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**SURVEY MIRRORS AND LENSES AND THEIR
REQUIRED SURFACE ACCURACY**

Semiannual Technical Progress Report, September 15, 1978—April 15, 1979

May 1979

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Honeywell
Energy Resources Center
Minneapolis, Minnesota

U.S. Department of Energy

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Solar Energy

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THEIR REQUIRED SURFACE ACCURACY

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ENERGY RESOURCES CENTER
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FOREWORD

This report was prepared under Contract Number DE-AC04-78CS35348 for the U. S. Department of Energy, Albuquerque Operations Office. Mr. Derrick Grimmer of Los Alamos Scientific Laboratory is the contract technical monitor. This report covers progress during the period from September 15, 1978 to April 15, 1979.

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TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
CONCENTRATOR PERFORMANCE	3
CONCENTRATOR LITERATURE SURVEY	3
Paraboloid of Revolution Dish	5
Heliostats	5
Fixed Mirror--Two Axis Tracking Receiver	8
Point Focus Fresnel	8
Faceted Mirror Solar Concentrator	11
Parabolic Trough Concentrator	11
Linear Segmented Arrays	13
Fixed Mirror Tracking Receiver - Line Focus	15
Line Concentrating Fresnel	16
Incremental Reflector	17
Dual Curvature Concentrator	20
Inflated Cylindrical Concentrator	21
Compound Parabolic (Winston) Concentrators	22
Vee Trough	25
Imaging Collapsing Collector	25
Fixed Evacuated Concentrator	26
CONCENTRATORS	28
MATHEMATICAL MODELING	29
Basic Formulation	30
Base Vectors	35
Surface Normals	38
Receiver Models	59
COMPUTER SOFTWARE	66
DEGRADATION EFFECTS	69

TABLE OF CONTENTS (Concluded)

	<u>Page</u>
APPROACH	69
STATUS	71
REFLECTIVE MATERIALS	72
LENSES	75
APPENDIX A DEGRADATION AND MAINTENANCE DATA SOLICITATION LETTER	A-1

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Program Schedule	1
2	Raytheon Point-Focusing Dish Concentrator Collector	6
3	Heliostat Concepts for Solar Central Receiver Applications	7
4	Fixed Mirror Tracking Receiver (Two-Axis) Cross Section	9
5	McDonnell Douglas Point Focus Fresnel	10
6	Collector in Focused Position	12
7	Solar Kinetics Parabolic Trough Concentrator	13
8	The Suntec SLATS ^R Linear Segmented Array	14
9	General Atomic's Fixed Mirror Solar Collector	16
10	MDAC Linear Fresnel Lens Collector	18
11	Incremental Reflector	19
12	Dual Curvature Collector	20
13	Inflated Cylindrical Concentrator Schematic	21
14	Compound Parabolic (Winston) Concentrator	23
15	Cross Section of CPC with Parabolic and Involute Reflector Surface	24
16	CPC Involute Reflector Cross Section	24
17	Imaging Collapsing Concentrator Schematic	26
18	Fixed Evacuated Concentrator Concept Cross Section and Side View	27
19	Base Vector Definitions	36
20	Incremental Reflector Section	36
21	Fixed Mirror Tracking Receiver Surface Geometry	40
22	Parabolic Trough Concentrator	43
23	Linear Fresnel Cross Section Geometry	45

LIST OF FIGURES (Concluded)

<u>Figure</u>		<u>Page</u>
24	Inflated Cylindrical Concentrator Cross Section	47
25	Vee Trough Concentrator and Cross Section	49
26	Section of Faceted Second-Surface Reflector	51
27	Incremental Reflector Surface Definition	52
28	Geometry for Finding Final Redirected Ray UR	54
29	Involute Surface Definition	56
30	Involute Concentrator Geometry	56
31	CPC Surface Geometry	58
32	Parabolic Trough Concentrator	61
33	Cylindrical Receiver Hit Test Geometry	63
34	Receiver Cone Geometry	64
35	Receiver Hit Test Geometry	65
36	Computer Software Flowchart	68
37	Degradation and Maintenance Data Base Formulation Process	70
38	Solar Reflector Construction Alternatives	73

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Variable Definitions for Math Models	34
2	Lens and Mirror Materials for Concentrating Solar Collectors	74

INTRODUCTION

This project will investigate and evaluate the potential performance of a variety of solar concentrators. Since the beginning of widespread research and development for solar energy, a major concern has been the effect of optical and surface quality of collector materials on collector performance and the changes in these properties due to environmental conditions. In many instances, this type of data has not been compiled. When data is available on surface quality, mirror or lens optical characteristics, surface deformations due to stress and other errors, it is difficult to quantify the effect these have on a particular concentrator design performance. To further investigate these errors, Honeywell is performing this study of concentrator designs and mirror and lens surfaces.

Figure 1 shows the original program schedule with a start date of September 15, 1978. There are two major tasks within this program, as indicated. The first task involves investigation and evaluation of concentrator performance. Within this task, Honeywell has conducted a survey of the literature, solar manufacturers and government information to obtain data on existing concentrator designs (i.e., V-troughs, parabolic mirror concentrators) and lens and mirror materials. Under contract approval, ten collector configurations have been selected to be mathematically modeled. These models will be incorporated into existing ray trace software and will be used to evaluate concentrator performance. Optical quality properties, structural deformations due to loading and stress, tracking errors and material property changes due to the environment will be included in this assessment of performance. At the conclusion of the contract, the models will be included as part of the final report to be made available to the solar researcher for use and information.

The second major task involves the expansion of an existing data base on mirror degradation due to environmental exposure and the collection of similar infor-

mation on lenses. This information will be used to evaluate the effects of degradation and to investigate maintenance requirements, operation procedures and design practices aimed at ensuring maximum concentrator lifetime.

This report summarizes progress to date on both major project elements--the Concentrator Performance task and the Degradation Effects Task.

This work has been supported by the Solar Heating and Cooling Research and Development Branch, Office of Conservation and Solar Applications, U. S. Department of Energy.

Figure 1. Program Schedule

CONCENTRATOR PERFORMANCE

As part of this major project task, we have identified solar concentrating collectors to be mathematically modeled for incorporation into a Monte Carlo ray trace computer code. The computer code will simulate the optical performance of each concentrator as a function of concentration ratio and other design geometry as specified by the user. At this stage of the project, we have completed nearly all of the required mathematical modeling and are developing the computer software.

CONCENTRATOR LITERATURE SURVEY

During the first portion of this contract, data was reviewed on existing concentrator designs and hardware to begin compiling a set of possible candidates for the math modeling and computer software development tasks of this program.

The literature survey was conducted to identify candidates and obtain performance data, material properties, life behavior, costs, and design descriptions for this group of concentrators. Manufacturers/developers were identified for the designs and design reports; conference papers and test reports were obtained for the concentrators wherever possible. Documentation was difficult to find for some designs since they were relatively new concepts. In these cases, contact was made with the vendor to obtain and clarify information. In addition to this information, the reflecting and lensing materials used in concentrator designs were identified to aid in working the second part of this program.

As a result of this survey, a list of representative concentrator candidates was compiled from which ten designs would be selected for math modeling. They are listed below, grouped according to relative concentration ratio.

High Concentration:

- Paraboloid of Revolution Dish
- Heliostats (Central Receiver)
- Fixed Mirror, Two-Axis Tracking Receiver
- Point Focus Fresnel
- Faceted Mirror Solar Concentrator

Medium Concentration:

- Parabolic Troughs
- Linear Segmented Arrays
- Fixed Mirror Tracking Receiver--Line Focus
- Line Concentrating Fresnels
- Incremental Reflector
- Dual Curvature Concentrator
- Inflated Cylindrical Concentrator

Low Concentration:

- Compound Parabolic (Winston Collectors)
- Vee-Trough
- Imaging Collapsing Concentrator
- Fixed Evacuated Concentrating Collectors

This list is intended to be representative of current and near-future concentrating collector technologies. All of the above are in production, under prototype development and testing, or under government research funding. A brief description of each collector type follows for clarification.

Paraboloid of Revolution Dish

This concentrator is a two-axis tracking parabolic dish, which redirects sunlight to a point focus overhead. This point focus concentrator achieves the highest concentration ratios of any collector currently under development. Concentration ratios well over 500 X are conceivable. The concentrator can achieve extremely high temperature ranges (800 - 1100°C) and has been proposed for use in providing power to heat engines that generate electricity. JPL is currently involved in managing a DOE industrial program directed toward development of this concentrator.

Raytheon and General Electric are active in prototype development of these concentrators. Raytheon's concept is illustrated in Figure 2. The reflective surface is spherical sagged mirror segments mounted on an aluminum substructure.

The GE concentrator is a modified Scientific Atlanta communications antenna. The reflector is an experimental 3M Company aluminized acrylic film designated FEK-244 bonded to solid aluminum substrate. The concentration ratio is about 250.

In addition, Omnium-G has a 6.9 m commercially available parabolic dish. The reflector is electroplated aluminum.

Heliostats

Heliostats are two-axis tracking concentrators usually designed with several individual mirror facets on one module. A field of heliostats directs the sun's energy to a central receiver positioned in the field. Each heliostat is focused individually to redirect energy. This concept produces high temperatures and is used for central power production rather than dispersed applications. Martin Marietta, McDonnell Douglas, Honeywell and Boeing have all developed heliostat designs. The different concepts are shown in Figure 3.

Figure 2. Raytheon Point-Focusing Dish
Concentrator Collector

BOEING

HONEYWELL

MARTIN
MARIETTA

MC DONNELL DOUGLAS

SOURCE: Prepared by OTA using manufacturer's data.

Figure 3. Heliostat Concepts for Solar Central Receiver Applications

Martin Marietta's heliostat is currently operating at the solar thermal test facility, Sandia Labs, Albuquerque.

Fixed Mirror--Two Axis Tracking Receiver

This concentrator utilizes a fixed segment of a concave spherical mirror as the reflecting surface. This surface concentrates beam radiation onto a tracking receiver that pivots about the center of curvature of the mirror.

The focus of this concentrator is a line along a conical or cylindrical receiver that is tracking the sun's position. E-Systems has been working in the development of this design. A cross section of this concept in its early development is illustrated in Figure 4. Their concept uses a spherical mirror surface, 60 to 90 meters in diameter to produce heat at about 500°C . The concentration ratio is near 1000. The advantage of this design is the potential lower cost that could result by eliminating tracking mechanisms for large dishes. However, this concept will have lower optical efficiency due to cosine losses.

Point Focus Fresnel

This concentrator uses a circular fresnel lens to focus sunlight at a point. This achieves higher concentration and higher temperature levels (300 to 500°C), making this concentrator applicable for both thermal and photovoltaic systems. Concentration is dependent on the properties of the lens, most of which are currently manufactured of acrylic and supplied by Swedlow, Inc.

Research and development of this concentrator type has been done by McDonnell Douglas for Sandia Laboratories. Sandia also installed a point focus fresnel, with a concentration of about 50 X, in its total energy facility for testing electrical power generation. McDonnell Douglas' concept, illustrated in Figure 5, uses several large point-focusing fresnels in one module to achieve

SOURCE: E-Systems Inc.

Figure 4. Fixed Mirror Tracking Receiver (Two-Axis) Cross Section

10

Figure 5. McDonnell Douglas Point Focus Fresnel

temperatures in the 300 to 400°C range. Concentration ratios are currently in the 100 to 200 X range with 600 X being the theoretical limit. Development of this concentrator is linked closely with the development and growth in manufacturing fresnel lenses, which are optically satisfactory and fairly inexpensive.

Faceted Mirror Solar Concentrator

This is a two-axis tracking point focusing concentrator. The reflector consists of column axes fitted with individual square mirrors. The mirrors are tilted to achieve a point focus. The columns then rotate to track in the elevation and the entire assembly is rotated to track azimuth. Concentration ratios of 10 to several hundred are predicted with this system.

This design is currently under research and prototype development at Rensselaer Polytechnic Institute. An early design prototype is shown in Figure 6. Several updates on this design have occurred since research began. Depending on the concentration achieved, this concept could be a new medium or high temperature concentrator.

Parabolic Trough Concentrator

This is a line concentrator with a parabolic reflector surface. The linear receiver is positioned above the surface at the focus of the parabola. The collector accepts direct normal radiation and tracks in one axis with a north-south or east-west orientation. Some designs will track in two-axis or be polar-mounted to achieve better performance. In most cases, both the receiver and the reflecting surface track the sun together, although a stationary receiver eliminates the need for flexible hoses and joints.

The parabolic trough concentrator is a good medium temperature range (150-300°C) collector with concentration ratios in the 10 to 50 X range. Several variations

Figure 6. Collector in Focused Position

of this collector are currently being produced (or are under development) by numerous companies including Solar Kinetics, Acurex, Del-Jacobs, Hexcel, Albuquerque Western, Honeywell, and others. As an example, Solar Kinetics trough concentrator is shown in Figure 7. The various designs utilize many reflective surfaces ranging from polished aluminum to back-silvered sagged glass. Receiver designs usually consist of a coated pipe with an insulating cover (i.e., glass tube).

This collector is currently leading the concentrator solar market in installed square footage. Applications include industrial process heat (hot water and steam), irrigation and heating/cooling systems. In addition to these demonstrations, many of these concentrators are undergoing testing at Sandia's Collector Module Test Facility. The parabolic trough is in the most advanced stage of development of medium to high concentrator types.

Figure 7. Solar Kinetics Parabolic Trough Concentrator

Linear Segmented Arrays

These concentrators have movable longitudinal facets, which track the sun and focus energy on a fixed overhead receiver. The facets have a slight curvature to provide some concentration of the sun's energy. The collector may be tilted southward at the latitude angle to provide better overall energy collection.

Temperature ranges for this concentrator are 100 - 300°C with concentration ratios of 20 to 40X.

Suntek, Itek, and AAI have designed concentrators of this type. The Suntek SLATS design has undergone government testing at Sandia Labs and on the early phase of the Ft. Hood program. This concentrator, shown in Figure 8, consists of 10 curved facets, which provide a 40:1 concentration. The receiver consists of several pipes arranged in a vee-shape and surrounded on all sides except the aperture opening by insulation. The receiver aperture is vee-shaped with a 60° included angle. Glass covers are double-glazed to enhance optical efficiency. This concentrator tracks in one axis and has been tested in the east-west orientation. AAI's design was proposed for a process hot water system. The linear segmented arrays have also been used in heating/cooling applications.

Figure 8. The Suntec SLATS^R Linear Segmented Array

Fixed Mirror Tracking Receiver - Line Focus

This line concentrator is a concave array of flat mirror facets fixed on a circular cross section. The reflecting facets produce a focal line that follows a circular path as the sun moves. The focal line is tracked by the movable receiver, which rotates about the center of curvature of the module.

The fixed mirror-line focus collector is another medium-to-high-temperature concentrator with operation at maximum temperatures of 200-300°C. Possible concentrations are in the range of about 6 to 60X.

General Atomic, Scientific Atlanta, and AAI have developed versions of this concentrator. General Atomic's collector, illustrated in Figure 9, has recently undergone testing at the collector module test facility at Sandia. Their reflector design uses second surface glass mirror facets bonded to a concrete surface. The receiver is an insulated heat pipe and a CPC (Winston) type secondary concentrator to enhance concentration of the solar energy and to reduce receiver heat losses.

Scientific Atlanta was licensed through General Atomic to build a prototype of this design. Their concentrator used sheet metal ribs rather than concrete as a frame for the back-silvered glass facets. The receiver design is a high-performance evacuated tubular collector. A small field of these concentrators is installed at the Georgia Institute of Technology.

AAI's design utilizes a circular trough with a concentration ratio of 8:1 and is more applicable to heating/cooling applications. The reflecting surface is glass mirror. The receiver is similar to a long, narrow, flat plate collector in construction and is mounted on long arms above the trough.

Figure 9. General Atomic's Fixed Mirror Solar Collector

These concentrators have undergone prototype testing and show good potential for medium range temperature applications.

Line Concentrating Fresnel

This type of collector uses either curved or flat linear fresnel lens to focus light on linear receivers under the fresnel surface. These concentrators may track in one or two axes depending on performance requirements. Chromatic aberrations become problematic with fresnel lenses when the sun's angle is far off-axis. Applications potential for these concentrators is possible in both the thermal and photovoltaic areas.

Currently Northrup and McDonnell Douglas have produced line concentrating fresnels. Northrup's design utilizes a curved acrylic fresnel as the focusing element for the concentrator. The units have been tested with good results at 100°C and higher. They usually are placed in a polar mount. The Northrup concentrator has been installed in several Government-funded projects (most of these are heating/cooling demos). Currently, Northrup is working on development of an advanced design with increased concentration for higher temperature applications.

McDonnell Douglas' concentrator, shown in Figure 10, has produced 300°C steam in Sandia's Solar Total Energy Program. The concentration ratio of the prototype (using Swedlow lenses) is 21:1. The receiver is a selectively surface-coated pipe enclosed in a glass tube. NASA at the George C. Marshall Space Flight Center has been actively involved in the research and development of the concentrator type and has directed most funding in this area.

Incremental Reflector

This concentrator utilizes reflective panels bonded to a flat backing surface. The reflective material is faceted in a manner similar to fresnel lenses and focuses the sun's energy on an overhead receiver. The concentrator may track in one or two axes. Concentration is in the range of 40X. The aberration from the sun's off-axis angle is of concern in performance as it is for linear fresnel lenses.

The design was developed for a total energy application providing electricity (from photovoltaic cells) and thermal energy to a university campus. The incremental reflector material is manufactured by 3M and the collector design was done by Honeywell. Figure 11 is a photograph of the prototype concentrator. The original receiver design was for photovoltaics, but thermal receivers are feasible as well.

Figure 10. MDAC Linear Fresnel Lens Collector

Figure 11. Incremental Reflector

Dual Curvature Concentrator

This collector is currently under development at Honeywell under contract to DOE. This concentrator uses a near hyperbolic paraboloid surface as the reflector. The surface contour is constructed by mounting a polyester reflective film under tension on a metal frame as illustrated in Figure 12.

This collector is capable of moderate concentration (in the range of 8 - 20X) with operating temperature up to 200°C. It is hoped that this concentrator

Figure 12. Dual Curvature Collector

will be a low-cost alternative to other collectors currently being used in this temperature range. Application potential is again in the heating and low temperature process heat areas.

Prototype builds and testing of this design are currently on-going. The concentrator will track the sun in one-axis and focus the sun's energy on a fixed overhead receiver.

Inflated Cylindrical Concentrator

A schematic of this concentrator type is given in Figure 13. The concentrator is an inflated plastic cylinder that has aluminized thin film on the bottom portion to concentrate sunlight on a receiver positioned on the focal axis at the point of maximal concentration of energy. This collector would probably achieve concentration ratios around 10X.

Figure 13. Inflated Cylindrical Concentrator Schematic

Lawrence Livermore Labs has been working with this concept to develop a low-cost concentrating collector for industrial process heat applications at temperatures of 170°C or below. By using inexpensive plastic films and eliminating automatic tracking, they are hoping to reduce costs. Currently, the collector is oriented with its axis east-west and is manually tilted in the north-south direction. The receiver design is a selectively coated tube with a plastic thin-film cover to reduce heat losses.

Compound Parabolic (Winston) Concentrators

This design was developed as an improvement on the flat-plate concentrator. The reflective surface, illustrated in Figure 14, is consecutive rows of parabolic sidewalls that focus the sun's energy on a receiver at the base of the concentrator. Concentration ratios of 1.5 to about 10X are possible depending on the acceptance angle of the collector. Other variations use different combinations of reflector shapes (e.g., involute) for different receiver types. The sidewalls in this case may not be parabolic in shape.

Argonne National Labs has performed most of the research and development on concentrators of this type. Currently Chamberlain Manufacturing under Argonne license has several CPC concentrator prototypes. Most of these designs are in the 1.5 to 5X range. One of Chamberlain's design has a 2X geometric concentration ratio. The reflective surface is a truncated CPC with a combined parabolic involute surface as shown in cross section in Figure 15. The receiver is a non-evacuated tube with a glass cover to minimize convection losses.

The CPC design is also being utilized with evacuated receivers. Owens-Illinois uses an involute reflector (Figure 16) with its evacuated receiver. The concentration for this collector is 1.5X.

SOURCE: Prepared by OTA using manufacturer's data.

Figure 14. Compound Parabolic (Winston) Concentrator

Figure 15. Cross Section of CPC with Parabolic and Involute Reflector Surface

Figure 16. CPC Involute Reflector Cross Section

Vee Trough

The vee trough, like the CPC, is an attempt to achieve higher temperatures in non-tracking collectors. The reflectors are wedged or V-shaped and concentrate the sun's energy onto a receiver at the bottom of the collector.

Jet Propulsion Laboratory is working on the design of this concentrator. One variation uses an asymmetric vee that is reversed 180° on the equinoxes. This provides a concentration around 2X for about 8 hours per day. The receiver is evacuated to minimize heat losses. Operating temperatures are expected to be in the range of $100\text{--}200^\circ\text{C}$. This concept is believed to be a good competitor for the heating/cooling market in the 120°C range.

Imaging Collapsing Concentrator

This non-tracking concentrator, illustrated in Figure 17, employs a wide-angle fresnel lens and reflective surface beneath the lens to focus energy on a tubular receiver along the normal axis of the reflector surface. The subreflectors correct for the large movement of the focal line and help collect diffuse radiation in the acceptance angle interval.

Solar Energy Technology is currently developing this concept under Government funding. The concentration is in the range of 2-4X, with expected operating temperatures of $100\text{--}150^\circ\text{C}$. The concentrator is non-tracking with an acceptance angle of $\pm 23^\circ$. Currently, the concentrator is under design. Construction of a prototype will be accomplished during the ongoing program.

Figure 17. Imaging Collapsing Concentrator Schematic

Fixed Evacuated Concentrator

This is another non-tracking design still under development. The reflector consists of evacuated tubes that in cross section are truncated Winston concentrators. The cross section of the concentrator and a side view of one tube are given in Figure 18. The sidewalls and bottom of the tube are coated with a front surface reflective material that redirects the sun's energy to the receiver within the reflective tube. As with a vee trough or CPC, each collector module consists of several tube/receiver combinations.

Figure 18. Fixed Evacuated Concentrator Concept
Cross Section and Side View

Research on this concentrator has been done at San Diego State University. The predicted temperature range is 80–200°C, with a concentration of 1.5–2X. As yet, no prototypes have been constructed.

Summary—The parabolic trough and line concentrating fresnel have the largest installed square footage and are considered to be at production status. The linear segmented arrays, fixed mirror concentrators parabolic dishes are in the beginning stages of the system installation. The other concentrator types are in the research and design phase, with several undergoing prototype build and tests.

Life test and long-term performance data are difficult to obtain as many of the designs do not have operational installations. For the most part, the concentrator installations that do exist have not been in operation

for very long periods of time and only limited performance data is available. Performance data over the short term is more readily available for most concentrator types.

CONCENTRATORS

Upon completion of the literature survey, the selection of the ten concentrator designs for the math modeling task was accomplished. Selection of the ten designs was based on the following criteria:

- The designs should cover the full range of concentration ratios. We wanted to emphasize the higher concentration collectors, the optical quality is more crucial.
- The concentrators should include some representatives of near future as well as current concentrator technology.
- The concentrators should show promise for solar applications as indicated by use in solar demonstration projects and by government/private interest in the concentrator designs.
- Availability of data on the concentrator design including performance and life test data.

Based on these criteria, the following list of candidates was initially submitted for approval.

- Paraboloid of Revolution Dish
- Point Focus Fresnel
- Faceted Mirror Concentrator
- Fixed Mirror - Two-Axis Tracking Receiver
- Parabolic Trough
- Linear Fresnel
- Incremental Reflector

- Fixed Mirror - Line Concentrator
- Compound Parabolic (Winston)
- Vee Trough

After deliberation by the project technical monitors, the list was revised to include more concentrators in the lower concentration range. Lower concentration collectors are more applicable to lower temperature (heating and cooling) applications. The final selection of designs for math modeling follow:

- Faceted Mirror Concentrator
- Fixed Mirror - Two-Axis Tracking Receiver
- Parabolic Trough
- Linear Fresnel
- Incremental Reflector
- Inflated Cylindrical Concentrator
- CPC - Involute Reflector with Evacuated Receiver
- CPC - Parabolic/Involute Reflector
- Vee Trough
- Imaging Collapsing Concentrator

MATHEMATICAL MODELING

The basic methodology to be used for the optical model computer software follows a Monte Carlo ray trace approach. Honeywell has been using this approach since beginning their studies of parabolic trough collectors, which is over 6 years ago.

The code was initially developed because of Honeywell's concern with the effect of mirror surface accuracy and tracking errors on the performance of the solar collectors. The ray trace Monte Carlo approach was selected because in most cases these errors are known only statistically. Further-

more, the ray trace approach allows the investigation of different optical elements such as mirrors and lenses. In most cases, the introduction of a single equation describing the optical surface (mirror or lens) in the ray path is sufficient for the simulation of a wide range of concentrator types.

Basic Formulation

Given a position of a mirror/lens surface relative to the receiver, the amount of energy carried from any point on the sun's surface monochromatically at any given instant depends on the exact path of the ray through the optical interfaces of the system. The angle made by any ray with respect to each surface is a function only of the angular position on the solar disk whence the ray came and the impact point on the particular surface. Thus, for any wavelength and perfect optics, the energy carried from the sun to the receiver surface can be found by specifying the four coordinates of the ray, independent of the number of optical elements in the optics train.

If the sun's disk coordinates are δ_1 and δ_2 and the surface impact point coordinates are X_1 and X_2 , then the total thermal power absorbed in a wavelength interval $d\lambda$ is

$$E_{d\lambda} = \int_{X_1} \int_{X_2} \int_{\delta_1} \int_{\delta_2} E(X_1, X_2, \delta_1, \delta_2) dX_1 dX_2 d\delta_1 d\delta_2 \quad (1)$$

where X_1 and X_2 are bounded by the actual surface extent of the mirror/lens system. To obtain the energy from the entire solar spectrum, integration over all wavelengths is required. This yields

$$E_p = \underbrace{\int_{\lambda}}_{\text{total spectrum}} \underbrace{\int_{x_1} \int_{x_2}}_{\text{mirror surface}} \underbrace{\int_{\delta_1} \int_{\delta_2}}_{\text{sun disk}} E(x_1, x_2, \delta_1, \delta_2, \lambda) dx_1 dx_2 d\delta_1 d\delta_2 d\lambda \quad (2)$$

Introducing finite quality optics into the model introduces uncertainty in tracking accuracy and mirror quality.

There can be four uncertain optical parameters that are known only statistically. The first two parameters are uncertainties in the angular position of two possible gimbaled tracking drives (θ_1, θ_2). The second two parameters are the singular uncertainties in the mirror/lens surface normal at any point on the mirror/lens surface (ϕ_1, ϕ_2). We assume that each of these four parameters is statistically independent of each other or any other design parameter. For example, a given error in a mirror normal is equally likely anywhere on the mirror surface. The mirror is not known as a continuous surface with smooth waves or ripples but rather as a probability distribution of mirror normals perturbed from the mathematically correct shape by an assumed probability distribution. For each statistically known variable, the distribution is understood to be a "normal" or "standard error" distribution. Tracking errors can be treated as a discrete error when single-time point optical characteristics are desired.

Now consider a random-variable Z defined by the normalized probability distribution $P(Z)$. If we wished to calculate the mean value of Z ($\bar{Z}$) or its expected value, we would form the integral of the product of $P_Z(Z)$ times Z over all allowed values of Z , i.e.,

$$\bar{Z} = \int_{-\infty}^{\infty} P_Z(Z) Z dZ \quad (3)$$

To simulate a specific error set $(\theta_1, \theta_2, \phi_1, \phi_2)$, one would have to evaluate

$$E_p(\theta_1, \theta_2, \phi_1, \phi_2) = \int_{\lambda} \int_{X_1} \int_{X_2} \int_{\delta_1} \int_{\delta_2} E(X_1, X_2, \delta_1, \delta_2, \lambda, \theta_1, \theta_2, \phi_1, \phi_2) dX_1 dX_2 d\delta_1 d\delta_2 d\lambda \quad (4)$$

Then the expected value of the thermal power absorbed ($\bar{E}_p$) is given by

$$\bar{E}_p = \int_{\theta_1} \int_{\theta_2} \int_{\phi_1} \int_{\phi_2} P_{\theta_1}(\theta_1) P_{\theta_2}(\theta_2) P_{\phi_1}(\phi_1) P_{\phi_2}(\phi_2) E_p(\theta_1, \theta_2, \phi_1, \phi_2) d\theta_1 d\theta_2 d\phi_1 d\phi_2 \quad (5)$$

because each distribution may be statistically independent. The above expression is

$$\bar{E}_p = \underbrace{\int_{\theta_1} \int_{\theta_2}}_{\text{tracking inputs}} \underbrace{\int_{\phi_1} \int_{\phi_2}}_{\text{mirror imperfections}} \underbrace{P_{\theta_1} P_{\theta_2} P_{\phi_1} P_{\phi_2}}_{\text{total spectrum}} \underbrace{\int_{\lambda} \int_{X_1} \int_{X_2}}_{\text{mirror area}} \underbrace{\int_{\delta_1} \int_{\delta_2}}_{\text{sun disk}} E d\delta_2 d\delta_1 dX_2 d\lambda d\phi_2 d\phi_1 d\theta_2 d\theta_1 \quad (6)$$

Furthermore, integration over the total number of hours of sunlight during any given time period results in the expression

$$W_T = \int_{\text{time period}} \bar{E}_p dt \quad (7)$$

The stochastic nature of four of the independent variables in the ten-integrals of Equation (7) and the prime objective of performing a parametric study of the performance of the system led to the decision that the experimental Monte Carlo approach was suitable.

Basically, the premise of the method used to solve Equation (7) is a Monte Carlo technique. Any Monte Carlo computation that yields quantitative results may be considered as estimating the value of a multiple integral. The simplest Monte Carlo approach is to observe random numbers, selected in such a way that they directly simulate the physical random processes of the problem at hand, and to deduce the required solution from the behavior of these numbers. In this project, that process involves the incident flux on the receiver over the direct solar flux on the mirror/lens aperture being equal to the convergent ratio of randomly drawn rays that reach the receiver divided by the total number of rays drawn uniformly over the concentrator aperture. Appropriate scaling of each ray value for reflectance and absorptance losses, tracking and reflective surface errors, etc., is included in the Monte Carlo simulation.

The simulation is accomplished by randomly selecting a sufficient number of sun rays to statistically represent the sun's intensity pattern as seen from the earth's surface. Solar limb darkening and atmospheric losses are taken into account. These same rays are allowed to impinge randomly upon the mirror/lens aperture and are reflected toward the receiver. The rays drawn must represent the sun's power at that time, so each ray is given a relative weighted value as a function of the time and the number of rays drawn. If annual energy is being calculated, then each ray carries the appropriate amount of energy.

The ray trace technique uses vector algebra to track each ray along its optical path. The following subsections describe the needed concentrator specific vector derivations, as well as some basic modeling philosophy. Other math models (e.g., solar limb darkening) are common to all concen-

trators and have been used and documented in other Honeywell reports. They are not included here but will be a part of the final report.

The following descriptions are done for perfect optics. Surface and tracking errors vector representations will be included as separate mathematical models in the final report.

A list of variable definitions used in the math model descriptions is contained in Table 1.

Table 1. Variable Definitions for Math Models

VARIABLES	DEFINITION
$\vec{US}, \vec{UE}, \vec{UP}$	LOCAL UNIT VECTOR TRIAD $\vec{US}$ - SOUTH $\vec{UE}$ - EAST $\vec{UP}$ - LOCAL VERTICAL
$\vec{UCA}, \vec{UCN}, \vec{UCP}$	COLLECTOR UNIT VECTOR TRIAD $\vec{UCN}$ - NORMAL TO APERTURE $\vec{UCP}$ - UNIT VECTOR ALONG WIDTH OF CONCENTRATOR $\vec{UCA}$ - UNIT VECTOR ALONG LENGTH OF CONCENTRATOR
x, y, z	DISTANCES IN THE $\vec{UCA}, \vec{UCP}, \vec{UCN}$ DIRECTIONS RESPECTIVELY
$x_{hit}, y_{hit}, z_{hit}$	COORDINATES OF SUN RAY HIT POINT ON SURFACE
$\vec{USUN}$	UNIT VECTOR IN DIRECTION OF SUN POSITION
$\vec{UN}$	UNIT NORMAL TO CONCENTRATOR SURFACE
$\vec{UR}$	UNIT VECTOR IN DIRECTION OF REFLECTED RAY OR REFRACTED RAY
α	SUN'S AZIMUTH ANGLE
ϵ	SUN'S ELEVATION ANGLE
n_1	INDEX OF REFRACTION FOR AIR
n_2	INDEX OF REFRACTION FOR LENS
RL	RECEIVER LENGTH
RW	RECEIVER WIDTH
r_{abs}	RECEIVER RADIUS (CYLINDRICAL)

Base Vectors

To determine the optical efficiency for any concentrator design, we will trace the sun's ray as it is redirected to the receiver by the concentrator. To determine the reflected/refracted ray, the sun ray's direction and the surface normal must be defined. The concentrator position and sun position will be represented relative to a local unit vector triad (see Figure 19) with $\vec{UP}$ being local vertical; $\vec{UE}$, local east; and $\vec{US}$, local south. The unit vector to the center of the sun at any particular time is:

$$\vec{USUN} = \sin(\alpha) \cos(\epsilon) \vec{UE} + \cos(\alpha) \cos(\epsilon) \vec{US} + \sin(\epsilon) \vec{UP} \quad (8)$$

The sun vector in combination with the surface unit normal will be used to calculate the redirected ray.

Before proceeding to the surface normals for the concentrators, a vector triad will be defined that is fixed with respect to the concentrator position. For all concentrators discussed, $\vec{UCN}$ is the vector normal to the aperture; $\vec{UCA}$, the vector along the concentrator axis (length); and $\vec{UCP}$, the vector along the concentrator width. These vectors will change depending on whether the concentrator is two-axis tracking, one-axis tracking, or stationary. However, a general formulation for the triad can be made. Referring to Figure 20, the vector $\vec{UCA}$ can be expressed as

$$\vec{UCA} = \cos(AX) \vec{UE} + \sin(AX) \vec{US} \quad (9)$$

Figure 19. Base Vector Definitions

Figure 20. Incremental Reflector Section

where AX is the angle between the $\overrightarrow{UCA}$ and local east direction (east is zero, south is positive). The vector along the concentrator width is

$$\overrightarrow{UCP} = -\sin(AX) \sin(CEL) \overrightarrow{UE} + \cos(AX) \sin(CEL) \overrightarrow{US} - \cos(CEL) \overrightarrow{UP} \quad (10)$$

where CEL is the collector elevation angle (angle between collector normal and horizontal plane).

The vector $\overrightarrow{UCN}$ is then

$$\overrightarrow{UCN} = -\cos(CEL) \sin(AX) \overrightarrow{UE} + \cos(CEL) \cos(AX) \overrightarrow{US} + \sin(CEL) \overrightarrow{UP} \quad (11)$$

These three equations apply to all concentrator orientations and tracking types. By varying the values of AX and CEL, we can define the concentrator triad for any tracking mode.

For a two-axis tracking concentrator, the angles AX and CEL follow the sun's movement and are changing with time. Thus, the vector triad is as given in Equations (8), (9), and (10), (NOTE: For perfect tracking, $AX = -\alpha$). If the azimuth, α , and elevation, ϵ , are known, CEL can be determined using the off-axis angle (the angle between $\overrightarrow{USUN}$ and $\overrightarrow{UCN}$). Perfect two-axis tracking occurs when the dot product of $\overrightarrow{UCN}$ and $\overrightarrow{USUN}$ is a maximum. This maximum is calculated by setting the partial derivative of $\overrightarrow{UCN}$ and $\overrightarrow{USUN}$ with respect to CEL to zero. This results in the solution

$$CEL = \tan^{-1} \left[\frac{\tan(\epsilon)}{\cos(\alpha + AX)} \right] \quad (12)$$

This equation also applies for all concentrators discussed.

For a single-axis tracking concentrator, the angle AX will be a constant: CEL will vary with time as described in Equation (12). For example, when the concentrator tracks north-south, AX = 90° and

$$\overrightarrow{UCA} = \overrightarrow{US} \quad (13)$$

$$\overrightarrow{UCP} = -\sin(\text{CEL}) \overrightarrow{UE} - \cos(\text{CEL}) \overrightarrow{UP} \quad (14)$$

$$\overrightarrow{UCN} = -\cos(\text{CEL}) \overrightarrow{UE} + \sin(\text{CEL}) \overrightarrow{UP} \quad (15)$$

When the concentrator is non-tracking, both AX and CEL will be constant. CEL in this case would be the collector angle tilt toward south (usually the latitude of the location). AX would be 0° in most cases.

Surface Normals

Using the concentrator base vectors and the concentrator geometry, we will define a unit normal vector on the concentrator surface at the randomly drawn hit point. Knowing the unit normal $\overrightarrow{UN}$ and the sun vector $\overrightarrow{USUN}$ the redirected sun's ray can be determined. We will now examine the surface geometry for the concentrator designs being modeled and formulate the equation for the reflected/refracted ray. In addition, a distance vector ($\overrightarrow{D}$), from the concentrator surface to a known point on the receiver is defined for use in the receiver hit tests. (The receiver models are described later in this section).

In most cases, the normal to the concentrator surface will be defined using the following general formulation

$$\overrightarrow{N} = \frac{\partial F}{\partial x} \overrightarrow{UCA} + \frac{\partial F}{\partial y} \overrightarrow{UCP} + \frac{\partial F}{\partial z} \overrightarrow{UCN} \quad (16)$$

where

- $\vec{N}$ = normal to concentrator surface
 F_s = surface equation as a function of x, y, z
 X, Y, Z = variable name in $\vec{UCA}, \vec{UCP}, \vec{UCN}$ directions, respectively.

Some of the designs will not be formulated in this manner, since their geometry is more easily defined using different methods.

Fixed Mirror, Two Axis Tracking Receiver--This concentrator is a fixed spherical dish reflector with a receiver that tracks in two axes.

The surface of the dish is described by

$$F_s = r^2 - x_{hit}^2 - y_{hit}^2 - z_{hit}^2 \quad (17)$$

where

$$0 \leq x \leq r \sin \theta_{rim} \quad (18)$$

$$0 \leq y \leq r \sin \theta_{rim} \quad (19)$$

The rim angle (θ_{rim}) is defined, as shown in Figure 21, as the angle between the line from the center to the edge of the concentrator and the normal axis of the concentrator.

The receiver tracks so that the axis of symmetry lies on the line determined by the center of the sun and the center of the sphere.

The unit normal ($\vec{UN}$) to the surface is determined by dividing $\vec{N}$ (Equation 16) by its magnitude. We have

Figure 21. Fixed Mirror Tracking Receiver Surface Geometry

$$\vec{N} = -2x_{hit} \vec{UCA} - 2y_{hit} \vec{UCP} - 2z_{hit} \vec{UCN} \quad (20)$$

and

$$\vec{UN} = \frac{-x_{hit}}{r} \vec{UCP} - \frac{y_{hit}}{r} \vec{UCA} - \frac{z_{hit}}{r} \vec{UCN} \quad (21)$$

The sign of $\vec{UN}$ is such that it points toward the center of the concentrator. The reflected ray is determined from Snell's law

$$\vec{UR} = 2 (\vec{UN} \cdot \vec{USUN}) \vec{UN} - \vec{USUN} \quad (22)$$

After $\vec{UR}$ is calculated, the ray can then be traced to the receiver to determine whether the ray impinges on its surface. For this concentrator design, a conical receiver has been used as the optimal receiver configuration, although a planar or cylindrical receiver could be employed. A vector $\vec{D}$ will be defined from the reflector surface hit point to a known point on the receiver. The receiver lies along a line between the sun's center and sphere center so the receiver will be positioned along a radial vector with the same direction as $\vec{US}$. The distance vector then is

$$\vec{D} = r \vec{UN} - (r - RL) \vec{USUN} \quad (23)$$

where RL is the receiver length.

Parabolic Trough Concentrator--This line concentrator consists of a parabolic surface that usually tracks the sun in one axis and redirects the sun's energy to a receiver at the focal line overhead.

The surface is defined by

$$F_s = -\frac{y_{hit}^2}{4F} + z_{hit} \quad (24)$$

where F is the focal length. In addition to the focal length and concentrator width, we also define a rim angle (θ_{rim}) for the parabola (Figure 22). The rim angle is the angle between the focal axis and the end point (edge) of the parabolic surface. Varying the rim angle for a fixed aperture will affect the optical efficiency. Optimal rim angles are usually in the range of 90-115°.

The normal to the collector surface is

$$\vec{N} = \frac{-y_{\text{hit}}}{2F} \vec{UCP} + \vec{UCN} \quad (25)$$

and the unit normal is

$$\vec{UN} = \frac{-y_{\text{hit}}}{2F |\vec{N}|} \vec{UCP} + \frac{1}{|\vec{N}|} \vec{UCN} \quad (26)$$

where

$$|\vec{N}| = \left(\frac{y_{\text{hit}}^2}{4F^2} + 1 \right)^{1/2} \quad (27)$$

The reflected ray calculated from Snell's law is the same as before.

$$\vec{UR} = 2(\vec{UN} \cdot \vec{USUN}) \vec{UN} - \vec{USUN}$$

To determine if $\vec{UR}$ hits the receiver, we again define a $\vec{D}$ vector from the surface hit point to a known point on the receiver. In this case,

$$\vec{D} = -x_{\text{hit}} \vec{UCA} - y_{\text{hit}} \vec{UCP} + (F - z_{\text{hit}}) \vec{UCN} \quad (28)$$

The receiver models used with the trough would be the cylindrical or planar receivers. In the case of a cylindrical receiver, $\vec{D}$ would have its endpoint at the center of the cylinder. For the planar receiver, it would be in the middle of the receiver width.

Figure 22. Parabolic Trough Concentrator

Linear Fresnel--This concentrator type focuses the sun's energy on a linear receiver through a fresnel lens. The fresnel surface has "grooves" such that light entering normal to the surface is focused in a line beneath the lens. The concentrator often is tracked in two axes so that the sun position is normal to the aperture. (This decreases optical losses due to off-axis aberrations.)

The surface geometry at any point is defined from the focal length (F), the distance from the lens center to a fresnel facet (y_f), and the index of refraction (n_2) for the lens material.

Figure 23 illustrates some of the surface geometry. If a point, Y_f , is chosen along the $\overrightarrow{UCP}$ direction, the surface will be defined such that a refracted ray, $\overrightarrow{UR}$, should be directed at an angle

$$\alpha = \tan^{-1} (F/y_f) \quad (29)$$

to reach the focal line. From the law of refraction (see Figure 23),

$$\sin \theta_2 = \sin \theta_1 (n_1/n_2) \quad (30)$$

From the diagram, we see that

$$\theta_2 - \theta_1 = 90 - \alpha \quad (31)$$

By substituting and rearranging these expressions, we can solve for the fresnel facet angle

$$\cos \theta_1 = \left(\frac{n_1}{n_2} \right) \sqrt{\frac{F^2 + y_F^2}{F^2}} - \frac{F}{y_F} \quad (32)$$

Figure 23. Linear Fresnel Cross Section Geometry

Rather than further manipulating this equation to find the surface equation, we can directly write the facet normal knowing θ_1 ;

$$\vec{UN} = \cos \theta_1 \vec{UCN} - \sin \theta_1 \vec{UCP} \quad (33)$$

Using the facet and collector normals, the reflected ray can be derived.

For example, at normal sun incidence (no off-axis), the redirected ray is simply

$$\vec{UR} = -\sin \alpha \vec{UCN} - \cos \alpha \vec{UCP} \quad (34)$$

As before, we need to define the distance vector for the receiver hit test. In this case, the focal point lies beneath the concentrator surface, and for now the depth of the fresnel facets is ignored. The distance vector is

$$\vec{D} = -y_{hit} \vec{UCP} - x_{hit} \vec{UCA} - F \vec{UCN} \quad (35)$$

This and the refracted ray vector, $\vec{UR}$, are used as inputs for either the cylindrical or planar receiver hit tests.

Inflated Cylindrical Concentrator--The inflated cylindrical concentrator is a thin-film plastic cylinder with an aluminized reflector bonded to the lower half. The sun's rays are reflected and concentrated along the normal axis of the cylinder. Receiver positioning along the axis is dependent on the receiver diameter.

The collector is usually oriented along the east-west axis and could be actively tracking (currently LLL recommends weekly tilt adjustments).

The surface definition for this concentrator is a semi-circle

$$F_s = r_{cyl}^2 - y_{hit}^2 - z_{hit}^2 \quad (36)$$

where

$z_{hit} \leq 0$ and r_{cyl} is the concentrator radius

A cross section of the concentrator illustrating the vector relationships is shown in Figure 24.

Figure 24. Inflated Cylindrical Concentrator Cross Section

The surface normal,

$$\vec{N} = -2y_{hit} \vec{UCP} - 2z_{hit} \vec{UCN} \quad (37)$$

and the unit surface normal

$$\vec{UN} = \frac{-y_{hit}}{r_{cyl}} \vec{UCP} - \frac{z_{hit}}{r_{cyl}} \vec{UCN} \quad (38)$$

If monthly or weekly tilt adjustments are used instead of active tracking, the local vector triad for the stationary concentrator would be used with changes in the tilt of the concentrator (θ_{tilt}).

The distance vector, $\vec{D}$, to be used in the receiver hit test has a simple formulation. For the inflated cylindrical concentrator,

$$\vec{D} = -x_{hit} \vec{UCA} - y_{hit} \vec{UCP} + (F + z_{hit}) \vec{UCN} \quad (39)$$

where F is measured from r_{cyl} along the normal axis to the center of the receiver.

In most cases, one will want to first determine the point of ideal receiver placement, as this concentrator does not focus at one point. In this case, the distance vector is defined to the center of the cylinder in the $\vec{UCA}$, $\vec{UCP}$ plane

$$\vec{D} = r_{cyl} \vec{UN} \quad (40)$$

Both the cylindrical and planar receiver models can be easily used with this design. The current receiver design is a cylindrical pipe positioned at $0.4-0.6 r_{cyl}$ along the normal axis of the concentrator.

Vee Trough--The vee trough concentrator is a stationary collector with several vee-shaped reflectors that concentrate the sun's energy (at low levels) onto receiver tubes. Figure 25 is a schematic and cross section indicating dimensions.

The concentrator surface can be described in terms of the angles θ_1 and θ_2 (Figure 25, cross section), which indicates the slope of each side of the vee. We will define a local origin, which will be at the vertex of each vee trough within the collector. The surface is described by

$$F = y \tan \theta - z \quad (41)$$

49

Figure 25. Vee Trough Concentrator and Cross Section

where

$$|y| \leq \frac{D_{ap}}{2}$$

The surface normal is

$$\vec{N} = -\tan \theta \vec{UCP} - \vec{UCN} \quad (42)$$

and the unit surface normal is

$$\vec{UN} = -\sin \theta \vec{UCP} - \cos \theta \vec{UCN} \quad (43)$$

The reflected ray will be calculated from Snell's law using the values of $\vec{USUN}$ and $\vec{UN}$.

The receiver will usually be cylindrical although a planar receiver could be employed. The distance vector, $\vec{D}$, from a surface hit point to the receiver end point would be

$$\vec{D} = -y_{hit} \vec{UCP} - x_{hit} \vec{UCA} - (z_{hit} - H) \vec{UCN} \quad (44)$$

where H is the height from the vertex to the center point of the receiver.

Incremental Reflector--This concentrator utilizes flat second surface faceted reflector panels as the concentrator surface. The facets work similar to a fresnel lens in that they focus the sun's energy to a line (Figure 26). Instead of refracting the rays, the second surface is a reflective material that redirects the sun's energy to an overhead receiver. The concentrator could be made to track in one or two axes. Tilt adjustments could be made with one-axis tracking to improve performance by eliminating large off-axis sun angles.

Figure 26. Section of Faceted Second-Surface Reflector

Because of the second surface material, the sun's ray will be refracted at the top surface before reflection.

The refracted sun's ray (assuming perfect tracking, alignment and a point source sun) is

$$\overrightarrow{USI} = \cos \phi_1 \overrightarrow{UCN} + \sin \phi_1 \overrightarrow{UCA} \quad (45)$$

where

$$\sin \phi_1 = n_1/n_2 \sin [\cos^{-1} (\overrightarrow{USUN} \cdot \overrightarrow{UCN})] \quad (46)$$

and where

n_2 = index of refraction for material

n_1 = index of refraction for air

The surface is defined such that direct rays (along $\overrightarrow{UCN}$) are reflected to the receiver center or focal line. The normal angle, α_n , shown in Figure 27, is found by

$$\sin 2\alpha_n = n_1/n_2 \sin (\cot^{-1} F/y_F) \quad (47)$$

Figure 27. Incremental Reflector Surface Definition

Again, the unit facet normal can be written directly from knowledge of the facet angle

$$\vec{UN} = \cos \alpha_n \vec{UCN} - \sin \alpha_n \vec{UCP} \quad (48)$$

The reflected ray is again found from Snell's law.

$$\vec{UR1} = 2(\vec{UN} \cdot \vec{US1}) \vec{UN} - \vec{US1}$$

Because this is a second surface reflector, a refraction will take place as the ray exits after reflection. The refraction is shown in Figure 28. This refraction takes place in the plane defined by $\vec{UR1}$ and $\vec{UCN}$. A unit vector in the $\vec{UCA}$, $\vec{UCP}$ and also in the $\vec{UR1}$, $\vec{UCN}$ planes is found by

$$\vec{UIJ} = \frac{(\vec{UR1} \cdot \vec{UCP})\vec{UCP} + (\vec{UR1} \cdot \vec{UCA})\vec{UCA}}{[(\vec{UR1} \cdot \vec{UCP})^2 + (\vec{UR1} \cdot \vec{UCA})^2]^{1/2}} \quad (49)$$

The redirected ray is

$$\vec{UR} = \cos \theta_2 \vec{UCN} + \sin \theta_2 \vec{UIJ} \quad (50)$$

where

$$\theta_2 = \cos^{-1} (\vec{UR1} \cdot \vec{UCN}) \quad (51)$$

and

$$\frac{\sin \theta_2}{n_1} = \frac{\sin \theta_2}{n_2} \quad (52)$$

Figure 28. Geometry for Finding Final Redirected Ray UR

The distance vector for the receiver hit test is defined as

$$\vec{D} = -y_{hit} \vec{UCP} + F \vec{UCN} - x_{hit} \vec{UCA} \quad (53)$$

This will be used as input with $\vec{UR}$ to one of the receiver models so the optical performance can be calculated.

Compound Parabolic - Involute Reflector--Although this design is usually referred to as a CPC concentrator, the geometrical configuration is not parabolic. This non-imaging concentrator utilizes the involute for the reflective surface shape. The involute can be thought of as the curve generated by the endpoint of a taut string as it is being unwound from a circular surface.

Because the formation of this surface model has been done using polar coordinates, the equations of the surface are somewhat complicated and the derivation for the surface normal does not follow the partial differential form. One could express the surface as a function of the polar coordinates, r and θ , and follow this method. Instead, we have taken a geometrical approach that will give the same result.

The involute surface can be defined as

$$y_{hit} = r \sin \theta + r\theta \cos \theta \quad (54)$$

$$z_{hit} = r \cos \theta - r\theta \sin \theta \quad (55)$$

where r is the radius of the circular surface (in this case the receiver pipe), and θ is the angle through which the string has been unwound (Figure 29). Note that y_{hit} is now restricted to the local values; $-D_{ap}/2 \leq y_{hit} \leq D_{ap}/2$, where D_{ap} is the distance across one reflector section. The normal to the surface for any hit point (y, z) can be calculated since the surface normal is tangent to the receiver at the point defined by r and θ . Referring to Figure 30,

$$\vec{UN} = -\cos \theta \vec{UCP} + \sin \theta \vec{UCN} \quad (56)$$

where

$$\theta = \alpha + \gamma \text{ and}$$

$$\alpha = \tan^{-1} \frac{y_{hit}}{z_{hit}}$$

$$\gamma = \cos^{-1} \frac{r}{\sqrt{y_{hit}^2 + z_{hit}^2}}$$

The reflected ray, $\vec{UR}$, is calculated as always.

The diagram illustrates a circular radar cross-section. A large circle represents the radar cross-section, with a radius vector r and an angle θ from the vertical. A smaller circle, labeled "REFLECTOR SURFACE", is shown with a radius vector n and an angle α from the vertical. A point on the reflector surface is labeled (Y_{HIT}, Z_{HIT}) and $X_{HIT} = 0$. A vector $\vec{UR}$ points from the origin to the hit point. A vector $\vec{UN}$ points from the origin to the center of the reflector surface. A vector $\vec{USUN}$ points from the origin to the center of the radar cross-section. The angle between $\vec{UN}$ and $\vec{USUN}$ is θ . The angle between $\vec{UR}$ and $\vec{UN}$ is α . The angle between $\vec{UR}$ and the vertical axis is θ . The angle between $\vec{UN}$ and the vertical axis is α . The angle between $\vec{USUN}$ and the vertical axis is θ . The angle between $\vec{UN}$ and the vertical axis is α .

Figure 30. Involute Concentrator Geometry

Once the reflected ray is found, a hit test using the cylindrical receiver model will be made. The vector from the hit point to the center of the receiver is defined as follows (the center of the receiver is the point (0, 0, 0)).

$$\vec{D} = -y_{hit} \vec{UCP} - z_{hit} \vec{UCN} - x_{hit} \vec{UCA} \quad (57)$$

Because multiple reflection hits are possible if the ray misses the receiver, we would repeat the process above to find a second reflected ray. The hit test would be repeated unless it is determined that the ray reflects out the concentrator aperture.

Compound Parabolic Concentrator - Involute/Parabolic Reflector--This concentrator utilizes a reflector that is a combination of an involute and an ideal (parabolic) reflector. The concentration is determined from the acceptance angle, θ_a

$$C_{ideal} = \frac{1}{\sin \theta_a} \quad (58)$$

The receiver may be flat (horizontal or vertical fin) or cylindrical. The mathematical definition of the surface will be somewhat different in these cases although they are derived similarly. The CPC with a cylindrical absorber will be used for this model.

The concentrator surface is defined first using polar coordinates (r, θ). Any point, P, on the reflector is characterized by its distance from the point on the absorber at which the tangent from P touches the absorber (Figure 31). If θ is measured from the vertical axis

$$e = r \theta \quad |\theta| \leq \theta_a + \frac{\pi}{2} \quad (59)$$

$$\rho = r \left[\frac{\theta + \theta_a + (\pi/2) - \cos(\theta - \theta_a)}{1 + \sin(\theta - \theta_a)} \right], \quad \theta_a + \frac{\pi}{2} \leq |\theta| \leq \frac{3\pi}{2} \quad (60)$$

Figure 31. CPC Surface Geometry

Knowing the value of θ and r , we can determine the y and z coordinates of the point P . Referring to Figure 31

$$y_{hit} = \sqrt{(\rho^2 + r^2)} \cos(\beta) \quad (61)$$

$$z_{hit} = \sqrt{(\rho^2 + r^2)} \sin(\beta) \quad (62)$$

$$\text{or } z_{hit} = y_{hit} \tan \beta \quad (63)$$

where

$$\beta = 90 - \theta + \gamma$$

$$\gamma = \tan^{-1} e/r$$

The surface normal using the partial derivative form is

$$\vec{N} = -\tan \beta \vec{UCP} + \vec{UCN} \quad (64)$$

Dividing by $|\vec{N}| = (1 + \tan^2 \beta)^{1/2} = \sec \beta$,

we have the surface normal

$$\vec{UN} = -\sin \beta \vec{UCP} + \cos \beta \vec{UCN}. \quad (65)$$

Once the reflected ray $\vec{UR}$ is determined using Snell's law, the $\vec{D}$ vector is calculated. In this case,

$$\vec{D} = -y_{\text{hit}} \vec{UCP} - x_{\text{hit}} \vec{UCA} + z_{\text{hit}} \vec{UCN} \quad (66)$$

Note that y_{hit} and z_{hit} in the case are measured locally using the center of one receiver tube as the origin.

This surface is compatible with the cylindrical receiver model. Slight variations in the surface definition would need to be made for a planar receiver.

Receiver Models

The optical efficiency of the concentrators being examined is determined from the number of rays per run that reach the receiver. Three receiver types have been modeled for this program: a plane, a cylinder and a cone. For each redirected ray, a hit test is performed. Using a distance vector, $\vec{D}$, and the vector $\vec{UR}$ from the concentrator models as inputs, one

can determine whether or not a ray has reached the receiver. For some of the concentrators, it may be possible for rays to reach the receiver after multiple bounces on the concentrator surface. These rays will be tested through a number of reflections before being considered lost.

The following discussion details the models for each of the receivers. Although the geometries are different, the same methodology is used for each receiver type.

Planar Receiver--The planar receiver is characterized by a receiver length and width, RL and RW respectively. To determine whether a reflected ray will impinge on this receiver, we will define a vector, $\overrightarrow{RHIT}$, from the known point to which the $\overrightarrow{D}$ vector is drawn to the hit point on the receiver.

If we define L as the distance along the reflected/refracted ray $\overrightarrow{UR}$ from the surface hit point to the receiver hit point, then

$$\overrightarrow{RHIT} = -\overrightarrow{D} + L \overrightarrow{UR} \quad (67)$$

This geometry is illustrated in Figure 32 for the parabolic trough. Because the vectors $\overrightarrow{D}$ and $L \overrightarrow{UR}$ are directed from the same point along the z-direction and have the same end point (i.e., $Z = F$ for the trough, $Z = -F$ for the linear fresnel), we can write

$$L(\overrightarrow{UR} \cdot \overrightarrow{UCN}) = \overrightarrow{D} \cdot \overrightarrow{UCN} \quad (68)$$

Solving for L and substituting in the expression for $\overrightarrow{RHIT}$, we obtain.

$$\overrightarrow{RHIT} = \left[\frac{\overrightarrow{D} \cdot \overrightarrow{UCN}}{\overrightarrow{UR} \cdot \overrightarrow{UCN}} \right] \overrightarrow{UR} - \overrightarrow{D} \quad (69)$$

Figure 32. Parabolic Trough Concentrator

If the ray hits the receiver plane, then

$$|\overrightarrow{RHIT} \cdot \overrightarrow{UCP}| \leq \frac{RW}{2} \quad (70)$$

$$0 < \overrightarrow{RHIT} \cdot \overrightarrow{UCA} < RL \quad (71)$$

It is also possible knowing the coordinates of $\overrightarrow{RHIT}$ to determine the energy distribution over the receiver plane. This is easily accomplished by dividing the receiver into zones along its width and length and calculating which zone the ray hits using the $\overrightarrow{RHIT}$ coordinates.

Cylindrical Receiver--To perform a receiver hit test for the cylindrical receiver, we again define L as the distance from the concentrator surface hit point to the receiver hit point in the direction of $\overrightarrow{UR}$. Referring to Figure 33, we define $\overrightarrow{RHIT}$ as a radial vector to the hit point from the center of the receiver at a distance q_{hit} from the end of the receiver along the collector axis ($\overrightarrow{UCA}$). Thus, we have

$$\overrightarrow{RHIT} = -q_{hit} \overrightarrow{UCA} - \overrightarrow{D} + L \overrightarrow{UR} \quad (72)$$

We know from the geometry that

$$q_{hit} (\overrightarrow{UCA} \cdot \overrightarrow{UCA}) = (-\overrightarrow{D} + L \overrightarrow{UR}) \cdot (\overrightarrow{UCA}) \quad (73)$$

$$q_{hit} = (-\overrightarrow{D} \cdot \overrightarrow{UCA}) + L (\overrightarrow{UR} \cdot \overrightarrow{UCA}) \quad (74)$$

If the ray hits the receiver, then $\overrightarrow{RHIT} \cdot \overrightarrow{RHIT} = r_{abs}^2$ and

$$\begin{aligned}
 \overrightarrow{RHIT} \cdot \overrightarrow{RHIT} &= L^2 [1 - (\overrightarrow{UR} \cdot \overrightarrow{UCA})^2] \\
 &- L [2(\overrightarrow{UR} \cdot \overrightarrow{UCA})(\overrightarrow{D} \cdot \overrightarrow{UCA}) - 2(\overrightarrow{D} \cdot \overrightarrow{UR})] \\
 &+ [\overrightarrow{D} \cdot \overrightarrow{D} - (\overrightarrow{D} \cdot \overrightarrow{UCA})^2] \quad (75)
 \end{aligned}$$

This quadratic can be solved for L . Real roots indicate a receiver hit; imaginary roots indicate a receiver miss. When real roots are found, one represents the ray entry point, and the other represents the exit point.

Figure 33. Cylindrical Receiver Hit Test Geometry

Conical Receiver--Figure 34 indicates the geometry for the cone-shaped receiver. To completely define this receiver, the following parameters are specified:

RL = length of receiver (along axis of symmetry)

S_o = the distance from the cone vertex to the top of the receiver (negative)

θ_c = the included angle of the cone

Figure 34. Receiver Cone Geometry

We again define a distance L along $\overrightarrow{UR}$ to the hit point on the receiver. We can now construct a radial vector from the cone axis to the hit point. Referring to Figure 35, the two-axis tracking receiver hit vector is

$$\overrightarrow{RHIT} = -L \overrightarrow{UR} + \overrightarrow{D} + S \overrightarrow{USUN} \quad (76)$$

Figure 35. Receiver Hit Test Geometry

where S is the distance to the plane of $\overrightarrow{RHIT}$ along the cone axis from the receiver end point.

In order for $\overrightarrow{RHIT}$ to have its endpoint on the cylinder surface,

$$\overrightarrow{RHIT} \cdot \overrightarrow{RHIT} = |\overrightarrow{RHIT}|^2 = (S - S_o)^2 \tan^2 \theta_c \quad (77)$$

Calculating this dot product with the previous expression for $\overrightarrow{RHIT}$,

$$\begin{aligned} \overrightarrow{RHIT} \cdot \overrightarrow{RHIT} = & -2L(\vec{D} \cdot \vec{UR}) + L^2 - 2LS(\vec{UR} \cdot \vec{USUN})(\vec{D} \cdot \vec{D}) + \\ & 2S(\vec{D} \cdot \vec{USUN}) + S^2 \end{aligned} \quad (78)$$

and

$$\overrightarrow{RHIT} \cdot \overrightarrow{RHIT} = (S^2 - 2SS_o + S_o^2) \tan^2 \theta_c \quad (79)$$

This gives two unknowns (S and L) but because both $L \vec{UR}$ and $(\vec{D} + S \vec{USUN})$ extend from the same point in space to the surface of the hit plane with unit normal $\vec{UN}$, we can solve for L as follows

$$L(\vec{UR} \cdot \vec{USUN}) = (\vec{D} + S \vec{USUN}) \cdot \vec{USUN} \quad (80)$$

Substituting the value of L in the dot product above, we obtain a quadratic in S

$$\begin{aligned} & S^2 [1/(\vec{UR} \cdot \vec{USUN})^2 - \tan^2 \theta_c - 1] \\ & + S [-2 \frac{\vec{D} \cdot \vec{UR}}{\vec{UR} \cdot \vec{USUN}} + 2 \frac{\vec{D} \cdot \vec{USUN}}{(\vec{UR} \cdot \vec{USUN})^2} + 2 S_o \tan^2 \theta_c] \\ & + [-\frac{(\vec{D} \cdot \vec{USUN})^2}{(\vec{UR} \cdot \vec{USUN})^2} + \vec{D} \cdot \vec{D} - S_o^2 \tan^2 \theta_c \\ & - 2 \frac{(\vec{D} \cdot \vec{USUN})(\vec{D} \cdot \vec{UR})}{\vec{UR} \cdot \vec{USUN}}] = 0 \end{aligned} \quad (81)$$

The solution of the quadratic gives the two piercing points (entry and exit) of the ray with the cone. Imaginary roots indicate that the ray failed to hit the cone.

COMPUTER SOFTWARE

The objective of this task is to develop a computer code using the ten concentrator math models and the reflecting/lensing materials data. These models will be incorporated in the ray trace software for use by the solar researcher. The code will be available for comparison of the optical performance of numerous concentrator designs and reflecting/lensing material combinations. The user will also have the option of including data for a particular concentration or material.

Figure 36 indicates the general program flow for any concentrator design. Input parameters will include the following user options:

- Concentrator type
- Receiver geometry
- Reflective or lensing material
- Error distribution
- Time integration or timepoint run
- Number of rays to trace
- Concentrator/receiver dimensions

For each concentrator/reflector that is being simulated, the Monte Carlo draw over the surface is made. Each time a ray is drawn at some point on the concentration surface, the surface normal at that point is calculated. The surface error will be a perturbation of the surface normal drawn at random over a normal distribution. This distribution will have a mean and standard deviation based on the backing material properties and the reflective/lensing materials being examined. The sun's ray is perturbed for the finite sun size and radiation intensity. An option to draw over wavelength will be provided. At this point, the redirected ray (reflected or refracted) can be found.

Next, the redirected ray must be traced to the receiver. Rays which impinge on the receiver are counted, and the user will have the option of examining the flux pattern on the receiver for a given configuration. If the ray misses the receiver, it will be considered lost or will be traced further if the concentrator has multiple bounce receiver hits (e.g., compound parabolic concentrator, imaging collapsing concentrator).

Figure 36. Computer Software Flowchart

At the end of each draw, the counting bins (arrays) for the run are computed and at the end of each run, performance will be calculated. User parameters, statistics, flux patterns, and optical performance are output.

The computer software development task is in process at this time.

DEGRADATION EFFECTS

An important component of any solar collector is the optical material used to concentrate solar energy on the receiver of the collector assembly. The operating efficiency and cost of the collector is directly dependent upon the performance and maintenance of the optical lens and reflector materials that function in this capacity. It is imperative, therefore, that the material be selected to meet the cost performance goals. At present, the material selection process is hindered by the lack of an adequate data base of materials performance and maintenance under the conditions experienced in solar systems. The objectives of this projects second major task is, therefore, to (1) formulate a state-of-the-art performance data base for candidate optical materials under various exposure conditions, and (2) include maintenance recommendations for minimizing the adverse affects caused by prolonged exposure of these materials in solar collector operating environments.

APPROACH

To accomplish the objectives of this task, data are being accumulated as described in the flow diagram, Figure 37. Potential sources for material degradation data and maintenance recommendations include computerized data banks, collector users and manufacturers, material suppliers, R/D organizations, and a miscellaneous category which includes workshops and seminars. The data base would be a compilation of material test results and experience, based on the letter survey, and extraction of relevant information from previously published and non-published research and development efforts. The data base will be useful for manufacturers and designers in selecting the best candidate material for a particular application. Although it is unlikely that the data base will ever be complete, it would serve as a quick-reference to material availability. No experimental activities are included within the scope of this program.

Figure 37. Degradation and Maintenance Data Base Formulation Process

STATUS

To assess the current technology and data availability from published sources, an extensive literature search was conducted. Two bibliographies, including 220 documents, were formulated based upon computerized searches of the Energy Data Base at DOE's Oak Ridge Tech Center. Searches were based on condensed combinations of key words included "Weathering and Reflectors" and "Solar Coating." Sixty-two documents were ordered based upon the results of the bibliography screens. Thirty-three documents

were received. Fifteen more documents were ordered based on the cross reference from the documents received and on recommendations from experts in the field.

Of the documents received, about ten contain potentially valuable information. Due to the lack of standard tests for weatherability and the lack of correlation between accelerated and real-time exposure testing, there is a large variability in data for some of the materials. Data availability on maintenance and degradation control is minimal. Extensive studies have been conducted on UV degradation of PMMA (acrylic), discoloration of polymers on exposure to sunlight, and on some of the mechanical effects. Other than this, efforts to characterize the individual effect of degradation due to humidity, moisture, temperature, solarization, etc., have been minimal. Studies to explain the degradation mechanisms should help in defining degradation control parameters and in performance modeling. Real-time and accelerated testing data are available for most of the reflective materials and acrylics. However, technological development in the materials field may have outdated the old exposure test results. Manufacturers, suppliers, and users of the mirror material are being contacted for any unpublished results.

Several organizations that have manufactured or used concentrating solar collectors, material suppliers, and R&D organizations which are engaged or have engaged in lens and reflector material characterization activities are a potential source of material degradation and maintenance data. A letter survey is being conducted. About 500 companies, including solar component manufacturers, research and development organizations, users and individuals will be contacted. A copy of the letter and requested information is shown in Appendix A. This will be followed by telephone contacts to selected companies.

REFLECTIVE MATERIALS

A variety of materials have been used, including anodized aluminum reflective sheet, metallized plastics, glass, and Fresnel reflectors. Table 2 gives a partial list of materials, brand names, and manufacturer/user companies. All of them are either aluminum or silver reflectors. Properties and weatherability vary with the type of protective layers, back layers, adhesives, and substrate used. Figure 38 shows types of reflectors, protective overlayers, and structure materials used in reflector construction. Besides aluminum and silver, gold, copper and rhodium have acceptable solar reflectivities, but cost prohibits their use in commercial applications. The spectral reflectance versus wavelength for gold matches the response curve for silicon photovoltaics. The use of gold in reflectors for photovoltaics is, therefore, under consideration.

Table 2. Lens and Mirror Materials for Concentrating Solar Collectors

MATERIAL	MANUFACTURER/USER
ALUMINIZED ACRYLIC REFLECTOR FEK 244 FEK 163	SOLAR KINETICS HONEYWELL, HEXCEL
COATED ALUMINUM SHEET COILZAK KINGLUZ	ACUREX SOLARTEC HONEYWELL DSET LAB
GLASS MIRROR CODE 0317	GENERAL ATOMIC, HONEYWELL DEL-JACOBS SANDIA, MDAC, MARTIN MARIETTA
ALUMINIZED TEFLON REFLECTOR	SANDIA SHELD AHL
ALUMINIZED POLYESTER REFLECTOR	SUNTEC BOEING HONEYWELL
INCREMENTAL REFLECTOR	HONEYWELL
FRESNEL LENS POINT FOCUS	MDAC NASA-MARSHALL SANDIA, RCA VARIAN, MARTIN-MARIETTA
LINE CONCENTRATING	MDAC, NORTHROP NASA-MARSHALL

PROTECTIVE OVERLAYER

1. PROTECTIVE BUBBLE
2. INTEGRALLY BONDED COVER MATERIAL SUCH AS TRANSPARENT OXIDE COATINGS
3. GLASS
4. PLASTIC OVERLAYS

REFLECTOR STRUCTURE

1. LAMINATES
2. HONEYCOMBS
3. GLASSES
4. GLASS AND PLASTIC FOAM
5. METALLIC STRUCTURE

Figure 38. Solar Reflector Construction Alternatives

The anodized aluminum reflectors like KingluxTM, etc., have shown good resistance to environmental effects. The surface is protected by anodized oxides of aluminum or silicon. However, these polished reflectors have relatively low specular reflectance, and the reflected beam is anisotropic due to polishing marks running in one direction.

The reflectance of metallized plastic films depends on the optical properties of plastic film, surface roughness of metallized side, lamination process, and the surface roughness of substrates. Aluminized acrylic reflectors have good specularly and resistance to solarization, but are much softer than glass and are subject to dust abrasion and abrasion due to mechanical cleaning. For plastic films, light scattering increases with surface abrasion.

The glass mirror reflectors have shown very good resistance to weatherability (Ref. Field Evaluation of Solar Mirror Survivability, by Robert M. Bethea, M. T. Barringer, Texas Tech University, presented at the Solar Reflective Materials Workshop in Denver, March 28-30, 1978). Light absorption in glass due to iron impurities decreases reflectance with increasing glass thickness. The use of glass mirror for solar concentrators is in a development stage.

LENSES

For solar applications, plastics are preferred over glass for several reasons. Plastics offer low cost, light weight, high light transmittance, configuration flexibility, and inexpensive high-volume production. A principal disadvantage of plastics is their lack of heat resistance and lower scratch resistance than glass. Acrylic (Polymethylmethacrylate) is by far the most widely used optical plastic. The optical plastics under consideration are polycarbonate, polystyrene, and cellulose acetate butyrate. The other transparent thermoplastics available include polysulfone, cellulose, vinyls, CTFE fluoropolymers, polyester copolymers and ionomers. However, these materials are seldom used for optical systems.

The lens of a solar energy collector also functions as a cover plate and, therefore, must provide good protection against environmental effects. All organic substances undergo changes, usually adverse, when exposed to sunlight. There are two main mechanisms by which polymers degrade when exposed

to UV light: (1) direct rupture of chemical bonds in the polymer structure by absorption of UV radiation followed by a rapid oxidation of the fragments, resulting in discoloration and embrittlement of the polymer; and (2) energy transfer sensitized by UV-excited impurities such as catalyst residues or hydroperoxides and carbonyl groups that may be present in the polymer chain or as contaminants in the matrix (Ref. Modern Plastics Encyclopedia, 1978-79, McGraw Hill publication).

Cast acrylic sheet was found to be extraordinarily resistant to oxidative photodegradation during more than 17 years of exposure near Albuquerque. (Ref. Cast Acrylic Lenses for Solar Energy Applications, by Charles Lingle; Seminar on Testing of Solar Energy Materials and Systems, Maryland, May 22-24, 1978.)

For other optical polymers like polycarbonate, a UV stabilizer is required, which may reduce light transmittance by as much as 5 percent. Scratch resistant coatings are being developed.

Thus, cast or extruded acrylics are the state-of-the-art for lensing materials, possessing excellent weatherability and optical characteristics according to the data reported (Ref. L. G. Rainhart and W. P. Schimel, Jr., Effect of Outdoor Aging of Acrylic Sheet, SAND-74-0291, Sandia Labs, September 1974).

A-1

APPENDIX A

DEGRADATION AND MAINTENANCE
DATA SOLICITATION LETTER

A-2

May 21, 1979

Dear

The Honeywell Energy Resources Center engages in a variety of activities relating to research, development and management of energy programs and concepts. We are presently engaged in a solar energy project for the Department of Energy under Contract No. EM-78-C-04-5438 entitled "Survey Mirrors and Lenses and Their Required Surface Accuracy." The technical monitor for the project is Dr. Derrick Grimmer of Los Alamos Scientific Laboratories, New Mexico.

One task the project includes is the expansion of an existing data base for mirror and lens degradation due to environmental exposure and cleaning requirements. The data collected will be presented in a format to aid potential users of reflective and lensing materials in establishing maintenance requirements, operation procedures and design practices aimed at ensuring long solar collector life and low cost. We expect the report on results of the study to be available from National Technical Information Service (NTIS) for general use sometime after September 15, 1979.

We would appreciate your cooperation and assistance in providing information on reflective materials and lens materials supplied or used by you. A data survey sheet is enclosed for presenting the information we are seeking. However, if you would like to present the information in some other way, please feel free to do so. Essentially, we are seeking weathering data on mirrors and lenses, recommended cleaning techniques and other maintenance requirements. We realize that the information we seek is not always readily quantified, nor does a standard format for reporting weatherability and maintenance requirements exist. Our own experience in installing, operating and maintaining solar systems has shown that degradation due to environmental effects can be described qualitatively but can be difficult and possibly costly to describe quantitatively. In cases where cleaning procedures have not yet been established, and weathering data are not available, we would appreciate your indicating any studies being conducted in-house or elsewhere that

are designed to yield such data in the future. When asking for your cooperation in responding to the attached, we would appreciate comments on observed (visual) degradation as well as measured. Also, any comments relative to maintenance found desirable or necessary would be helpful.

Thank you very much for any assistance you can provide us. We would appreciate hearing from you before June 15, 1979. If you will not be responding for any reason, please complete and return the enclosed acknowledgement form as soon as possible.

If you have any questions, please contact myself, (612) 378-4273, or Mr. Roger Rausch, (612) 378-4920.

Sincerely,

A handwritten signature in cursive script, reading "Anoop Mathur", written in dark ink. The signature is fluid and somewhat stylized, with a horizontal line drawn underneath the name.

Anoop Mathur,
Development Engineer

Honeywell Inc.
Energy Resources Center
Mail Station MN19-T123
2600 Ridgway Parkway
Minneapolis MN 55413

AM/ms
Enclosures

DATA SURVEY SHEET

1. MATERIAL

REFLECTOR ☐ YES ☐ NO
LENS ☐ YES ☐ NO

2. MATERIAL TRADENAME (IF ANY)

REFLECTOR _____

LENS _____

3. REFLECTOR TYPE

☐ FIRST SURFACE	☐ PROTECTED FIRST SURFACE
☐ SECOND SURFACE	☐ DIELECTRIC
☐ LAMINATE	☐ THICK FILM
☐ COMPOSITES	☐ PROTECTIVE COVER ONLY
OTHER _____	

LENS TYPE

☐ CAST
☐ EXTRUDED
OTHER _____

4. MATERIAL DESCRIPTION, (I.E., FOR REFLECTORS: OUTER PROTECTIVE LAYER, REFLECTIVE LAYER, BONDING AGENT, BACK PROTECTIVE LAYER, SUBSTRATE, ETC.)

REFLECTOR _____

LENS _____

5. STATE OF DEVELOPMENT

REFLECTOR

☐ EXISTING COMMERCIAL ☐ UNDER DEVELOPMENT ☐ CONCEPTUAL DESIGN

LENS

☐ EXISTING COMMERCIAL ☐ UNDER DEVELOPMENT ☐ CONCEPTUAL DESIGN

6. OPTICAL PROPERTIES (UNAGED):

REFLECTOR

REFLECTANCE _____

SPECULARITY _____

OTHER _____

LENS

TRANSMITTANCE _____

OPTICAL CONSTANTS _____

OTHER _____

7. WEATHERABILITY

REFLECTOR

HUMIDITY _____
TEMPERATURE _____
SOLARIZATION _____
BIOLOGICAL ATTACK _____
ABRASION RESISTANCE _____
REALTIME EXPOSURE TEST DATA _____
OTHER _____

LENS

HUMIDITY _____
TEMPERATURE _____
SOLARIZATION _____
BIOLOGICAL ATTACK _____
ABRASION RESISTANCE _____
REALTIME EXPOSURE TEST DATA _____
OTHER _____

8. MAINTENANCE

REFLECTOR

DUST CONTAMINATION RATE _____
EASE OF CLEANABILITY _____
CLEANING SOLUTIONS (USED/PROPOSED) _____
CLEANING PROCEDURE _____
OTHER _____

LENS

DUST CONTAMINATION RATE _____
EASE OF CLEANABILITY _____
CLEANING SOLUTIONS (USED/PROPOSED) _____
CLEANING PROCEDURE _____
OTHER _____

ACKNOWLEDGEMENT

We have received your letters requesting information on reflective or lens materials. We:

- ☐ Have not manufactured or have not used any reflective or lens material for solar application.
- ☐ Will not respond because our information is proprietary
- ☐ Will not respond
- ☐ Other

For subsequent inquiries contact:

Name:

Company:

Address: