations as three distinct steps.

The second calculational step in optimizing a system design is to do the actual optimization. A two step optimization of tower and receiver dimensions is generally more efficient. A search over a coarse grid of optimization variables locates an approximate optimum design rapidly. A search over a fine grid of optimization variables centered on the coarse grid optimum then finds a more exact optimum. Both of these runs would use the same initial performance run as described above; specifically, the annual average performance of each zone is used during field buildup, so that no time calculation is done during the optimization. Because calculations are based on a specific system performance, the user should consider doing a modified initial performance calculation if the optimized system design varies significantly from the parameters chosen during the original initial performance calculation. However, in most instances the scaling of performance is adequate and no iteration is required.

During the optimization process, the variables described in Table IV-2 will and should remain fixed. A REC Namelist is the first namelist read as part of the optimization process, and any variables which are not defined in REC at this time default to the values defined in that namelist during the initial performance calculation. This is important, because any receiver or tower variables which are not being optimized will be set to the values specified as a result of this input namelist.

The requested solar multiple can be specified in both the OPT Namelist and the NLEFF namelist, but only the last specified value will be used. If a solar multiple other than the default (SMULT=1.5) is desired, it must be specified during the optimization calculation in one of these Namelists. The solar multiple value is not used during an initial performance calculation, and is only used in a final performance calculation for calculation of detailed annual energy, after the system has already been designed and optimized. Thus, it is recommended that a solar multiple value be specified only during the optimization procedure, since that value will also be used in the final performance energy evaluation.

The most appropriate aiming strategy on the receiver should be used during optimization. For designing flux limited receivers during system optimization, a field of flux points can be specified in Namelist NLFLUX. However, during optimization, flux will only be calculated and examined at four specified points out of the field of flux points. It is suggested that the allowable fluxes for each of these four points be specified individually, since the allowable flux will be different at different receiver locations due to different receiver temperatures and flow rates. It is further suggested that the four points checked during optimization also be checked during the final performance run to determine the effect of the optimization assumptions on the flux calculation during optimization.

During optimization DELSOL also sizes the heliostat field to meet the requested design point power. This means that zones of heliostats are added by the code to get the required power at the best energy cost. If heliostat density optimization is not requested, the code will add zones or portions of zones of heliostats at the default heliostat densities until the power is reached. The result of this process is a heliostat field which is no longer a uniform circular or north biased field ($IUSERF = 0$ or 1), but is instead a heliostat field specified zone by zone ($IUSERF = 2$). Thus the value of $IUSERF$ will be changed during system optimization.

As a further step in field design, heliostat densities can be optimized as described in Section IV.B-1. DELSOL can simultaneously optimize the heliostat densities and receiver dimensions. However, DELSOL cannot vary the tower height while optimizing the densities. Therefore, the user must first do the above system optimizations to find an optimum tower height for use during heliostat density optimization. Unless the optimum tower height is the same as was chosen during the initial performance calculation, a new performance calculation is also required before optimizing the heliostat densities. Note that if optimizing heliostat densities results in a higher levelized energy cost at that design point power level, then that optimization did not help, despite the fact that for a constant annual energy the heliostat density optimization would have given a lower energy cost.

Once an optimized system has been chosen, DELSOL will assign component costs to each part of the system, based on its internal cost algorithms. This is done at the end of system optimization, and is the only place in DELSOL where component costs are determined, other than for the exception below.

If it is desired to optimize storage size for a fixed field size, that option should be requested during the system optimization procedure. However, the actual calculation is not done until a final performance run is done. Thus, output from system optimization will always refer to the default calculated storage size, and costs will be set accordingly. During a final performance calculation, the code will then trade off the cost of storage against the cost of discarding energy and determine

an optimum storage size based on energy cost. At the conclusion of this optimization, storage capital costs and energy costs are adjusted to account for the optimized storage.

The last step in finding an optimized system using DELSOL is to determine a more accurate performance of the chosen system by doing a final detailed performance calculation (IPROB \neq 4). For this calculation, the system definition must be read from a file which was created during system optimization. This is done by specifying ITAPE=3 in Namelist BASIC. No parameters should be changed or specified on the namelist input which would change the system in any way. However, different aiming strategies can be examined and different flux point locations can be requested, although varying aiming strategies may cause receiver flux limits to be exceeded.

During a final performance calculation, field and system performances are again calculated at points in time, as during an initial performance calculation. However, now that a specific system has been defined, an average annual performance can be calculated as well, if IPROB=0. Furthermore, if IPROB=0, an annual energy detailed summary is provided, and a more accurate calculation of annual energy is done. Both of these calculations are done at several times during several days to get a good energy prediction for this specific system. Since this annual energy calculation is more accurate than that used during system optimization, energy costs are recalculated using this energy value and the costs which were calculated during the optimization.

A detailed flux map on the receiver will be provided during a final performance calculation if requested by the user. This flux map will reflect the aiming strategy specified by the user, and will only represent one point in time. If a flux map for a different time is desired, a separate performance calculation is required for generation of that flux map. Further, the flux will always be calculated using REFSOL insolation for a system which was previously optimized by DELSOL, so that the flux map must be manually adjusted if a time having a lower insolation is of interest. Finally, flux maps at different locations can be generated (one per performance calculation), which might be useful in modifying the interior of a cavity receiver.

VI.A. Description of Files Used/Created by DELSOL

Several files are created or used by the DELSOL computer code during execution of different parts of the code. Briefly, there is an input file, an output file, an interactive file, a file to which an initial performance of a system is written, a comparable file from which a previous initial performance is read, a file to and from which an optimized system is written/read, a file to which an azimuth-elevation table of field performance is written, a file to which only a flux map is written, and an internal scratch file.

VI.A-1. Input File (Unit 5)—This file is a formatted file, created by the user, which contains all of the namelist input data required to run a particular job.

The namelists should be ordered as described in Appendix A. This file is only read by DELSOL.

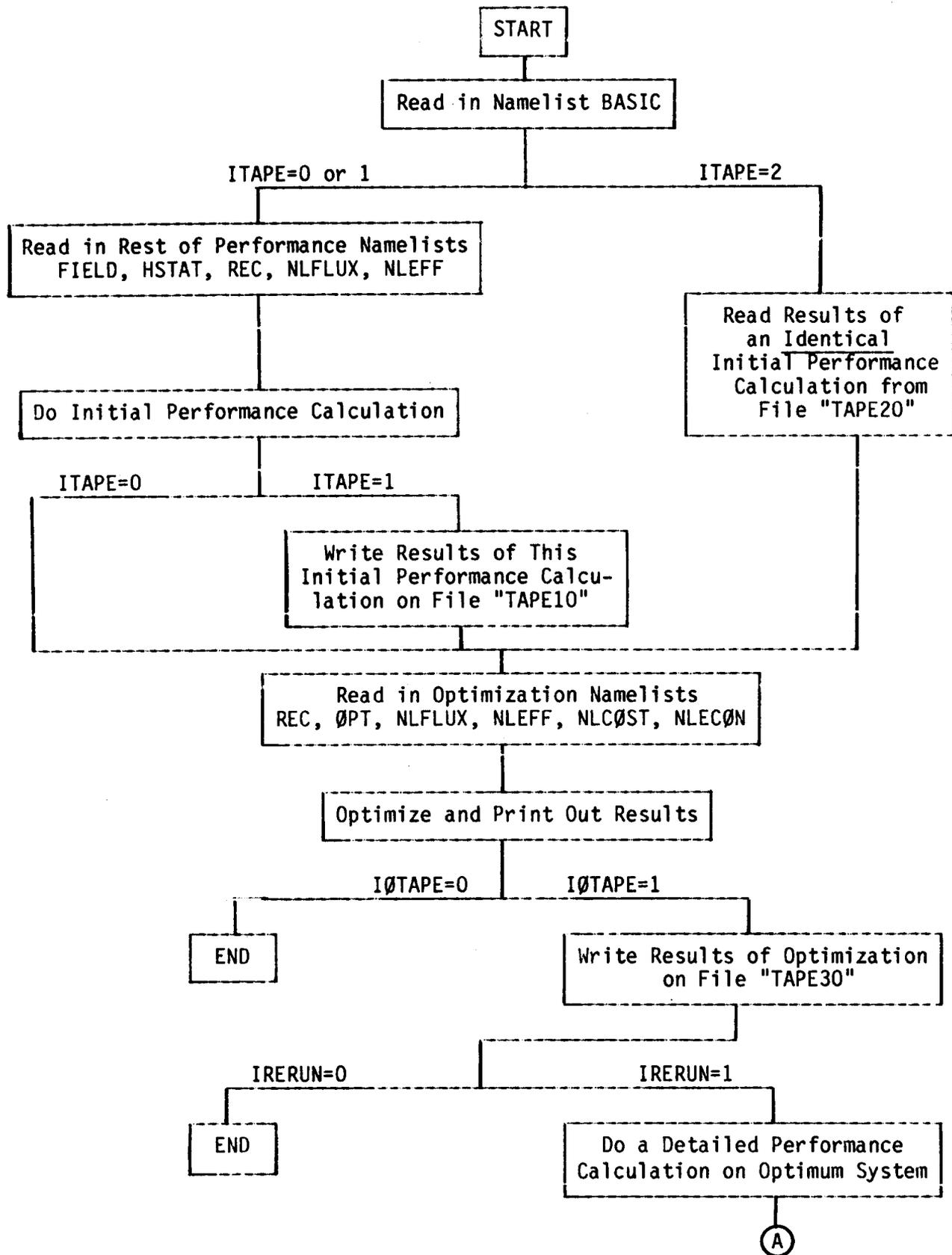
VI.A-2. Output File (Unit 6)—This file is a formatted file, created by DELSOL, which contains all of the standard output from a DELSOL execution. Samples of the type of information contained in this file are shown in the outputs to sample problems in Appendix B. DELSOL only writes, and does not read, this file.

VI.A-3. Interactive File (Unit 1)—This file is a formatted file which can be used to provide limited output to a computer terminal screen during job execution. DELSOL uses this file in an interactive mode when interactive user aiming of heliostats is being performed (Section II.F-6). The file could also be used for such things as repeating input back to the screen or to output error or termination messages that also were written to Unit 6. The user should take the appropriate steps to make sure this file is printed to a terminal screen.

VI.A-4. Initial Performance File (Units 10 and 20)—This file is an unformatted file which is written by DELSOL (Unit 10) if requested at the end of an initial performance calculation, and which can be read by DELSOL (Unit 20) at the start of any future optimization calculations. This is a useful option, since it may be desirable to use the same initial performance calculation for several different design optimizations. This can result in significant savings in computer time. However, the user should be certain that a performance calculation which has previously been saved on Unit 10 has the same site characteristics, heliostat zoning (including north vs. surround field), heliostat design, and approximate tower height as is desired for the new optimization calculation. Otherwise, a new initial performance calculation will be required.

Figure VI-1 illustrates the options for the initial performance calculations. In all cases the first Namelist, BASIC, is read from Unit 5. The value of the variable ITAPE in that Namelist determines which branch is followed. If ITAPE=0 the remaining performance Namelists are read in, the performance calculation is executed, and then the code begins reading in the optimization Namelists, without writing to Unit 10. If ITAPE=1, the remaining performance Namelists are also read in and the performance calculation is executed. However, in this case the performance is written to Unit 10, and then the code begins reading the optimization Namelists. (Setting $W < 0$ in the REC Namelist in the optimization section will terminate job execution without performing optimization calculations, if the user desires only to produce a Unit 10 file.) The user should take appropriate action to save the Unit 10 file.

To use a performance calculation which has been previously saved on Unit 10, the user should attach the file to the code as a Unit 20 file, and ITAPE=2 should be specified in Namelist BASIC. In this case, no other performance Namelists are read, and so they should be omitted from the Unit 5 input file. When ITAPE=2 is specified, DELSOL prints a short summary to the output file of the information on the Unit 20 file, skips the initial performance calculation, and proceeds



See Figure VI-2

Figure VI-1. Options on Initial Performance Calculations

directly to the optimization calculations. The next Namelist read after the BASIC Namelist in this case is the REC Namelist that begins the optimization group of Namelists.

VI.A-5. Optimized System File (Unit 30)—This file is an unformatted file, written during optimization and read during a final performance run, which contains the description of an optimized design. The user must specify IOTAPE=1 (Namelist OPT) to request that this file be written, and this file must be written if the user plans to do a final performance calculation on the optimized system. Once the Unit 30 file is written, the code can either go directly into a final performance calculation if IRERUN=1 is specified (Namelist OPT) or execution can be terminated before doing a performance calculation if IRERUN=0. This latter option allows the user to save the optimized design file for either a later performance calculation, multiple flux map calculations, or as input to a user provided plotting program.

The options for saving and rerunning optimized systems are illustrated in Figures VI-1 and VI-2. As seen in the lower part of Figure VI-1, when DELSOL has finished optimizing a system the optimum design(s) are written to the Unit 30 file. The user should take appropriate action to save the Unit 30 file. To read the optimized system for a performance calculation, the user attaches a copy of the Unit 30 file to the program and specifies ITAPE=3 on Namelist BASIC. Remember that if IRERUN=1 (Namelist OPT) DELSOL does not stop after system optimization is complete, but immediately starts a new performance calculation using the optimized system.

The information stored on the Unit 30 file describing the optimum system becomes the default values for a final performance calculation when that file is read by specifying ITAPE=3. Specifically, the following are stored on the Unit 30 file:

- site (latitude, weather, insolation, etc.)
- field (number and type of zones, heliostat layout)
- heliostat (dimensions, reflectivity, canting, focusing)
- receiver (type and dimensions)
- tower height
- flux points (only if flux was calculated during optimization)

The user, therefore, does not have to define these variables. Generally, when rerunning a system in a performance calculation the only variables that the user redefines are: (1) type of problem (e.g., single time, single day, annual performance); (2) flux calculation if different from optimization (more flux points or different flux surfaces may be examined); or (3) heliostat aim strategies or the

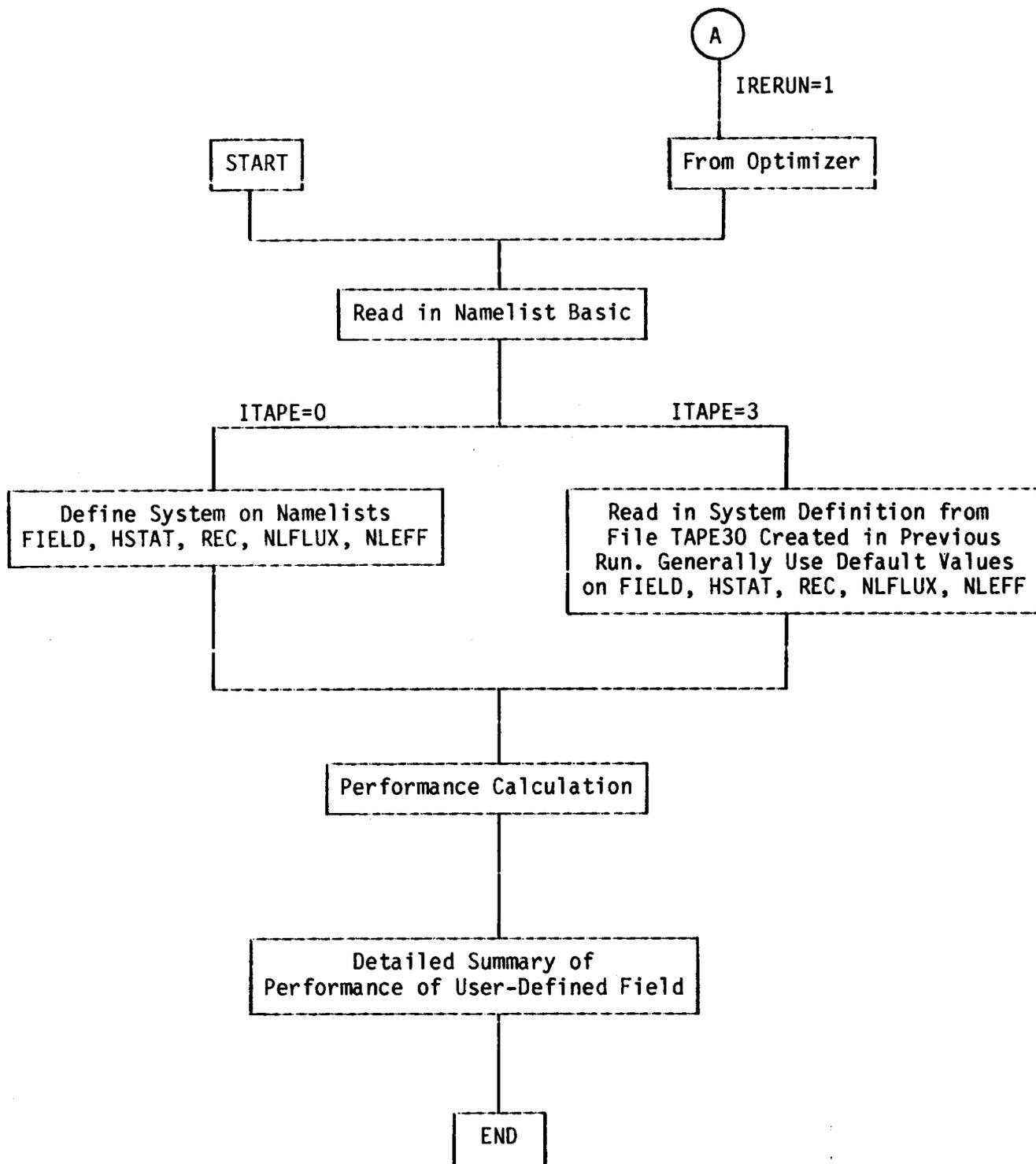


Figure VI-2. Options on Performance Calculations

option for more accurate heliostat images (INDC=1, Namelist HSTAT) may be varied. This last may significantly affect the results obtained for small systems.

The user must select the design point power level(s) which will be saved on a Unit 30 file or rerun during a final performance calculation. Although DELSOL can simultaneously optimize up to 20 design point power levels, the code only writes (to a Unit 30 file) a detailed field description for a maximum of five of these power levels. The user selects these power levels via the IPLFL(I) parameters in Namelist OPT. When using IOTAPE=1, all non-zero IPLFL(I) power levels are written on Unit 30 to be stored for future use. When reading the Unit 30 file in a final performance run, the user specifies which single power level from the file is to be used in the performance calculations (TDESP, Namelist BASIC).

The order of information on the Unit 30 file is given in Table VI-2.

VI.A-6. Performance File at Specified Sun Angles (Unit 31)—This file is a formatted file to which the field performance information is written for the user specified sun angles using the option IPROB=3. The same information is printed in the output file (Unit 6). This information, when the default sun angles are used, is the information needed for use in the STEAEC or SOLERGY codes, although the information cannot be read directly from the Unit 31 file by these codes.

VI.A-7. Flux Map File (Unit 11)—This file is a formatted file containing only flux maps generated during performance calculations. This is the same flux map information which is printed in the output file (Unit 6). The information on this file can be used to generate graphic contour profiles of the flux on a receiver. The user must remember that the flux map may not completely cover the surface of a receiver, or may not even be on the receiver heat absorbing surface. However, the information can still be plotted to give qualitative information quickly as to peak flux locations and flux uniformity.

TABLE VI-2
OUTPUT FROM OPTIMIZATION RUN STORED ON UNIT 30

<u>Variable</u>	<u>Namelist or Definition</u>
a) Common to all power levels	
WM, HM	HSTAT
IROUND	"
ICANT	"
NCANTX, NCANTY	"
ROUND	
ASTAT	Surface area of heliostat including gaps (=WM*HM)
AMIRRO	Total mirror area in field
NRAD	FIELD
NAZM	"
RMIRL	HSTAT
DENSMR	"
XFOCUS	"
YFOCUS	"
SIGAZ, SIGEL	"
SIGSX, SIGSY	"
SIGTX, SIGTY	"
HEAD	Hollerith heading (title) of job
IFOCUS	HSTAT
XFOCAL	"
YFOCAL	"
HCANT	"
DCANT	"
RADMIN, RADMAX	FIELD
RCANT	HSTAT
RANGE	Slant range
ILAY	FIELD
INDC	"
IROTFL	FIELD
REFSOL	BASIC
ATM1, ATM2, ATM3, ATM4, IATM	"
INORTH, AMAXN	FIELD
PLAT	BASIC
ALT	"
REFDAY, REFTIM	"
NSUNPT, SUNR, SUNI, NSUN	"
ICPANL, WPANL, HPANL, HXCANT, HYCANT	HSTAT
NUMCAV, IREC, RELV, RAZM	REC

RRECL	"
IAUTOP	"
II	Total number of designs written on TAPE30 (≤ 5)
HROP	Total annual hours of plant operation
WEATH,DPRES,DH2O, DWEATH,IWEATH	BASIC
ALP	FIELD
ASTART	BASIC
REFTHP,AREF,REFRC	NLEFF
REFLP,REFPIP,FPLH,FPLC	"
ITHEL,ETAREF,FEFF	"
REFPRL,FSP	"
PF	"
SMULT	"
CCMUL,CCMULY,CCMULC	Multipliers on direct capital cost
FCR,RHOML,RNHOML	Economic parameters
CSTREF,VSTREF,ESTREF,XST CSRMD,VMAX,EMPTY	NLCOST
ISTR,NSTR	OPT
NAX,NAY,NUMPT, XAIM,YAIM	REC
EFFSTR	NLEFF
FEP	"
IPH	"
FLXLIM	NLFLUX
ICAVF	"
IFLAUT	"
IFLX	"
IFXOUT	"
NFLXMX,NMXFLX	"
ISB	HSTAT
AZMSEP,DENSIT	FIELD
FSLIP	"
IDENS	"
IHPR	"
IUSERF	"
NRADMN,NRADMX	"
REFRC1,REFRC2,REFRC3	NLEFF
IRADFL	"
HRPRE,HRSTRT,HRWEATH	Annual hours of operations for parasitics
PARL1,PARL2,PARL3, PARL4,PARL5,PARL6, PARL7,PARL8,PARL9, PARL10,TPRE,TSTRT	NLEFF

b) Power level specific for detailed performance calculation
(1 set for each power saved)

Y2(N)	Power level
NTMIN(K),NTMAX(K) (K=1,NAZM)	Minimum, maximum zone occupied
AZMTR(L),DENTR(L) (L=1,NLAND)	Azimuthal separation, density
FLAND,XTOWER,YTOWER,SLEW SLNS,CLE,CLN,NLAND	FIELD,OPT
THT	REC
RX,RY,W,H,RWCAV	"
TOWD,TOWL	"
ACWOSY,ACWOSC	Capital cost without storage (escalated current)
ACHY,ACHC	First year capital cost intermediate value
ESTOR	Maximum storage capacity
XFC,YFC,ZFC,DIAMF, POLF,AZMF	NLFLUX
NXFLX,FAZMIN,FAZMAX, NYFLX,FZMIN,FZMAX	"

c) Arrays for plotting (all power levels: N=1,NP)

NP	Total number power levels (≤ 20)
Y2(N)	Power levels
ALLBUSC(N)	Levelized energy costs (current \$)
HSTSAVE(N)	Number of heliostats
ARESAVE(N)	Total land area (km ²)
ALLCC(N)	Total capital cost
ALLPCL(N)	% capital cost in land
ALLPCW(N)	" wiring
ALLPCH(N)	" heliostats
ALLPCT(N)	" tower
ALLPCR(N)	" receiver
ALLPCP(N)	" piping
ALLPCB(N)	" pumps
ALLPCS(N)	" storage
ALLPCE(N)	" turbine/generator
ALLPCA(N)	% capital cost in steam generators
ALLPCF(N)	" fixed costs
ALLTOA(N)	Overall system total efficiency
ALLHR(N)	Hours of storage
ALLKWH(N)	Net energy production
ALLCOS(N)	Cosine
ALLSAB(N)	Shadowing and blocking (net efficiency)
ALLATM(N)	Atmospheric transmittance
ALLSPL(N)	Intercept
ALLRCR(N)	Annual average receiver efficiency

	(radiation and convection)
ALLRCP(N)	Annual average piping efficiency
ALLTOB(N)	Overall system thermal efficiency
ALLETA(N)	Average thermal to electric conversion efficiency
ALLTOA(N)	Overall system total efficiency
ALLFLU(N,I) (I=1,4)	Design point flux on receiver at point I

VI.B. Description of Subroutines in DELSOL

This Section will provide a brief summary of each subroutine or function used in the DELSOL code, including which subroutines call a particular routine and which subroutines are called by a particular routine. Figure VI-3 shows a diagram of the relationships between the routines in DELSOL.

PROGRAM DELSOL

C THE DELSOL PROGRAM AND ITS SUBROUTINES CALCULATES FIELD
C PERFORMANCE, FIELD LAYOUT, AND OPTIMAL SYSTEM DESIGN FOR SOLAR
C CENTRAL RECEIVER PLANTS. THEY PERFORM AN INITIAL,
C DETAILED FIELD PERFORMANCE CALCULATION FOR A USER DEFINED OR
C DEFAULT FIELD, OR FOR A CIRCULAR GRID OF ZONES. THE LATTER OPTION
C IS USED FOR AN OPTIMAL DESIGN RUN, WHILE EITHER OF THE FIRST TWO
C APPLIES WHEN THE FIELD PERFORMANCE OF A SPECIFIC SYSTEM IS
C DESIRED. PERFORMANCE AND OPTIMIZATION SUBROUTINES ARE CALLED
C BY DELSOL.

C
C THIS MAIN ROUTINE CALLS
C GENER, OPTCAL, PERCAL
C

FUNCTION FLUX(XX,YY)

C
C FLUX = FLUX DENSITY AT THE POINT (X,Y) IN THE IMAGE
C PLANE DUE TO A HELIOSTAT IN THE (K,L) ZONE

C THIS ROUTINE IS CALLED BY
C FLXMAP

C THIS ROUTINE CALLS
C NONE

SUBROUTINE FLXMAP (K,L)

C
C THIS SUBROUTINE CALCULATES THE FLUX AT NFLXPTS
C PRODUCED BY HELIOSTATS IN THE (K,L) ZONE

C THIS ROUTINE IS CALLED BY
C OPTCAL
C PERCAL

C THIS ROUTINE CALLS
C FUNCTION FLUX

SUBROUTINE GENER

C
C THIS ROUTINE GENERATES VARIABLES NECESSARY FOR EITHER A
C PERFORMANCE OR OPTIMIZATION CALCULATION

C THIS ROUTINE IS CALLED BY
C DELSOL
C

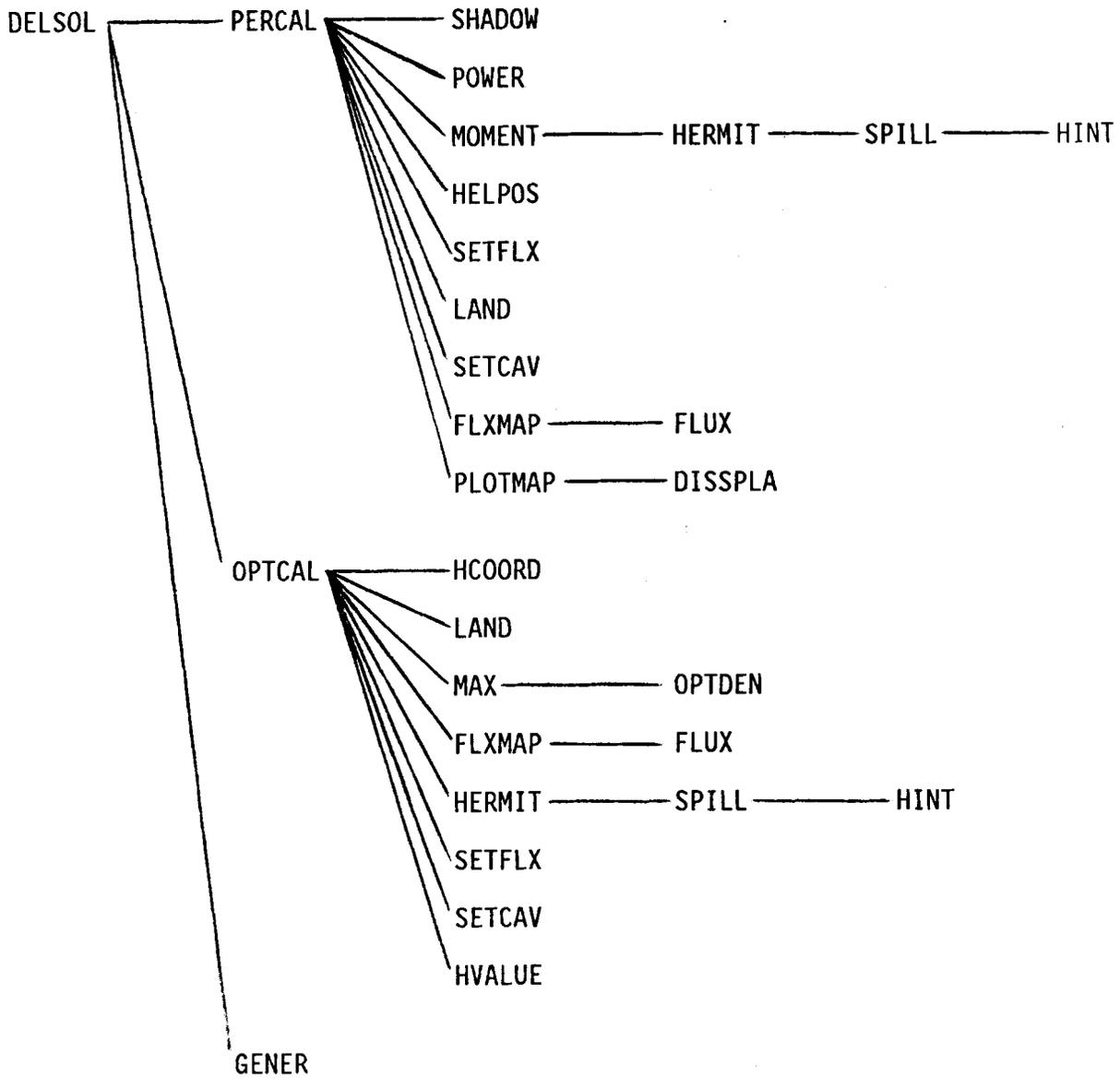


Figure VI-3. Relationships Between DELSOL Subroutines

C THIS ROUTINE CALLS
C NONE

SUBROUTINE HERMIT

C
C THIS SUBROUTINE EVALUATES THE HERMITE COEFFICIENTS.
C
C THIS ROUTINE IS CALLED BY
C OPTCAL
C MOMENT(PERCAL)
C
C THIS ROUTINE CALLS
C SPILL
C
C

SUBROUTINE HINT (G1,G2,G3,G4,G5,F1,F2,F3,F4,F5,XMAX,XMIN,AXI,AYI,
1WT)

C
C THIS SUBROUTINE CALCULATES THE INTEGRAL OF
C $HI(X/AX)*HJ(Y/AY)*EXP(-.5*(X**2/AX2+Y**2/AY2))$ OVER
C OVER THE PROJECTION OF THE RECEIVER ON THE IMAGE PLANE

C
C 8 POINT GAUSSIAN INTEGRATION FORMULAE ARE USED

C THIS ROUTINE IS CALLED BY
C SPILL(HERMIT(OPTCAL,MOMENT(PERCAL)))

C THIS ROUTINE CALLS
C NONE

C

SUBROUTINE LAND

C
C SUBROUTINE LAND DETERMINES THE FRACTION, F(K,L) OF
C THE AREA OF THE (K,L) ZONE THAT SATISFIES THE LAND
C CONSTRAINT WHEN THE TOWER IS XTOWER*THT METERS TO
C THE EAST AND YTOWER*THT METERS TO THE NORTH WITH
C RESPECT TO THE ORIGIN USED TO DEFINE THE LAND
C CONSTRAINT.

C
C THIS SUBROUTINE CALCULATES THE FRACTION OF EACH
C HELIOSTAT ZONE THAT SATISFIES A USER DEFINED
C CONSTRAINT ON THE LAND AVAILABLE FOR HELIOSTATS

C THIS ROUTINE IS CALLED BY
C OPTCAL
C PERCAL

C THIS ROUTINE CALLS
C NONE

C

SUBROUTINE SETCAV

C
C SUBROUTINE SETCAV IS USED WHEN A CAVITY RECEIVER IS SPECIFIED.
C IT ASSIGNS EACH ZONE TO THE CAVITY AT WHICH IT SHOULD POINT. THIS
C IS NECESSARY FOR THE SPILLAGE CALCULATION. FOR ZONES SPLIT
C BETWEEN TWO APERTURES, SETCAV DETERMINES THE FRACTION POINTED
C TOWARD EACH OPENING.
C
C THIS ROUTINE IS CALLED BY
C OPTCAL
C PERCAL
C
C THIS ROUTINE CALLS
C NONE
C

SUBROUTINE SETFLX

C
C SUBROUTINE SETFLX GENERATES THE COORDINATES OF THE POINTS ON
C AN EXTERNAL RECEIVER AT WHICH THE FLUX IS TO BE CALCULATED
C
C THIS ROUTINE IS CALLED BY
C OPTCAL
C PERCAL
C
C THIS ROUTINE CALLS
C NONE
C

SUBROUTINE SPILL

C
C THIS SUBROUTINE CALCULATES THE AMOUNT OF FLUX
C INTERCEPTED BY THE RECEIVER FOR EACH TERM IN THE
C
C THIS ROUTINE IS CALLED BY
C HERMIT(OPTCAL,MOMENT(PERCAL))
C
C
C THIS ROUTINE CALLS
C NONE
C

SUBROUTINE OPTCAL

C
C SUBROUTINE OPTCAL IS ACCESSED FOR OPTIMIZATION RUNS. THE
C USER SPECIFIED ARRAYS FOR TOWER HEIGHT AND RECEIVER DIMENSIONS
C ARE SELECTIVELY SEARCHED AT EACH REQUESTED POWER LEVEL TO FIND
C THE SYSTEM DESIGN GIVING THE LOWEST COST ENERGY. FOR EACH
C TOWER AND RECEIVER COMBINATION CONSIDERED, THE AVERAGE YEARLY
C PERFORMANCE IS RECALCULATED. SUBROUTINE MAX IS THEN CALLED
C TO PERFORM THE FIELD LAYOUT AND ENERGY COST CALCULATION.
C
C THIS ROUTINE IS CALLED BY
C DELSOL
C

C
C THIS ROUTINE CALLS
C HVALUE
C SETCAV
C SETFLX
C HERMIT
C FLXMAP
C MAX
C LAND
C HCOORD
C

SUBROUTINE HCOORD (II)

C
C THIS SUBROUTINE CALCULATES AND PRINTS THE FIELD LAYOUT
C PARAMETERS FOR AN OPTIMIZED SYSTEM CONFIGURATION.
C
C THIS ROUTINE IS CALLED BY
C OPTCAL
C
C THIS ROUTINE CALLS
C NONE
C

SUBROUTINE HVALUE

C
C THIS SUBROUTINE DOES THE HELIOSTAT LAYOUT OPTIMIZATION
C THE INPUT IS A GRID OF NUMFF DENSITIES X NUMTT ASPECT
C RATIOS. AT EACH GRID POINT THE ANNUAL AVERAGE AND DESIGN
C POINT SHADOWING AND BLOCKING LOSSES HAVE BEEN DETERMINED
C BY THE INITIAL PERFORMANCE RUN. THE LAYOUTS ARE
C CONSTRAINED TO LIE WITHIN THIS GRID.
C
C THIS ROUTINE IS CALLED BY
C OPTCAL
C
C THIS ROUTINE CALLS
C NONE
C

SUBROUTINE MAX

C
C SUBROUTINE MAX PERFORMS FIELD LAYOUT BY SELECTING ZONES IN
C THE ORDER OF DECREASING PERFORMANCE/COST. WITH EACH ZONE
C ADDED, BALANCE OF PLANT LOSSES ARE CALCULATED. ON REACHING
C A REQUESTED DESIGN POWER LEVEL, PLANT CAPITAL AND ENERGY
C COSTS ARE CALCULATED. ONLY THAT COMBINATION OF FIELD
C LAYOUT, TOWER HEIGHT, AND RECEIVER SIZE
C YIELDING THE LOWEST ENERGY COST IS SAVED AND RETURNED TO
C SUBROUTINE OPTCAL.
C
C THIS ROUTINE IS CALLED BY
C OPTCAL
C

C THIS ROUTINE CALLS
C OPTDEN
C

SUBROUTINE OPTDEN(I,II,K,L)

C THIS ROUTINE IS USED IF YOU ARE OPTIMIZING DENSITIES.
C
C THIS ROUTINE IS CALLED BY
C MAX
C
C THIS ROUTINE CALLS
C NONE
C

SUBROUTINE PERCAL

C
C THIS ROUTINE IS ACCESSED FOR PERFORMANCE RUNS. IT PERFORMS
C AN INITIAL, DETAILED FIELD PERFORMANCE CALCULATION FOR A USER
C DEFINED OR DEFAULT FIELD, OR FOR A CIRCULAR GRID OF ZONES.
C
C THIS ROUTINE IS CALLED BY
C DELSOL
C
C THIS ROUTINE CALLS
C SETCAV
C LAND
C SETFLX
C HELPOS
C MOMENT
C POWER
C SHADOW
C FLXMAP
C PLOTMAP
C

SUBROUTINE HELPOS

C THIS SUBROUTINE GENERATES THE COORDINATES OF THE
C NEAREST NEIGHBORS FOR SHADOWING AND BLOCKING CALCULATIONS
C
C THIS ROUTINE IS CALLED BY
C PERCAL
C
C THIS ROUTINE CALLS
C NONE
C

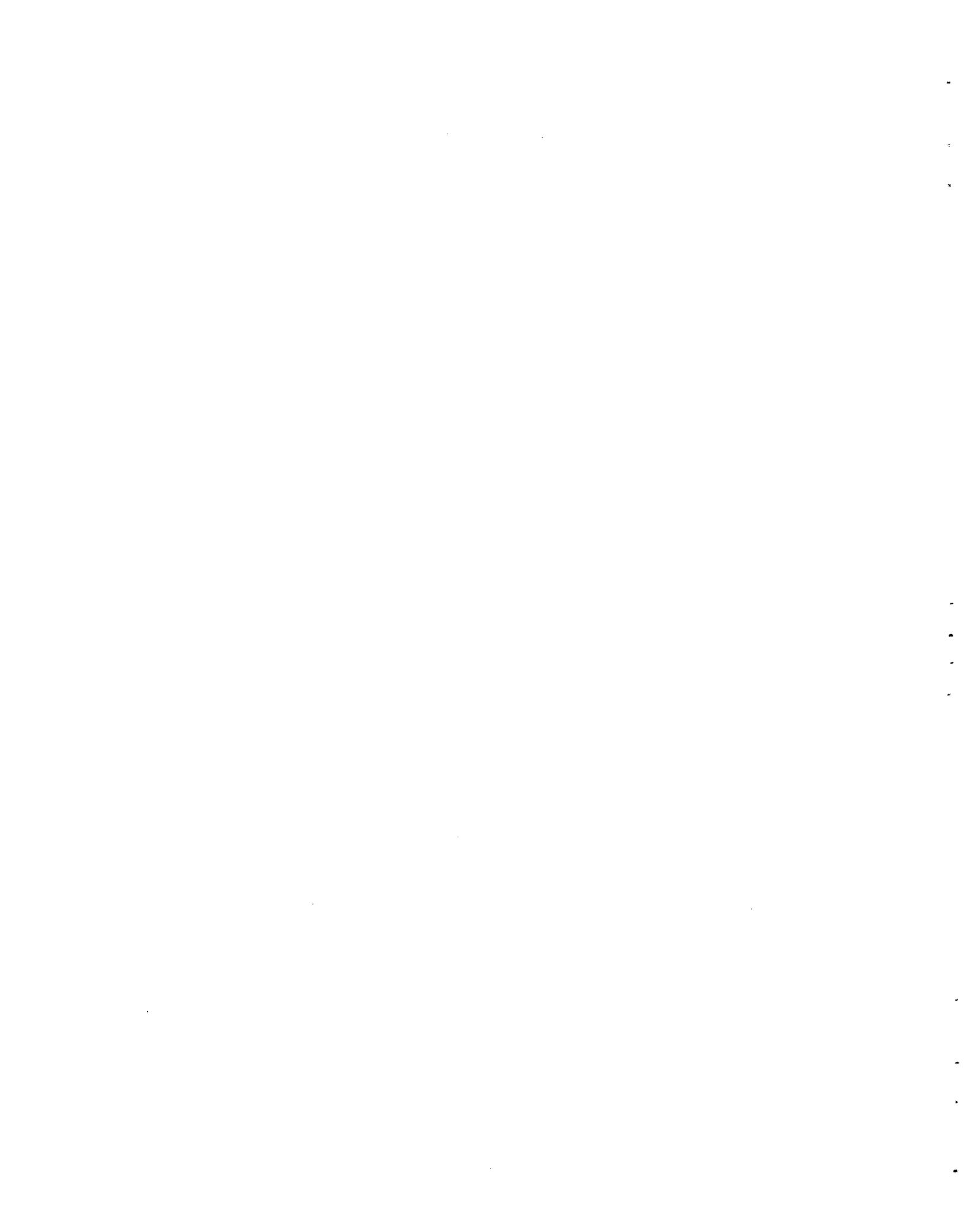
SUBROUTINE MOMENT

C THIS SUBROUTINE CALCULATES THE MOMENTS OF THE
C SUNSHAPE, HELIOSTAT ERROR DISTRIBUTION, AND
C

```

C HELIOSTAT SHAPE ON THE IMAGE PLANE AND THEN CONVOLVES
C THESE TO FIND THE MOMENTS OF THE HELIOSTAT IMAGE
C
C THIS ROUTINE IS CALLED BY
C PERCAL
C
C THIS ROUTINE CALLS
C HERMIT
C
SUBROUTINE POWER
C
C THIS ROUTINE CALCULATES THE POWER PRODUCTION FROM
C A USER DEFINED FIELD
C
C THIS ROUTINE IS CALLED BY
C PERCAL
C
C THIS ROUTINE CALLS
C NONE
C
SUBROUTINE SHADOW (SSP,CSP,SSA,CSA,SBNS,CBNS)
C
C SUBROUTINE SHADOW IS CALLED IN THE INITIAL PERFORMANCE CALCU-
C LATION IN DELSOL FOR FIRST THE SHADOWING, THEN THE BLOCKING
C CALCULATION. THE 12 NEAREST HELIOSTATS ARE CONSIDERED.
C
C THIS ROUTINE IS CALLED BY
C PERCAL
C
C THIS ROUTINE CALLS
C NONE
C
SUBROUTINE PLOTMAP(XAIM1,XAIM2,YAIM1,YAIM2,DPSPILL,HSPILL,
1CON1,NXFLX,NYFLX,FLFLX,IREFLX,IFXOUT,XNFLX,YNFLX,
2RADIUS,AZM)
C
C THIS ROUTINE USES DISPLAY TO GIVE INSTANT EFFECTS OF CHANGING
C USER AIMPOINTS
C STARTED 8-20-85 BY B. L. KISTLER
C CALLED BY PERCAL ONLY WHEN IAUTOP=1 AND IFXOUT(I,J)=-2
C CALLED FOR EACH ZONE
C
C THIS ROUTINE IS CALLED BY
C PERCAL
C
C THIS ROUTINE CALLS
C DISSPLA
C

```



VII. Comparison of DELSOL, MIRVAL and HELIOS Performance Predictions

The performance predictions of the MIRVAL, HELIOS and DELSOL computer codes are all in good agreement. A small system comparison is presented in this section since larger heliostat size/tower height ratios produce greater (but not necessarily significant) errors in the DELSOL predictions. The agreement of DELSOL in this more difficult application is good.

The system considered is a *preliminary* design for the CESA-1 (Central Energia Solar de Almeria) plant being built in Almeria, Spain. The complete system description, including heliostat coordinates, and details of the HELIOS and MIRVAL calculations are given in Reference 43. A summary of the system is given in Table VII-1. The DELSOL calculations were performed using the option in which the individual heliostat coordinates are specified in Namelist FIELD. Two calculational times are considered: 10 AM and 4 PM on winter solstice. The 4 PM case involves an extreme sun zenith angle of 82° , which leads to considerable off-axis aberration of the canted heliostat images.

TABLE VII-1

SYSTEM USED IN DELSOL, MIRVAL, HELIOS COMPARISON

Site:	37.099° N latitude
Field:	North only 282 Heliostats
Heliostats:	6.25 x 6.3 m (overall) 5 (horiz.) x 2 (vert.) cant panels Canted for noon on equinox
Receiver:	3.4 x 3.4 m square, tilted aperture
Tower Height:	56.345 m
Insolation:	0.7 kW/m ²
Sunshape:	Rectangular

At the time of the comparisons MIRVAL and HELIOS used different descriptions of the heliostat errors. MIRVAL used a 1.65 mrad error in each component of the surface normal (corresponding to the DELSOL variables SIGSX and SIGSY). HELIOS used a 3.3 mrad ($=2 \times 1.65$ mrad) error in each component of the reflected vector (SIGTX and SIGTY). These two error descriptions are not exactly equivalent whenever the cosine < 1 . For the 10 AM case the DELSOL calculation was done twice: once with the MIRVAL error description and once with the HELIOS error description.

The final complication in the comparisons is a difference in defining the effect of the individual loss terms. The cosine, spillage, total power and flux definitions are identical. However, there is a small difference between DELSOL and the other two codes in defining the shadowing/blocking and between DELSOL and HELIOS (but not MIRVAL) in defining attenuation. Comparisons of shadowing/blocking and attenuation are therefore not as meaningful as comparing the other quantities.

The comparison of the power production is given in Table VII-2. The comparison of the flux distribution along a horizontal line through the aperture center is shown in Figures VII-1(a) (10 AM) and VII-1(b) (4 PM). The agreement is good. There are small differences (approximately 1% or less) in some of the predictions. These differences are not practically significant since the uncertainties in the input (e.g., heliostat errors) generally produce larger effects. The differences result from slightly different assumptions in the models, numerical errors, etc. For example, the DELSOL flux is symmetrical about the receiver center while the MIRVAL and HELIOS results show a slight asymmetry. The approximately 1% difference in the flux profiles results from the fact that in order to speed up the calculation DELSOL assumes that the mirror panels are canted symmetrically. In actuality, for canting at a fixed time (off-axis cant), the cant of the heliostat panels is slightly asymmetric because the sun angle is slightly different on each cant panel. MIRVAL and HELIOS include this small effect and therefore produce the small asymmetry in the image. The asymmetry would not arise for on-axis canting schemes.

While the predictions are very close, the running times are very different. Users will probably find that DELSOL is 10-100 times faster than either MIRVAL or HELIOS.

TABLE VII-2
COMPARISON OF PERFORMANCE PREDICTIONS
FOR A SMALL SYSTEM

Code	10 AM				4 PM	
	MIRVAL	HELIOS	DELSOL	DELSOL	HELIOS	DELSOL
Error Type ¹	MIRVAL	HELIOS	MIRVAL	HELIOS	HELIOS	HELIOS
Cosine	0.949	0.949	0.949	0.949	0.873	0.873
Shadow + Block ²	0.925	0.924	0.920	0.920	0.651	0.658
Atmospheric Attenuation	0.973	0.974	0.973	0.973	0.974	0.973
Spillage	0.921	0.922	0.921	0.917	0.902	0.888
Power on Receiver (MWth)	4.79±0.2	4.76±0.1	4.76	4.74	2.99	3.02
Peak Flux (MWth/m ²)	-	1.83	-	1.82	0.923	0.922
Avg. Flux Around Peak (MWth/m ²)	1.68	1.63	1.66	1.62	-	-

¹MIRVAL errors are 1.65 mrad in each surface component.

HELIOS errors are 3.30 mrad in each component of reflected ray.

²MIRVAL and HELIOS give an area loss, DELSOL gives an average area loss weighted by the cosine.

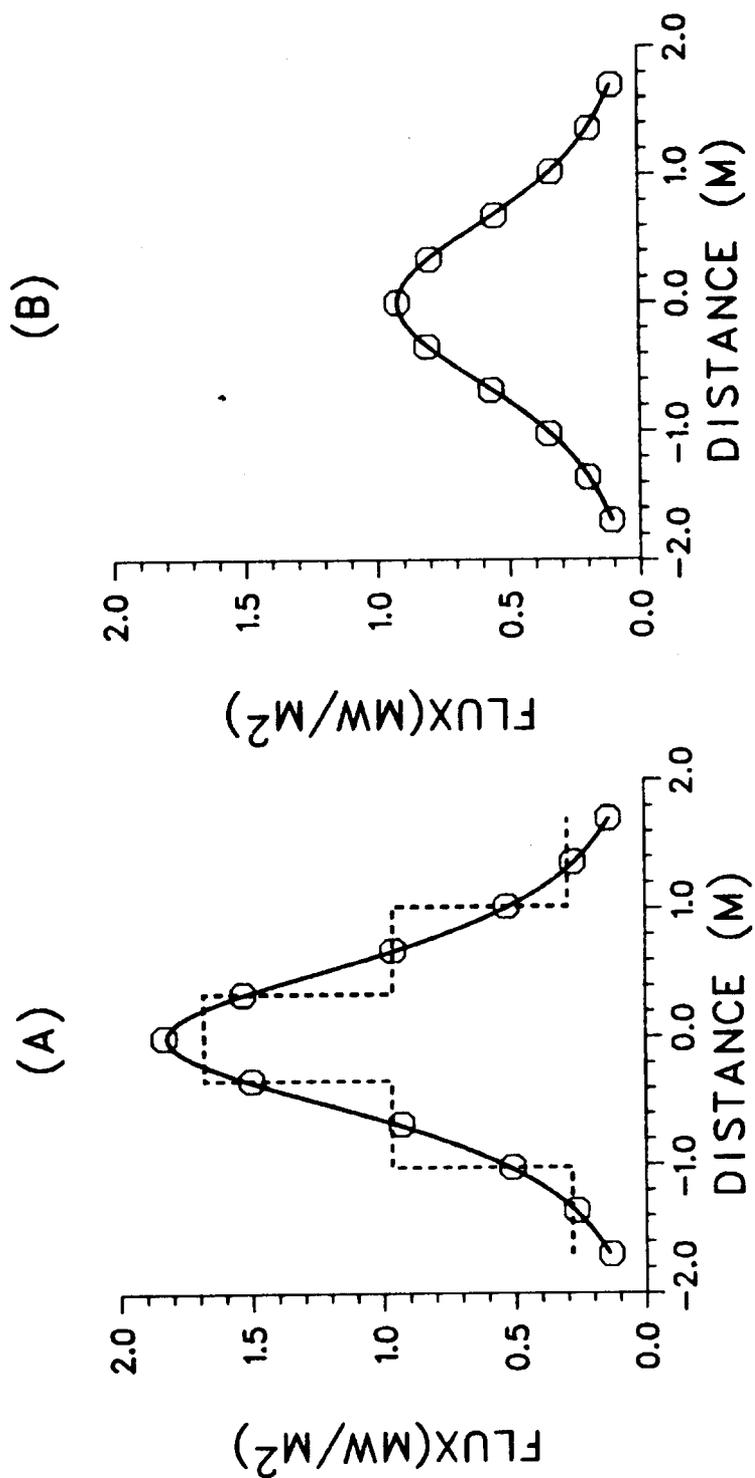


Figure VII-1. Comparison of DELSOL (solid line), MIRVAL (dashed histogram, 10 AM only) and HELIOS (O) predictions for the flux at 10 AM (A) and 4 PM (B) on Winter Solstice. Distance is measured along a horizontal line whose center coincides with the aperture center.

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APPENDIX A-INPUT CARDS

The input to DELSOL is accomplished through the use of namelists. Namelists are a convenient form of input because any format can be used for the input variables, the variables can be specified in any order and the only variables that need to be input are those which differ from the default values. However, each namelist must be input in the order shown in Tables A-1 and A-2, even if no variables in a namelist are redefined. The namelists are grouped into similar types of variables (e.g., Namelist HSTAT contains all of the heliostat definition inputs).

There are two types of problems that are run on DELSOL: performance calculations and design optimization calculations. In a performance calculation the user defines a single system and DELSOL calculates the optical performance for that system at a single time or day and/or on an annual basis. In a design optimization calculation the user specifies the heliostat, receiver geometry, and range of all the optimization variables and DELSOL searches for the set of optimization variables that minimizes the energy cost. In the design search DELSOL analytically "scales" the results of an initial performance calculation. These initial performance results can be generated in the same computer run as the design optimization or can be read off a file that was generated during a previous computer run. Finally, the results of the design optimization can be automatically used as input to a detailed performance run or can be written on a file for subsequent calculations or for plotting.

The input cards for a performance calculation are listed in Table A-1. The first card is a title card. The six namelists that follow specify the system to be analyzed. If the user wants to read in the coordinates of the heliostats instead of specifying zones of heliostats, these data cards follow the NLEFF namelist. Finally, the REC namelist with $W=-100$ terminates the problem. This arrangement of input cards should be used for either a user specified system or for a performance rerun of a system previously optimized by DELSOL and stored on a file on Unit 30.

The input cards for a design optimization calculation are shown in Table A-2. The first card is the title card. The next six namelists (BASIC....NLEFF) define the initial performance calculation. The values on these cards fix the zoning, latitude, insolation model, heliostat design and heliostat focusing/canting strategy to be used during the optimization. If these values will be used again in another design optimization calculation, the results should be saved. To do this, set ITAPE=1 in Namelist BASIC and store the local file generated on Unit 10 as a permanent file. When this initial performance calculation is to be used in a subsequent design run, attach a copy of the stored data to DELSOL as a local file on Unit 20, set ITAPE=2 in Namelist BASIC and omit the FIELD, HSTAT, REC, NLFLUX, and NLEFF namelists that follow the BASIC namelist. The REC, OPT, NLFLUX, NLEFF, NLCOST, and NLECON namelists define the optimization values. If a detailed performance calculation of the optimized design is required, set IRERUN=1 in Namelist OPT and provide the six namelists after the NLECON namelist as shown in Table A-2. Usually it is not necessary to redefine any variables in these namelists

since the values have been already defined. Finally, all problems are terminated with a REC namelist with the value $W=-100$.

Descriptions of all namelist variables follow. Included are constraints on the variables, if any, and default values. References to the main text for further details appear by section number in parentheses at the right hand side of the page. Note that in the main text, if the code input variable name differs from the variable name used in the discussion, the input variable name is indicated in parentheses when default values are listed at the end of each section.

TABLE A-1

INPUT CARDS FOR PERFORMANCE ONLY CALCULATION

Title Card (not a namelist)

\$BASIC\$

\$FIELD\$

\$HSTAT\$

\$REC\$

\$NLFLUX\$

\$NLEFF\$

**data cards for individual
heliostat coordinates**

**(required only for calculations in which
the user specifies the coordinates of
each heliostat, IUSERFL=3 on Namelist
FIELD)**

\$REC W=-100.\$

TABLE A-2

INPUT CARDS FOR DESIGN OPTIMIZATION CALCULATION

Title Card

\$BASIC\$

\$FIELD\$

\$HSTAT\$

\$REC\$

\$NLFLUX\$

\$NLEFF\$

Omit if the initial performance run is a previous calculation stored on Unit 20 (ITAPE=2, Namelist BASIC).

\$REC\$

\$OPT\$

\$NLFLUX\$

\$NLEFF\$

\$NLCOST\$

\$NLECON\$

Title Card

\$BASIC\$

\$FIELD\$

\$HSTAT\$

\$REC\$

\$NLFLUX\$

\$NLEFF\$

Required only if an annual performance run is to be performed on the optimized design (IRERUN=1, Namelist OPT).

\$REC W=-100.\$

Termination Card

TITLE CARD

Columns 1-40

Short title with less than 40 spaces.

Namelist BASIC

IPROB	<p>Control parameter specifying type of performance calculation; note additional variables in namelist BASIC to be defined with each option.</p> <ul style="list-style-type: none"> = 0, annual performance calculation based on NYEAR and HRDEL values; = 1, single day performance calculation defined by UDAY and HRDEL; = 2, single time performance calculation defined by UDAY and UTIME; = 3, performance calculation at user specified sun angles defined by NUAZ, NUEL, UAZ(M), and UEL(N) (this option with default values for angles will generate input required for the STEAEC code or SOLERGY code). = 4, performance calculation for <i>design/optimization run only</i>, based on NYEAR and HRDEL; unnecessary spillage calculations eliminated in initial performance calculation. <p>Constraints: IPROB=4 for design/optimization run. IPROB≠4 for flux calculation</p> <p>Default: IPROB=0 (III.A)</p>
NYEAR	<p>Number of days in the half year used in the initial performance calculation.</p> <p>Constraints: $3 \leq \text{NYEAR} \leq 9$; must be odd</p> <p>Default: NYEAR=5 (III.A-1,III.A-5)</p>
HRDEL	<p>Time step, in hours, used to calculate daily performance when IPROB=0, 1, 4.</p> <p>Constraint: HRDEL ≥ 0.5</p> <p>Default: HRDEL = 1.0 (III.A-1,III.A-2,III.A-5)</p>
UDAY	<p>Day of the year for performance calculation when IPROB=1 or 2.</p> <p>Default: UDAY=81.0 (III.A-2,III.A-3)</p>
UTIME	<p>Hour past <i>solar</i> noon for performance calculation when IPROB=2.</p> <p>Default: UTIME=0. (III.A-3)</p>
NUAZ NUEL UAZ(M)(M=1,NUAZ) UEL(N)(N=1,NUEL)	<p>Variable to specify sun angles for performance calculation when IPROB=3. NUAZ (NUEL) azimuthal (zenith) angles with values of UAZ(M) (UEL(N)) degrees are defined; performance is calculated for the NUAZ×NUEL matrix of sun angles.</p> <p>Constraints: NUAZ ≤ 20, NUEL ≤ 9</p> <p>Default: NUAZ=7 NUEL=6 UAZ=0., 30., 60., 75., 90., 110., 130. UEL=0.5, 25., 45., 65., 75., 85. (III.A-4)</p>

DHOPT

During heliostat optimization the density and aspect ratio will be varied by no more than $1 \pm \text{DHOPT}$ from the initial values. The larger DHOPT the wider the search for the optimum and the poorer the numerical approximations used in finding the optimum.

Constraint: $0 < \text{DHOPT} \leq 0.20$

Default: $\text{DHOPT} = 0.2$ (IV.B-2,IV.C-7)

IPRINT(I) (I=1, NYEAR)

Control parameter for zone by zone output of performance calculation. The annual zone by zone performance is always printed. The average performance of a user defined field at all times is always printed. In addition, for the Ith day of the NYEAR days (if IPROB=1 or 2 the only day of the year is I=1), IPRINT(I)

- = 0, no zone by zone output for this day;
- = 1, daily average printed;
- = 2, each time step and daily average printed.

If IPROB=3 then IPRINT(I)

- = 0, no zone by zone performance printed for the I zenith angle, UEL(I);
- = 2, zone by zone performance printed for every combination of the I solar zenith angle, UEL(I), and the NUAZ values of the solar azimuthal angle (UAZ(1) . . . UAZ(NUAZ)).

Default: $\text{IPRINT} = 9^{\circ}0$

ITAPE

Control parameter for reading and writing files

- = 0, no reading or writing of files;
- = 1, output of performance run *written* on local file Unit 10 for use in subsequent design calculations; this option eliminates need to duplicate initial performance calculation for different design runs when location and field options (latitude, dimensions, heliostat design, etc.) remain unchanged;
- = 2, initial performance input for design run *read* from local file Unit 20, which should be the file created on Unit 10 in a previous performance run with ITAPE=1; input Namelists FIELD, HSTAT, REC, NLFLUX, and NLEFF in performance group are omitted with this option (see Table A-2).
The user must be sure that the latitude, insolation model, sunshape, heliostat design, and receiver/field configuration read from Unit 20 are those desired in the present run.
- = 3, system input for performance calculation *read* from local file Unit 30, which should be the file created in a design/optimization

run using IOTAPE=1 in Namelist OPT. The data includes field layout, heliostat design, receiver dimensions, tower height, etc. so that the required performance input Namelists FIELD, HSTAT, REC, NLFLUX, and NLEFF should not redefine any of these values.

Constraint: ITAPE = 2 for design calculations only
Default: ITAPE = 0 (III.A-1,VI,VI.A)

TDESP

Power level, in MW, of optimized system stored on Unit 30 to be rerun in detailed performance calculation.

Constraint: ITAPE = 3
Default: TDESP = 100.0 (MW) (VI.A-5)

PLAT

Latitude, in degrees, of solar plant location.

Constraints: $0 \leq \text{PLAT} \leq 90.0$ (northern hemisphere)
Default: PLAT = 35.0 ($^{\circ}$) (Barstow) (III.B-1,III.B-3)

ALT

Altitude, in km, of solar plant location.

Default: ALT = 0.65 (III.B-2)

INSOL

Parameter specifying insolation vs. time model: Note additional variables in namelist BASIC to be defined with each option:

- = 0, Meinel model; value for ALT required;
- = 1, Hottel model; value for ALT required;
- = 2, constant equal to SOLCON;
- = 3, Allen model; values for PRES or DPRES, and H2O or DH2O required;
- = 4, Moon model; values for PRES or DPRES required.

Default: INSOL = 0 (III.B-2,III.B-3,III.H)

SOLCON

Value of constant insolation, in kw/m^2 , used with INSOL=2 option.

Constraint: INSOL=2
Default: SOLCON=0.95 (kw/m^2) (III.B-2)

IWEATH

Control parameter for site dependent weather factors:

- = 0, uniform weather factor for entire year; defined by WEATH if INSOL = 0, 1, 2 or by PRES (INSOL = 3, 4) and H2O (INSOL = 3);
- = 1, varying weather factor for each of the NYEAR calculational days defined by DWEATH(I) if INSOL = 0, 1, 2 or by DPRES(I) (INSOL = 3, 4) and DH2O(I) (INSOL = 3).
- = 2, uniform weather factor for entire year, based on reference latitude; calculated by code.

Constraint: If IWEATH = 0, define WEATH, PRES, and/or H2O for site.
If IWEATH = 1, define DWEATH, DPRES, and/or DH2O for site.

Default: IWEATH = 0 (III.B-3)

WEATH
DWEATH(I)
(I=1,NYEAR)

Fraction of energy calculated from the clear sky insolation models when $INSOL = 0, 1, 2$ that is actually produced due to weather effects. WEATH is the uniform correction for cloudiness on an annual basis ($IWEATH = 0, 2$); DWEATH(I) is the individual correction for cloudiness to the Ith calculational day.

Default: WEATH = 0.83
DWEATH = 9*0.83 (III.B-3)

H2O
DH2O(I)
PRES
DPRES(I)
(I=1,NYEAR)

Site specific atmospheric conditions. H2O is the constant mm of precipitable water in the atmosphere ($IWEATH=0$). DH2O(I) is the individual mm of precipitable water on the Ith calculational day ($IWEATH=1$). PRES is the constant *relative* atmospheric pressure compared to sea level, 760 mm of Hg ($IWEATH=0$). DPRES(I) is the relative atmospheric pressure on the Ith day ($IWEATH=1$).

Default: H2O = DH2O(I) = 20.0
PRES = 1.0
DPRES(I) = 1.0 (III.B-1,III.B-2,III.B-3)

NSUN

Control parameter specifying sunshape model:

- = 0, point sun (unrealistic, but useful for debugging);
- = 1, limb darkened sun, U. of Houston form;
- = 2, square wave sun;
- = 3, user defined sunshape through variables NSUNPT, SUNI, SUNR.

Default: NSUN = 1 (III.B-4)

NSUNPT
SUNI(I)
SUNR(I)
(I=1,NSUNPT)

Variable for defining sunshape: NSUNPT is number of pairs of points of sun intensity, SUNI (arbitrary units) vs. angle from the center of the sun, SUNR (radians). Points do *not* have to be equally spaced.

Constraints: NSUN = 3
NSUNPT \leq 50
Points start at center of sun; i.e.,
SUNR(1) = 0. Points decrease monotonically with increasing radius.

Default: None. (III.B-4)

REFDAY

Day of the year chosen for the design point; day 1 is January 1st. REFDAY

- = UDAY if IPROB = 1 or 2 (automatically set by code);
- = 354.75, winter solstice (~ Dec. 21);
- = 81.0, equinox (Mar. 21);
- = 172.25, summer solstice (~June 21).

Constraint: REFDAY must occur on one of the days determined by NYEAR if IPROB = 0 or 4.

Default: REFDAY = 81.0 (III.A-5,V.C-1)

REFTIM Design point hour on or past noon on the REFDAY of the year. If IPROB = 2, REFTIM is set equal to UTIME by code.
Constraint: REFTIM must be an integer multiple of HRDEL.
Default: REFTIM = 0.0 (noon) (III.A-5,V.C-1)

REFSOL Design point insolation, in kw/m².
Default: REFSOL = 0.95 (kw/m²) (II.G-2,IV.C-1)

ASTART Maximum sun angle (in degrees), with respect to the vertical, at which the plant will begin operation.
Default: ASTART = 75.0 (°) (III.A-1,III.A-5)

IATM Control parameter specifying atmospheric attenuation model:
= 0, 25 km visibility, Barstow, CA;
= 1, 5 km visibility, Barstow, CA;
= 2, user defined through variables ATM1, ATM2, ATM3, ATM4.
Default: IATM = 0 (III.G-1)

ATM1
ATM2
ATM3
ATM4

Variables for defining attenuation according to:
Fractional loss = ATM1 + ATM2*R + ATM3*R² + ATM4*R³
where R is the slant range (km) from the heliostat to the receiver.
Constraint: IATM = 2 for user defined variables.
Default: ATM1 = 0.006789
ATM2 = 0.1046
ATM3 = -0.0170
ATM4 = 0.002845 (III.G-1)

Namelist FIELD

NAZM	Number of zone divisions azimuthally around the tower. Constraint: NAZM \leq 12; NAZM, even. Default: NAZM = 12 (II.B-1,II.B-2,II.F-6)
NRAD	Number of zone divisions in the radial direction from the tower. Constraint: NRAD = \leq 13 (II.B-1,II.B-2,II.F-6) Default: NRAD = 12
RADMIN RADMAX	Minimum and maximum radial position of heliostats, expressed in normalized units of distance based on the tower height, THT (REC namelist). Default: RADMIN = 0.75 RADMAX = 7.5 (II.B-1,IV.C-6)
INORTH	Control parameter for surround vs. north-only field (used primarily in small systems) = 0, Surround field with equally spaced azimuthal zones surrounding the tower; = 1, Finer zoning of the north part of the field set by AMAXN. Constraint: If INORTH = 1, IREC > 0 NUMCAV = 1 RAZM(1) = 180.0 in namelist REC. Default: INORTH = 0 (II.B-1)
AMAXN	Maximum angle, in degrees, from north-south axis for north field zoning option (INORTH = 1). There are (NAZM-1) zones from -AMAXN to +AMAXN($^{\circ}$) about the north-south axis; remaining zone is a "dummy" for the south part of the field. Constraint: INORTH = 1 Default: AMAXN = 82.5($^{\circ}$) (II.B-1,II.B-2)
ILAY	Control parameter for heliostat layout pattern: = 0, radial stagger (only option at present) Default: ILAY = 0 (II.C)
IDENS	Parameter specifying heliostat density; options 1, 2 and 4 based on U. of Houston results: = 1, high reflectivity (\sim 0.9) rectangular heliostats; = 2, low reflectivity (\sim 0.6) round heliostats; = 3, user specified (see below). = 4, 1984 cost data base, updated shading/blocking Default: IDENS = 1 (II.C,IV.B-1,IV.B-2)
IUSERF	Parameter specifying field option for initial performance calculation:

- = 0, circular field defined by NAZM, NRAD, RADMIN, RADMAX; only zone by zone performance reported;
- = 1, code defined north biased field of Figure II-6;
- = 2, user defined field specified zone by zone (see below);
- = 3, user defined field specified by individual heliostat coordinates (see below).

Constraint: IUSERF = 0 for optimization run
Default: IUSERF = 0 for ITAPE = 1 (II.B-2,VI)
 IUSERF = 2 for ITAPE = 3

IHPR

Parameter controlling the printout of the coordinates of the individual heliostats for the IUSERF=3 option.

- = 0, no coordinates printed
- = 1, coordinates printed

Default: IHPR=0

NLAND

Parameter specifying land constrained field parameters

- NLAND = 0 No land constraint.
- ≠ 0 Land available for heliostat field constrained to NLAND rectangles defined by ALP, CLE, CLN, SLEW, SLNS, XTOWER, YTOWER.

Constraint: NLAND ≤ 5
Default: NLAND = 0 (II.B-4,IV.C-4)

- ALP(I)
- CLE(I)
- CLN(I)
- SLEW(I)
- SLNS(I)
- XTOWER
- YTOWER
- (I=1,NLAND)

Variables defining land constraints for field layout:
 ALP(I) = angle (°) of rotation of Ith rectangle from N-S and E-W axes (> 0 clockwise viewed from above);
 CLE(I),CLN(I) = displacements (m) east and north, respectively, of center of Ith rectangle relative to the 1st;
 SLEW(I),SLNS(I) = length (m) of sides of Ith rectangle parallel to E-W and N-S axes, respectively, prior to rotation;
 XTOWER, YTOWER = tower coordinates (m) east and north, respectively, from the center of first land constraint rectangle.

Constraint: NLAND > 0
Default: ALP = 5*0.0
 CLE,CLN = 5*0.0
 SLEW,SLNS = 5*0.0
 XTOWER, YTOWER = 0.0 (II.B-4)

- FLAND(K,L)
- (K=1,NRAD)
- (L=1,NAZM)

Fraction of the area of the (K,L) zone that can be used for heliostats. If a land constraint is specified (preceding variables) then DELSOL will calculate FLAND. FLAND can also be used to adjust the field trim or to simulate partial cloud cover.

Default: FLAND = 156*1.0 (II.B-2,II.B-4)

1	1-40	5A8	Alphanumerical heading to identify field
2	1-10	I10	Total no. of heliostats in field
	11-20	I10	Total no. of rows in field
3	1-10	I10	Number of row
	11-20	I10	Number of heliostats in row, starting with first row
4	1-10	F10.4	Displacement, to the east, of the 1st heliostat in this row relative to the tower (meters)
	11-20	F10.4	Displacement, to the north, of the 1st heliostat in this row relative to the tower (meters)
	21-30	F10.4	Not used at present
	31-40	F10.4	Aim point horizontal displacement (meters)
	41-50	F10.4	Aim point "vertical" displacement (meters)
	51-60	F10.4	Focal length (1/2 radius of curvature) (meters)
5+			Repeat card 4 for all heliostats in this row
6			Repeat cards 3, 4, 5+ for each row (II.B-2)

Namelist HSTAT

<p>WM HM</p>	<p>Width (WM) and height (HM), in meters, of the rectangular or circular boundary of the heliostat, including any edge supports or enclosures.</p> <p>Default: WM = 9.91(m) HM = 9.93(m) (II.C,II.D,II.D-3)</p>
<p>ICPANL</p>	<p>Parameter for optional specification of location of individual cant panels:</p> <p>= 0, no panel input = 1, individual panel location set by WPANL, HPANL, HXCANT, HYCANT (for more accurate images in small systems)</p> <p>Default: ICPANL = 0 (II.D)</p>
<p>WPANL HPANL HXCANT(I) HYCANT(I) I=1,NCANTX,NCANTY</p>	<p>Variables defining individual cant panels; size WPANL(m) wide, HPANL(m) high in heliostat plane; center of Ith panel HXCANT(I) m from heliostat center parallel to horizontal edge, HYCANT(I) m parallel to vertical edge.</p> <p>Constraint: ICANPL = 1 Default: WPANL = 4.88 (II.D) HPANL = 1.22 HXCANT = 8*2.475,8*(-2.475) HYCANT = 4.27, 3.05, 1.83, 0.61, -0.61, -1.83, -3.05, -4.27, 4.27, 3.05, 1.83, 0.61, -0.61, -1.83, -3.05, -4.27</p>
<p>DENSMR</p>	<p>Ratio of mirror area to total area of the heliostat defined by WM×HM.</p> <p>Default: DENSMR = 0.970 (II.C,II.D,II.D-3)</p>
<p>IROUND</p>	<p>Heliostat shape parameter.</p> <p>= 0, rectangular = 1, round</p> <p>Default: IROUND = 0 (II.D,II.D-3)</p>
<p>RMIRL</p>	<p>Average reflectivity of the mirrored surface, including transmission losses in the dome, if present.</p> <p>Default: RMIRL = 0.91 (II.D,III.D,III.G-2)</p>
<p>SIGEL SIGAZ</p>	<p>Standard deviations, in radians, of the normal error distribution of the elevation angle (SIGEL) and azimuthal angle (SIGAZ).</p> <p>Constraint: SIGAZ+SIGSX+SIGTX>0 SIGEL+SIGSY+SIGTY>0 Default: SIGEL = 0.00075 (rad) SIGAZ = 0.000 (rad)* (II.D-1,II.D-3)</p>
<p>SIGSX SIGSY</p>	<p>Standard deviations, in radians, of the normal error distribution of the heliostat reflective surface normal; SIGSX is in the horizontal direction, SIGSY in the direction perpendicular to the SIGSX direction (vertical when the heliostat is vertical).</p>

*See note on page 47 about default error values.

	<p>Constraint: Same as SIGEL, SIGAZ Default: SIGSX = 0.001 (rad) SIGSY = 0.000 (rad)* (II.D-1,II.D-3)</p>				
SIGTX SIGTY	<p>Standard deviations, in radians, of the normal error distribution of the reflected vector; caused by atmospheric refraction, tower sway, etc. SIGTX is in the horizontal direction; SIGTY in the direction perpendicular to the SIGTX direction</p> <p>Constraint: Same as SIGEL, SIGAZ Default: SIGTX = 0.000 (rad) SIGTY = 0.000 (rad) (II.D-1,II.D-3)</p>				
ICANT	<p>Canting parameter:</p> <ul style="list-style-type: none"> = 0, no canting; = -1, individual on-axis cant at a distance equal to the slant range; = 1, user defined on-axis canting. The canting is specified by the RCANT array defined below; (can be used to produce a single cant for the whole field). = 3, individual off-axis cant at time defined below by DCANT, HCANT. <p>Default: ICANT = 1 (II.D-2,II.D-3)</p>				
NCANTX NCANTY	<p>Number of submirror panels in a canted heliostat equals NCANTX times NCANTY; there are NCANTX panels in the \hat{i}_n direction, NCANTY in the \hat{j}_n direction.</p> <p>Constraint: NCANTX*NCANTY \leq 25 Default: NCANTX = 2 NCANTY = 8 (II.D-2,II.D-3)</p>				
HCANT DCANT	<p>Parameters defining off-axis cant; heliostats are canted at HCANT hours past noon on the DCANT day of the year.</p> <p>Default: HCANT = 0.0 DCANT = 81.0 (III.A-5,II.D-2)</p>				
RCANT(K) (K=1, NRAD)	<p>Focal length, in units of tower heights, THT (Namelist REC), at which all heliostats in the Kth radial zones are canted; can be used to define one canting for the whole field.</p> <p>Constraint: ICANT = 1 Default: RCANT = 13*6.00 (II.D-2,II.D-3)</p>				
XFOCUS YFOCUS	<p>Parameters specifying focusing or no focusing of mirror panel or subpanels (submirrors can be focused as well as canted). XFOCUS specifies focusing in the \hat{i}_n direction, YFOCUS in the \hat{j}_n direction.</p> <table border="0" style="margin-left: 40px;"> <tbody> <tr> <td>XFOCUS or YFOCUS = 0.0</td> <td>No focusing in corresponding direction</td> </tr> <tr> <td>XFOCUS or YFOCUS = 1.0</td> <td>Focusing in corresponding direction</td> </tr> </tbody> </table>	XFOCUS or YFOCUS = 0.0	No focusing in corresponding direction	XFOCUS or YFOCUS = 1.0	Focusing in corresponding direction
XFOCUS or YFOCUS = 0.0	No focusing in corresponding direction				
XFOCUS or YFOCUS = 1.0	Focusing in corresponding direction				

*See note on page 47 about default error values.

Default: XFOCUS = 1.0 (II.D-2,II.D-3)
YFOCUS = 1.0

IFOCUS

Types of focusing:

- = 0, individual focus with focal length equal to the slant range;
- = 1, user defined focal length determined by XFOCAL and YFOCAL if zoning is used or focal length read off of individual heliostat data cards if this is an individual heliostat field (IUSERF = 3, Namelist FIELD); (can be used to produce a single focal length for the whole field).

Constraint: XFOCUS = YFOCUS = 1.0

Default: IFOCUS = 1 (II.D-2,II.D-3)

XFOCAL(K)
YFOCAL(K)
(K=1, NRAD)

User defined focal lengths for the Kth radial zone (note: the focal length = 1/2 radius of curvature); XFOCAL(K) is the focal length in units of tower heights (THT in namelist REC) in the \hat{i}_n direction and YFOCAL(K) is in the \hat{j}_n direction.

Default: XFOCAL = 13*6.00
YFOCAL = 13*6.00 (II.D-2,II.D-3)

INDC

Control parameter for more accurate heliostat images during performance only calculations:

- = 0, regular images;
- = 1; separate image generated from each cant panel instead of a single image from the whole heliostat. This significantly increases the running time. This option can only be used with a performance calculation and cannot be used in design optimization calculations.

Constraint: INDC = 0 for a design calculation
IAUTOP = 0 (Namelist REC) if INDC = 1
ICANPL = 1 if INDC = 1

Default: INDC = 0 (III.F-1,VI.A-5)

ISB

Parameter controlling overlapping of shadowing and blocking:

- = 0, no overlap. Most conservative assumption as shading and blocking losses are maximized.
- = 1, complete overlap. Lower bound on shading and blocking losses.

Default: ISB = 0 (III.E)

Namelist REC

THT	<p>“Tower height.” The elevation, in meters, of the center of external receiver or cavity aperture <i>above the heliostat pivot point</i>, not ground level.</p> <p>Default: THT = 175.0 (m) (II.E,IV.C-2,V.A-4)</p>
TOWL TOWD	<p>The shadow cast by the tower and receiver is modeled as the shadow cast by a cylinder that is TOWL meters tall (measured above the heliostat pivot points) and has a diameter of TOWD meters.</p> <p>Default: TOWL = 175.0 (m) TOWD = 10.0 (m) (III.E-2,IV.A-4)</p>
IREC	<p>Parameter specifying type of receiver:</p> <ul style="list-style-type: none"> = 0, vertical cylindrical external receiver; = 1, cavity with aperture(s) of elliptical cross section; = 2, cavity with aperture(s) of rectangular cross section. = 3, elliptical shape flat plate receiver(s) = 4, rectangular shape flat plate receiver(s) <p>Default: IREC = 0 (II.E,IV.C-3)</p>
W	<p>Diameter, in meters, of an external receiver. For flat plates or cavities, W is twice the horizontal distance from the center of the aperture or flat plate to the tower centerline.</p> <p>Default: W = 16.0 (m) (II.E,IV.C-3)</p>
H	<p>Height, in meters, of an external receiver. Height of cavity heat absorbing surface. If H = 16.0, defaults to 1.1×RY (cavity). Not needed for flat plates.</p> <p>Default: H = 16.0 (m)(external) (II.E,IV.C-3) H = 1.1×RY (m)(cavity)</p>
RRECL	<p>Fraction of the incident power absorbed by the receiver <i>before</i> radiation and convection losses, but <i>after</i> receiver reflection loss:</p> $\text{RRECL} = \frac{\text{Power incident} - \text{Power reflected}}{\text{Power incident}}$ <p>Default: RRECL = 0.965 (III.G-2)</p>
IAUTOP	<p>Control parameter identifying aiming strategy:</p> <ul style="list-style-type: none"> = 0, single aim point at center of receiver; = 1, code calculated time dependent 1-d “smart” aiming strategy; heliostat images are spread out along the “height” of the receiver or aperture to reduce the peak flux and flux gradients with no increase in spillage.

NAY(K,L)
 NAX(K,L)
 XAIM(K,L,M)
 YAIM(K,L,M)
 (K=1,NRAD)
 (L=1,NAZM)

- This option should be used with external cylinder, elliptical flat plate and elliptical aperture cavity receivers with flux limits (Namelist NLFLUX);
- = 2, same as 1 except that the images are spread out in 2-d. This option should be used only with rectangular flat plate or rectangular aperture receivers with flux limits;
 - = 3, time dependent aiming strategy to reduce radiation/convection losses, to reduce thermal-mechanical damage, or to minimize the size of a heat absorbing surface inside a cavity. For each zone the image is centered across the "width" of the receiver or aperture and is positioned as close to the bottom of the receiver as possible without increasing spillage significantly;
 - = 4, same as 3 except the images are spread out along the width of the receiver. This option should only be used with a rectangular flat plate or rectangular aperture receiver;
 - = 5, user defined, time independent, uniform aiming. For the (K,L) zone the aim points are arranged in a rectangular grid that is in the plane of the cavity aperture or flat plate or is in the plane that is tangent to the external receiver at the azimuthal angle of the zone. There are NAX(K,L) aim points along the horizontal direction from a minimum value of XAIM(K,L,1) meters to a maximum value of XAIM(K,L,2) meters. Similarly, there are NAY(K,L) aim points along the "vertical" direction from a minimum value of YAIM(K,L,1) meters to a maximum value of YAIM(K,L,2) meters. Note that *this option should only be used for performance runs.*
 - < 0, combination of options 2 and 4. Inner heliostats are aimed according to option 4. Heliostats at a radial zone position \geq -IAUTOP are aimed according to option 2. This option is most useful for cavity receivers.

Constraint: Maximum of 25 user defined aim points/zone. Code will only automatically generate up to 100 aim points.

IREC = 2 or 4 if IAUTOP = 2 or 4

IPROB \neq 4 (namelist BASIC) if IAUTOP = 5

Default: IAUTOP = 0

NUMPT(K,L) = NAX(K,L) = NAY(K,L) = 1

XAIM(K,L,M) = YAIM(K,L,M) = 0.0

(II.F,II.G-2)

For cavities or flat plates, the following must be defined:

NUMCAV Number of apertures in cavity receiver or number of flat plate receivers.

Constraint: NUMCAV \leq 4
Default: NUMCAV = 1 (II.E)

RELV(I)
RAZM(I) Orientation of \hat{r} vector; i.e., outward normal of surface stretched across the aperture or flat plate receiver. For the Ith (I=1, NUMCAV) aperture, RELV(I) is the polar angle, θ_r , and RAZM(I) the azimuthal angle β_r , both in degrees (see Figure II-1 in main text).

$$\text{RELV(I)} = \begin{cases} 90.0^\circ & \text{Vertical} \\ > 90.0^\circ & \text{Down facing} \end{cases}$$

$$\text{RAZM(I)} = \begin{cases} 0.0^\circ & \text{South facing} \\ 90.0^\circ & \text{West facing} \\ 180.0^\circ & \text{North facing} \\ 270.0^\circ & \text{East facing} \end{cases}$$

Constraint: RAZM(I) < 360. Angles must be in order clockwise.

Default: RELV = 4*90.0(°)
RAZM = 180., 270., 0., 90. (°) (II.E)

RX(I)
RY(I)
(I=1,NUMCAV) Dimensions, in meters, of Ith cavity aperture or flat plate receiver. RX(I) is the horizontal dimension, and RY(I) perpendicular to RX(I).

Default: RX = 4*6.0 (m)
RY = 4*6.0 (m) (II.E,IV.C-3)

RWCAV(I)
(I=1,NUMCAV) Ratio of the radius of the vertical cylindrical heat absorbing surface centered on the Ith aperture to the radius, W/2, of the receiver. This option is used only with cavity receivers and allows the cavities to have different depths. The greater RWCAV the larger the heat exchanger surface within the cavity and the lower the peak flux.

Default: RWCAV = 4*1.0 (II.E)

Namelist NLFLUX

IFLX

Parameter specifying flux calculation. For performance runs flux calculations are made at the one time of the year specified by IFXOUT. For optimization runs, flux calculations are made only at the design point.

- = 0, no flux calculations;
- = 1, flux calculations desired.

Constraint: IFLX = 1 if any IFXOUT \neq 0

Default: IFLX = 0 (II.G,II.F-2)

IFXOUT(I,J)
(I=1,NYEAR;
J=1, 16)

Parameter allowing selection of the one time of the year at which the flux is calculated. For the Jth time step (i.e., (J-1)*HRDEL hours past noon) on the Ith day (I=1 at winter solstice, = (NYEAR + 1)/2 at equinox, = NYEAR at summer solstice, as shown in Table III-1), IFXOUT:

- = 0, no flux calculated at this time;
- = 1, total flux from user defined field (i.e., IUSERF = 1 or 2 in FIELD namelist) calculated and reported for this time;
- = -1, flux from every zone printed plus total flux if IUSERF = 2 at this single time.

Constraint: One IFXOUT \neq 0 for flux maps in performance runs, *including reruns*.

All IFXOUT = 0 if IFLX = 0.

Default: IFXOUT = 144*0 (II.G)

IFLAUT

Parameter specifying the type of surface on which a grid of flux points will be automatically generated. In all cases the "center" of the receiver is on the tower centerline THT meters (Namelist REC) above the plane of the heliostat pivots (XFC=YFC=ZFC=0). If IFLAUT:

XFC
YFC
ZFC
POLF
AZMF
DIAMF

- = 1, points are on the outside surface of a cylinder with a vertical axis. The cylinder has a diameter of DIAMF meters and is offset by XFC meters to the east, YFC meters to the north and ZFC meters up from the "receiver center". This option with DIAMF=W (Namelist REC) and XFC=YFC=ZFC=0 generates the flux points on the surface of an external receiver.
- = 2, same as = 1 except the points are on the inside surface of a hollow vertical cylinder (Figure II-16). If RWCAV \neq 1.0, DIAMF must be set by the user to be $W \times RWCAV$ (default is DIAMF=W).
- = 3, points are on a plane. The center of the origin that is used to define the grid of flux points is XFC meters to the east, YFC meters to the north and ZFC meters up from the "receiver center". The outward surface normal of the plane on the side that the flux is incident on has an azimuthal angle of

AZMF (North = 180°, E = 270° etc.) and a polar angle POLF (90° = vertical, > 90° downward facing).
 = 4, automatic generation of the flux points on the code assumed heat absorbing surface of the receiver specified in the REC Namelist. For this option the code sets values for DIAMF, XFC, YFC, ZFC, POLF, and AZMF. The user must still specify all other values.

NOTE: For multiple aperture cavity or multiple flat plate receivers, flux calculations can be made for only *one* heat absorbing surface at a time.

External Cylinder Receiver (IREC = 0)

The flux points are located on the outside of a cylinder whose DIAMF = W and XFC = YFC = ZFC = 0. If the default values of NXFLX, FAZMIN, FAZMAX, NYFLX, FZMIN, FZMAX are used then a single flux point on the center of the north side of the cylinder will be generated.

Cavity Receiver (IREC = 1 or 2)

The flux points are located on the inner surface of a vertical cylinder centered on the first aperture DIAMF = W * RWCAV(1), XFC = $-(W/2.) * \sin(\text{RAZM}(1))$, YFC = $-(W/2.) * \cos(\text{RAZM}(1))$. If the default values of NXFLX, FAZMIN, FAZMAX, NYFLX, FZMIN, FZMAX are used then a single flux point is generated in the center of the heat absorbing surface of the first cavity aperture at a height equal to the height of the center of the heat absorbing surface, where the height for this purpose will always be that specified as H in namelist REC. It is further assumed that the first aperture faces north.

Flat Plate Receiver (IREC = 3 or 4)

The flux points are located on the surface of the first flat plate receiver. XFC = $-(W/2.) * \sin(\text{RAZM}(1))$, YFC = $-(W/2.) * \cos(\text{RAZM}(1))$, ZFC = 1., POLF = RELV(1), and AZMF = RAZM(1). If the default values of NXFLX, FAZMIN, FAZMAX, NYFLX, FZMIN, FZMAX are used then a single flux point is generated at the center of the first plate, assumed to be facing north.

Default: IFLAUT=4

XFC=YFC=ZFC=0.0 (m)

POLF=90.0 (°)

AZMF=180.0 (°)

DIAMF=W (m)

(II.G-1,II.G-2)

NXFLX
 FAZMIN
 FAZMAX

IFLAUT= 1 or 2

Number of divisions around the circumference of the cylinder for automatically generated grid of flux points, NXFLX; points equally spaced at azimuthal angles starting at

FAZMIN and ending at FAZMAX (in degrees); angles increase clockwise when viewed from above the receiver:

IFLAUT=1	IFLAUT=2
0° or 360° → South	North
90° → West	East
180° → North	South
270° → East	West

IFLAUT=3

NXFLX equally spaced points along a horizontal axis of the plane defined by (XFC, YFC, ZFC, POLF, AZMF) from a minimum value of FAZMIN meters to a maximum value of FAZMAX meters.

Constraint: $FAZMAX \geq FAZMIN$ (note that in some cases with IFLAUT=1 or 2 it may be necessary to add 360° to FAZMAX).

$NXFLX \cdot NYFLX \leq 169$

Default: NXFLX = 1
 FAZMAX = 180.0 (°)
 FAZMIN = 180.0 (°) (II.G-1)

NYFLX
 FZMIN
 FZMAX

Number of divisions along the "height" of the surface used for automatically generated grid of flux points, NYFLX; points equally spaced from FZMIN to FZMAX, in meters; measured from the origin, up being positive.

Constraint: $FZMAX \geq FZMIN$
 $NXFLX \cdot NYFLX \leq 169$

Default: NYFLX = 1
 FZMIN = 0.0 (m)
 FZMAX = 0.0 (m) (II.G-1)

NOTE: For cavity receivers, the default is FZMIN=FZMAX = center of height of the heat absorbing surface as specified by H (Namelist REC), although that is not necessarily the "center of receiver".

ICAVF(I)
 (I=1, NUMCAV)

Parameter specifying aperture(s) through which incident light can reach the flux surface under consideration:
 = 0, no light reaches flux surface from aperture I;
 ≠ 0, light reaches flux surface from aperture I.

Constraint: IREC = 1 or 2
 Code default values apply to first aperture.

Default: ICAVF = 1,0,0,0 (II.G)

The following are specified only for layout/optimization runs:

NFLXMX
 NMXFLX(I)
 (I=1, NFLXMX)

NFLXMX points on the receiver tested during field layout to check if FLXLIM limit exceeded; these are a subset of the NXFLX by NYFLX points defined above.

NMXFLX(I) identifies the exact point to be evaluated.
as follows (see Figure II-16).

If M = azimuthal location between 1 and NXFLX
N = vertical location between 1 and NYFLX

then $NMXFLX(I) = M + (N-1)*NXFLX$

Constraints: $NFLXMX \leq 4$
 $NFLXMX \leq NXFLX*NYFLX$
 $NMXFLX(I) \leq NXFLX*NYFLX$

Default: $NFLXMX = 1$
 $NMXFLX(I) = I (I=1,4)$ (II.G-2,IV.D-1)

FLXLIM(I)
(I=1,NFLXMX)

Maximum allowed flux on the receiver in W/m^2 at
NMXFLX(I) flux point.

Default: $FLXLIM(1) = 0.6E+06$
 $FLXLIM(I) (I=2,NFLXMX) = 1.0E+10$
(II.G-2,IV.D-1)

Namelist NLEFF

REFTHP	<p>Gross thermal power (watts) absorbed by a reference receiver (area AREF) before receiver and piping radiation and convection losses.</p> <p>Constraint: Data should be for same type receiver (i.e., external, cavity, etc.) as in REC namelist.</p> <p>Default: REFTHP = 4.10×10^8 (watts) (IREC=0,3,4) REFTHP = 2.10×10^8 (watts) (IREC=1,2) (III.G-3)</p>
AREF	<p>Reference receiver area (m²); for cavities, this should be total aperture area.</p> <p>Default: AREF = 2780.0 (m²) (IREC=0,3,4) AREF = 761.0 (m²) (IREC=1,2) (III.G-3)</p>
REFRC	<p>Fraction of REFTHP transferred to receiver working fluid after radiation and convection losses.</p> <p>Default: REFRC = 0.83 (III.G-3)</p>
REFLP	<p>Reference pipe length (m) for calculating piping insulation losses.</p> <p>Default: REFLP = 170.0 (m) (III.G-4)</p>
REFPIP	<p>Fraction of REFRC + REFTHP delivered to storage and EPGS after piping losses.</p> <p>Default: REFPIP = 0.99 (III.G-4)</p>
FPLH	<p>Factor multiplying tower height to give total hot piping run in a single module.</p> <p>Default: FPLH = 2.6 (III.G-4,V.A-7)</p>
FPLC	<p>Factor multiplying tower height to give total cold piping run in a single module (may be different from FPLH if expansion allowance different).</p> <p>Default: FPLC = 2.6 (V.A-7)</p>
ITHEL	<p>Parameter for design point thermal/electric conversion efficiency:</p> <p style="padding-left: 40px;">= 0, efficiency assumed constant at all design power levels, value specified by ETAREF;</p> <p style="padding-left: 40px;">≠ 0, efficiency varies with design power level as described in Figure III-3.</p> <p>Default: ITHEL = 0 (III.G-5,III.G-6)</p>
ETAREF	<p>Design point thermal/electric conversion efficiency; constant at all power levels (only used when ITHEL = 0).</p> <p>Default: ETAREF = 0.42 (III.G-5,III.H,V.A-11)</p>
FEFF	<p>Fraction of design point efficiency describing average off-design operation.</p> <p>Default: FEFF = 0.90 (III.G-5,III.G-6,III.H)</p>

REFPRL	Design point parasitic load, expressed as a fraction of the gross electrical output. Default: REFPRL = 0.103 (III.G-6,III.G-8)
FSP	Fraction of design point parasitic load required for operation from storage. Default: FSP = 0.66 (III.G-6,III.G-8)
FEP	Fraction of design point parasitic load for operation electrical generating pumps (feedwater pumps, cooling tower, etc.). Default: FEP = 0.0 (III.G-6,III.G-8)
EFFSTR	Round trip efficiency through storage. Default: EFFSTR = 1.0 (III.G-7)
PF	Plant factor; expected fraction of the year in which the plant will be on line. In a realistic calculation of busbar energy cost, PF should be some value less than 1.0. Default: PF = 0.90 (III.G-8,III.H,IV.B-2)
SMULT	Solar multiple at design point; 1/SMULT of the thermal power at the base of the tower goes directly to the industrial or electrical process at the design point; the rest is sent to storage. This variable should also be defined in Namelist OPT. Constraint: SMULT \geq 1.0 Default: SMULT = 1.5 (IV.C-5,VI)
IPH	Parameter identifying industrial process heat run instead of electrical plant run: = 0, electrical plant; output in MW _e , mills/kw-hr, etc. ≠ 0, industrial process heat; code automatically sets ETAREF=1.0, FEFF=1.0, REFPRL=0.0, CEGREF=0.0. Default: IPH = 0 (III.G-6,V.A-11)
REFRC1 REFRC2 REFRC3	Coefficients for calculating thermal losses based on receiver area. REFRC1 is related to radiative losses, the rest to convective losses. Constraint: IRADFL = 0, IREC < 3 Default: (IREC=0) REFRC1=16403.0 REFRC2=460.0 REFRC3=0.0 (IREC>0) REFRC1=16403.0 REFRC2=7631.0 REFRC3=5077.0 (III.G-3)

IRADFL Flag to indicate which radiation/convection loss algorithm to use.
 = 0, use the loss algorithm based on receiver area and experimental loss data through 1985
 = 1, use the DELSOL2 receiver loss algorithms
Constraint: IREC<3 for IRADFL=0
Default: IRADFL = 0 (III.G-3)

PARL1,PARL2
PARL3,PARL4
PARL5,PARL6
PARL7,PARL8
PARL9,PARL10 Nonoperating parasitic loss algorithm coefficients, where
 $\text{loss (MWe)} = \text{PARL}_n + \text{PARL}_{n+1} \times P_{c,\text{gross}}$
 and n is odd. PARL1 and PARL2 are for startup/shutdown losses, PARL3 and PARL4 are for prestartup/postshutdown losses, PARL5 and PARL6 are for nighttime parasitics, PARL7 and PARL8 are for weather outage parasitics, and PARL9 and PARL10 are for maintenance outage parasitic losses.
Default: PARL1=0.5, PARL2=0.103
 PARL3=0.5, PARL4=0.103
 PARL5=0.5, PARL6=0.008
 PARL7=0.5, PARL8=0.008
 PARL9=0.18, PARL10=0.009 (III.G-8)

TPRE
TSTRT Times associated with nonoperating parasitics. This amount of time (in hours) is spent every morning and again every evening for calculation of parasitic losses for prestartup/postshutdown and startup/shutdown, respectively, outside of the time of actual operation as specified by ASTART (Namelist BASIC).
Default: TPRE=TSTRT=1.0 hr. (III.G-8)

Namelist OPT*

- IHOPT** Control parameter for optimizing the heliostat densities.
= 0, no heliostat density optimization. The "default" densities (which are a function of the tower height) are used.
The heliostat field boundaries are optimized;
= 1, heliostat densities are optimized.
Constraint: Tower height cannot be varied if IHOPT = 1.
Default: IHOPT = 0 (II.C,IV.B,IV.C-7)
- NUMTHT**
THTST
THTEND In optimization run, NUMTHT discrete, equally spaced values of the tower height are tested from THTST to THTEND (in meters). If NUMTHT = 1, then the tower height is set equal to THT specified in the REC namelist; THTST and THTEND need not be specified.
Constraints: $THTST \leq THTEND$
 $1 \leq NUMTHT \leq 20$
Default: NUMTHT = 1
THTST = 75.0 (m)
THTEND = 400.0 (m) (IV.C-2,IV.E)
- NUMREC**
WST
WEND *External receivers (IREC = 0 in REC namelist):* NUMREC discrete, equally spaced values of the diameter tested from WST to WEND (in meters). If NUMREC = 1, the only value of the diameter considered is that defined by W in the REC namelist.
Cavity (IREC = 1, 2) and Flat Plate (IREC = 3,4) Receivers: NUMREC discrete, equally spaced values of the horizontal dimension of the first aperture or flat plate, RX(1), tested from WST to WEND (in meters). If NUMREC = 1, the only value considered is that defined for RX(1) in the REC namelist.
Constraints: $WST \leq WEND$
 $1 \leq NUMREC \leq 20$
Default: NUMREC = 1
WST = 8.0 (m)
WEND = 26.0 (m) (IV.C-3,IV.E)
- NUMHTW**
HTWST
HTWEND
IOPTUM *External receivers (IOPTUM = 1):* NUMHTW equally spaced values of the receiver height to diameter ratio (H/W) tested from HTWST to HTWEND. If NUMHTW = 1, only the ratio defined by H and W in namelist REC is used.
Cavity and flat plate receivers (IOPTUM = 1): NUMHTW equally spaced values of the ratio of the height to width, RY(1)/RX(1), of the first cavity or flat plate tested from HTWST to HTWEND. If NUMHTW = 1, only the ratio defined by RX(1) and RY(1) on Namelist REC is used. The width W is held constant.
Cavity receivers (IOPTUM = 2): NUMHTW equally spaced values of W tested from HTWST to HTWEND. If NUMHTW = 1, only the W defined by namelist REC is used. The aspect

*For all design/optimization runs, set IPROB = 4 in namelist BASIC.

ratios of the cavity apertures. RY(I)/RX(I) are held constant. This option is appropriate for a flux limited cavity receiver.

Constraints: $HTWST \leq HTWEND$
 $1 \leq NUMHTW \leq 20$

Default: NUMHTW = 1
HTWST = 1.0
HTWEND = 1.0
IOPTUM = 1 (II.E,IV.C-3,IV.E)

RYTRX
RX2TRX
RX3TRX
RX4TRX

Cavity and flat plate receivers: RYTRX is the ratio RY(I)/RX(I), assumed the same for all apertures or flat plates. RX2TRX is the ratio RX(2)/RX(1), etc. (See REC namelist for definitions of RX's and RY's.)

Default: RYTRX = 1.0
RX2TRX = 1.0
RX3TRX = 1.0
RX4TRX = 1.0 (II.E,IV.C-3)

NUMOPT
POPTMN
POPTMX

NUMOPT equally spaced net electrical design power levels from POPTMN to POPTMX (in watts) considered for optimal design.

Constraint: $1 \leq NUMOPT \leq 20$
 $POPTMN \leq POPTMX$
Cost models not necessarily accurate below $\sim 10^7$ watts.

Default: NUMOPT = 20
POPTMN = 2.0×10^7 (watts)
POPTMX = 4.0×10^8 (watts) (IV.B-1,IV.C-1)

NUMPOS
XTPST
YTPST
XTPEND
YTPEND

In a land constrained design (NLAN > 0, below) NUMPOS discrete, equally spaced values of the tower location relative to the origin used to describe the land constraints are tested. The tower positions lie along a line specified by the coordinates of the first tower position (XTPST m east, YTPST m north) and the last tower position (XTPEND m east, YTPEND m north).

Constraint: $1 \leq NUMPOS \leq 20$
Default: NUMPOS = 1
XTPST = XTPEND = YTPST = YTPEND = 0.0 (II.B-4,IV.C-4,IV.E)

NLAND
ALP(I)
CLE(I)
CLN(I)
SLEW(I)
SLNS(I)
(I=1,NLAND)

Land constrained field parameters.

NLAND = 0 No land constraint

> 0 The land available for the heliostat at field is constrained to be within NLAND rectangles. CLE(I) and CLN(I) are the displacements in m to the east and north, respectively, of the center of the Ith

rectangle relative to the center of the first rectangle. ALP(I) is the angle in degrees that the Ith rectangle is rotated about its center from the N-S, E-W orientation (positive angles represent a clockwise rotation when viewed from above). SLEW(I) and SLNS(I) are the lengths of the sides of the Ith rectangle that, prior to rotation by ALP(I), were parallel to the E-W and N-S axes, respectively.

Constraint: NLAND \leq 5

Default: NLAND = 0

ALP, CLE, CLN, SLEW, SLNS = 0
(II.B-4,IV.C-4)

SMULT

Solar multiple at design point; 1/SMULT of the thermal power at the base of the tower goes directly to the industrial or electrical process at the design point; the remainder is sent to storage. This variable should be consistently defined in Namelist NLEFF.

Constraint: SMULT \geq 1.0

Default: SMULT = 1.5 (IV.C-5,VI)

IPLFL(I)
(I=1,NUMOPT)

Parameter identifying the subset of the NUMOPT power levels at which field layouts are printed and descriptions of optimized system are written on Unit 30 if desired:

= 0, no field layout output for the Ith power level;

= 1, output generated for Ith power level.

Constraint: Maximum number of nonzero IPLFL's = 5

Default: IPLFL = 20*0 (VI.A-5)

IPROPT

Parameter for detailed output of zone by zone field buildup (IPROPT = -1 is strongly recommended):

= 0, output suppressed;

= 1, output printed. (Note: this option generates a *large* amount of output);

= -1, limited output printed during optimization.

Shows some detail of search and provides useful output even when program runs out of time.

Default: IPROPT = -1

IHOPTP

Parameter for detailed print out of heliostat density optimization:

= 0, output suppressed

= 1, output printed (Note: this option generates a *large* amount of output).

Default: IHOPTP = 0

IOTAPE

Parameter specifying if user desires to write the results of an optimization run on Unit 30 to save as a permanent file, or to rerun for a detailed performance calculation, or both:

- = 0, no information written on Unit 30;
- = 1, information written on Unit 30.

Default: IOTAPE = 0 (II.B-2,VI.A-5)

IRERUN

Parameter for automatically rerunning a detailed performance calculation of an optimized system:

- = 0, no performance calculation;
- = 1, performance calculation of optimized system according to the choice of the non-zero IPLFL's (namelist OPT) and TDESP (namelist BASIC). See Figure VI-2 and Table A-2 for required Namelists.

Constraint: IOTAPE = 1 if IRERUN = 1.

Default: IRERUN = 0 (VI.A-5)

IALL

Parameter controlling search algorithm:

- = 0, "smart" search (selected subset of THT, W, H, etc);
- = 1, all possible combinations of optimization variables evaluated (long running times required).

Default: IALL = 0 (IV.E)

ISTR

Parameter identifying storage optimization in the detailed performance calculation of DELSOL optimized design:

- = 0, no optimization on storage size; maximum size as determined in subroutine MAX used;
- ≠ 0, optimum storage size determined; NSTR discrete values between 0 and ISTR times the maximum size determined in system optimization (MAX) are evaluated.

Default: ISTR = 0 (IV.C-5,V.A-8)

NSTR

Number of storage sizes, between 0 and ISTR times the maximum size, evaluated to find optimum storage capacity for a given design.

Default: NSTR = 1 (IV.C-5,V.A-8)

Namelist NLCOST*

CH Cost of heliostats including wiring; \$/m² mirror surface.
Default: CH = 120.00 (\$/m²) (V.A-1)

CL Cost of land including site preparation; \$/m².
Default: CL = 0.62 (\$/m²) (V.A-2)

CWR Wiring cost parameters; CW, total wiring cost in
CWDR \$/heliostat, given by
CWDA

$$CW = CWR \times RAD + CWDR \times RSEP + CWDA \times AZMSEP$$

where RAD, RSEP, AZMSEP are calculated from variables in the FIELD namelist. The cost CW is already included in heliostat cost, but is separated by the code using this algorithm.

Default: CWR = 0.03077 (\$/m)
 CWDR = 15.0 (\$/m)
 CWDA = 9.0 (\$/m) (V.A-3)

ITHT Parameter for tower cost:
 = 0, cost based on Sandia studies for concrete and steel towers;
 = 1, user supplied values for CTOW1 and CTOW2 to be used for all THTB.
Default: ITHT = 0 (V.A-4)

CTOW1 Tower cost parameters; CTOW, tower cost in \$, given by
CTOW2
CTOW3
XTOW

$$CTOW = CTOW1 \times e^{CTOW2 \times THTB} \quad THTB \geq 120.0(m)$$

$$CTOW = CTOW3 \times e^{XTOW \times THTB} \quad THTB < 120.0(m)$$

where THTB is the actual tower height from the ground to the receiver base.

Default: CTOW1 = 0.78232 × 10⁶(\$)
 CTOW2 = 0.0113(1/m)
 CTOW3 = 1.09025 × 10⁶(\$)
 XTOW = 0.00879(1/m) (V.A-4)

CREC1 Receiver cost parameters; CREC, receiver cost in \$, given by:
ARECRF
XREC

$$CREC = CREC1 \times (AREC / ARECRF)^{XREC}$$

See text for definition of AREC and ARECRF for cavity designs.

Default: CREC1 = 23.0 × 10⁶
 ARECRF = 758 (m²)
 XREC = 0.8 (V.A-5)

* All reference powers in the cost models refer to the rated power at the design conditions, not to the power at the base of the tower (unless the corresponding solar multiple is 1.0).

CRPREF
TRPREF
SMRP
PRPREF
XRP

Receiver/tower pump cost parameters; CRP, receiver pump cost in \$, given by:

$$CRP = CRPREF * \left(\frac{THT * SMULT * PTH}{TRPREF * SMRP * PRPREF} \right)^{XRP}$$

where THT is defined in namelist REC or OPT, SMULT in OPT, and PTH is the design thermal power delivered by the heat exchangers. The denominator consists of the corresponding terms for a reference design costing CRPREF.

Default: CRPREF = 2.10×10^6 (\$)
 TRPREF = 170.0 (m)
 SMRP = 1.5
 PRPREF = 2.6×10^8 (watts)
 XRP = 0.85 (V.A-6)

CSPREF
PSPREF
XSP

Storage pump cost parameters; CSP, storage pump cost in \$, given by:

$$CSP = CSPREF * (PTH / PSPREF)^{XSP}$$

Default: CSPREF = 0.470×10^6 (\$)
 PSPREF = 3.0×10^8 (watts)
 XSP = 0.15 (V.A-6)

CHPREF
CCPREF
SMPI
PPIREF
XPI

Piping cost parameters; CPIPE, piping cost in \$, consists of hot (CHPREF) and cold (CCPREF) pipe contributions. Each of these includes the pipe material itself, fittings, supports, insulation, and field erection costs.

$$CPIPE = THT * (FPLH * CHPREF + FPLC * CCPREF) * \left(\frac{SMULT * PTH}{SMPI * PPIREF} \right)^{XPI/2}$$

where FPLH and FPLC are defined in namelist NLEFF, THT in REC or OPT, SMULT in OPT on NLEFF. SMPI and PPIREF are the reference solar multiple and thermal power corresponding to the reference hot and cold pipe costs.

Default: CHPREF = 2.84×10^4 (\$/m)
 CCPREF = 0.0 (\$/m)
 SMPI = 1.5
 PPIREF = 2.6×10^8 (watts)
 XPI = 1.06 (V.A-7)

CSTREF
CSTRMD
VSTREF
ESTREF
XST
VMAX
EMPTY

Storage cost parameters; CSTOR, total storage cost in \$, consists of media containment equipment (tanks with insulation, foundation; storage heat exchangers; etc.) and storage media costs

$$CSTOR = N_{STOR} * \left(CSTREF * \left(1 + \frac{EMPTY}{N_{STOR}} \right) * \left(\frac{V_{STOR}}{V_{STREF}} \right)^{XST} + CSTRMD * \left(\frac{V_{STOR}}{V_{STREF}} \right) \right)$$

where $N_{STOR} = \text{integer}(V_{STOR}/V_{MAX}) + 1$

EMPTY = number spare tanks

$V_{STOR} = V_{STREF} \cdot (ESTOR/ESTREF)$

$V_{STOR} = V_{STOR}/N_{STOR}$

CSTREF (\$) and CSTRMD (\$) are reference containment and media costs, respectively, for a system of volume VSTREF (m³) and stored energy capacity ESTREF (watt-hrs). VMAX (m³) is the maximum practical volume.

Default: CSTREF = 9.70×10^6 (\$)
CSTRMD = 6.80×10^6 (\$)
VSTREF = 3740.0 (m³)
ESTREF = 6.88×10^8 (watt-hrs)
XST = 0.6
VMAX = 1.23×10^4 (m³)
EMPTY = 0.0 (V.A-8)

ICHE

Parameter for heat exchanger cost:

= 0, cost scales with thermal power;

≠ 0, cost scales with individual heat exchanger areas.

Default: ICHE = 0 (V.A-10)

CHEREF
PHEREF
XHEP

Heat exchanger cost parameters for scaling with thermal power; CHTXCHG, total heat exchanger cost in \$, given by:

$CHTXCHG = CHEREF \cdot (PTH/PHEREF)^{XHEP}$

where CHEREF (\$) and PHEREF (watts) are the cost and associated thermal power of a reference design.

Constraint: ICHE = 0

Default: CHEREF = 1.50×10^6 (\$)
PHEREF = 1.73×10^8 (watts)
XHEP = 0.8 (V.A-10)

Preheater:

CPHREF
APHREF
PPHREF
APHMAX

Evaporator:

CEVREF
AEVREF
PEVREF
AEVMAX

Superheater:

CSHREF
ASHREF
PSHREF
ASHMAX

Heat exchanger cost parameters for scaling with individual heat exchanger areas; CHTXCHG in \$ given by:

$CHTXCHG = N_{PH} \times CPHREF \times (APH'/APHREF)^{XHEA}$
 $+ N_{EV} \times CEVREF \times (AEV'/AEVREF)^{XHEA}$
 $+ N_{SH} \times SHREF \times (ASH'/ASHREF)^{XHEA}$
 $+ N_{RH} \times CRHREF \times (ARH'/ARHREF)^{XHEA}$

where $N_{PH} = \text{integer}(APH/APHMAX) + 1$

$APH = APHREF (PTH/PPHREF)$

Reheater:
 CRHREF
 ARHREF
 PRHREF
 ARHMAX

XHEA

$$APH' = APH/N_{PH}$$

and similarly for the other heat exchangers. CPHREF (\$) is the cost of a preheater of reference surface area APHREF (m²) and thermal power rating PPHREF (watts), and similarly for the others. APHMAX is the maximum practical size preheater, etc.

Default: CPHREF = 0.0 (i.e., no preheater in default case)
 APHREF = 1.0
 PPHREF = 1.0
 APHMAX = 10¹⁰
 CEVREF = 3.77 × 10⁶ (\$)
 AEVREF = 1300.0 (m²)
 PEVREF = 2.6 × 10⁸ (watts)
 AEVMAX = 10¹⁰ (m²) (i.e., no size limit)
 CSHREF = 1.24 × 10⁶ (\$)
 ASHREF = 400.0 (m²)
 PSHREF = 2.6 × 10⁸ (watts)
 ASHMAX = 10¹⁰ (m²)
 CRHREF = 1.38 × 10⁶ (\$)
 ARHREF = 310.0 (m²)
 PRHREF = 2.6 × 10⁸ (watts)
 ARHMAX = 10¹⁰ (m²)
 XHEA = 0.6 (V.A-10)

CEGREF
 PEGREF
 XEPGS

EPGS cost parameters; CEPGS, total EPGS subsystem cost in \$, given by:

$$CEPGS = CEGREF * (PTH * ETAREF / PEGREF)^{XEPGS}$$

where PEGREF is the nameplate rating (watts) for the reference turbine-generator costing CEGREF (\$). ETAREF, the design thermal-electric conversion efficiency, is defined in namelist NLEFF.

Default: CEGREF = 37.5 × 10⁶ (\$)
 PEGREF = 1.12 × 10⁸ (watts)
 XEPGS = 0.8 (V.A-11)

CFIXED

Fixed costs associated with all plants independent of power level (master control, buildings and roads, etc.). This variable should be used only for unusual fixed costs, since other fixed costs are also included based on direct capital costs and power levels.

Default: CFIXED = 0.0 (\$) (V.A-12)

ICKN

Flag for including a sodium-to-salt heat exchanger:
 = 0, component is not included
 = 1, component is included.

Default: ICKN = 0 (V.A-9)

CKNREF
PKNREF
XKN

Sodium-to-salt heat exchanger cost parameters. This cost is included in total heat exchanger costs in DELSOL output summaries as $\text{cost} = \text{CKNREF} \times (\text{P}/\text{PKNREF})^{\text{XKN}}$ where powers refer to thermal power at the tower base.

Constraint: ICKN = 1

Default: CKNREF = 9.0×10^6 (\$)

PKNREF = 320.0×10^6 (MWth)

XKN = 0.8 (V.A-9)

Namelist NLECON

CONT	Contingencies, expressed as a fraction of the total capital cost. Default: CONT = 0.12 (V.A)
SPTS	Spare parts investment, also expressed as some fraction of the total capital cost. Default: SPTS = 0.01 (V.A)
EXT	Distributable and indirect charges (contractor fees, A&E services, etc.), specified as a fraction of the total capital cost. Default: EXT = 0.16 (V.A)
ESC	Yearly capital escalation rate, fraction between 0 and 1 (not %). Default: ESC = 0.0 (V.B)
RINF	Yearly general inflation rate, fraction between 0 and 1. Default: RINF = 0.0 (V.B)
NYTCON	Years to the beginning of the construction period from the year in which the capital cost estimate is made. Default: NYTCON = 0 (V.B)
AFDC	Allowed funds during construction to cover interest charges, expressed as a fraction of the total capital cost. Default: AFDC = 0.0318 (3-year construction period) (V.B)
IFCR	Parameter for determining the fixed charge rate, FCR: = 0, FCR supplied by user or default value used; code does not calculate it; ≠, FCR calculated by the code based on user supplied values for DISRT, PTI, TC, TR, FDEBT, RDEBT, ROE, IDEP, NDEP (see below). Default: IFCR = 0 (V.B)
FCR	Fixed charge rate (fraction between 0 and 1); i.e., required yearly fractional recovery of total capital investment. Default: FCR = 0.0615 (V.B)
DISRT	Discount rate (between 0 and 1); must be consistent with value chosen for FCR if IFCR = 0. Default: DISRT = 0.0315 (V.B)
PTI	Property tax and insurance rate, expressed as a fraction of the total capital cost. Default: PTI = 0.010 (V.B)

TC	Investment tax credit expressed as a fraction of the total investment. Default: $TC = 0.10$ (V.B)
TR	Income tax rate, expressed as a fraction, not %. Default: $TR = 0.48$ (V.B)
FDEBT	Fraction of debt financing. Default: $FDEBT = 0.5431$ (V.B)
RDEBT	Debt cost; i.e., appropriate interest rate for borrowed funds, expressed as a fraction, not %. Default: $RDEBT = 0.11$ (V.B)
ROE	Before tax return on equity, expressed as a fraction, not %. Default: $ROE = 0.15$ (V.B)
IDEP	Parameter identifying depreciation schedule to be used: = 1, straight line method; = 2, sum-of-years digits method. Default: $IDEP = 2$ (V.B)
NDEP	Depreciation period (in years) of solar plant equipment. Default: $NDEP = 24$ (V.B)
NYOP	Operating life (years) of a plant for investment recovery. Default: $NYOP = 30$ (V.B)
RHOM	Heliostat operating and maintenance charge, expressed as a fraction of field related capital costs. Default: $RHOM = 0.015$ (V.B)
RNHOM	Balance of plant O&M charge, expressed as a fraction of non-field related capital costs. Default: $RNHOM = 0.015$ (V.B)

APPENDIX B-SAMPLE INPUT AND OUTPUT

The following pages discuss DELSOL sample problems which illustrate many of the features of the code and provide example input formats for the most common types of problems. The related output listings, as generated on a CRAY computer, are attached in microfiche version in the back of this manual.

Sample Problem 1a - Optimization of an External Receiver Design

Problem Statement

The optimum external molten salt receiver design at power levels of 75 to 150 MWe with no storage is desired. An incident flux level of 0.85 MW/m^2 is not to be exceeded anywhere on the receiver. The initial performance data should be saved for subsequent calculations, and the optimized field layouts should be printed. The optimized design and field layout for a power level of 125 MWe should be saved for a separate performance rerun.

Input Cards

```
SAMPLE PROBLEM 1a
$BASIC IPROB=4, ITAPE=1 $
$FIELD $
$HSTAT $
$REC $
$NLFLUX $
$NLEFF $
$REC IAUTOP=1 $
$OPT NUMTHT=6, THTST=100., THTEND=200., NUMREC=6, WST=8., WEND=18.,
  NUMHTW=3, HTWST=1.0, HTWEND=2.0, NUMOPT=4, POPTMN=75.E+06,
  POPTMX=150.E+06, SMULT=1.0, IPLFL=4*1, IOTAPE=1 $
$NLFLUX IFLX=1, FLXLIM=0.85E+06 $
$NLEFF SMULT=1.0 $
$NLCOST $
$NLECON $
$REC W=-1. $
```

Analysis of Input

For any initial performance calculation in a design/optimization run IPROB=4 must be specified. The results of this initial performance run are saved on a file on Unit 10 by setting ITAPE=1. It is assumed that the solar subsystems are the same technology as specified by the default values in the code, and so no changes are necessary for the remaining performance input. Flux calculations and automatic aiming should not be done for an initial performance calculation.

The next set of cards is read at the start of the optimization calculation. At this point in the calculation, the design will be affected by flux limits and aim strategies. IAUTOP=1 on the \$REC\$ card specifies the 1-dimensional smart aiming option necessary for a flux limited external receiver design. In the \$OPT\$ namelist, tower height and receiver dimensions are varied over a range compatible with the range of power levels. The variation in receiver height to width is specified to allow spreading of the flux along the height. IFLX=1 in \$NLFLUX\$ turns on the flux calculation, and the flux limit is set by FLXLIM. Since the maximum flux should occur at the center of the north panel for the default design point, only that one point is tested for flux levels. The default values in \$NLFLUX\$ will result in the flux being calculated at the correct point and compared to the limit FLXLIM.

The absence of storage is indicated by setting SMULT=1.0 in both \$OPT\$ and \$NLEFF\$. It is not necessary to set the reference costs to zero because the code will calculate zero storage costs if no energy is available to charge storage.

The optimum systems for all power levels specified by the non-zero values of IPLFL will be saved on a file on Unit 30 because the value of IOTAPE=1 is specified.

Comments on Output

The first part of the output consists of the printing of the performance namelists, followed by summaries of the heliostat design and receiver used in the initial performance calculation, zone by zone density and heliostat counts, an insolation table, and the zone by zone yearly average performance. A printing of the optimization namelists follows, then a summary of the optimization variables and design constraints. The default choice of IPROPT in \$OPT\$ produces the abbreviated list indicating the combinations of optimization variables searched, along with pertinent information related to each set considered.

The optimization results are then presented in a series of tables. Note in the system design summary that all design variables fall within the ranges searched except for the receiver height in the three smallest power sizes, which is at the maximum allowed height to width ratio. Although energy costs would probably not change significantly, a thorough user would want to rerun this case to allow consideration of larger height to width ratios. Note also in the field layout summary that the field extends to RADMAX in all cases for a number of azimuthal zones. The user could rerun this case with a larger value for RADMAX to allow the code more flexibility in zone selection for field build-up.

In no case was the flux limit met for this series of calculations. It is likely that a finer grid of choices for receiver dimensions and tower height would have resulted in optimum systems in which the peak flux was much closer to the allowed flux on the receiver. Sample Problem 1b looks at the flux distribution over the receiver for one of these systems in which the flux limit was not met.

Sample Problem 1b - Performance/Flux Run for an Optimized Design

Problem Statement

For the 125 MWe system optimized in Sample Problem 1a, produce a detailed performance summary of the system on an annual basis, and show that the flux at any point on the receiver does not exceed the flux limit of 0.85 MW/m^2 .

Input Cards

```
SAMPLE PROBLEM 1b
$BASIC IPROB=0, ITAPE=3, TDESP=125.0 $
$FIELD $
$HSTAT $
$REC $
$NLFLUX IFLX=1, IFXOUT(3,1)=1, IFLAUT=1,
        DIAMF=12.0, NXFLX=13, NYFLX=13,
        FAZMIN=0.0, FAZMAX=360.0, FZMIN=12.0, FZMAX=-12.0 $
$NLEFF $
$REC W=-1. $
```

Analysis of Input

For an annual performance calculation, IPROB=0 is specified. ITAPE=3 indicates that the optimized system is stored on a file on Unit 30, and TDESP specifies the power level of the system to be so analyzed. All values relating to the heliostats, field, and receiver will be defined from the file on Unit 30, and should not be redefined in these namelist inputs, even though the namelist cards must still remain in the input in the correct order.

A flux map over the whole receiver is specified by the appropriate choices of the values in Namelist \$NLFLUX\$. The values of FZMIN, FZMAX, FAZMIN, and FAZMAX are distances from the point specified by the values of XFC, YFC, and ZFC, which in this case were the default values. IFXOUT(3,1)=1 specifies that the flux map will be for the third of NYEAR days (in this case, day 81) at the first time for which calculations are done, that is, solar noon (time=0.0). The value of DIAMF would have defaulted to the receiver diameter anyway, but was included as a precautionary/informational action.

Comments on Output

As for the first part of Problem 1a, printouts of namelists and then summaries of heliostats and the receiver are printed. Positions of flux points are next printed, followed by field and insolation summaries. Next, yearly average and design point performance summaries are printed, followed by an annual power production table and summary. Finally, a table of fluxes at the requested locations is printed.

Note that the insolation value used in the design point summary and calculation of fluxes is different from the value used in the annual power production table. The former uses the value REFSOL, while the latter uses the calculated

value of insolation from the specified insolation model. If the values were significantly different, the user might want to redesign his systems using a modified value of REFSOL.

Close examination of the flux map reveals that peak flux does not occur at the north center of this receiver. What happened is that, because of the discrete steps in receiver size which were taken in designing the receiver, the height of this receiver is too large. Thus, heliostats were aimed to spread out the flux and mostly ended up being aimed not at the center of the receiver. However, if a more optimum receiver were designed by using a finer grid of size variables, the peak flux would be shifted back to the north center point of the receiver and would come much closer to meeting the allowable flux level.

Sample Problem 2a - Optimization of a Multi-Aperture Cavity Depth

Problem Statement

A 4-aperture receiver, including storage size, is to be optimized for a 125 MWe molten salt system with a solar multiple of 1.5. The receiver is a cavity design configured so that the north aperture is the largest, the south the smallest, and the east and west of intermediate size. The depth of each cavity varies in a similar fashion. A flux limit of 0.6 MW/m² is specified. A flux map of the optimum north cavity surface is required for subsequent detailed design studies. The optimized field layout should be printed and the optimization data saved.

A reminder: As discussed in Section IV.C-3(c), optimum cavity receiver design should be carried out in two steps. First, the optimum depth of each cavity should be calculated, and in a second run (Sample Problem 2b) the optimum aperture size. These sequential runs are discussed as Problems 2a and 2b.

Input Cards

```
SAMPLE PROBLEM 2A
$BASIC ITAPE=2 $
$REC IREC=2, W=20., IAUTOP=2, NUMCAV=4,
  RWCAV=1.0,0.75,0.5,0.75 $
$OPT NUMTHT=4, THTST=160., THTEND=220., NUMREC=5, WST=14., WEND=22.,
  IOPTUM=2, NUMHTW=7, HTWST=30., HTWEND=45.0, RYTRX=1.0, RX2TRX=0.8,
  RX3TRX=0.6, RX4TRX=0.8, NUMOPT=1, POPTMN=125.E+06, POPTMX=125.E+06,
  IPLFL=1 $
$NLFLUX IFLX=1, NXFLX=5, FAZMIN=135., FAZMAX=225., NYFLX=4, FZMIN=-1.68,
  FZMAX=4.92, NFLXMX=4, NMXFLX=3,8,13,18, FLXLIM=4*0.6E+06 $
$NLEFF $
$NLCOST CREC1=4.735e+06, ARECRF=1749.0 $
$NLECON $
$REC W=-100. $
```

Analysis of Input

The problem statement is somewhat general, so some choices must be made by the user. First, because this is a surround cavity receiver of approximately the same power level as in Sample Problem 1a, that surround field performance file (Unit 10) can be used, making a new initial performance calculation unnecessary. For this option, the variable ITAPE=2 is defined. No other namelist cards will be read in the performance group. The \$REC\$ card is the first of the optimization group and defines a cavity with four rectangular apertures (IREC, NUMCAV) and automatic 2-d aiming for cavity apertures (IAUTOP=2). Relative cavity depths are specified by RWCAV. (Values used here are reasonable ones, but could be varied according to the user's previous experience or to examine sensitivity of the design to these choices.) The value of W is chosen strictly to allow convenient specification of flux point locations, since the cavity depth is to be optimized in this run.

For optimizing cavity depth, the IOPTUM=2 option is specified. NUMREC, WST, and WEND refer to the width of the first aperture (in this case, the north aperture). NUMHTW, HTWST, and HTWEND define the width of the receiver and therefore the depth of the cavities. The aperture dimensions will have the fixed ratios RYTRX, RX2TRX, RX3TRX, and RX4TRX as the north aperture width is varied. Other input variables in \$OPT\$ are analogous to those in Sample Problem 1a.

Testing for flux limits on a cavity wall requires some care with the input data. The bottom of the wall is calculated and input as described in Section V.A-5. The default height (since H was not specified in Namelist \$REC\$) is $H=1.1 \times RY$. The maximum angle active for the north cavity sets the width of the flux surface (FAZMIN, FAZMAX). A 20 point grid is set up covering the active wall area of the north cavity, and the 4 points along the centerline (NMXFLX) are checked for a flux limit of 0.6 MW/m^2 . The flux map is initially referenced to the values in \$REC\$, and is scaled in the optimization search so that the same relative part of the cavity wall is covered by the flux map.

Parameters for the reference receiver cost (CREC1 and ARECRF in \$NLCOST\$) are provided to illustrate that receiver cost may be user defined based on the user's previous experience.

Comments on Output

The Namelist \$BASIC\$ is printed in the output, followed by a code generated list (\$FMTP\$) of the data read from the file on Unit 20. The heliostat design is summarized as in Sample Problem 1a, but no initial performance data is printed. The optimization namelists are printed, a summary of the optimization parameters is given, and a limited summary of the optimization search is printed.

The design summary tables are similar to those of Sample Problem 1a, except they are modified for the appropriate output cavity dimensions and include a summary of the cavity design. The height of the cavity wall is still determined by the new choice for aperture height ($H=1.1 \times RY$).

Sample Problem 2b - Optimization of a Multi-Aperture Cavity Size

Problem Statement

Using the system optimized in Sample Problem 2a for cavity depth, optimize aperture dimensions, and then determine annual system performance and energy output. Flux on the receiver wall should be limited to 0.6 MW/m^2 .

Input Cards

```
SAMPLE PROBLEM 2B
$BASIC ITAPE=2 $
$REC IREC=2, THT=180., W=30., IAUTOP=2, NUMCAV=4,
  RX=18.0,14.4,10.8,14.4, RY=18.0,14.4,10.8,14.4,
  RWCAV=1.0,0.75,0.5,0.75 $
$OPT NUMTHT=4, THTST=160., THTEND=220., NUMREC=5, WST=14., WEND=22.,
  NUMHTW=4, HTWST=0.75, HTWEND=1.5,
  NUMOPT=1, POPTMN=125.E+06, POPTMX=125.E+06, IPLFL=1, IOTAPE=1,
  IRERUN=1, ISTR=2, NSTR=11 $
$NLFLUX IFLX=1, NXFLX=5, FAZMIN=90., FAZMAX=270., NYFLX=4, FZMIN=-7.08,
  FZMAX=12.72, NFLXMX=4, NMFLX=3,8,13,18, FLXLIM=4*0.6E+06 $
$NLEFF $
$NLCOST CREC1=4.735E+06, ARECRF=1749. $
$NLECON $
PERFORMANCE RERUN
$BASIC ITAPE=3, TDESP=125., IPROB=0 $
$FIELD $
$HSTAT $
$REC $
$NLFLUX IFLX=1, IFXOUT(3,1)=1 $
$NLEFF $
$REC W=-100. $
```

Analysis of Input

As in Problem 2a, the performance data created in Problem 1a will suffice for initial performance input (ITAPE=2 in \$BASIC\$). The user must input on Namelist \$REC\$ the dimensions which were optimized in Problem 2a, specifically W. Values of THT, RX, and RY which are specified will not affect the system, since these variables are being optimized in this run. However, the parameters in \$NLFLUX\$ must be consistent with these values as defined in order to locate the flux map points in the correct positions. Also, a smart user would probably narrow the range being optimized over for tower height and aperture width, based on the results from Sample Problem 2a. The aperture size variation is specified by selecting NUMHTW values of the first aperture height to width ratio from HTWST to HTWEND and by using the default value for IOPTUM. The other three apertures will be sized by the same ratio and by the relative size with respect to the first aperture given by RX2TRX, RX3TRX, and RX4TRX, or as defined by RX and RY values in \$REC\$ as done in this example. These should be kept the same as in Problem 2a. To save the optimization results on a file, the IOTAPE=1 option is used. The storage optimization is flagged in Namelist \$OPT\$ (ISTR, NSTR) to look at 11 storage sizes varying from twice that for the longest day to no storage. The actual optimization is not done until a final performance calculation. In this case, that calculation is part of the same job because IRERUN=1 is specified. Again, the four flux points along the centerline of the north cavity wall are tested for flux limits.

For the final detailed performance calculation on the optimized system, the input set of Table A-2 is included. ITAPE=3 specifies that a user defined system is to be read from the file on Unit 30, and TDESP indicates the power level in MW of the system to be analyzed. IPROB=0 specifies that an annual performance is desired. Since a flux map is desired, the flux calculation must be turned on with IFLX=1, where IFXOUT determines which point in time is to be used for the flux calculation. The flux point positions default to the positions defined in the previous optimization calculation, since they are not specifically redefined.

Comments on Output

The initial output is similar to the output of Problems 1a and 2a. Note that the code chose the same system design as in Problem 2a. The smart user probably would have used a finer grid of flux test points and of tower height and aperture width optimization variables to further refine the system in this step.

The form of the remaining output is the same as for Problem 1b. The optimized storage size is printed at the front of the annual power production table. In this case the size was unchanged from that for the longest day of the year (used earlier during system optimization). If the storage size had changed due to optimization, the cost numbers also printed there would have been adjusted by the code and would no longer have matched those numbers printed as part of system optimization output. These new numbers are the best numbers DELSOL can provide. The levelized cost of energy printed here may also be different because the final performance calculation predicts a more accurate annual energy estimate, which is printed in the yearly energy production summary and is used in this energy cost calculation.

The flux map shows that at angles greater than those by which the field "sees" the cavity wall, flux is negligible. However, at the top of the wall the flux is still significant. The user might wish to reoptimize this system to allow a larger wall height for the same aperture dimensions. Also, Sample Problem 3b will show how to examine the roof of a similar cavity design for fluxes. The active cavity area should only be enlarged to limit fluxes on uncooled surface (such as the roof) to acceptable values. Internal reradiation will occur so that the energy incident on uncooled surfaces will mostly not be lost for power production purposes.

Sample Problem 3a - Optimization of a Single-Aperture Cavity Receiver

Problem Statement

A preliminary 125 MWe cavity receiver design with some amount of storage is to be generated for a north field. A preliminary power production estimate is required. Flux should not exceed 0.6 MW/m^2 on the cavity absorbing wall.

Input Cards

```
SAMPLE PROBLEM 3A
$BASIC IPROB=4, ITAPE=1 $
$FIELD INORTH=1 $
$HSTAT $
$REC IREC=2 $
$NLFLUX $
$NLEFF $
$REC IREC=2, W=20., IAUTOP=2 $
$OPT NUMTHT=4, THTST=200., THTEND=260., NUMREC=5, WST=14., WEND=22.,
  IOPTUM=2, NUMHTW=7, HTWST=30., HTWEND=45.0, RYTRX=1.0,
  NUMOPT=1, POPTMN=125.E+06, POPTMX=125.E+06,
  IPLFL=1, IRERUN=1, IOTAPE=1 $
$NLFLUX IFLX=1, NXFLX=5, FAZMIN=135., FAZMAX=225., NYFLX=4, FZMIN=-1.68,
  FZMAX=4.92, NFLXMX=4, NMFLX=3.8.13,18, FLXLIM=4*0.6E+06 $
$NLEFF $
$NLCOST CREC1=4.735e+06, ARECRF=1749.0 $
$NLECON $
SAMPLE PROBLEM 3A RERUN
$BASIC IPROB=0, ITAPE=3, TDESP=125.0 $
$FIELD $
$HSTAT $
$REC $
$NLFLUX IFLX=1, IFXOUT(3.1)=1, FAZMIN=90., FAZMAX=270.0 $
$NLEFF $
$REC W=-100. $
```

Analysis of Input

This problem is similar in scope to Problem 2, except that this is for a north field, storage optimization is not required, and only a preliminary receiver design is required. This last requirement allows the user to skip the normal second part of cavity design optimization, that of optimizing aperture height-to-width ratios. Because no previous initial performance calculation has been done for a north field, one is required for this problem. The north field is specified with the variable INORTH=1 in Namelist \$FIELD\$. The default system in the initial performance is close enough to be used without change for this problem. The cavity receiver is specified by IREC=2, and the number of apertures defaults to one north aperture. This is consistent with the north field specification.

The inputs for optimization are similar to those for Problem 2a. The tower height range is extended, since north field designs will typically have taller towers. Also, IRERUN=1 is specified along with IOTAPE=1, since the results of this optimization will be used directly for a final performance run, without doing the normal second step of cavity optimization.

The inputs for the final performance calculation are similar to those presented for earlier sample problems. In this case, the width of the flux map was changed

from that specified during the optimization. This does not affect anything other than the flux calculation. That is, the system performance of the optimized system will be unchanged. However, the values specified during optimization did not completely cover the cavity wall, and this change “fixes” that oversight.

Comments on Output

The output is similar to that of Sample Problem 2b, although the chosen system and cavity description is different. The fluxes at the 90 degree edge of the cavity are no longer insignificant, as they were for the multiple-aperture cavity. However, fluxes at the top of the wall are still large. Sample Problem 3b will generate a flux map of the roof of this cavity design.

Sample Problem 3b - Generating a Flux Map for a Cavity Roof

Problem Statement

For the system of Problem 3a, determine the incident flux on the roof of the cavity receiver.

Input Cards

```
SAMPLE PROBLEM 3b
$BASIC IPROB=0, ITAPE=3, TDESP=125.0 $
$FIELD $
$HSTAT $
$REC $
$NLFLUX IFLX=1, IFXOUT(3,1)=1, IFLAUT=3,
        XFC=0.0, YFC=0.0, ZFC=16.10, POLF=180.0, AZMF=180.0,
        NXFLX=5, NYFLX=5, FAZMIN=-22.5, FAZMAX=+22.5,
        FZMIN=0.0, FZMAX=22.5 $
$NLEFF $
$REC W=-100. $
```

Analysis of Input

This is a performance rerun of a previously optimized system, as indicated by the specified values in Namelist \$BASIC\$. The system description is read from the file on Unit 30. The flux points are specified to be on a plane (IFLAUT=3) whose center is at the location XFC, YFC, ZFC. The values of FAZMIN, FAZMAX, FZMIN, and FZMAX are measured from that location. The plane is downward facing (POLF=180.0). Because the center of the flux plane is also the center of the tower, and because the cavity design (RWCAV and W) specify this design's back wall to be at the center of the tower, FZMIN is set to zero, and FZMAX is set to the depth of the cavity (W/2). This means that the point (0,0) on the plane is the same point as the top point on the centerline of the cavity wall used in Sample Problem 3a.

Comments on Output

All of the output except for flux points and the flux map will be exactly the same as for the final performance run of Problem 3a. The smart user might have specified IPROB=2 on Namelist \$BASIC\$ as a means of saving computer time, since the purpose of this run was only to generate a flux map.

The flux map is generated by DELSOL assuming that the flux surface is the only surface within the aperture. Thus, for points on the flux surface which are outside the semi-circular area of the cavity, the flux levels would in real life be nonsense, since the flux would strike the wall of the cavity instead. At the flux point common with Problem 3a, the flux is calculated to be 56% of that calculated in 3a. The difference is caused by the difference in the incident angle of flux on the two different flux surfaces. The cavity wall is more nearly normal to the flux, and so has a higher normal flux level than the roof, which is closer to being parallel to the incident radiation.

Sample Problem 4 - User Defined Field with Individual Heliostat Coordinates

Problem Statement

The example of the CESA-1 system discussed in Chapter VII and Reference 43 is used here to illustrate the input and output of the IUSERF=3 option in \$FIELD\$. The performance and a flux map on winter solstice at 10 a.m. are desired. The insolation is 0.7 kw/m², and a square wave sun is to be assumed. Other information comes from Reference 43.

Input Cards

```

SAMPLE PROBLEM 4
$BASIC IPROB=2, UDAY=355., UTIME=-2., IPRINT=2,
      PLAT=37.099, INSOL=2, SOLCON=0.7, NSUN=2,
      IATM=2, ATM1=0.679, ATM2=11.76, ATM3=-1.97,
      ATM4=0. $
$FIELD IUSERF=3 $
$HSTAT WM=6.25, HM=8.3, ICPANL=1, WPANL=2.9, HPANL=1.25,
      HXCANT=5*-1.675, 5*1.675, HYCANT=2.525, 1.263,
      0., -1.263, -2.525, 2.525, 1.263, 0., -1.263, -2.525,
      DENSMR=0.92063, RMIRL=0.85, SIGAZ=0., SIGEL=0.,
      SIGSX=0., SIGSY=0., SIGTX=0.0033, SIGTY=0.0033,
      ICANT=3, NCANTY=5, ISB=1 $
$REC THT=56.345, TOWL=67.345, TOWD=11., IREC=4,
      W=10.8, RX=3.4, RY=3.4, IAUTOP=0, RELV=111.8 $
$NLFLUX IFLX=1, IFXOUT(1,1)=1, IFLAUT=4, NXFLX=11,
      FAZMIN=-1.7, FAZMAX=1.7, NYFLX=11, FZMIN=-1.7,
      FZMAX=1.7 $
$NLEFF $
SPANISH FIELD
      282      16
       1       7
      0.0      45.      85.0
     10.0      45.      85.0
     20.0      45.      85.0
     30.0      45.      85.0
    -30.0      45.      85.0
    -20.0      45.      85.0
    -10.0      45.      85.0
       2      10
       5.0      57.      85.0
-----
    -26.56     259.
     -8.83     259.
$REC W=-100. $
                                255.0
                                255.0

```

Analysis of Input

The detailed input describing the site location, sunshape, atmospheric attenuation (\$BASIC\$), the heliostat (\$HSTAT\$), and tower and receiver (\$REC\$) are consistent with the system definition of Reference 43. To calculate the performance and flux at a particular time, IPROB=2, UDAY, and UTIME are specified in \$BASIC\$. IPRINT is set to 2 in order to get the single time results printed. IUSERF=3 in \$FIELD\$ sets up the code to do a run on a field with the individual heliostat coordinates defined. The values defined in \$NLFLUX\$ are chosen for a finely gridded flux map. After \$NLEFF\$ comes the individual heliostat input in the format described in the \$FIELD\$ section of Appendix A. Only the first few values are shown here. For each heliostat, the focal length must be defined, or the heliostat will be defocused.

Comments on Output

The output is similar to those of the other sample problems up to the zoning summary, which is now simply a flag that the individual coordinate option is employed. The performance summary of the heliostats is then printed. Total field performance, a waterfall trace at the specified time, and a flux map follow.

GLOSSARY

Absorber: The portion of the receiver that absorbs radiant energy.

Attenuation Loss: The loss of solar power by absorption and scattering as a result of atmospheric conditions between the concentrator and the receiver.

Beam Alignment: The adjustment of individual mirror facets of a heliostat to place their images in the desired relationships to one another.

Beam Characterization System: A video-based system for the rapid and automatic measurement and characterization of flux delivered by any single heliostat onto a target.

Blocking: The interception of part of the reflected sunlight from one heliostat by the backside of a second heliostat.

Capacity Factor: Energy production in a given time interval (generally one year) divided by the energy that would have been generated if the plant had operated at its full capacity for the same time interval.

Cavity Receiver: A solar energy receiver in the shape of a cavity in which the solar radiation enters through one or more openings (apertures) and is absorbed by interior heat exchanger surfaces.

Central Receiver System: See **Solar Thermal Central Receiver Power System**.

Cloud Cover: That portion of the sky cover which is obscured by clouds, usually measured in tenths of sky covered.

Cogeneration: The production of electricity or mechanical energy, or both, in conjunction with industrial process heat.

Concentration Ratio: The ratio of the reflected radiant power impinging on a surface to the radiant power incident upon the reflecting surface.

Concentrator Efficiency: The ratio of the energy collected by a heliostat field to the radiant energy that strikes it under steady-state conditions (includes cosine loss).

Concentrator Subsystem: An array of heliostats, included the wiring and controls, that redirects the available insolation onto a receiver.

Cosine Loss: The reduction of the projected heliostat area visible to the sun

caused by the tilt of the heliostat, proportional to the cosine of the angle of inclination of the normal of the heliostat surface to the sun's rays.

Cost/Performance Ratio: A measure used in comparing system design alternatives wherein both cost and system performance are taken into account.

CRTF: The Central Receiver Test Facility at Sandia National Laboratories in Albuquerque, New Mexico.

Design Point: The time of day and day in a year for which the system or component performance is specified.

Direct Normal Insolation: The solar energy incident on a surface that comes from within the solid angle subtended by the solar disk; that sunshine which can cast a sharply defined shadow.

Discount Rate: The annual rate used in present worth analyses that takes into account inflation and the potential earning power of money while moving the present worth forward or backward to a single point in time for comparison of value.

Diurnal: Recurring every day.

DOE: The United States Department of Energy.

Downcomer: The pipe carrying the hot heat transport fluid down the receiver tower.

Emissivity: The ratio of the radiant energy given off by a surface to that given off by a blackbody at the same temperature.

End Use: The final use of the thermal output of a solar central receiver plant, *e.g.*, in a turbine to generate electricity or in an industrial process.

External Receiver: A solar energy receiver in which the solar radiation is absorbed on the external surfaces. External receiver configurations include billboard (flat plate) and cylindrical.

Fixed Charge Rate: The amount of revenue per dollar of capital expense that must be collected annually to pay for the fixed charges associated with plant ownership, *e.g.*, return on equity, interest payment on debt, depreciation, income taxes, property taxes, insurance and repayment of initial investment. It may also include operations and maintenance expenses expressed as a fraction of the capital cost.

Flux (Radiant): The time rate of flow of radiant energy.

Flux Density: The radiant flux incident per unit area.

Heat Exchanger: A component in which thermal energy is transferred from one fluid to another—for example, a steam generator that transfers thermal energy from the Heat Transport Fluid to the Working Fluid for a Rankine cycle steam turbine, or that transfers thermal energy from the Receiver Fluid to the Heat Transport Fluid (if different).

Heat Tracing: An auxiliary heating system that prevents the freezing of liquids within pipes.

Heat Transport Fluid: The fluid used for transporting or transferring thermal energy from one area to another within the system. See **Receiver Fluid**; **Working Fluid**.

Heliostat: An assembly of mirrors, support structure, drive mechanism, and mounting foundation which tracks the sun in two axes of motion to continuously reflect sunlight onto a fixed receiver.

Heliostat Characterization System: See **Beam Characterization System**.

Heliostat Packing Density: The ratio of total reflective surface area to the total land area used by the heliostats (concentrator subsystem). Also referred to as the Ground Cover Ratio.

Hot/Cold Tank Storage: A thermal energy storage system utilizing separate tanks for the charged (hot) and uncharged (cold) storage media.

Hours of Storage: The number of hours a plant can produce power at a stated output level, normally at full-rated system load, when operating exclusively from an initially fully-charged storage unit.

Insolation: The solar energy incident on a unit surface per unit time. (Acronym for *incident solar radiation*.)

Intercept Factor: The fraction of direct or reflected rays incident on the receiver aperture whose trajectories reach the absorber.

Irradiance: See **Flux Density**.

Levelization: The process by which a series of non-uniform future payments is converted into a uniform (level) series of payments whose present worth is equal to that of the original non-uniform series.

Levelized Busbar Energy Cost: The constant annual revenue per unit of energy required over the lifetime of a plant to compensate for its fixed and variable cost.

Levelized Fixed Charge Rate: The fixed charge rate that produces a constant level of payments over the life of a plant whose present worth is the same as the present worth of the actual cash flow.

Nameplate Rating: The full-load continuous rating of a power plant under specified conditions as designated by the manufacturer.

Output Factor: The ratio of the plant energy output for a period of time to the plant rating over that same time period.

Parasitic Power, Parasitic Energy: The parasitic power is the power required at any time to operate the power plant (*e.g.*, the power to operate pumps, motors, computers, lighting, air conditioning, etc.). The parasitic energy is the energy consumed by such uses for a specified period. The *net power* produced by a solar thermal plant is the gross power generated less the parasitic power losses, and similarly for *net energy* production.

Peak Load: The maximum load in a given time interval.

Plant Availability: The percentage of time a plant is able to provide power if so required. Since there is an insolation threshold below which the plant cannot generate net power, the *availability factor* is defined as the fraction of total daylight hours when the solar irradiance exceeds the threshold value.

Pointing Error per Axis: The standard deviation (RMS), for each axis, of the difference between the desired aimpoint and the beam centroid location. This error is in the heliostat reflected ray coordinate system and is expressed in milliradians.

Power Tower: A term used in the popular press to describe a solar thermal central receiver power system.

Process Heat: The heat which is used in agricultural, chemical, or industrial operations.

Radiant Power: See Flux (Radiant).

Radiation: The emission and propagation of energy through space (or through material medium) in the form of waves (or photons).

Rankine Cycle: The thermodynamic cycle upon which water-steam turbines are based, in which the working fluid is pressurized as a liquid, evaporated and perhaps superheated, put through a turbine to extract its energy, and subsequently condensed at low pressure.

Receiver: That element of a solar central receiver system to which solar radiation is directed by the heliostats and where it is absorbed and converted to thermal energy.

Receiver Fluid: The fluid that is circulated through the receiver to absorb solar radiation as thermal energy. The Receiver Fluid is normally the same as the Working Fluid used elsewhere in the system, but may be different (in which case a Heat Exchanger is required. See **Working Fluid; Heat Exchanger**).

Receiver System Efficiency: The ratio of the thermal power absorbed by the receiver working fluid and delivered to the base of the tower to the solar radiant power delivered to the receiver under reference conditions.

Reflectance: The ratio of the reflected radiant flux to the incident radiant flux on a surface. For a solar thermal system, the specular reflectance is of interest.

Repowering: The retrofitting of existing fossil-fueled utility or process heat power plants with solar energy systems in order to displace a portion or all of the fossil fuel normally used.

Riser: The pipe carrying the cold heat transport fluid up the receiver tower.

Shadowing or Shading: The shading of the reflective surface of one heliostat from the sun's rays by another heliostat.

Smart Aiming: An aiming strategy of heliostats in which aimpoints on the receiver are spread out to reduce peak flux levels. This usually refers to the option IAUTOP=1 for external receivers and IAUTOP=3 for cavity or flat plate receivers.

Smart Optimization: The process in DELSOL of finding the optimum system based on levelized energy cost, where not every possible combination of receiver and tower dimensions allowed by the user will be examined. Instead, DELSOL will assume that each variable has a single minima which is not affected by other variables and that all dimensions tend to increase as the power level increases. Also, if a receiver power cannot be obtained for a given tower height for any size receiver, no further systems will be examined for that tower height. This option, which is controlled by the input variable IALL, is used as a method of reducing computer execution time during system optimization.

Solar Multiple: The ratio of the thermal power that is absorbed in the receiver fluid and delivered to the base of the tower at the system design point to the peak thermal power required by the turbine-generator (or other end use).

Solar Noon: See **Solar Time**.

Solar One: See **Ten Megawatt Electric (10 MWe) Solar Thermal Central Receiver Pilot Plant**.

Solar Thermal Central Receiver System: A solar power system which concentrates the available solar energy by means of an array of computer controlled heliostats to a tower-mounted receiver. The energy absorbed at the receiver is removed as thermal energy in a working fluid.

Solar Time: The time as reckoned by the apparent position of the sun. Solar noon occurs when the sun reaches its zenith.

Specular: Having the qualities of a mirror which reflects with no scattering.

Spillage: The radiation which is reflected from the concentrator subsystem but which misses the receiver's absorber surface.

Storage Capacity: The amount of net energy ($MW_{th}\text{-hr}$) which can be delivered from a fully charged storage subsystem.

Storage-Coupled: The use of an energy storage system to permit operation of the end-use system during periods when solar energy from the receiver cannot satisfy the load.

Stow: A position or act of reaching a position of safe storage for the heliostats.

Sun Position: The azimuth and elevation angles for specifying the direction to the central ray from the sun.

Sunshape: The relative intensity of solar energy across the solar disk.

Ten Megawatt Electric (10 MWe) Solar Thermal Central Receiver Pilot Plant (also known as Solar One): A prototype solar thermal central receiver power system near Barstow, California. The plant has been operating since 1981 with the capability of producing 10 MWe of electricity for use in the Southern California Edison utility system.

Thermal Energy Storage Subsystem: A rechargeable unit capable of storing thermal energy for later use. Examples are storage as sensible heat in nitrate salt, sodium, rocks, water, or oil.

Thermocline Storage: The storage of thermal energy in which the hot and cold media are in the same container (tank) and which uses the thermocline principle. Such storage relies on a lower density hot fluid floating atop a higher density cooler fluid of the same type, or on hot solid material being separated from cooler solid materials by a thermal gradient as in air-rock, air-ceramic-brick applications. The *thermocline* is the zone or layer in which the vertical temperature profile changes rapidly.

Trace Heating: See **Heat Tracing**.

Tracking Systems: The motors, gears, and actuators that are instructed by computer command to maintain a proper heliostat orientation with respect to the sun and receiver positions.

Turbine-Generator: The component which converts thermal energy into electrical energy.

Working Fluid (also known as Heat Transport Fluid): The fluid that performs work for the end-use system—for example, the steam in a steam turbine-generating system, hot gas in a Brayton cycle gas turbine, or fluid providing thermal energy for a process heat application. The Working Fluid may or may not be the Receiver Fluid. See **Receiver Fluid; Heat Exchanger**.

VARIABLE INDEX BY SECTION

<u>Variable</u>	<u>Namelist</u>	<u>Section</u>
AEVMAX	NLCOST	(V.A-10)
AEVREF	NLCOST	(V.A-10)
AFDC	NLECON	(V.B)
ALP(I)	FIELD	(II.B-4)
ALP(I)	OPT	(II.B-4,IV.C-4)
ALT	BASIC	(III.B-2)
AMAXN	FIELD	(II.B-1,II.B-2)
APHMAX	NLCOST	(V.A-10)
APHREF	NLCOST	(V.A-10)
ARECRF	NLCOST	(V.A-5)
AREF	NLEFF	(III.G-3)
ARHMAX	NLCOST	(V.A-10)
ARHREF	NLCOST	(V.A-10)
ASHMAX	NLCOST	(V.A-10)
ASHREF	NLCOST	(V.A-10)
ASTART	BASIC	(III.A-1,III.A-5)
ATM1	BASIC	(III.G-1)
ATM2	BASIC	(III.G-1)
ATM3	BASIC	(III.G-1)
ATM4	BASIC	(III.G-1)
AZMF	NLFLUX	(II.G-1,II.G-2)
AZMSEP(K)	FIELD	(II.B-2,II.C)
CCPREF	NLCOST	(V.A-7)
CEGREF	NLCOST	(V.A-11)
CEVREF	NLCOST	(V.A-10)
CFIXED	NLCOST	(V.A-12)
CH	NLCOST	(V.A-1)
CHEREF	NLCOST	(V.A-10)
CHPREF	NLCOST	(V.A-7)
CKNREF	NLCOST	(V.A-9)
CL	NLCOST	(V.A-2)
CLE(I)	FIELD	(II.B-4)
CLE(I)	OPT	(II.B-4,IV.C-4)
CLN(I)	FIELD	(II.B-4)
CLN(I)	OPT	(II.B-4,IV.C-4)
CONT	NLECON	(V.A)
CPHREF	NLCOST	(V.A-10)
CREC1	NLCOST	(V.A-5)

<u>Variable</u>	<u>Namelist</u>	<u>Section</u>
CRHREF	NLCOST	(V.A-10)
CRPREF	NLCOST	(V.A-6)
CSHREF	NLCOST	(V.A-10)
CSPREF	NLCOST	(V.A-6)
CSTREF	NLCOST	(V.A-8)
CSTRMD	NLCOST	(V.A-8)
CTOW1	NLCOST	(V.A-4)
CTOW2	NLCOST	(V.A-4)
CTOW3	NLCOST	(V.A-4)
CWDA	NLCOST	(V.A-3)
CWDR	NLCOST	(V.A-3)
CWR	NLCOST	(V.A-3)
DCANT	HSTAT	(III.A-5,II.D-2)
DENSIT(K,L)	FIELD	(II.B-2,II.C)
DENSMR	HSTAT	(II.C,II.D,II.D-3)
DH2O(I)	BASIC	(III.B-1,III.B-2,III.B-3)
DHOPT	BASIC	(IV.B-2,IV.C-7)
DIAMF	NLFLUX	(II.G-1,II.G-2)
DISRT	NLECON	(V.B)
DPRES(I)	BASIC	(III.B-1,III.B-2,III.B-3)
DWEATH(I)	BASIC	(III.B-3)
EFFSTR	NLEFF	(III.G-7)
EMPTY	NLCOST	(V.A-8)
ESC	NLECON	(V.B)
ESTREF	NLCOST	(V.A-8)
ETAREF	NLEFF	(III.G-5,III.H,V.A-11)
EXT	NLECON	(V.A)
FAZMAX	NLFLUX	(II.G-1)
FAZMIN	NLFLUX	(II.G-1)
FCR	NLECON	(V.B)
FDEBT	NLECON	(V.B)
FEFF	NLEFF	(III.G-5,III.G-6,III.H)
FEP	NLEFF	(III.G-6,III.G-8)
FLAND(K,L)	FIELD	(II.B-2,II.B-4)
FLXLIM(I)	NLFLUX	(II.G-2,IV.D-1)
FPLC	NLEFF	(V.A-7)
FPLH	NLEFF	(III.G-4,V.A-7)
FSLIP	FIELD	(II.C-1)
FSP	NLEFF	(III.G-6,III.G-8)
FZMAX	NLFLUX	(II.G-1)
FZMIN	NLFLUX	(II.G-1)

<u>Variable</u>	<u>Namelist</u>	<u>Section</u>
H	REC	(II.E,IV.C-3)
H2O	BASIC	(III.B-1,III.B-2,III.B-3)
HCANT	HSTAT	(III.A-5,II.D-2)
HM	HSTAT	(II.C,II.D,II.D-3)
HPANL	HSTAT	(II.D)
HRDEL	BASIC	(III.A-1,III.A-2,III.A-5)
HTWEND	OPT	(II.E,IV.C-3,IV.E)
HTWST	OPT	(II.E,IV.C-3,IV.E)
HXCANT(I)	HSTAT	(II.D)
HYCANT(I)	HSTAT	(II.D)
IALL	OPT	(IV.E)
IATM	BASIC	(III.G-1)
IAUTOP	REC	(II.F,II.G-2)
ICANT	HSTAT	(II.D-2,II.D-3)
ICAVF(I)	NLFLUX	(II.G)
ICHE	NLCOST	(V.A-10)
ICKN	NLCOST	(V.A-9)
ICPANL	HSTAT	(II.D)
IDENS	FIELD	(II.C,IV.B-1,IV.B-2)
IDEP	NLECON	(V.B)
IFCR	NLECON	(V.B)
IFLAUT	NLFLUX	(II.G-1,II.G-2)
IFLX	NLFLUX	(II.G,II.F-2)
IFOCUS	HSTAT	(II.D-2,II.D-3)
IFXOUT(I,J)	NLFLUX	(II.G)
IHOPT	OPT	(II.C,IV.B,IV.C-7)
IHOPTP	OPT	
IHPR	FIELD	
ILAY	FIELD	(II.C)
INDC	HSTAT	(III.F-1,VI.A-5)
INORTH	FIELD	(II.B-1)
INSOL	BASIC	(III.B-2,III.B-3,III.H)
IOPTUM	OPT	(II.E,IV.C-3,IV.E)
IOTAPE	OPT	(II.B-2,VI.A-5)
IPH	NLEFF	(III.G-6,V.A-11)
IPLFL(I)	OPT	(VI.A-5)
IPRINT(I)	BASIC	
IPROB	BASIC	(III.A)
IPROPT	OPT	
IRADFL	NLEFF	(III.G-3)
IREC	REC	(II.E,IV.C-3)

<u>Variable</u>	<u>Namelist</u>	<u>Section</u>
IRERUN	OPT	(VI.A-5)
IROTFL	FIELD	(II.B-3)
IROUND	HSTAT	(II.D,II.D-3)
ISB	HSTAT	(III.E)
ISTR	OPT	(IV.C-5,V.A-8)
ITAPE	BASIC	(III.A-1,VI,VI.A)
ITHEL	NLEFF	(III.G-5,III.G-6)
ITHT	NLCOST	(V.A-4)
IUSERF	FIELD	(II.B-2,VI)
IWEATH	BASIC	(III.B-3)
NAX(K,L)	REC	(II.F,II.G-2)
NAY(K,L)	REC	(II.F,II.G-2)
NAZM	FIELD	(II.B-1,II.B-2,II.F-6)
NCANTX	HSTAT	(II.D-2,II.D-3)
NCANTY	HSTAT	(II.D-2,II.D-3)
NDEP	NLECON	(V.B)
NFLXMX	NLFLUX	(II.G-2,IV.D-1)
NLAND	FIELD	(II.B-4,IV.C-4)
NLAND	OPT	(II.B-4,IV.C-4)
NMXFLX(I)	NLFLUX	(II.G-2,IV.D-1)
NRAD	FIELD	(II.B-1,II.B-2,II.F-6)
NRADMN(L)	FIELD	(II.B-2)
NRADMX(L)	FIELD	(II.B-2)
NSTR	OPT	(IV.C-5,V.A-8)
NSUN	BASIC	(III.B-4)
NSUNPT	BASIC	(III.B-4)
NUAZ	BASIC	(III.A-4)
NUEL	BASIC	(III.A-4)
NUMCAV	REC	(II.E)
NUMHTW	OPT	(II.E,IV.C-3,IV.E)
NUMPOS	OPT	(II.B-4,IV.C-4,IV.E)
NUMREC	OPT	(IV.C-3,IV.E)
NUMTHT	OPT	(IV.C-2,IV.E)
NXFLX	NLFLUX	(II.G-1)
NYEAR	BASIC	(III.A-1,III.A-5)
NYFLX	NLFLUX	(II.G-1)
NYOP	NLECON	(V.B)
NYTCON	NLECON	(V.B)
PARL1,PARL2	NLEFF	(III.G-8)
PARL3,PARL4	NLEFF	(III.G-8)
PARL5,PARL6	NLEFF	(III.G-8)

<u>Variable</u>	<u>Namelist</u>	<u>Section</u>
PARL7,PARL8	NLEFF	(III.G-8)
PARL9,PARL10	NLEFF	(III.G-8)
PEGREF	NLCOST	(V.A-11)
PEVREF	NLCOST	(V.A-10)
PF	NLEFF	(III.G-8,III.H,IV.B-2)
PHREF	NLCOST	(V.A-10)
PKNREF	NLCOST	(V.A-9)
PLAT	BASIC	(III.B-1,III.B-3)
POLF	NLFLUX	(II.G-1,II.G-2)
PPHREF	NLCOST	(V.A-10)
PPIREF	NLCOST	(V.A-7)
PRES	BASIC	(III.B-1,III.B-2,III.B-3)
PRHREF	NLCOST	(V.A-10)
PRPREF	NLCOST	(V.A-6)
PSHREF	NLCOST	(V.A-10)
PSPREF	NLCOST	(V.A-6)
PTI	NLECON	(V.B)
RADMAX	FIELD	(II.B-1,IV.C-6)
RADMIN	FIELD	(II.B-1,IV.C-6)
RAZM(I)	REC	(II.E)
RCANT(K)	HSTAT	(II.D-2,II.D-3)
RDEBT	NLECON	(V.B)
REFDAY	BASIC	(III.A-5,V.C-1)
REFLP	NLEFF	(III.G-4)
REFPIP	NLEFF	(III.G-4)
REFPRL	NLEFF	(III.G-6,III.G-8)
REFRC	NLEFF	(III.G-3)
REFRC1	NLEFF	(III.G-3)
REFRC2	NLEFF	(III.G-3)
REFRC3	NLEFF	(III.G-3)
REFSOL	BASIC	(II.G-2,IV.C-1)
REFTHP	NLEFF	(III.G-3)
REFTIM	BASIC	(III.A-5,V.C-1)
RELV(I)	REC	(II.E)
RHOM	NLECON	(V.B)
RINF	NLECON	(V.B)
RMIRL	HSTAT	(II.D,III.D,III.G-2)
RNHOM	NLECON	(V.B)
ROE	NLECON	(V.B)
RRECL	REC	(III.G-2)
RWCAV(I)	REC	(II.E)

<u>Variable</u>	<u>Namelist</u>	<u>Section</u>
RX(I)	REC	(II.E,IV.C-3)
RX2TRX	OPT	(IV.B-1,IV.C-1)
RX3TRX	OPT	(IV.B-1,IV.C-1)
RX4TRX	OPT	(IV.B-1,IV.C-1)
RY(I)	REC	(II.E,IV.C-3)
RYTRX	OPT	(IV.B-1,IV.C-1)
SIGAZ	HSTAT	(II.D-1,II.D-3)
SIGEL	HSTAT	(II.D-1,II.D-3)
SIGSX	HSTAT	(II.D-1,II.D-3)
SIGSY	HSTAT	(II.D-1,II.D-3)
SIGTX	HSTAT	(II.D-1,II.D-3)
SIGTY	HSTAT	(II.D-1,II.D-3)
SLEW(I)	FIELD	(II.B-4)
SLEW(I)	OPT	(II.B-4,IV.C-4)
SLNS(I)	FIELD	(II.B-4)
SLNS(I)	OPT	(II.B-4,IV.C-4)
SMPI	NLCOST	(V.A-7)
SMRP	NLCOST	(V.A-6)
SMULT	NLEFF	(IV.C-5,VI)
SMULT	OPT	(IV.C-5,VI)
SOLCON	BASIC	(III.B-2)
SPTS	NLECON	(V.A)
SUNI(I)	BASIC	(III.B-4)
SUNR(I)	BASIC	(III.B-4)
TC	NLECON	(V.B)
TDESP	BASIC	(VI.A-5)
THT	REC	(II.E,IV.C-2,V.A-4)
THTEND	OPT	(IV.C-2,IV.E)
THTST	OPT	(IV.C-2,IV.E)
TOWD	REC	(III.E-2,IV.A-4)
TOWL	REC	(III.E-2,IV.A-4)
TPRE	NLEFF	(III.G-8)
TR	NLECON	(V.B)
TRPREF	NLCOST	(V.A-6)
TSTRT	NLEFF	(III.G-8)
UAZ(M)(M=1,NUAZ)	BASIC	(III.A-4)
UDAY	BASIC	(III.A-2,III.A-3)
UEL(N)(N=1,NUEL)	BASIC	(III.A-4)
UTIME	BASIC	(III.A-3)
VMAX	NLCOST	(V.A-8)
VSTREF	NLCOST	(V.A-8)

<u>Variable</u>	<u>Namelist</u>	<u>Section</u>
W	REC	(II.E,IV.C-3)
WEATH	BASIC	(III.B-3)
WEND	OPT	(IV.C-3,IV.E)
WM	HSTAT	(II.C,II.D,II.D-3)
WPANL	HSTAT	(II.D)
WST	OPT	(IV.C-3,IV.E)
XAIM(K,L,M)	REC	(II.F,II.G-2)
XEPGS	NLCOST	(V.A-11)
XFC	NLFLUX	(II.G-1,II.G-2)
XFOCAL(K)	HSTAT	(II.D-2,II.D-3)
XFOCUS	HSTAT	(II.D-2,II.D-3)
XFOCUS	HSTAT	(II.D-2,II.D-3)
XHEA	NLCOST	(V.A-10)
XHEP	NLCOST	(V.A-10)
XKN	NLCOST	(V.A-9)
XPI	NLCOST	(V.A-7)
XREC	NLCOST	(V.A-5)
XRP	NLCOST	(V.A-6)
XSP	NLCOST	(V.A-6)
XST	NLCOST	(V.A-8)
XTOW	NLCOST	(V.A-4)
XTOWER	FIELD	(II.B-4)
XTPEND	OPT	(II.B-4,IV.C-4,IV.E)
XTPST	OPT	(II.B-4,IV.C-4,IV.E)
YAIM(K,L,M)	REC	(II.F,II.G-2)
YFC	NLFLUX	(II.G-1,II.G-2)
YFOCAL(K)	HSTAT	(II.D-2,II.D-3)
YTOWER	FIELD	(II.B-4)
YTPEND	OPT	(II.B-4,IV.C-4,IV.E)
YTPST	OPT	(II.B-4,IV.C-4,IV.E)
ZFC	NLFLUX	(II.G-1,II.G-2)

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