DOE/CS/35348-T1(Vol.1)

SURVEY MIRRORS AND LENSES AND THEIR REQUIRED SURFACE ACCURACY

Volume 1: Technical Report
Final Report for September 15, 1978—December 1, 1979

January 1980

Work Performed Under Contract No. EM-78-C-04-5348

Honeywell Inc.
Technology Strategy Center
Minneapolis, Minnesota

U.S. Department of Energy

Solar Energy

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DOE/CS/35348-T1(Vol.1)
Distribution Category UC-59c

SURVEY MIRRORS AND LENSES AND THEIR REQUIRED SURFACE ACCURACY

VOLUME I

TECHNICAL REPORT

CONTRACT NO. DE-AC04-78CS35348

JANUARY 1980

PERIOD COVERED

SEPTEMBER 15, 1978
THROUGH
DECEMBER 1, 1979

PREPARED FOR

U.S. DEPARTMENT OF ENERGY
ALBUQUERQUE OPERATIONS OFFICE

PREPARED BY

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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 and Mr. John Krall of Los Alamos Scientific Laboratory were the contract technical monitors. The report covers progress during the period from September 15, 1978 to December 1, 1979.

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There are two volumes in this final report. Volume I is the Final Technical Report on all project aspects and Volume II is a User's Manual for the Concentrator Optical Performance Software (COPS) computer program developed as a portion of the project.

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.

ABSTRACT

An investigation of the optical performance of a variety of concentrating solar collectors is reported. The study addresses two important issues: the accuracy of reflective or refractive surfaces required to achieve specified performance goals, and the effect of environmental exposure on the performance concentrators. To assess the importance of surface accuracy on optical performance, 11 tracking and nontracking concentrator designs were selected for detailed evaluation. Mathematical models were developed for each design and incorporated into a Monte Carlo ray trace computer program to carry out detailed calculations. Results for the 11 concentrators are presented in graphic form. The models and computer program are provided along with a user's manual. A survey data base was established on the effect of environmental exposure on the optical degradation of mirrors and lenses. Information on environmental and maintenance effects was found to be insufficient to permit specific recommendations for operating and maintenance procedures, but the available information is compiled and reported and does contain procedures that other workers have found useful.

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SECTION 1
INTRODUCTION AND SUMMARY

This project investigated the optical performance of a variety of solar concentrating collectors. A major concern for all concentrating collectors is the effect of the reflector or lens surface optical quality on concentrator performance. The optical quality can be controlled, to some extent, in the manufacture of the actual reflecting or lens material. The more accurately the surface is controlled, the more the surface will cost in most instances. Therefore, optical performance of the collectors as a function of surface quality is an important consideration for design.

The first task of this project was a review of concentrator designs of which 11 were selected for further evaluation:

- 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.
- Paraboloid of Revolution (Dish).

For each of these designs, a mathematical model was created and incorporated into a Monte Carlo ray trace computer program called COPS (Concentrator Optical Performance Software). This computer program was exercised for selected design configurations; optical performance as a function of optical quality and concentration ration was investigated, the computer program and the COPS program User's Manual (Volume II) allow the solar researcher to investigate the optical performance of concentrating collector designs. Optical performance must be combined with thermal performance and cost data to determine cost-effective design configurations.

In addition to the computer program investigation results, the project's second task involved the expansion of an existing data base on mirror degradation due to environmental exposure. The task included the collection of similar degradation information on lens materials. In many cases the type of data we sought was never compiled by researchers or, when data on mirror or lens optical characteristics was obtained, it was difficult to evaluate quantitatively. The difficulty comes from several factors. One factor is simply the lack of complete reporting. All reflectance and transmittance values do not fit a standard format. Most values are reported for one--sometimes unknown--wavelength. Other values are integrated over a solar spectrum of unknown origin. A standard needs to be specified for adherence by all investigators. Other difficulties are caused by the need for expediency. Cleaning techniques have been invented by building maintenance staff in some instances. Degradation effects in the long range are uncertain because no controlled testing has been done. In short, the gathered data base cannot lead to recommended maintenance and operating procedures. At best, we present the data and point out shortcomings and procedures which others have found useful in their own solar energy systems.

SECTION 2
CONCENTRATOR PERFORMANCE

As part of this major project task, we identified solar concentrating collectors to be mathematically modeled for incorporation into a Monte Carlo ray trace computer code. The computer code simulates the optical performance of each concentrator as a function of concentration ratio and other design geometry as specified by the user.

CONCENTRATOR LITERATURE SURVEY

During the first portion of this contract, data were reviewed on existing concentrator designs and hardware to begin compiling a set of possible candidates for the mathematical 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 lens 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 mathematical modeling. They are listed in Table 2-1, grouped according to relative concentration ratio.

Table 2-1. List of Representative Concentrator Candidates

RELATIVE CONCENTRATION	CONCENTRATOR
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 CONCENTRATION COLLECTORS

This list is intended to be representative of current and near-future concentrating collector technologies. All of the concentrators listed in Table 2-1 are in production, under prototype development and testing, or under government research funding. A brief description of each collector type follows for clarification.

Concentrator Descriptions

Paraboloid of Revolution (Dish)--This concentrator is a two-axis tracking parabolic dish, which redirects sunlight to an overhead point focus. This point-focus concentrator achieves the highest concentration ratios of any collector currently under development. Concentration ratios well over 500X are conceivable. The concentrator can achieve extremely high temperature ranges (800 to 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 2-1. The reflective surface is composed of 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 250X.

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

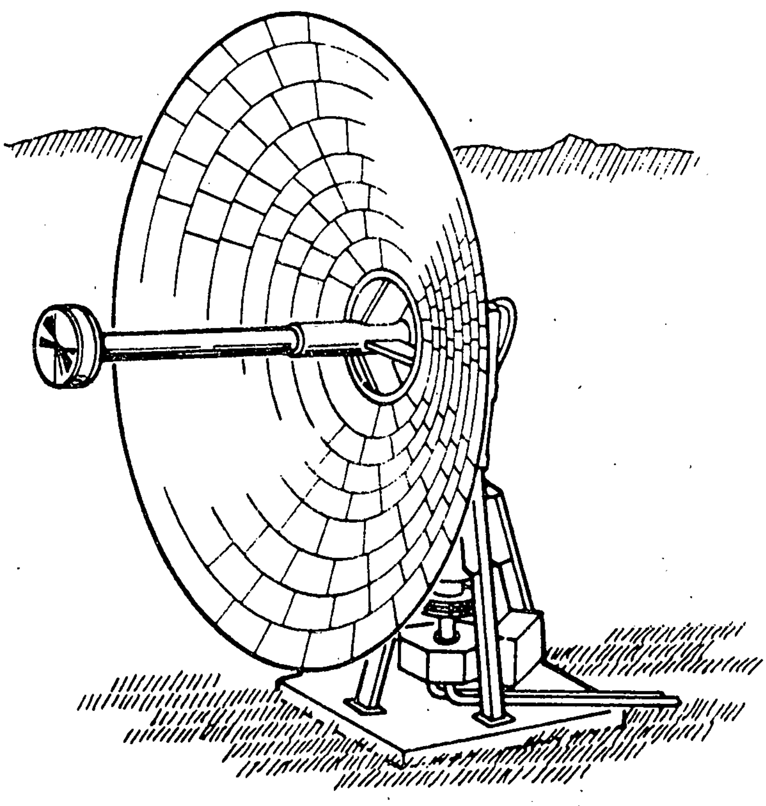
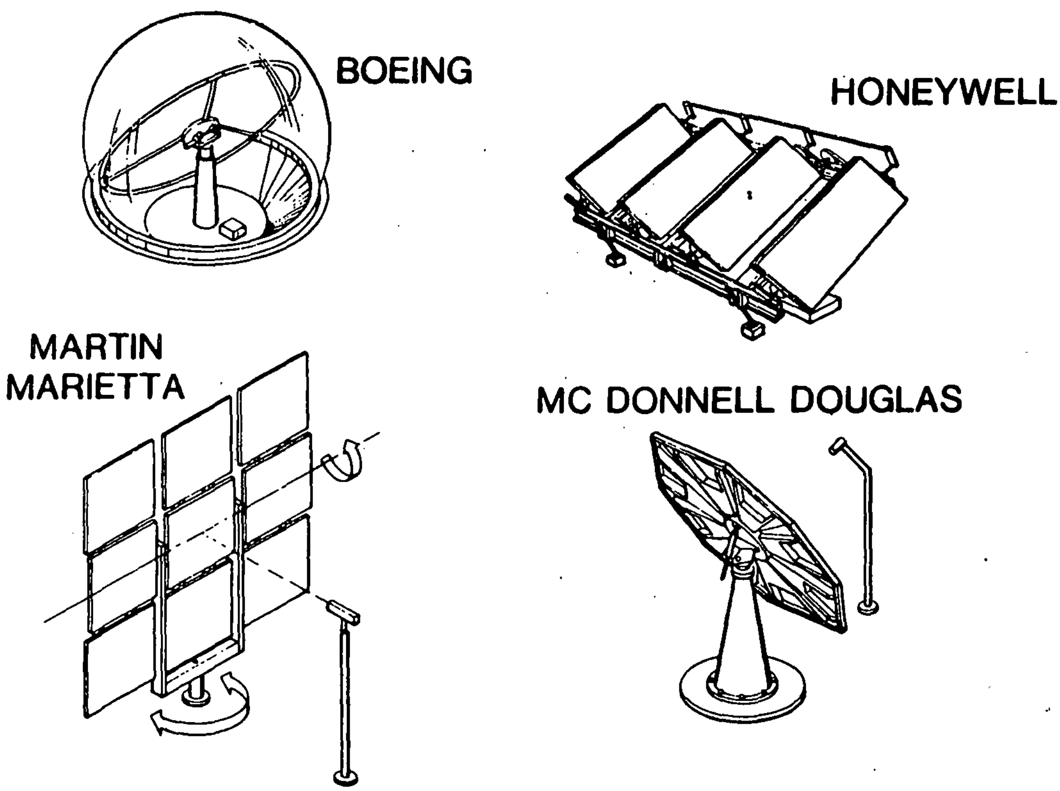


Figure 2-1. Raytheon Point-Focusing Dish Concentrator Collector

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 all have developed heliostat designs. The different concepts are shown in Figure 2-2.

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

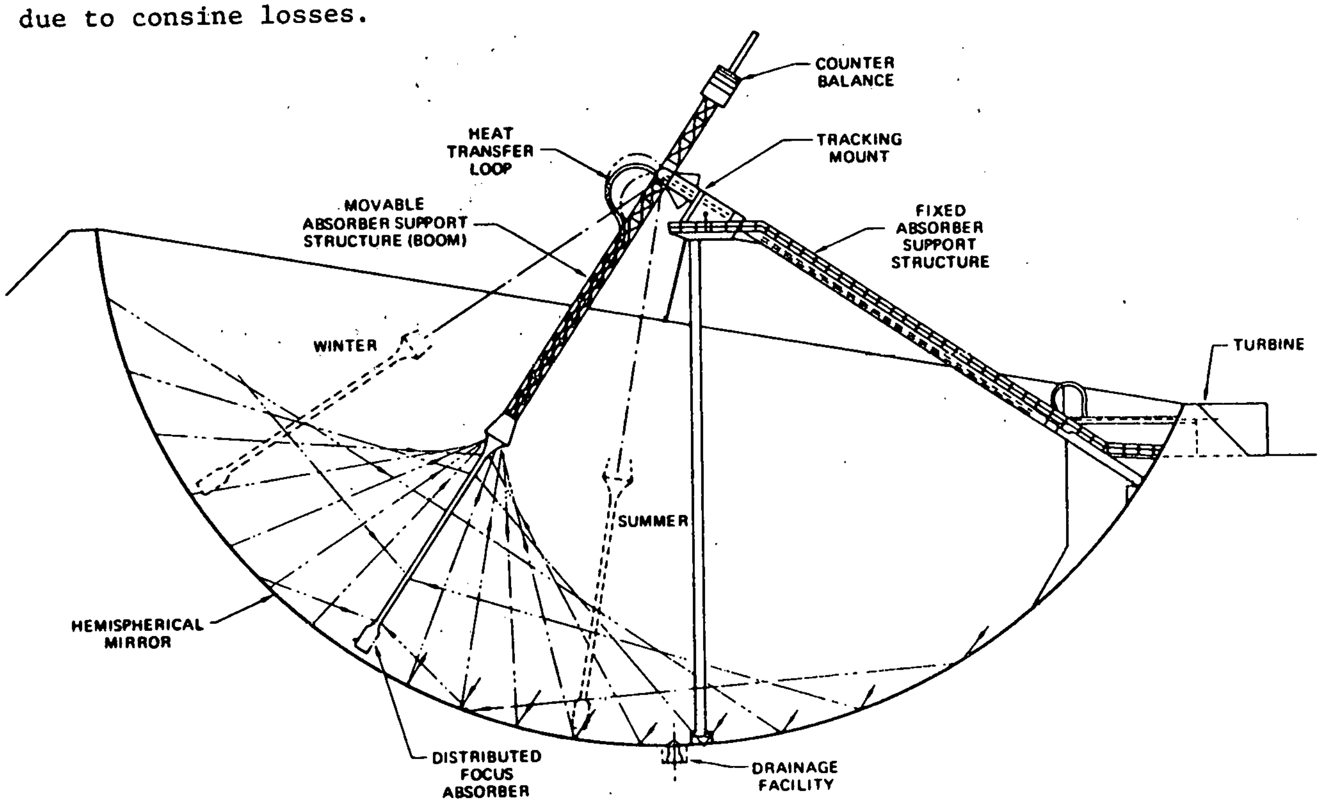


SOURCE: Prepared by OTA using manufacturer's data.

Figure 2-2. Heliostat Concepts for Solar Central Receiver Applications

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 tracks 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 2-3. Its concept uses a spherical mirror surface, 60 to 90 meters in diameter to produce heat at about 500°C. The concentration ratio is near 1000X. The advantage of this design is the potentially lower cost that could result by eliminating tracking mechanisms for large dishes. However, this concept will have lower optical efficiency due to consine losses.



SOURCE: E-Systems Inc.

Figure 2-3. Fixed-Mirror Tracking Receiver (Two-Axis) Cross Section

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 lenses 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 50X, in its total energy facility for testing electrical power generation. McDonnell Douglas' concept, illustrated in Figure 2-4, uses several large point-focusing Fresnels in one module to achieve temperatures in the 300-to-400°C range. Concentration ratios are currently in the 100-to-200X range with 600X being the theoretical limit. Development of

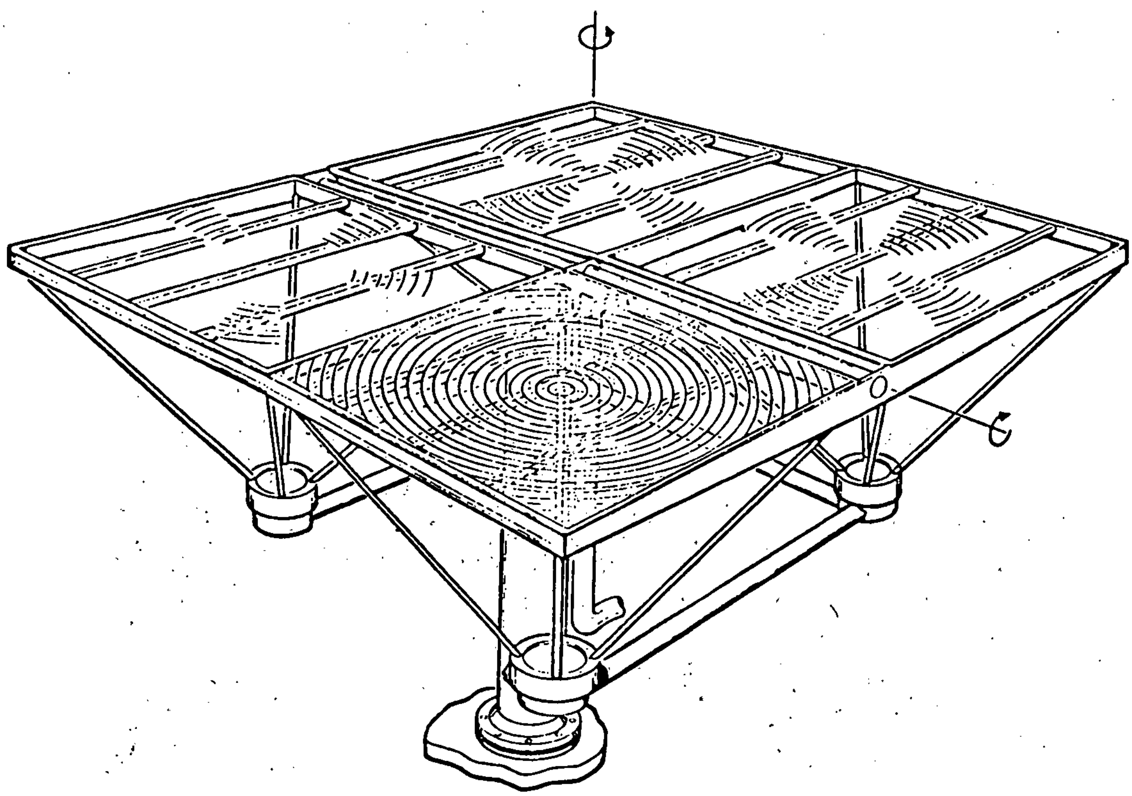


Figure 2-4. McDonnell Douglas Point-Focus Fresnel

this concentrator is linked closely with development and growth in the manufacturing of 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 10X to several hundred X 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 2-5. 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.

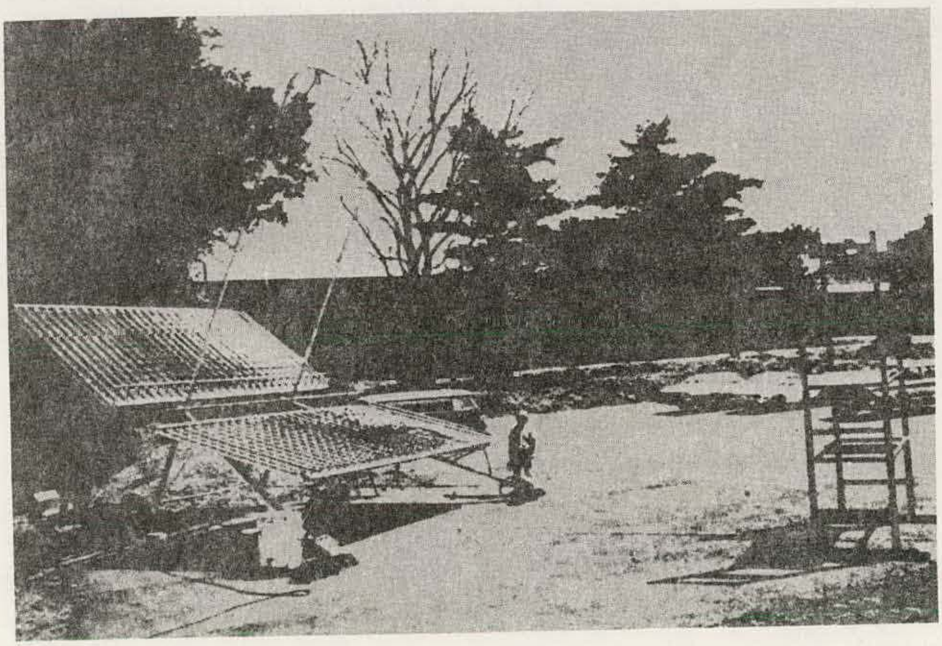


Figure 2-5. Collector in Focused Position

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 axes 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 to 300°C) collector with concentration ratios in the 10-to-50X range. Several variations of this collector currently are 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 2-6. 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 tests at Sandia's Collector Module Test Facility. The parabolic trough is in the most advanced stage of development of medium-to-high-concentrator types.

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 these concentrators are 100 to 300°C with concentration ratios of 20 to 40X.

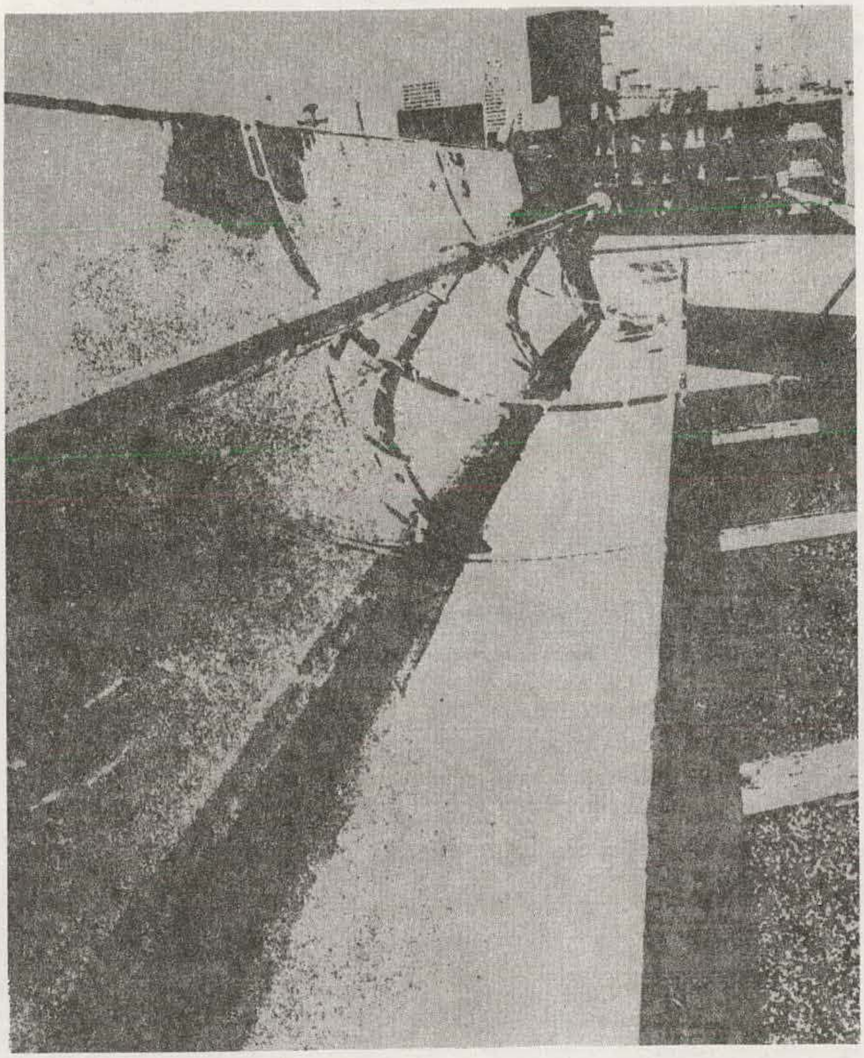


Figure 2-6. Solar Kinetics Parabolic Trough Concentrator

Suntek, Itek, and AAI have designed concentrators of this type. The Suntek SLATS® design has undergone government testing at Sandia Laboratories and in the early phase of the Fort Hood program. This concentrator, shown in Figure 2-7, consists of ten curved facets, which provide a 40:1 concentration. The receiver consists of several pipes arranged in a vee-shape and surrounded by insulation on all sides except the aperature opening. The receiver aperature is vee-shaped with a 60^{o} included angle. Glass covers are double-glased 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.

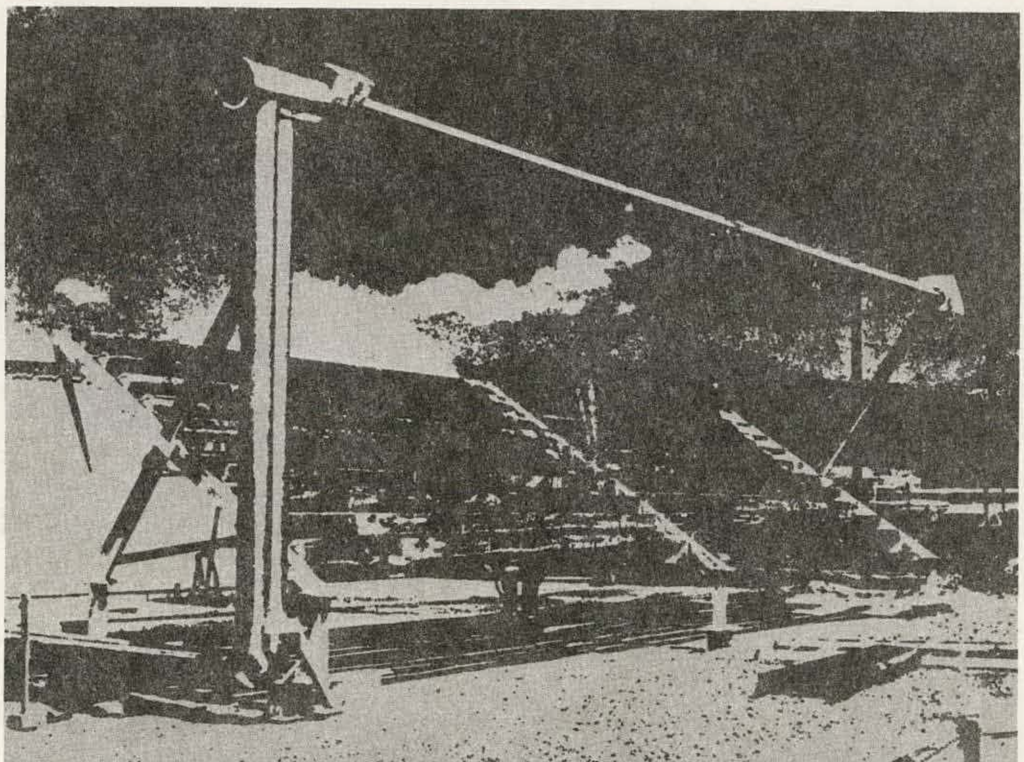


Figure 2-7. The Suntec SLATS[R] Linear Segmented Array

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 to 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 2-8, has recently undergone testing at the collector module test facility at Sandia.

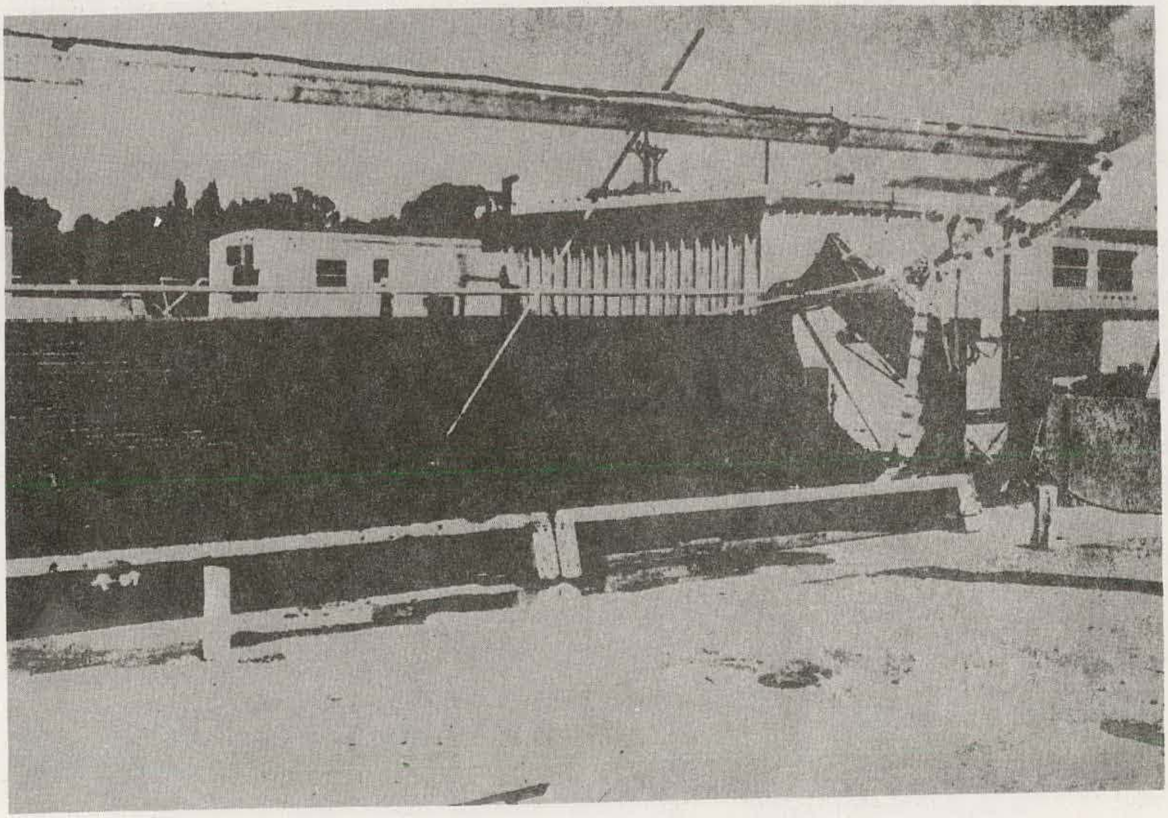


Figure 2-8. General Atomic's Fixed-Mirror Solar Collector

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 Atomoic 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 in construction to a long, narrow, flat plate collector and is mounted on long arms above the trough. These concentrators have undergone prototype testing and show good potential for medium-range temperature applications.

Line Concentrating Fresnel--This type of collector uses either a 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^{o}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 demonstrations). Currently, Northrup is working on development of an advanced design with increased concentration for higher temperature applications.

McDonnell Douglas' concentrator, shown in Figure 2-9, 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.

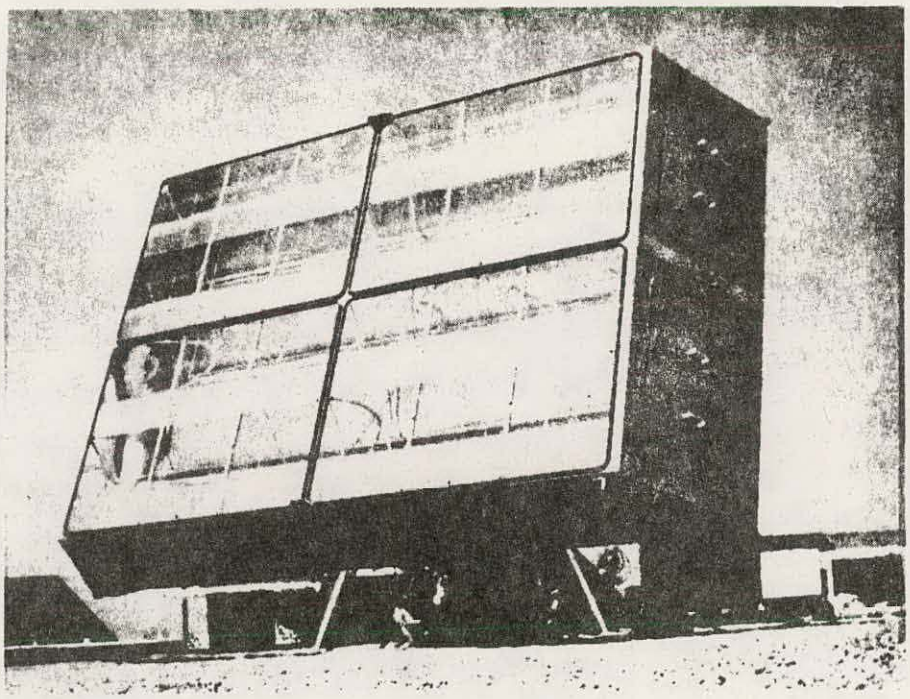


Figure 2-9. McDonnell Douglas' Linear Fresnel Lens Collector

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 its 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 2-10 is a photograph of the prototype concentrator. The original receiver design was for photovoltaics, but thermal receivers are feasible as well.

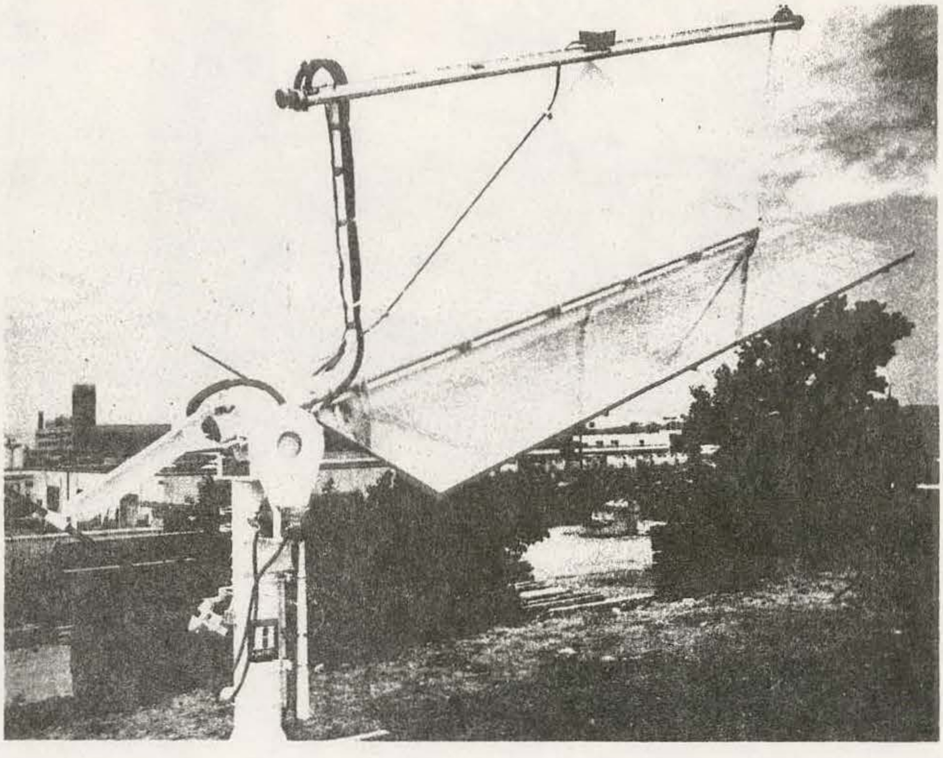


Figure 2-10. Incremental Reflector

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 2-11.

This collector is capable of moderate concentration (in the range of 8 to 20X) with operating temperature up to 200°C. It is hoped that this concentrator will be a low-cost alternative to other collectors currently being used in this temperature range. Application potential is in the heating and low temperature process heat areas.

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

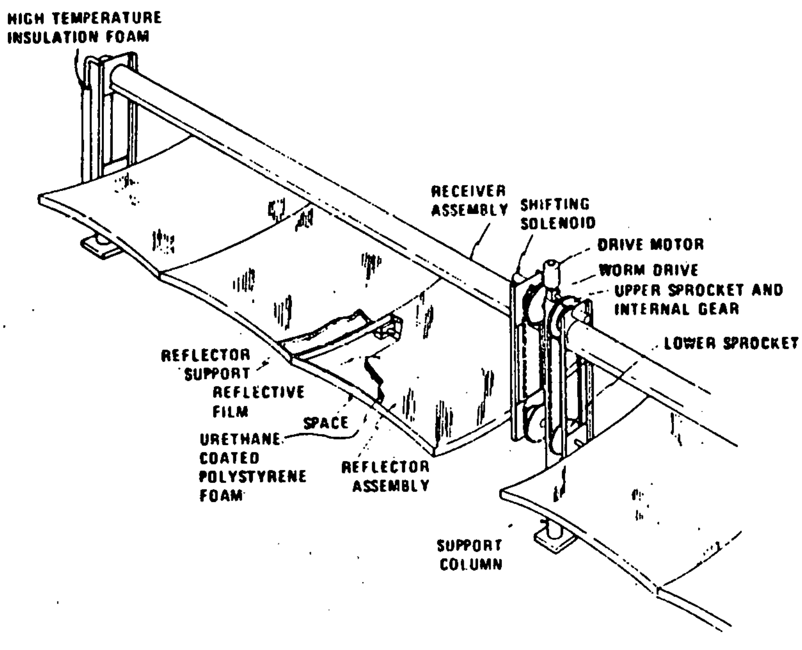


Figure 2-11. Dual-Curvature Collector

Inflated Cylindrical Concentrator--A schematic of this concentrator type is given in Figure 2-12. The concentrator is an inflated plastic cylinder that has thin aluminized 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.

Lawrence Livermore Laboratories 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.

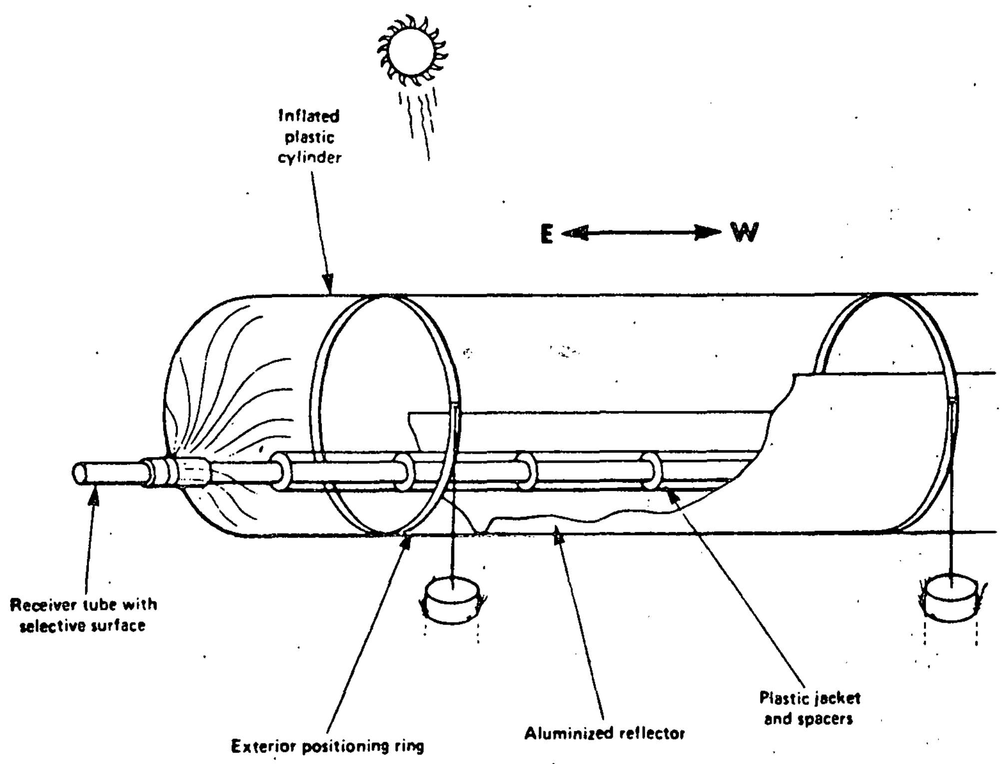
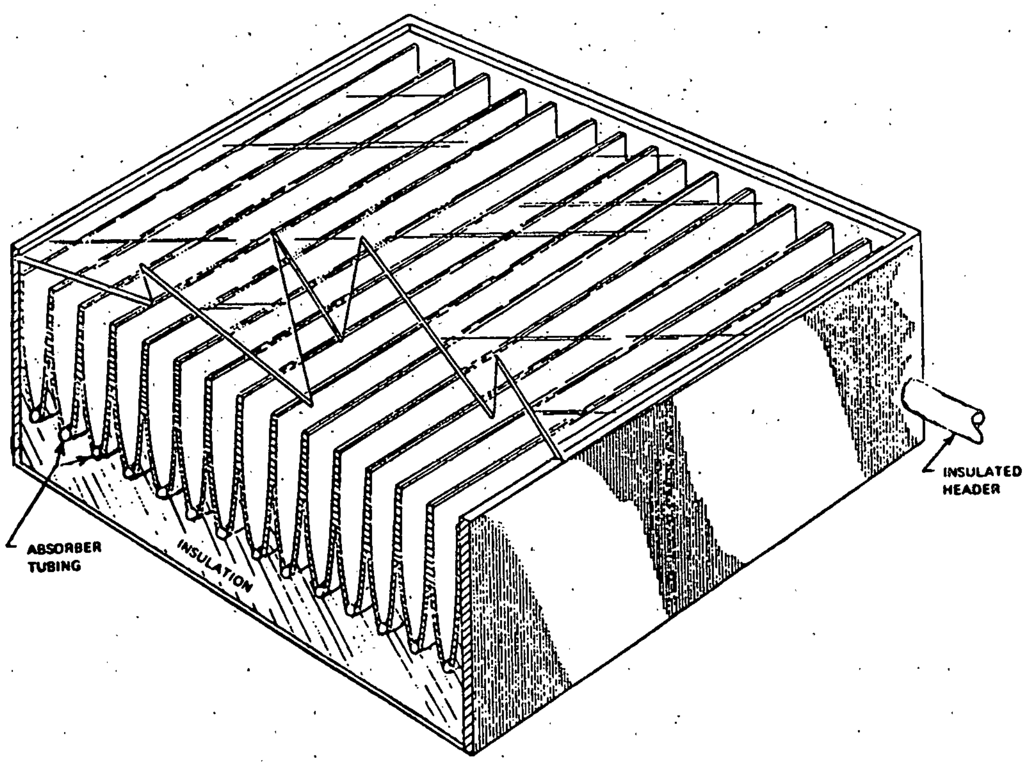


Figure 2-12. Inflated Cylindrical Concentrator.

Compound Parabolic (Winston) Concentrators (CPCs)--This design was developed as an improvement on the flat-plate concentrator. The reflective surface, illustrated in Figure 2-13, 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.



SOURCE: Prepared by OTA using manufacturer's data.

Figure 2-13. Compound Parabolic (Winston) Concentrator

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 designs has a 2X geometric concentration ratio. The reflective surface is a truncated CPC with a combined parabolic involute surface as shown in the corss section in Figure 2-14. 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 2-15) with its evacuated receiver. The concentration for this collector is 1.5X.

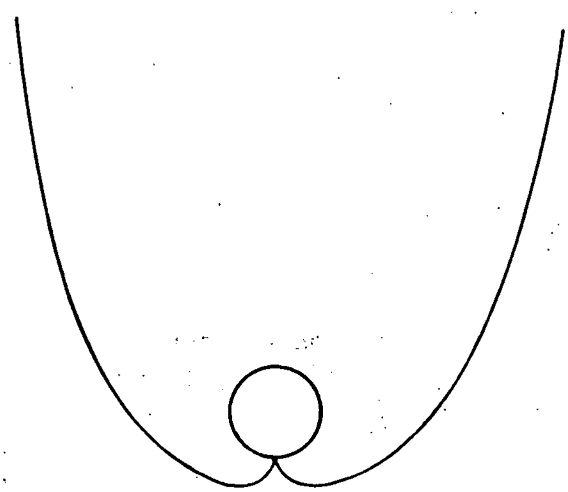


Figure 2-14. Cross Section of CPC with Parabolic and Involute Reflector Surface

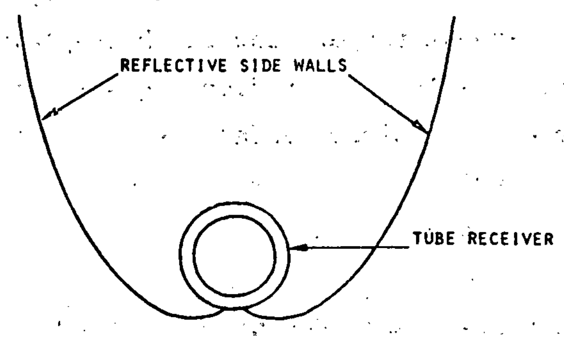


Figure 2-15. Cross Section of CPC with Involute Reflector

<u>Vee Trough</u>--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^{o} 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 to 200^{o}C. This concept is believed to be a good competitor for the heating/cooling market in the 120^{o}C range.

Imaging Collapsing Concentrator--This non-tracking concentrator, illustrated in Figure 2-16, 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 to 4X, with expected operating temperatures of 100 to 150°C. The concentrator is nontracking with an acceptance angle of ±23°. Currently, the concentrator is under design. Construction of a prototype will be accomplished during the ongoing program.

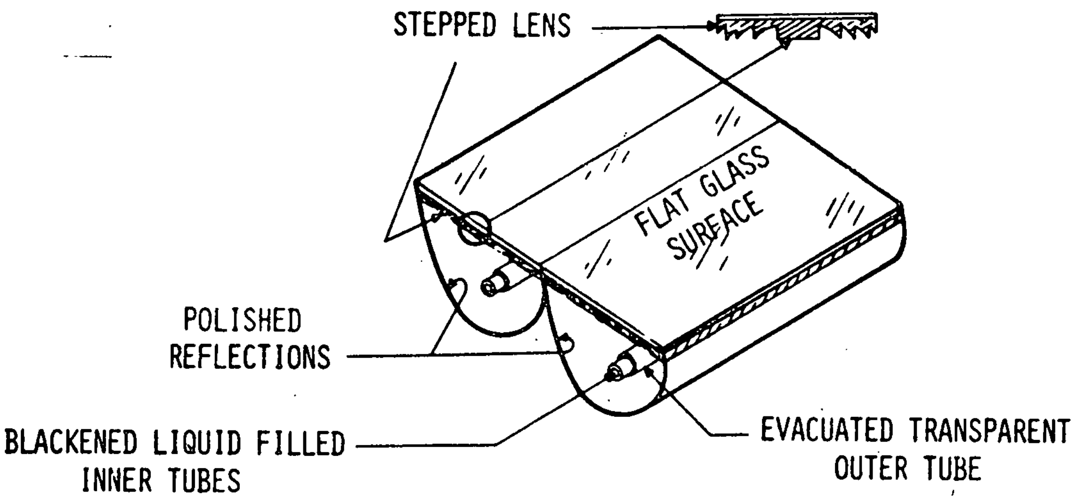


Figure 2-16. Imaging Collapsing Concentrator

<u>Fixed Evacuated Concentrator</u>--This is another nontracking 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 2-17. 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.

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

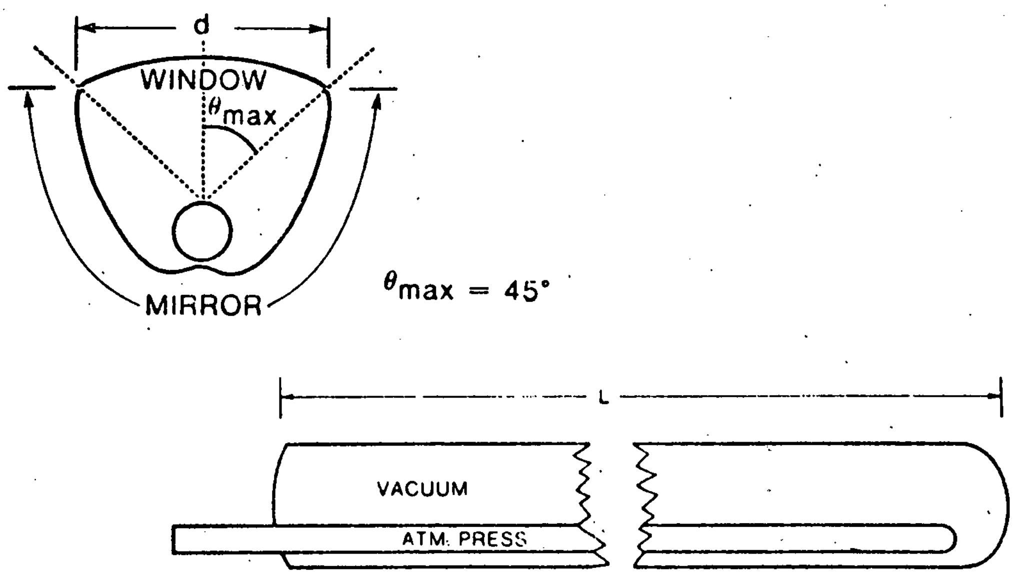


Figure 2-17. Fixed Evacuated Concentrator Concept Cross Section and Side View

Summary

The parabolic trough and line concentrating Fresnel have the largest installed square footage and are considered to be near production status. The linear segmented arrays, fixed-mirror concentrators and 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 and only limited performance data are available. Performance data over the short term are more readily available for most concentrator types. Unfortunately, these data often do not separate optical performance from system performance. Therefore, very little is possible in the way of comparing predicted and actual optical performance.

Upon completion of the literature survey, the selection of the ten concentrator designs for the mathematical 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, in which 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.

- Data should be available 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 mathematical modeling includes:

- 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.

We later added back to the list a Paraboloid of Revolution (Dish) collector.

MATHEMATICAL MODELING

The basic methodology 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 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. Furthermore, 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 from which 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:

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

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:

$$E_p = \underbrace{\int_\lambda}_{\text{Total Spectrum}} \overbrace{\int_{X_1} \int_{X_2}}^{\text{Mirror Surface}} \overbrace{\int_{\delta_1} \int_{\delta_2}}^{\text{Sun Disk}} E(X_1, X_2, \delta_1, \delta_2, \lambda) dX_1 dX_2 d\delta_1 d\delta_2 d\lambda$$

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 angular 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 (= $\overline{Z}$) 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.,

$$\overline{Z} = \int_{-\infty}^{\infty} P_Z(Z)Z\,dZ$$

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

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

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

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

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

$$\overline{E}_p = \underbrace{\int_{\theta_1}\int_{\theta_2}}_{\text{Tracking Inputs}}\underbrace{\int_{\phi_1}\int_{\phi_2}}_{\text{Mirror Imperfections}} P_{\theta_1}P_{\theta_2}P_{\phi_1}P_{\phi_2}\underbrace{\int_{\lambda}}_{\text{Total Spectrum}}\underbrace{\int_{X_1}\int_{X_2}}_{\text{Mirror Area}}\underbrace{\int_{\delta_1}\int_{\delta_2}}_{\text{Sun Disk}} E\,d\delta_2\,d\delta_1\,dX_2\,dX_1\,d\lambda\,d\phi_2\,d\phi_1\,d\theta_2\,d\theta_1$$

The stochastic nature of four of the independent variables in this equation 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 the multiple integral 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.

Approach

Figure 2-18 indicates the general program flow for any concentrator design. Input parameters include the following user options:

- Concentrator type.
- Receiver geometry.
- Reflective or lensing material.
- Error distribution.
- Number of rays to trace.
- Concentrator/receiver dimensions.

For each concentrator/reflector that is being simulated, the Monte Carlo draw is made over the surface.

The simulation is accomplished by randomly selecting a sufficient number of sun rays to statistically represent the sun's intensity pattern as seen from

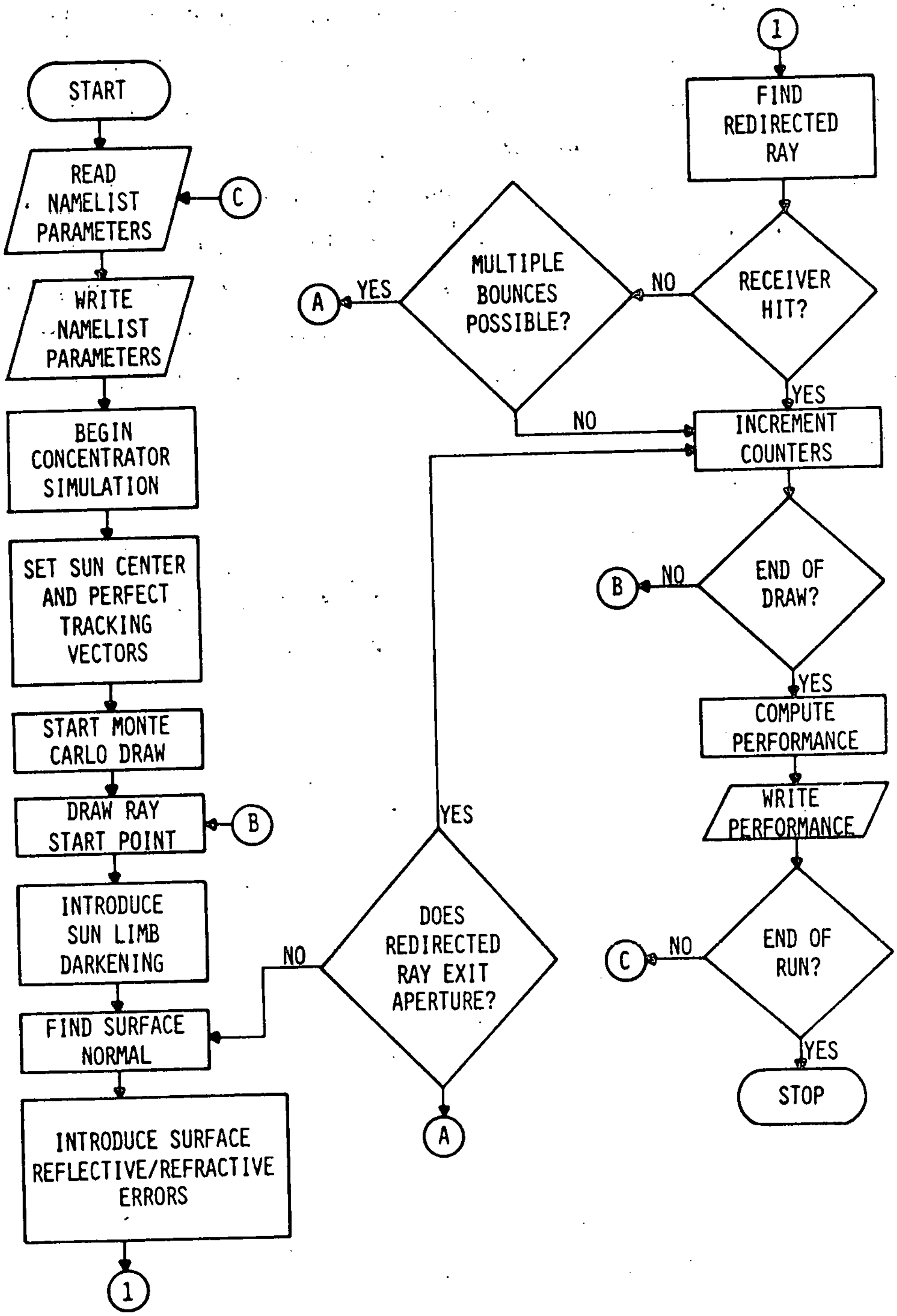


Figure 2-18. Generalized Computer Software Flowchart

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 drawn rays 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.

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 properties of the backing material and reflective/lensing materials being examined.

The ray trace technique uses vector algebra to track each ray along its optical path. The exact mathematical models incorporated into the computer program are discussed in detail in Volume II, "Concentrator Optical Performance Software (COPS) Program User's Manual". These models are discussed here; however, some general statements about the modeling are made so that the reader may get a feel for the Monte Carlo ray trace technique without wandering through the details of Volume II.

The maximum concentration which can be achieved by any solar collector is a function of the sun size, tracking characteristics, surface shape, surface slope errors and the reflective or refractive material's characteristics. The computer program developed for this project treats all of these aspects of the optical problem using a Monte Carlo ray trace technique.

Sun Size--The sun size, or the angular distribution of incoming solar radiation, has been experimentally measured by Lawrence Berkeley Laboratories [1]. Circumsolar profiles vary with time of day, haze conditions and other environmental factors. The present code has one relatively narrow profile for the solar limb darkened sun. Changes in this profile must be accomplished with FØRTRAN changes in subroutine LIMDR.

Solar limb darkening involves the process of accounting for the finite size of the sun and the degradation in solar intensity as a function of angular distance from the sun's center. The limb darkened solar intensity profile used in the simulation code is shown in Figure 2-19. When used with the Monte Carlo technique, the intensity profile creates a weighted draw of rays over the sun radius. The weighted draw must be accomplished such that a sufficient number of randomly selected rays will statistically represent the sun's intensity pattern at the earth's surface.

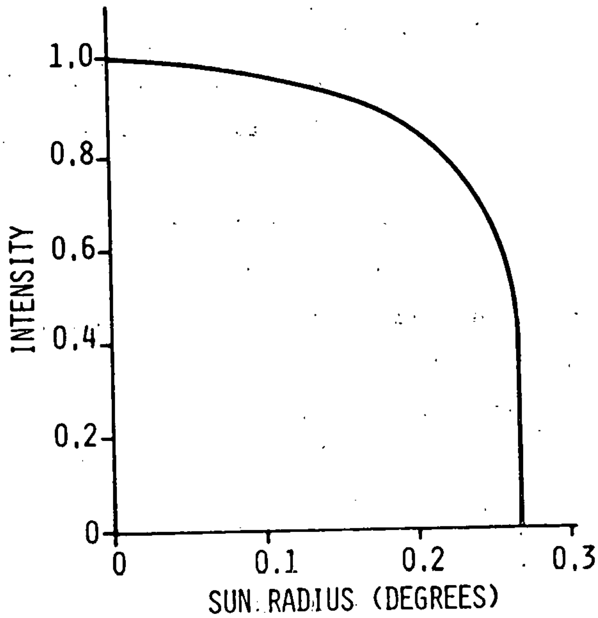


Figure 2-19. Solar Limb Darkening

The assumed intensity distribution shown in Figure 2-19 is based on measured data excluding the effect of circumsolar radiation. An option to model the sun with limb darkening and circumsolar radiation does exist in the code; however, we have primarily used the limb darkened sun only. Errors in the redirected flux profile will be present to the extent that this data is in error.

Tracking Characteristics--Tracking errors are treated as discrete, fixed errors for an individual simulation. That is, a single value of tracking error--not a random or in some fashion distributed set of error values--is used. When addressing the net impact of tracking errors on collector system performance, we recommend that the concentrator performance first be established as a function of discrete tracking error. Using a curve fit of this type of data, an analysis of the tracking problem can be done using statistical methods for time-varying tracking errors [2]. The end result is then a statiscally-averaged optical performance depending upon the error band of the tracking control.

Surface Shape--The treatment of concentrator surface shapes is discussed in detail in Volume II, the COPS User's Manual. Each concentrator surface is mathematically defined such that the ideal surface normal and tangent vectors can be derived.

Surface Slope Errors--Finite quality optics are introduced into the model to account for uncertainties in the surface mirror quality. There are two optical parameters that are assumed to be known only statistically. The two parameters are angular uncertainties in the mirror surface normal at any point on the mirror surface. We assume that each of these two parameters is statistically independent of each other or any other design parameter. For example, a given error in the 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.

Figure 2-20 shows how the surface error varies from the ideal normal. For the mirror surface normal, the angular error from the ideal normal is also assumed to be a normal distribution and this error is assumed to be equally likely in any rotational direction. No dependence of these errors on wind, mirror attitude or position on the mirror has currently been included on our analysis. However, these errors can be introduced through the normal distribution function for surface errors by changing the mean value of the distribution to something other than zero. If it is known that an error in the surface shape has in some manner been created, then the mean angular slope error would not be zero. If this mean angular error were a function of position on the concentrator surface, this also could be accounted for within the computer software.

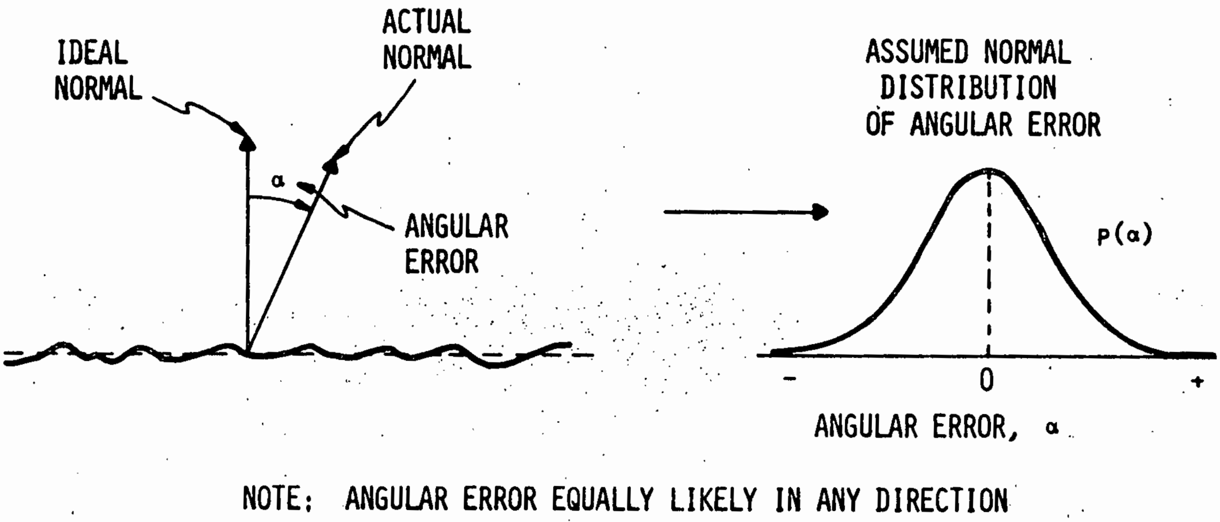


Figure 2-20. Mirror or Lens Surface Error Distribution

Material Characteristics--For reflective materials, the most available and accepted data have been developed by Pettit and Butler at Sandia, using bi-directional reflectometry. Data are available for about 15 materials and we have included ten of these in the computer code.

The ten selected materials and their measured data are shown in Table 2-2. This table indicates the hemispherical reflectance, $R_s(2\pi)$ and one or two reflectance values and standard deviations which characterize the reflected beam profile of the specific material as a normal (or sum of normal) distribution. In a method identical to the surface slope error, these distributions are a material slope error for the purposes of the computer program.

In the program, the reflectance error standard deviation (σ_r) is one-half that of the standard deviation given in Pettit and Butler's data for various materials. The reason for this is that reflection magnifies the errors by a factor of two. As with surface errors, the error is drawn over a normal distribution with standard deviation σ_r.

For lens materials, the absence of 15 different materials being supplied for collectors has prevented a similar data set compilation. Lens materials seem to be in an earlier stage of development than reflective materials. Therefore, the computer program does not contain various lens material options. Instead, the most commonly used material, PMMA (acrylic) is represented by the program. The index of refraction as a function of wavelength is used in the optical analysis. This data can be used in combination with a user-specified lens facet size to create an infinite variety of lenses [3].

COMPUTER CODE SAMPLE RESULTS

This section presents sample results from the Concentrator Optical Performance Software (COPS) computer program. Output formats and input instructions to run the example of the COPS program are provided in Volume II of this report.

Table 2-2. Reflective Material Characteristics

MATERIAL	SUPPLIER	COST ($\$/FT^2$)	λ (RM)	R_1	C_1 (MRAD)	R_2	σ_2 (MRAD)	$R_s(2\pi)$
1. ALZAK TYPE I SPECULAR PARALLEL TO ROLLING MARKS	ALCOA	1.50	505.	0.29	0.29	0.27	7.1	0.85
2. 3M SCOTCHCAL 5400 LAMINATED TO BACKING SHEET	3M COMPANY	0.50	500.	0.86	1.9	--	--	0.85
3. 3M FEK-163 LAMINATED TO BACKING SHEET	3M COMPANY	~1.00	500.	0.86	0.90	--	--	0.85
4. ALUMINIZED 2 MIL FEP TEFLON (G405600) LAMINATED TO BACKING SHEET	SHELDAHL	1.00-1.50 (PROJECTED)	500.	0.80	1.3[illegible]	0.07	30.9	0.87
5. SILVERED 2 MIL FEP TEFLON (G400300) MOUNTED ON OPTICALLY FLAT PLATE	SHELDAHL	EXPERIMENTAL	550.	0.67	0.77	0.28	6.9	0.96
6. FRONT SURFACE ALUMI NIZED MYLAR (200XM648A) STRETCHED MEMBRANE	BOEING	0.20	500.	0.90	<0.25	--	--	0.88
7. KINGLUX NO. C4 PERPENDICULAR TO ROLLING MARKS	KINGSTON IND.	1.50	498.	0.65	0.37	0.23	16.1	0.85
8. TYPE 3002 HIGH PURITY AL BUFFED AND BRIGHT ANODIZED	METAL FABRICATIONS, INC.	EXPERIMENTAL	550.	0.44	1.4	0.43	10.3	0.84
9. CORNING 0317 GLASS 1.5 MM THICK EVAPORATED SILVER	CORNING GLASS	EXPERIMENTAL	500.	0.95	<0.25	--	--	0.95
10. LAMINATED LOW-IRON SHEET GLASS 3.35 MM THICK SILVERED	GARDNER MIRROR CO.	2.13	500.	0.92	<0.05	--	--	0.90

SOURCE: PETTIT AND BUTLER, "LASER RAY TRACE AND BI-DIRECTIONAL REFLECTOMETRY MEASUREMENTS OF VARIOUS SOLAR CONCENTRATORS," SANDIA LABORATORIES.

Monte Carlo Errors

No straightforward error analysis can be carried out for the Monte Carlo ray trace simulation as used in the COPS program. However, speaking in a general manner, the error in the results can be expected to be roughly proportional to the square of the number of observations. Thus, it requires four times the number of observations to reduce an error by a factor of two. This can be quite costly in terms of computer time if very accurate answers are required for a quantity which involves a small portion of the ray trace procedure. For example, if the power density on a particular region of a receiver is desired to within 5 percent accuracy, the user of a Monte Carlo ray trace approach may have to trace more than 100,000 rays to achieve the desired accuracy. On the other hand, a ratio of hits to misses on the receiver can be obtained accurately with 10,000 rays or fewer. Fortunately, in most cases, the desired answers are not minute details. Further, the mathematical modeling accuracy often will limit the accuracy of the results more than the constraint of a reasonable number of observations.

As an example of the errors with which we deal in the COPS program, we ran the parabolic trough configuration with a 5,000-ray draw over the aperture. This was done ten times with ten independent sets of pseudorandom numbers. The results of the ten runs are shown below:

RUN NUMBER	1	2	3	4	5	6	7	8	9	10
OPTICAL EFFICIENCY	.867	.859	.870	.861	.869	.868	.876	.867	.864	.870

This run set gives a mean of 0.867 and standard deviation of 0.005. This seems to be a reasonable approximation. In all the optical efficiency results which follow we have used a 5,000-ray draw.

Concentrator Optical Performance

The COPS program was exercised for each type of concentrating collector modeled. For some concentrator types, the choice of design was rather arbitrary since we did not have exact dimensions or design specifications for all collectors. For some concentrators we attempted to match published collector configurations that were studied or tested. In either case, we make no claims as to the design effectiveness. That is, we did not exercise the COPS program to optimize iteratively the optical performance of any of the concentrator designs.

In fact, optical performance alone should not be maximized without regard to the overall collector performance and cost. The output of the COPS program must be combined with a thermal analysis and cost projections to arrive at the optimal (most cost-effective) design. We have not evaluated the thermal performance of any of the concentrators. Further, we can make no definitive statements about collector costs. Although the literature survey of this project did find some sources of cost data, the costs always seemed to be highly variable. Therefore, the ranking of collectors by cost involves a subjective judgement on the part of the ranker. We have not attempted to do this.

For any of the concentrators, the literature survey did result in a gathering of data sources. The sources most used in the mathematical modeling and code exercising are given for each concentrator type in Table 2-3. Where possible we used dimensions from these sources when making the test runs of the computer program.

When making the test runs of the computer code, we attempted to look at the effects of optical quality (surface errors) and concentration ratio on concentrator performance. In some cases the concentration is closely fixed by the design (e.g., Involute CPC); studies of the combined influence of surface

Table 2-3. References for Modeled Concentrators

MODELED CONCENTRATOR	REFERENCE
FACETED MIRROR SOLAR CONCENTRATOR - RPI	ROGERS, W., AND BORTON, D., "EVALUATION OF A FACETED MIRROR SOLAR CONCENTRATOR," RENSSELAER POLYTECHNIC INSTITUTE, SOLAR CONCENTRATING COLLECTORS, PROCEEDINGS OF THE ERDA CONFERENCE ON CONCENTRATING SOLAR COLLECTORS, PP.4-37, ATLANTA, 1977. PHONE CONVERSATIONS WITH D. BORTON.
FIXED-MIRROR, TWO AXIS TRACKING RECEIVER	REICHERT, DR. JOHN D., "THE CROSBYTON SOLAR POWER PROJECT: FIXED SPHERICAL MIRROR/TRACKING RECEIVER," SOLAR CONCENTRATING COLLECTORS, PROCEEDINGS OF THE ERDA CONFERENCE ON SOLAR CONCENTRATING COLLECTORS, PP.3-61, ATLANTA, 1977. WALTERS, R.R., O'NEILL, M.J., AND GUPTA, Y.P., "FIXED MIRROR DISTRIBUTED FOCUS SOLAR THERMAL ELECTRIC POWER SYSTEMS DEVELOPMENT," PROCEEDINGS OF THE 1977 ANNUAL MEETING, AMERICAN SECTION ISES, VOLUME 1 (SECTION 14-25), PP.21-26. 1977. OPTICAL ANALYSIS OF THE FIXED MIRROR DISTRIBUTED FOCUS COLLECTOR, REPORT 9-10100/TR75-02, E-SYSTEMS INC., DALLAS, DECEMBER, 1975 (REVISED APRIL, 1976). CLAUSING, A.M., "THE PERFORMANCE OF A STATIONARY REFLECTOR TRACKING A BSORBER SOLAR CONCENTRATOR," SHARING THE SUN, VOLUME 2, P.304, WINNIPEG, 1976.
PARABOLIC TROUGH CONCENTRATOR	DATA SHEETS FROM: HEXCEL SOLAR KINETICS ACUREX DEL MANUFACTURING
LINEAR FRESNEL	NORTHRUP MANUFACTURER'S DATA SHEET, NORTHRUP, INC. HASTINGS, L.J. AND ALLUMS, S.L., "PERFORMANCE CHARACTERISTICS OF A 1.8 BY 3.7 METER FRESNEL LENS SOLAR CONCENTRATOR," NASA/MARSHALL, SOLAR CONCENTRATING COLLECTORS, PROCEEDINGS OF THE ERDA CONFERENCE ON CONCENTRATING SOLAR COLLECTORS, PP.2-71, ATLANTA, 1977. HASTINGS. L.J., ALLUM, S.L., AND CROSBY, R.M., "AN ANALYTICAL AND EXPERIMENTAL EVALUATION OF THE PLANS - CYLINDRICAL FRESNEL LENS SOLAR CONCENTRATOR," NASA/MARSHALL/BALL STATE UNIVERSITY, SHARING THE SUN, VOLUME 2, P.275, WINNEPEG, 1976. NIXON, GENE, "COST ACRYLIC FRESNEL LENS SOLAR CONCENTRATOR," SWEDLOW INC., SOLAR CONCENTRATING COLLECTORS, PROCEEDINGS OF THE ERDA CONFERENCE ON SOLAR CONCENTRATING COLLECTORS, PP.5-33, ATLANTA, 1977. COSBY, R., "THE LINEAR FRESNEL LENS: SOLAR OPTICAL ANALYSIS OF TRACKING ERROR EFFECTS," PROCEEDINGS OF THE 1977 ANNUAL MEETING, AMERICAN SECTION ISES, VOLUME 1, PP.35-14, ORLANDO, 1977.
INCREMENTAL REFLECTOR	MCCC PHOTOVOLTAIC CONCENTRATING COLLECTOR QUARTERLY PROJECT REVIEW, HONEYWELL INC. ENERGY RESOURCES CENTER, 15 NOV., 1977.

Table 2-3. References for Modeled Concentrators (concluded)

INFLATED CYLINDRICAL CONCENTRATOR (JPL)	GERICH, JERRY W., "AN INFLATED CYLINDRICAL CONCENTRATOR FOR PRODUCING INDUSTRIAL PROCESS HEAT," SOLAR CONCENTRATING COLLECTORS, PROCEEDINGS OF THE ERDA CONFERENCE ON SOLAR CONCENTRATING COLLECTORS, PP.2-103, ATLANTA, 1977.
CPC INVOLUTE REFLECTOR	MATHER, G.R., AND BUKLEY, D.C., "PERFORMANCE OF AN EVACUATED TUBULAR COLLECTOR USING NON-IMAGING REFLECTORS," OWENS-ILLINOIS, SHARING THE SUN, VOLUME 2, PP.64-78, 1976.
CPC - CHAMBERLAIN (PARABOLIC/INVOLUTE)	RABL, ARI, "SOLAR CONCENTRATORS WITH MAXIMAL CONCENTRATION FOR CYLINDRICAL CONCENTRATORS," APPLIED OPTICS, VOLUME 15, NUMBER 7, 1976.
CPC - GENERAL INFORMATION	RABL, ARI, "OPTICAL AND THERMAL PROPERTIES OF COMPOUND PARABOLIC CONCENTRATORS," SOLAR ENERGY, VOLUME 18, PP.497-511, 1976. COLE, R., "LONG TERM AVERAGE PERFORMANCE PREDICTIONS FOR COMPOUND PARABOLIC CONCENTRATING SOLAR COLLECTORS," ARGONNE NATIONAL LABORATORIES. PATTON, R., "DESIGN CONSIDERATIONS FOR A STATIONARY CONCENTRATING COLLECTOR," SOLAR CONCENTRATING COLLECTORS, PROCEEDINGS OF THE ERDA CONFERENCE ON SOLAR CONCENTRATING COLLECTORS, PP.3-37, ATLANTA, 1977. COLE, ALLEN, LEVITZ, MCINTIRE, AND SCHERTZ, "PERFORMANCE AND TESTING OF A STATIONARY CONCENTRATING COLLECTOR," SOLAR CONCENTRATING COLLECTORS, PROCEEDINGS OF THE ERDA CONFERENCE ON SOLAR CONCENTRATING COLLECTORS, PP.3-31, ATLANTA, 1977.
VEE TROUGH	SELCUK, M.K., "A FIXED MODERATELY CONCENTRATING COLLECTOR WITH REVERSIBLE ASSYMETRIC VEE-TROUGH AND VACUUM TUBE RECEIVER," SOLAR CONCENTRATING COLLECTORS, PROCEEDINGS OF THE ERDA CONFERENCE ON CONCENTRATING COLLECTORS, PP.3-93, ATLANTA, 1977.
IMAGING COLLAPSING CONCENTRATOR (SET)	SLETTEN, CARLYLE, J., IMAGING COLLAPSING CONCENTRATORS, CONTRACT EG-77G-04-4163, SOLAR ENERGY TECHNOLOGY INC., 3RD ANNUAL SOLAR HEATING AND COOLING R&D CONTRACTORS. PHONE CONVERSATIONS AND DATA FROM C. SLETTEN.

errors and concentration ratio are limited. For the lower concentration ratio collectors, the surface errors are not much of a factor in the optical performance. Optical efficiency, as computed by the COPS program, is defined as the fraction of total possible direct radiation which the concentrator successfully redirects to the receiver surface. Thus, optical efficiency includes the cosine effect, end losses, reflectance or transmittance losses and spillage losses at the receiver. By multiplying optical efficiency by direct normal radiation and the concentrator aperture area, the power striking the receiver is obtained. As an example, a vee trough with a concentration ratio of 3X (as defined by aperture opening to receiver diameter ratio) was examined. The vee trough design was as shown in Figure 2-21.

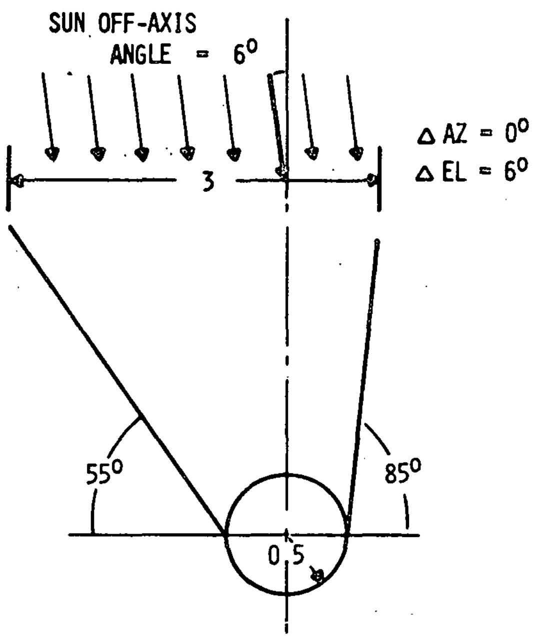


Figure 2-21. Vee Trough Design

The optical efficiency computed as a function of surface error was:

SURFACE ERROR STANDARD DEVIATION	OPTICAL EFFICIENCY
0 mr	0.88
5 mr	0.88
10 mr	0.88
15 mr	0.88

Obviously, the side reflectors need not be made "optically flat" for this concentrator configuration.

As an opposite example, we ran the COPS program for the FMTR concentrator at a concentration ratio of 115X. This corresponds to a 1/2-degree cone angle receiver. The optical efficiency as a function of surface error is shown in Figure 2-22. If a concentration ratio of 115X is desired, then Figure 2-22 shows that surface errors should not exceed the 2-to-3 mr range. Lower concentration ratios could tolerate higher errors and vice versa.

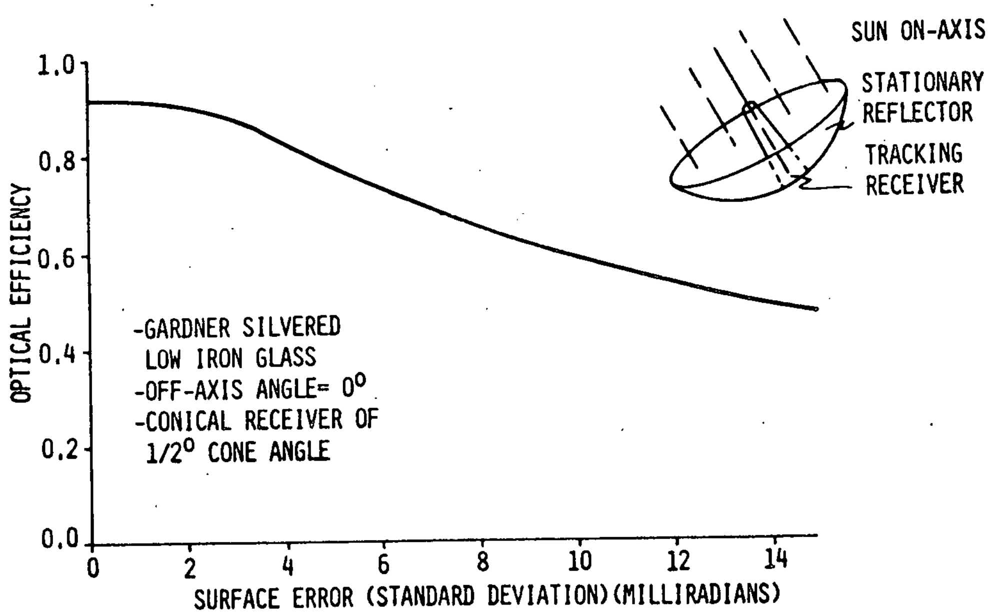


Figure 2-22. Optical Efficiency as a Function of Surface Error: Fixed-Mirror Tracking Receiver Collector

Figure 2-23 shows the same type of data in a slightly different format for the paraboloid of revolution (dish) collector. In this figure, the effect of higher surface errors is shown to be greater as concentration ratio is increased. Thus, a tradeoff in manufacturing tolerance and optical/thermal performance can be started using this data. One needs to create a similar data set defining thermal performance as a function of concentration ratio.

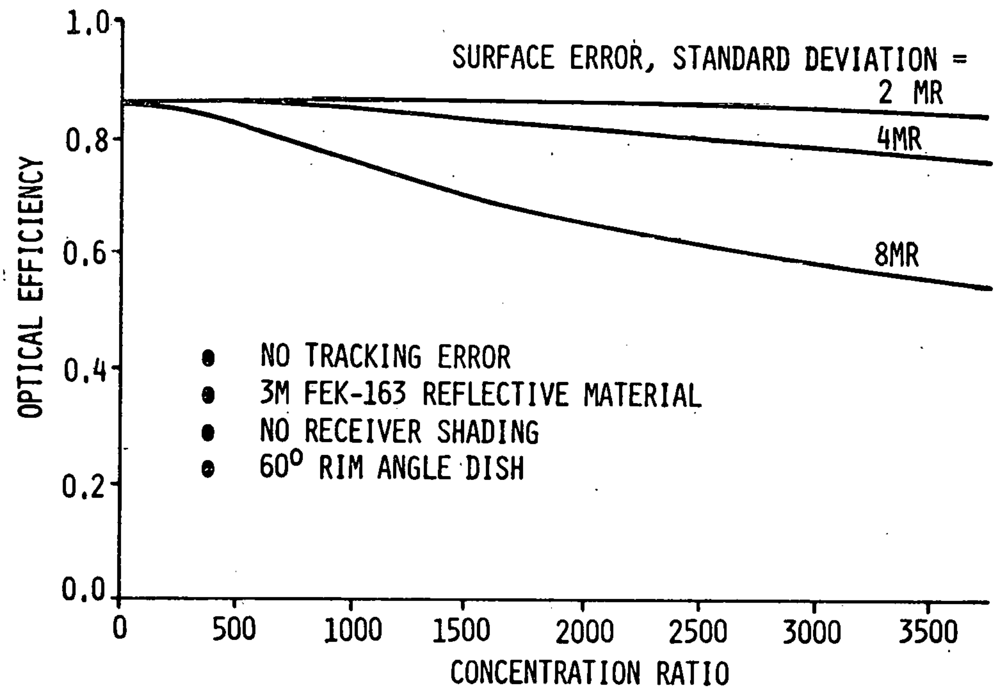


Figure 2-23. Optical Efficiency as a Function of Surface Error: Paraboloid of Revolution (Dish)

Figure 2-23 has no tracking error in the efficiency results. When a finite tracking error is introduced, the results are affected to show lower optical efficiency. For example, at a 4-mr surface error and a concentration ratio of 2100X, the optical efficiency as a function of tracking accuracy is as shown in Table 2-4.

Table 2-4. Paraboloid of Revolution (Dish) Performance as a Function of Tracking Error (4 mr Surface Error, Concentration Ratio = 250X)

TRACKING ERRORS		OPTICAL EFFICIENCY
AZIMUTH AXIS	ELEVATION AXIS	
0.0 mr	0.0 mr	0.82
1.4	1.4	0.82
2.8	2.8	0.81
5.6	5.6	0.79

The small decline in optical efficiency indicates that the 4-mr surface error budget has greater impact than these tracking errors. At a smaller surface error we can expect that the dish would be much more sensitive to tracking errors. This would not be true for lower concentration ratios.

The optical performance of a parabolic trough concentrator is shown in Figure 2-24. The basic Corning 0317 silvered glass has a total reflectance of 0.95. For the trough examined, it was assumed that incoming radiation which fell on the top of the receiver was lost. This would be true optically for an insulated receiver. For a concentration ratio of 60X, the fraction lost on the receiver top would be 1.67 percent of the total available. Therefore, if no spillage were encountered, either wide of the receiver or off the ends, then the optical efficiency could be at best 0.93. The upper dashed curve in Figure 2-24 then represents the best possible efficiency at all off-axis sun angles. This best would be true for an infinitely long receiver. The two solid curves show the computed efficiency for 3-mr and 6-mr surface error budget. At 3-mr error, the spillage wide of the receiver is negligible (less than 1 percent), so that the difference between the dashed and 3-mr solid curve is due to end losses. These would vary as the collector length-to-width ratio varies. The smaller this ratio the larger the end losses at a given off-axis angle.

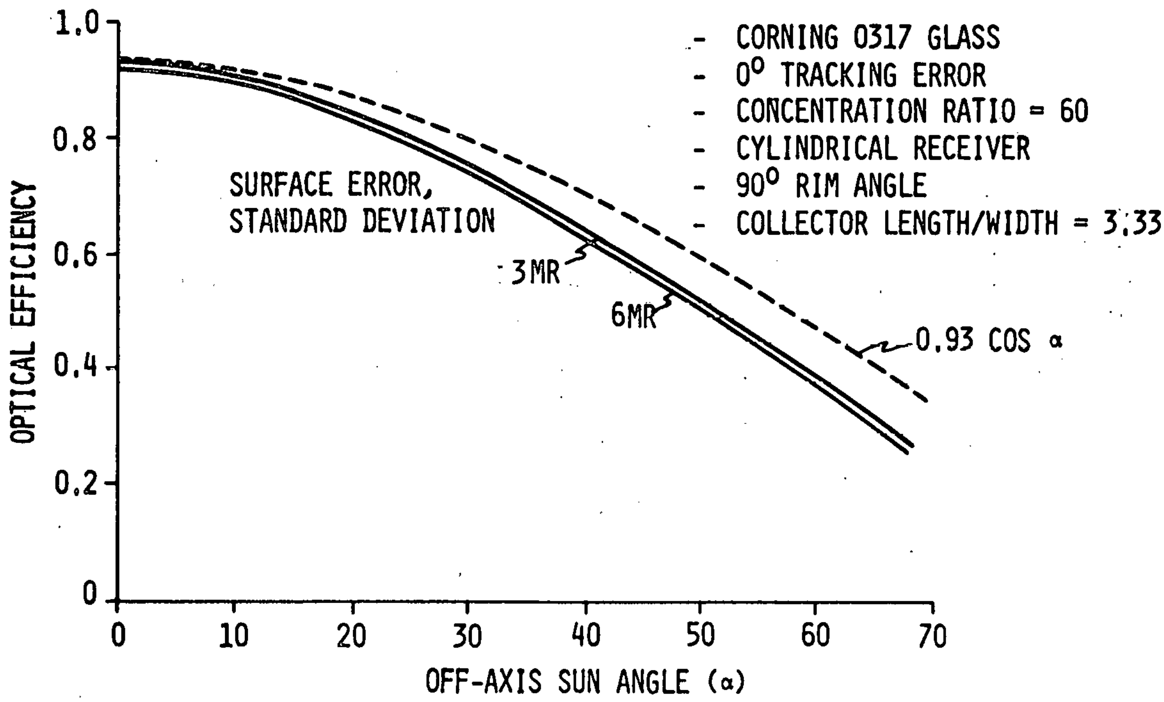


Figure 2-24. Parabolic Trough Performance

Optical efficiency data from test runs on the Inflatible Cylindrical Concentrator are shown in Figure 2-25. Three different concentration ratios were examined at a 4-mr surface error. Since the concentration is fairly low, the surface error is not a large factor in finding the best design.

Data for the linear Fresnel concentrator is shown in Figure 2-26. In this example we examined the effect of varying the lens facet width and concentration ratio. A surface error standard deviation of 3-mr was used. It is apparent that the aberrations due to increased facet size can dramatically affect performance. At the more reasonable, smaller facet size of 16 mm, a concen-

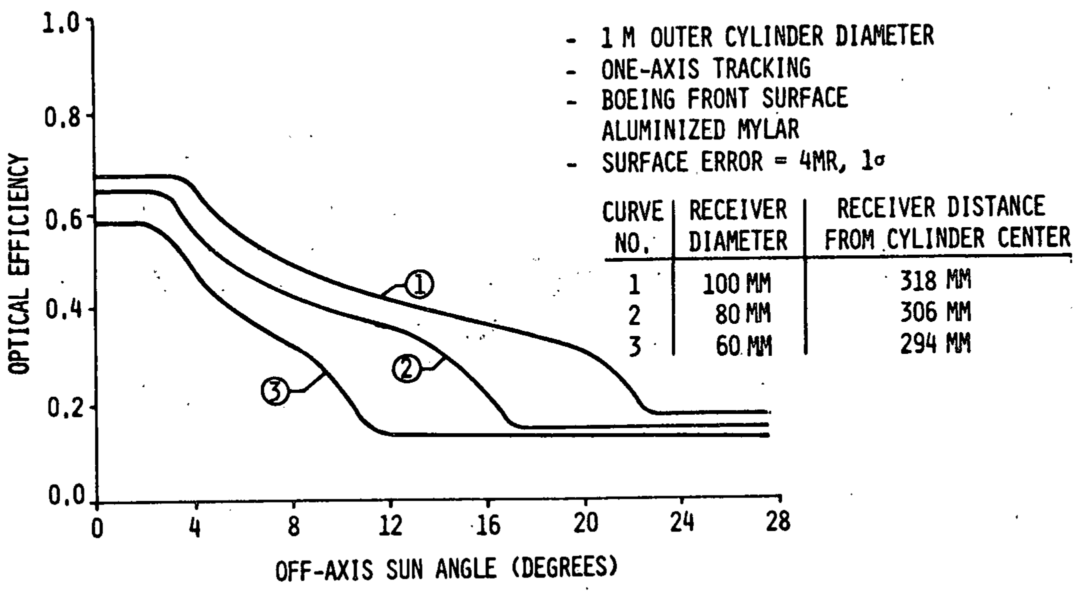


Figure 2-25. Inflated Cylindrical Solar Concentrator

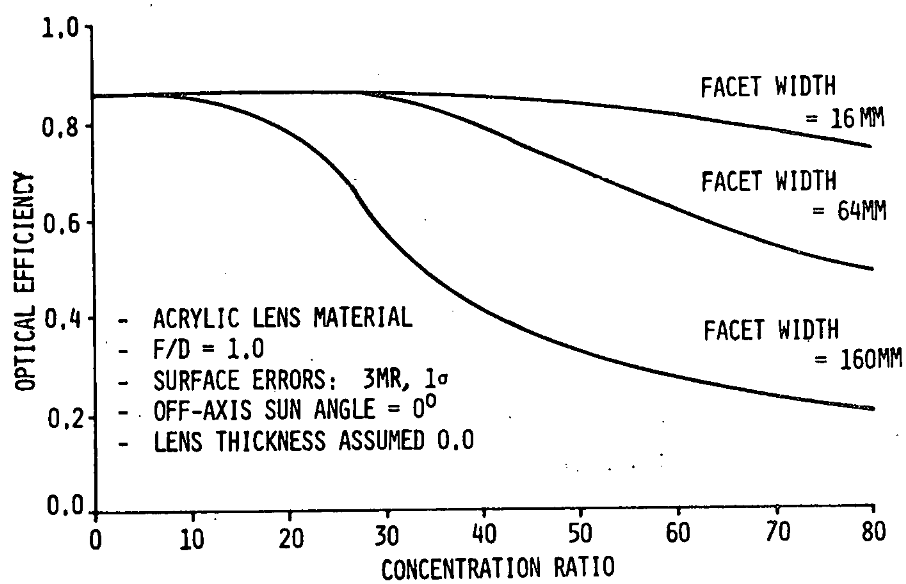


Figure 2-26. Linear Fresnel Lens Concentrator

tration ratio of 45 to 55X can be achieved before surface errors and color abberations begin to reduce performance.

Optical efficiency as a function of off-axis sun angle for the two CPC-type concentrators is shown in Figure 2-27. The involute CPC has a slightly higher optical efficiency since more rays directly strike the receiver for the lower concentration ratio. These rays striking directly do not bounce off the reflecting surface and lose some energy. The involute CPC performance falls off slightly with increasing off-axis angle due to increased ray bounces. Actually, the optical efficiency here is lower than it should be because the ray trace accounts only for direct radiation and deals only with specular reflections. All diffuse is assumed lost. The modification of the ray trace to include this effect was not possible within the time constraints of the current project. However, it could be accomplished if a user were interested in the minor details this extra modeling could add. We do not believe this is an issue for the CPC concentrators.

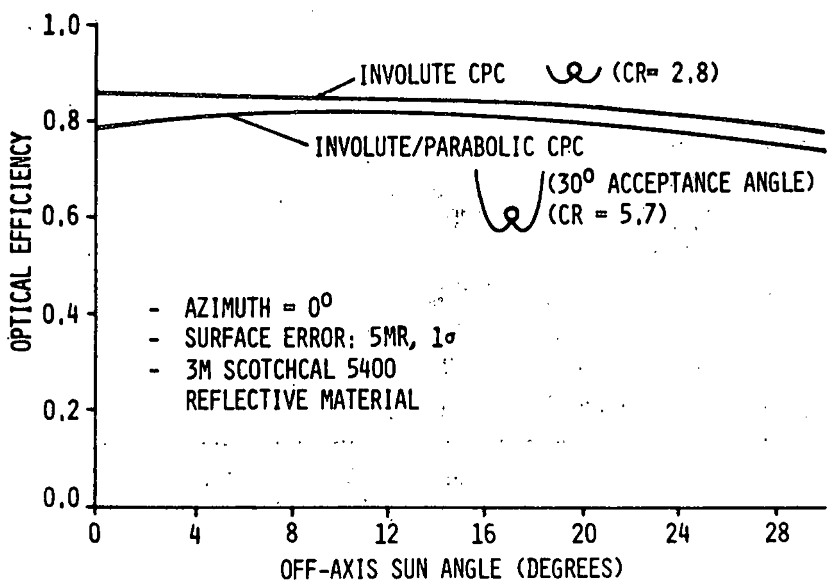


Figure 2-27. Compound Parabolic Concentrators

A test run of the RPI Faceted-Mirror Concentrator resulted in the data plotted in Figure 2-28. The Figure shows performance as a function of concentration ratio for two off-axis sun angles. At low concentration ratio, the decrease in performance with increased off-axis angle is simply due to a decreased average cosine between the morror facet and the sun. Computed average cosines are:

OFF-AXIS SUN ANGLE	AVERAGE COSINE
0^{o}	0.97
18^{o}	0.96

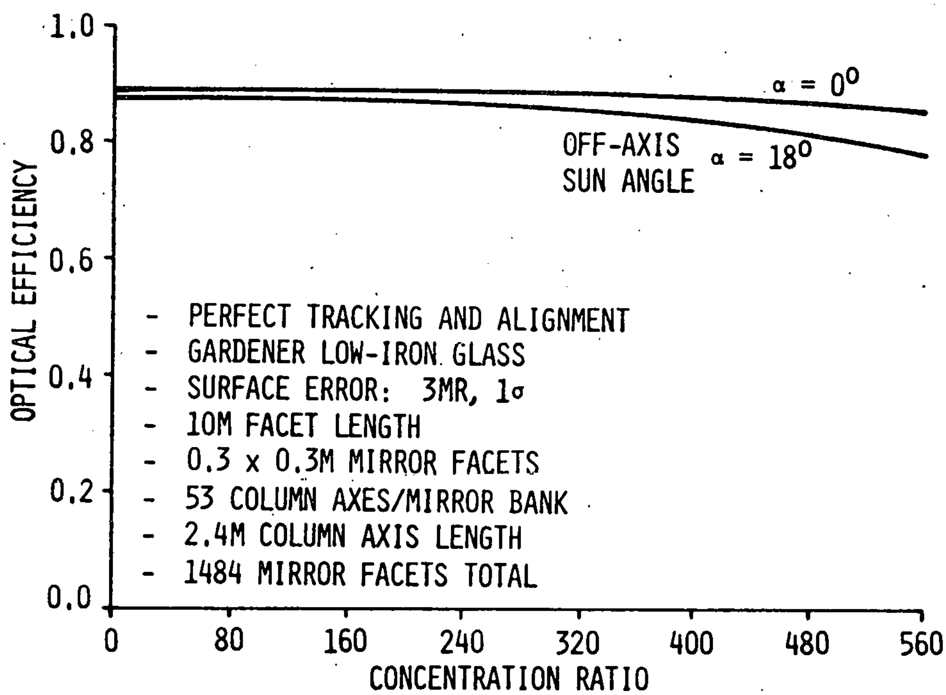


Figure 2-28. RPI Faceted Mirror Concentrator

At higher concentration ratios the drop in performance from a 0^{o} off-axis angle to an 18^{o} off-axis angle is due to both cosine effects and focusing aberrations of the concentrator configuration. We have made no attempt to optimize this design and in phone conversations with Dave Borton of RPI, we learned that newer versions of this concentrator effectively average out the aberrations by curving the column axes.

Figure 2-29 shows the optical efficiency of an incremental reflector collector as a function of concentration ratio for two off-axis sun angles. The results shown assume that, without absorbing, the receiver blocks incoming radiation. Thus, it would be as though only redirected rays on a photovoltaic array are used and the top of the receiver is insulated. The optical efficiency first increases with increasing concentration ratio because the receiver blockage is more important than the reflected power spillage. At larger concentrations, the receiver blockage is smaller and reflected ray spillage is larger, causing a decrease in optical efficiency.

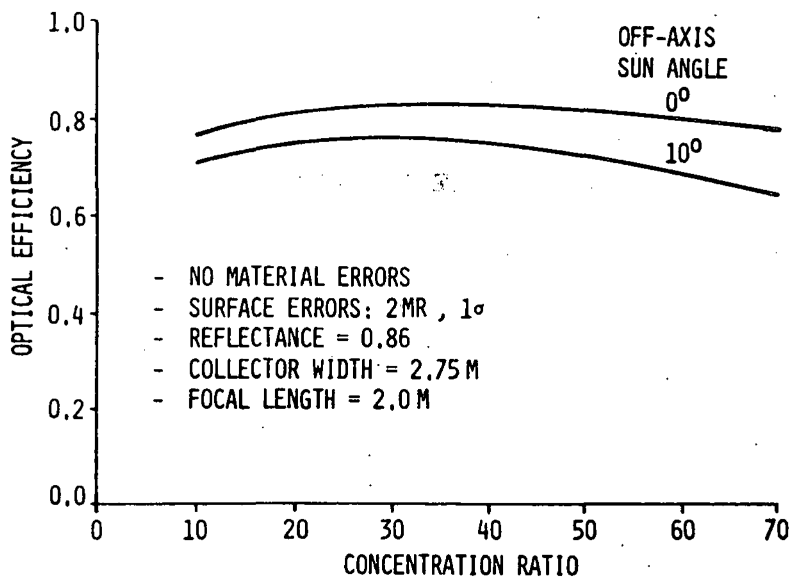


Figure 2-29. Incremental Reflector Concentrator

The imaging collapsing concentrator, as designed by Solar Energy Technology Inc. (SET), was mathematically modeled after a first version of the design where the lens consists of a circle arc inner surface and lens facets on the outer surface. The configuration and model is described in detail in Volume II of this report. The subreflector surface was modeled as though a simple polynominal could represent the surface. Unfortunately, when SET supplied details of the subreflector surface, as built and tested, it was apparent that a polynominal representation would be inadequate. Nevertheless, the computer program was exercised using the best curve fit we could obtain. The curve fit was fairly accurate on the lower part of the subreflector surface. Thus, for small off-axis sun angles the code is acceptable. However, at larger sun angles, when reflections off the upper subreflector surface are not needed, the curve fit method fails. Results for the cases we did run are presented in Table 2-5. In all cases the sun has no aximuth angle (the sun is perpendicular to the concentrator tracking axis).

Table 2-5. SET Optical Performance Results

OFF-AXIS SUN ANGLE (DEGREES)	FRACTION OF INCOMING POWER LOST BY REFRACTIONS OFF PRISM VERTICAL FACES	OPTICAL EFFICIENCY (NO MISSES)
0	8.8 PERCENT	0.78
15	9.7 PERCENT	0.73
27	11.3 PERCENT	0.67

For these results the lens transmittance was 0.9, the subreflector reflectance was 0.9 and the surface error standard deviation was 3 mr for all surfaces. Because of the low concentration a surface waviness of 3 mr is unimportant. The exact curve fit of the subreflector would be much more important to the analysis. The results in Table 2-5 are for a lens surface built by SET.

The details of the design are proprietary to SET and not given here. The general features can be described as a 40-facet lens with a minimum lens thickness of 0.488 inches. The lens is 12 inches wide and the absorber is 3.125 inches high. Because we could not accurately model the subreflector with a curve fit, the optical efficiency results assume all rays reach the receiver.

For more detailed analysis, a point-to-point subreflector surface definition and corresponding point-to-point ray trace, as suggested by SET, is needed. We attempted to incorporate such a method into the computer program but were unable to thoroughly debug this approach. However, the method is quite straightforward and potential users can use this approach if desired. In any case, the design we modeled mathematically will soon be made obsolete by SET's new design of a smoother outer lens with the facets inside. The mathematical model now in the program would need be changed to incorporate this change in design.

SECTION 3
MIRROR AND LENS DEGRADATION EFFECTS

An important component of any concentrating solar energy collector is the optical material used to concentrate the incoming solar radiation. The operating efficiency and cost of the collector is directly dependent upon the performance and maintenance of the optical lens or reflector material that functions in this capacity. It is imperative, therefore, that the material selected has the required characteristics to meet the cost and performance goals.

The desired optical requirements for the solar reflectors are high solar reflectance and specularity. For refractors, the optical parameters of interest are high transmittance and low chromatic aberration. Yet another important requirement of solar reflectors and refractors is their ability to sustain these optical properties under the conditions experienced in solar systems. Solarization (UV radiation), moisture, thermal cycling, deposition of dust or other pollutants and various other environmental factors could degrade the performance of the solar collector. Some of these factors could permanently degrade the material and may require replacement. Degradation due to nonpermanent factors like dust contamination will require periodic maintenance. The optimum maintenance schedule can be set up by life-cycle cost analysis. Therefore, resistance to weathering is a significant attribute of solar collector optical materials.

Resistance to weathering of base reflective or refractive materials may be achieved by providing protective coatings, proper backing layers, adhesive layers, substrate and others. Today, a number of reflectors and refractors of different constructions, and therefore of varying performance and weather resistance, are available in the market or are being developed. To select the best candidate material for a given application, a data base of material performance and maintenance under the conditions experienced in solar systems is required. At present, the material selection process is hindered by the lack of such a data base.

The objective of this project's second major task was, therefore, to formulate a state-of-the-art performance data base for candidate optical materials under various exposure conditions and to include maintenance recommendations for minimizing the adverse effects caused by prolonged exposure of these materials in the solar collector operating environment.

APPROACH

To accomplish the objectives of this task, data were accumulated as described in the flow diagram, Figure 3-1. Potential sources for material degradation data and maintenance recommendations included computerized data banks, collector users and manufacturers, material suppliers, R & D organizations, and a miscellaneous category which includes workshops and seminars. The data base is a compilation of material test results and experience, based on a letter survey and extraction of relevant information from previously published and unpublished 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.

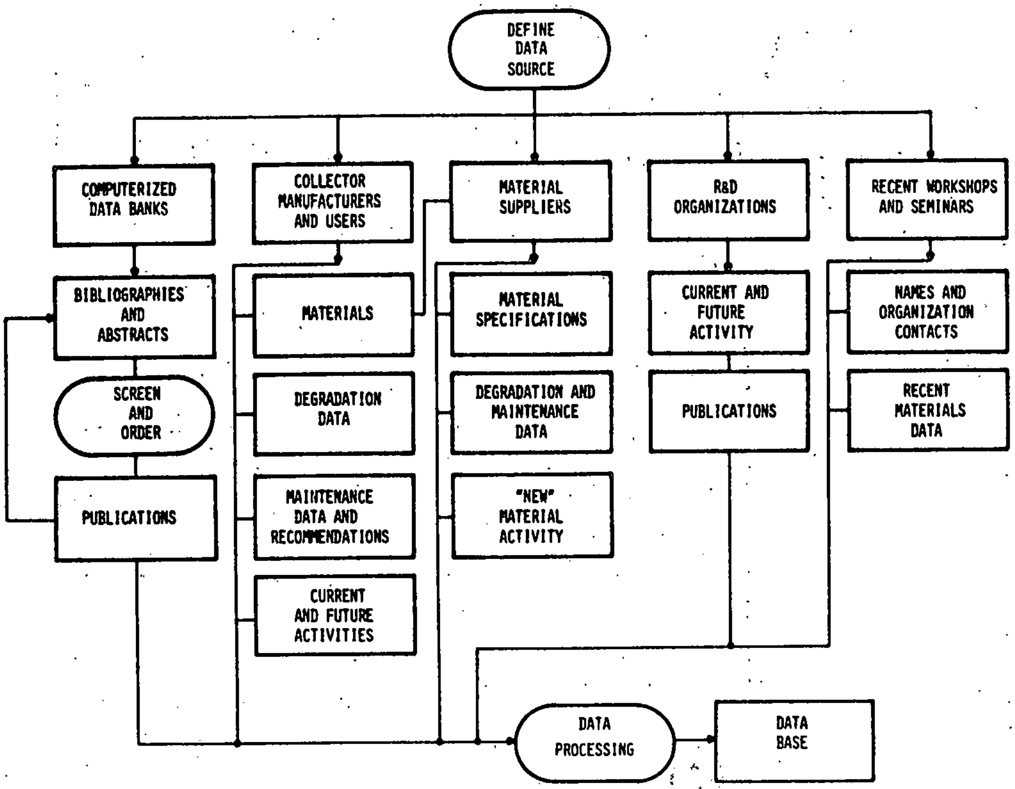


Figure 3-1. Degradation and Maintenance Data Base Formulation Process

To assess current technology and data availability from published sources, an extensive literature search was conducted. Two bibliographies, including 220 documents, were formulated based on computerized searches of the Energy Data Base at DOE's Oak Ridge Technology Center. Searches were based on condensed combinations of key words including "weathering and reflectors" and "solar coating."

Of the documents received, about fifteen contained 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 were contacted for any unpublished results.

Several organizations that have manufactured or used concentrating solar collectors, material suppliers, and R&D organizations which are or have engaged in lens and reflector material characterization activities are a potential source of material degradation and maintenance data. A letter survey was conducted to try to reach these sources. About 500 companies, including solar component manufacturers, research and development organizations, users and individuals were contacted. A copy of the letter and requested information is shown in Appendix A. Thirty-three positive responses were received. Ninety-three letters were returned as undeliverable, 130 said that they do not manufacturer or use any reflective or refractive material and seven said they cannot supply data to us for proprietary reasons. The rest have not acknowledged.

The data obtained from these surveys are presented in the following sections.

MATERIAL DESCRIPTION

Reflectors

A typical reflector consists of a transparent outer protective layer (superstrate), reflecting surface, backing layer(s), and a support structure substrate as shown in Figure 3-2.

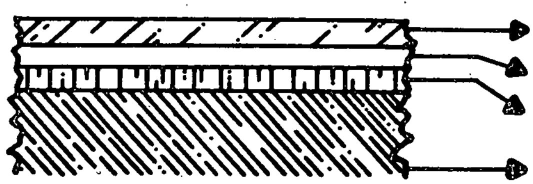


Figure 3-2. Typical Reflector Construction

Three families of reflectors--polished metals, metalized films and metalized glass (mirrors)--are marketed under various trade names. All of them use silver or aluminum as the reflecting surface. The protective coatings and backing layers include materials such as polymer paints and films, inorganic coatings such as silicon oxide, aluminum oxide, magnesium flouride, and thin glass. The support structures include polymer foams; cellular glass; and honeycombed structures of aluminum, paper, wood, steel, fiberglass and epoxy composites [4,5]. Figure 3-3 shows types of reflectors, protective layers and structure materials used in reflector construction. Table 3-1 gives a partial list of reflectors in use for solar collectors.

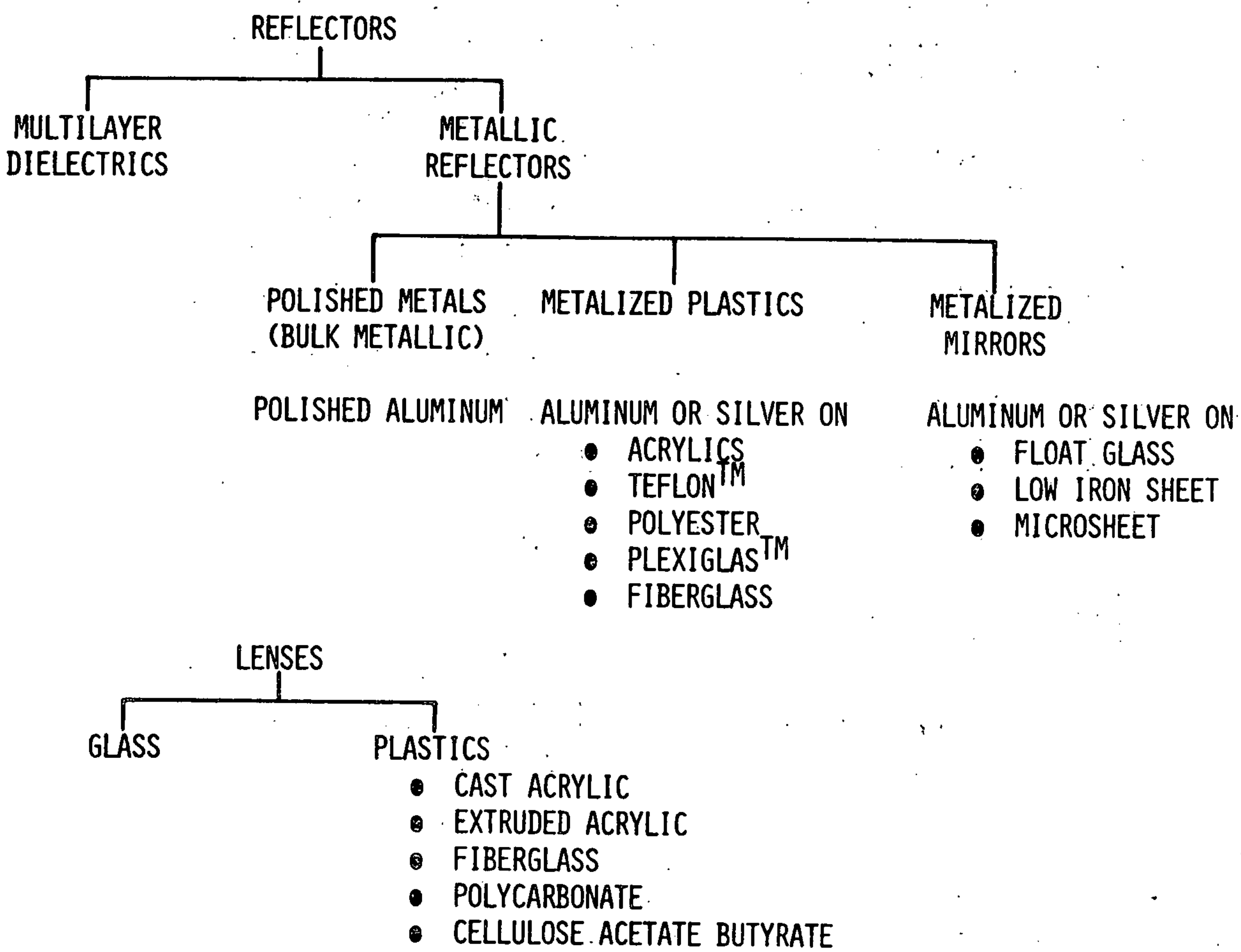


Figure 3-3. Types of Reflectors and Lenses

Table 3-1. Lens and Mirror Materials for Concentrating Solar Collectors

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

Polished Metal Reflectors--Polished metal reflectors, like Alcoa's Coilzak™ or Type I™ and Kingston Industry's Kinglux™, are bulk aluminum surfaces. They can be procured in sheets or in coils and can be readily bent and fastened to curved substrates. The surface is protected by anodized oxides of aluminum or silicon and is either mechanically, chemically or electrochemically polished. These reflectors have high solar average hemispherical reflectance, are very durable, and have shown good resistance to weathering. However, they have relatively low specular reflectance; i.e., they have a significant amount of large-angle scattering due to residual scratches, pits or polishing marks on the surface [6]. Also, the reflected beam is anisotropic due to polishing marks running in one direction. The bulk aluminum reflectors have hemispherical reflectance of about 0.84 to 0.87, and specular reflectance to a 1^{o}-receiving aperture of between 0.78 and 0.82. The specular reflectance for other aperture angles can be obtained from bidirectiontal spectrometry [7].

Metalized Plastic Films--Metalized plastic films like 3M's FEK-244™ or Scotch-cal 5400™, Martin Processing's Llumar ™ are aluminized plastics. Other plastic films available or being developed are aluminized and silvered mylar, teflon, acrylics and polyester. A typical metalized film consists of metal deposited (vapor deposited or chemical deposited) on plastic sheet with a pressure sensitive adhesive applied to the metalized side of the film. After the adhesive is applied, a paper or plastic backing is attached.

The films may be bonded directly to the concentrator structure or to sheet metal for subsequent attachment to the structure. The reflectance of these reflectors depends on the optical properties of plastic films, surface roughness or the metalized side, the lamination process, and the surface roughness of substrates. Of the metalized plastic film reflectors, aluminized acrylic reflectors have good specularity and resistance to solarization. But these are much softer than glass and are subject to dust abrasion and abrasion due to mechanical cleaning. Light scattering increases with surface abrasion. The hemispherical reflectance is from 0.85 to 0.88 for aluminized reflectors and from 0.93 to 0.96 for silvered reflectors. The initial specular reflectance for aluminized reflectors is about 0.83 to 0.86 and in high 0.80's for silvered reflectors.

Metalized Glass--Metalized glass ("mirrors") like Corning's silvered 0317 glass, Carolina Mirror Co.'s silvered laminated float glass and others are second surface mirrors. A typical mirror may consist of a glass outer surface, a silver reflector and a metallic protector. Glass mirrors are readily available in flat sheets. Unfortunately, most of the solar conentrators have curved surfaces. Glass can be bent only to very large radii. Compound shapes and smaller radii of curvature will need sagging into molds.

At present, this process is expensive due to large tooling and labor costs. Honeywell, Corning and Parson's of California are working as a team on sagging glass onto aluminized steel substrates. One of the problems encountered is maintaining the accuracy of the mold after annealing. The mold appears to relax. Another problem forseen is the bonding of sagged glass to the substrate. The adhesive flows out to the edges, which could result in slope errors.

The reflectance of glass mirrors generally decreases with increasing glass thickness because of iron impurities in the glass that cause light absorption. The reflectance of silvered mirrors is from 0.83 to 0.95, depending on the glass thickness and iron content. Glass mirror reflectors have shown good resistance to weathering.

Lenses

An optical lens could be made from glass or transparent plastics. For solar applications, plastics are preferred over glass for several reasons. Plastics offer low cost, light weight, high light transmission, configuration flexibility, and inexpensive high volume production [8]. The lens of a solar energy collector also functions as a cover plate and, therefore, must provide protection against environmental effects. A principal disadvantage of plastics is their lack of heat resistance and lower scratch resistance than glass. Acrylic is by far the most widely used optical plastic. Other optical plastics under consideration are polycarbonate, polystyrene, and cellulose acetate butyrate. The other transparent thermoplastics available include polysulfone, cellulosics, vinyls, CTFE flouropolymers, polyester copolymers and ionomers. However, these materials are seldom used for optical systems. Some of these--like cast acrylic, extruded acrylic, and fiberglass--have been used for solar applications either as a coverplate or lens.

DEGRADATION MECHANISMS

Material degradation may result from dust, solarization (UV radiation), moisture, thermal cycling, mechanical effects, hail and other environmental conditions. Degradation could occur due to the action of any one or a combination of environmental factors. Table 3-2 shows degradation factors categorized as permanent and nonpermanent.

Dust accumulation can result in performance loss of up to 50 percent in a few weeks depending on reflector construction and atmospheric conditions. Dust particles deposit on the surface by complex fluid-mechanical interactions of the dirt-laden airstream with collector structure and reflector surface. This includes convective diffusion, impact or sedimentation [9, 10]. Very small particles ($\lesssim 0.1\,\mu m$) are transported by convective diffusion to the surface where they adhere because of high surface energy-to-volume ratio. Larger particles fall by sedimentation onto the surface. The adhesion

Table 3-2. Degradation Factors

NONPERMANENT	PERMANENT
• ACCUMULATED DUST	• TEMPERATURE
• PLASTIC DEFORMATION OF REFLECTOR STRUCTURE DUE TO WIND AND THERMAL LOADING	• MOISTURE
	• HUMIDITY
• ORGANIC CONTAMINANTS	• SOLAR RADIATION
	• MECHANICAL EFFECTS
	• ORGANIC CONTAMINANTS

mechanisms are affected by environmental conditions, particularly humidity. Under normal dry conditions adhesion is dominated by surface energetics. Under high humidity conditions, water can leach soluble materials from dirt, air and the reflector surface. The resulting chemicals can produce intense chemical and physical bonds. The optical loss is caused by absorption and scattering of light by dirt. Different techniques can be used to reduce dirt accumulation and clean the mirror surface. The rate of deposition of dust or degradation depends on the angle at which the sample is mounted (see Figure 3-4). In this Figure, the accumulated sample exposure time amounted to 127.5 hours (about 5.1 days); the total test period lasted 4 weeks.

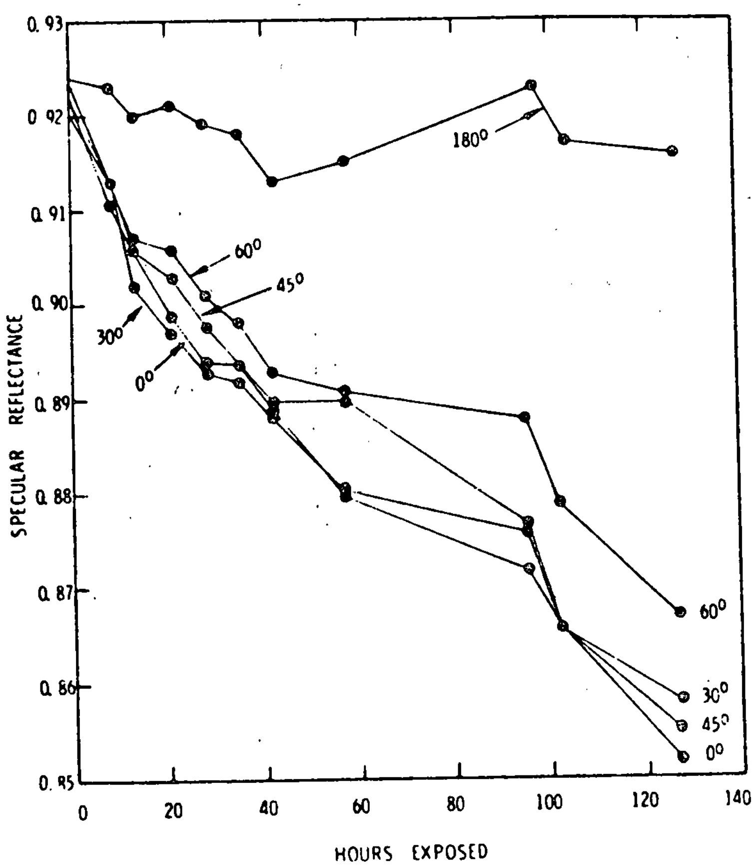


Figure 3-4. Dust Accumulation on Five Mirrors Mounted at Different Angles to the Horizontal [18]

Plastic deformation of the reflector surface due to wind and thermal loading can result in a temporary performance loss. Measurements of power output with a parabolic solar concentrator-photovoltaic receiver, showed large variations in a 30-mph wind [11].

Thermal cycling can generate or amplify internal stress in the material, which can lead to micorstructure cracking and eventual fracture. Delamination or fracture can occur due to the difference in thermal expansion coefficients of the reflector and substrate [11].

Moisture penetration can cause loss of performance by fogging or delaminating the mirror surface.

Mechanical effects due to wind and particle bombardment, hail or other hard objects, can result in permanent figure damage. Blowing dust can cause surface abrasion. The effects of a severe hailstorm are described in a Sandia report [12].

All organic substances undergo changes, usually adverse, when exposed to sunlight. The damaging effect of light is largely determined by its spectral composition or by the different absorption coefficient and UV sensitivity of different materials. For most materials, the absorptive power and consequently the damage produced by light increases sharply with decreasing wavelength. Most of the damage caused by UV is particularly due to the short wave length UV radiation called actinic radiation. Most polymers absorb strongly at 280 nm, and their maximum UV sensitivity varies between 280 and 400 nm [13]. The relative damage on paper due to light is shown below [14]:

λ, nm	300	320	340	360	380	400	440	480	520	560	600	640	680
$D\lambda$, rel. units	100	58	30	10	14	8.5	2.6	0.8	0.3	0.1	0.03	0.01	0

The absorption of UV light by plastics produces similar effects to those of thermal oxidative degradation, resulting in embrittlement, discoloration, and a general reduction in physical properties. There are two main mechanisms by which polymers degrade when exposed to UV light:

- 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

- Energy transfer sensitized by UV-excited impruities such as catalyst resudues or hydroperoxides and carbonyl groups that may be present in the polymer chain or as contaminants in the matrix [13].

A colorless product becomes visually objectionable at a Yellowness Index of 4 to 6 [15]. Data on Yellowness Index and physical property changes on exposure for lensing material and plastics is presented elsewhere.

Other environmental effects which can cause performance lowering include organic contaminants such as bird droppings, dead insects, fungus and mold growth, and bacterial attack. Alkaline or marine salt dust and such other active particles from industries can have a corrosive effect. The growth of microorganisms occurs on the polymer surface and is supported by compound ingredients in the polymer which can provide nutrients for the development of organisms such as bacterias, fungi or algae. Microbial growth can also develop on accumulation of incidental environmental debris deposited on the plastic surface during use. In some cases, the relatively inert plastic system is combined with materials such as paper and textiles, which are easily susceptible to microorganisms, and the who construction then becomes susceptible to microorganism attack. The damage can be from complete failure to embrittlement or cracking to loss of aesthetic values from odors, stains or defacement of surface [13].

DEGRADATION TEST METHODS

Degradation tests include exposure of the material to natural aging processes and periodic measurements of the optical properties. Natural aging processes can be accelerated by exposing the material to concentrated solar radiation by use of solar concentrating mirrors.

There are various facilities for exposure testing of materials, including [16]:

1. Desert Sunshine Exposure Tests, Inc., Phoenix, Arizona--desert condition.
2. Carribean Testing, Inc., Caguas, Puerto Rico--tropical rain forest condition.
3. Solar Testing Services, Inc., Pompano Beach, Florida--subtropical condition
4. Sub-Tropical Testing Services, Miami, Florida--subtropical condition.
5. South Florida Testing Services, Miami, Florida--subtropical, sea air atmosphere.
6. Air Pollution Control Center, Cleveland Ohio--very heavy industrial environment.
7. NASA-Lewis Research Center, Cleveland, Ohio--ordinary urban environment.

Some of the test apparatus at Desert Sunshine (DSET) is described as follows [17]:

- EEK and EEKQUA. The EEK uses an equatorial mount to follow the sun with a nonconcentrating exposure rack. Samples for testing are mounted on the test rack. EEKQUA is the same as EEK but incorporates a water spray system.

- EMMA and EMMAQUA. EMMA test racks are equatorially-mounted and use ten coated-aluminum mirrors for accelerating sunlight exposure. The mirrors have a reflectance of 75 to 85 percent and about eight times sunlight concentration is achieved. Air is blown continually across the sample surfaces to prevent overheating. The samples are protected from the environment when the sun is not shining. EMMAQUA is the same as EMMA except that distilled water is sprayed onto the samples for eight minutes of each sunny hour.

Artificial test devices designed to correlate the results with those obtained by natural weathering are the Carbon-Arc, Florescent Lamp, Xenon Arc and Mercury Arc. Correlation varies from good to poor depending on the test used and the nature of material under investigation [13].

To evaluate the biological attack on plastics, outdoor test fence exposure, soil burial, humidity cabinet and agar plate tests are used. The agar plate test, in various modifications of ASTM procedure G-21-70, is the most frequently used [13]. For solar applications there are no standard tests yet recommended, even though EEK, EMMA and EMMAQUA tests are popularly used. No significant effort has been made to correlate the accelerated testing to predict material lifetimes under outdoor conditions. EMMAQUA testing was noted to be very stringent and not a representative test for evaluation of reflective materials [17].

The results of some tests of the reflective materials using these exposure methods are given elsewhere.

About Accelerated Testing Methods: Under natural conditions, the aging process is due to direct solar radiation scattered by the atmosphere. The concentrating systems concentrate only the direct component of sunlight. Studies have shown that, under a clear sky, the scattered radiation contains more of the ultraviolet component than the direct radiation. Generally, for most materials, damage produced by sunlight is due to the ultraviolet radiation. Concentration of only the direct component leads not only to reduction of UV fraction but also to enhanced heating of the material. The material could be damaged not so much by the action of sunlight as by heating of the specimens to temperatures in excess of a critical value or a combination of both. Besides, the reflector material used for the concentration system can modify the spectral composition due to different spectral reflectance and contamination. For example, dust results in a substantial reduction in UV reflectance. Thus, in accelerated systems the spectral composition of direct radiation and also the properties of the reflecting surface influence the UV fraction of light falling on the specimen. Therefore, these factors should be taken into account when correlating accelerated aging data with actual exposure data. The relationship between acceleration time and concentration is obviously not linear; that is, eight times concentration of sunlight doesn't mean eight times the normal one-sun exposure time.

DEGRADATION CONTROL

Studies on degradation control or cleaning studies are scarce. Material or performance degradation can be controlled by the use of UV stabilizers and coatings on reflectors or refractors by incorporating continuous dust removal techniques as a system design feature, and by periodic maintenance that includes washing with detergents. Rain and melting snow on the surface of a mirror is very effective in cleaning the dust and dirt off the surface [10, 18].

Suggested cleaning strategies for dust control are [10]:

- Keeping dust from settling and adhering to the surfaces.
- Washing them off with a low surface energy detergent-type solution.

- Using chemically- or mechanically-active cleaning techniques capable of breaking the chemical or mechanical bonds.

- Modifying the surface so that strong bonding cannot develop.

Suggested techniques for continuous dust removal include electrostatic biasing to reject dust particles, vibrating the surface, and aerodynamic streamlining. Laboratory tests conducted with electrostatic techniques showed the resulting dust accumulation on the glass sample to be significantly less than the control sample.

Several commercial cleaning solutions for glass and plastics were evaluated. Cleaning techniques included

- High pressure water above 500 psi.

- Jet X--with detergent.

- A mist spray of a commercial cleaner.

- Hot soapy water with a cloth wipe.

Table 3-3 shows cleaning techniques used or recommended for glass, aluminum, and plastics. For rinsing, deionized water or distilled water is recommended. Rinsing with tap water leaves water spots (deionized water is better than distilled water).

Addition of effective UV stabilizers, in conjunction with appropriate heat stabilizers and antioxidants, can make polymers more resistant to UV light and to other adverse effects encountered during weathering. The UV stabilizer selected should:

Table 3-3. Recommended Cleaning Techniques for Glass, Aluminum and Plastics

CLEANING OF GLASS MIRRORS	1. APPLICATION: REFLECTOR CLEANING STUDY SOURCE: BATTELLE, NW MATERIAL: SURFACE HELIOSTAT GLASS CLEANING METHOD: • TURCO 5663LPH CLEANER • TURCO RINSE
CLEANING OF ALUMINUM MIRRORS	1. APPLICATION: SOLAR EXPOSURE TEST STANDS SOURCE: DESERT SUNSHINE EXPOSURE TESTS INC. MATERIAL: ALZAK™, ANODIZED AL, SURFACE CLEANING METHOD: • DAILY • NEUTRAL (P_h) WATER • HIGH-SPEED WATER JET • CHAMOIS WIPE 2. APPLICATION: LIGHTING REFLECTORS AND MISCELLANEOUS EXPOSED SOURCE: ALCOA MATERIAL: TYPE-I AND COILZAK™ WITH ALZAK™ COAT CLEANING METHOD: • MILD ALKALINE CLEANER-COMMON HOUSEHOLD (IVORY OR EQUIVALENT, FOAM) • PUMICE POWDER FOR TOUGH SPOTS • WET SPONGE 3. APPLICATION: AIRCRAFT SKIN SOURCE: ECONOMICS LAB, INC. MATERIAL: ALUMINUM CLEANING METHOD: • MAGNUS 728, HIGH CONCENTRATION • PORTA-WASHER FOR PRESSURIZING • H_2O AND CLEANER
CLEANING OF PLASTIC MIRRORS	1. APPLICATION: CONCENTRATING SOLAR REFLECTOR SOURCE: 3M/ECONMICS LAB, INC. MATERIAL: FEK 163/244 ALUMINIZED ACRYLIC FILM CLEANING METHOD: • SPRAY WITH MAGNUS 728 (1-TO-2 PERCENT CONCENTRATION) • PRESSURIZED H_2O RINSE • PORTA-WASHER APPLICATION • CLEANER/WATER PRESSURES TO 750 PSI AND 450 PSI, RESPECTIVELY

- Absorb strongly at the wavelengths of maximum sensitivity of the polymer.
- Be compatible with the polymer.
- Be stable at processing temperatures.
- Contribute no color.

Hydroxybenzophenones and hydroxyphenylbenzotriazoles are the most popular UV stabilizers for acrylics and polycarbonates.

DATA BASE

Data on reflectors and refractors were obtained through letter surveys, literature surveys and private communications. Table 3-4 gives data as supplied by manufacturers and users in response to our letter survey. The general observations made by some of the respondants appear in the GENERAL REMARKS column. Among the bulk metallic reflectors, data are given for Kinglux™ from Kinston Industries, Coilzak and Type-I™ from Alcoa. (The product Type-I has been mistakenly referred to as "Alzak" in the solar industry; Alzak is a coating process used on both Coilzak and Type-I. Coilzak with Alzak coating on it is sold in coils and Type-I, which also has Alzak coating on it, is sold in sheets; Type-I has better specular properties and is costly. This information was supplied by Alcoa in a telephone conversation.) Data on plastic film reflectors are given for 3M's Scotchcal-5400, 3M's FEK-224, Martin Processing's Llumar. Data supplied on glass reflectors included Corning's low iron fusion glass, Northrup's float glass mirror, MDAC's float glass mirror, laminated glass, and acrylic coated mirror. Table 3-5 gives data on reflectors exposed on EEK, and EMMA and EMMAQUA in Phoenix. The exposure period was between July, 1972 and October, 1977 with some breaks in between. Visual observation

Table 3-4. Letter Survey Materials Data

MATERIAL	SUPPLIER/USER, R & D ORGANIZATION	STATE OF DEVELOPMENT	REFLECTANCE AND SPECULARITY	SOLARIZATION	HUMIDITY	ABRASION RESISTANCE	REAL TIME EXPOSURE	BIO-ATTACK	OTHER	EASE OF CLEANABILITY	CLEANING SOLUTION	CLEANING PROCEDURE	GENERAL REMARKS
CORNING LOW IRON FUSION GLASS	GENERAL ATOMICS	UD	94%	OK	SEE GENERAL COMMENTS	GOOD	2 YEARS	GOOD	-		WATER - DETERGENT SOLUTION		THE SILVERING CORRODED FROM THE EDGES.
TRU-FLEET (1/8-INCH FLOAT GLASS LAMINATED WITH 15-MIL POLYVINYL BUTYRAL)	BINSWANGER MIRROR CO.	-	97% SPECULAR ρ=90-96%	-	-	-	-	-	-		-		NO DATA
FLOAT GLASS MIRROR (0.125 INCH)	NORTHRUP	UD	92% SPECULAR ρ=83%	-	-	-	1 YEAR EXPOSURE; DALLAS TEXAS	-	-		SPRAY WASH		REFLECTOR: MEDIUM IRON FLOAT GLASS, SILVER, COPPER, PPG PROTECTIVE PAINT, ACRYLIC ENAMEL PAINT, EC3549 ADHESIVE, POLYSTYRENE FOAM, 0.020-INCH GALVANIZED STEEL.
FLOAT GLASS MIRROR	MC DONNELL-DOUGLAS	-	$\bar{\rho}$=83.3%*	-	-	-	113 DAYS IN NEW MEXICO	-	0.10% REFLECTANCE LOSS PER DAY DUE TO DUST.		A-69M SOLUTION AND CB-120 SOLUTION AVAILABLE FROM MC GEAN CHEMICAL		
LAMINATED GLASS MIRROR (SECOND SURFACE)	MC DONNELL DOUGLAS	-	$\bar{\rho}$=81%*	-	-	-	113 DAYS IN NEW MEXICO	-	0.36% REFLECTANCE LOSS PER DAY DUE TO DUST.		A-69M SOLUTION AND CB-120 SOLUTION AVAILABLE FROM MC GEAN CHEMICAL		
ACRYLIC COATED MIRROR (FIRST SURFACE)	MC DONNELL DOUGLAS	-	$\bar{\rho}$=68-80%*	-	-	-	113 DAYS EXPOSURE IN NEW MEXICO	-	0.37% REFLECTANCE LOSS PER DAY DUE TO DUST.		A-69M SOLUTION AND CB-120 SOLUTION AVAILABLE FROM MC GEAN CHEMICAL		

KEY EC = Existing Commercial
UD = Under Development

*TIME-AVERAGED REFLECTIVITY OVER 113 DAYS OF EXPOSURE WITH IN BETWEEN CLEANING CYCLES.

Table 3-4. Letter Survey Materials Data (continued).

MATERIAL	SUPPLIER/USER, R & D ORGANIZATION	STATE OF DEVELOPMENT	REFLECTANCE AND SPECULARITY	SOLARIZATION	HUMIDITY	ABRASION RESISTANCE	REAL TIME EXPOSURE	BIO-ATTACK	OTHER	EASE OF CLEANABILITY	CLEANING SOLUTION	CLEANING PROCEDURE	GENERAL REMARKS
SCOTCHCAL -5400 (3M)	MINNESOTA MINING AND MANUFACTURING (3M)	EC	84.2% APERTURE, ρ 2°, 84.2 1°, 82 1/2°, 48	MINNESOTA YR.; ρ 5, 82.4 6.7, 80.7 TEXAS 5.2, 78.3 5.5, 77.8 FLORIDA 1.2, 81.2 4.3, 80.9 5.6, 78.3 6.9, 78.6	HYDRO-PHOBIC	SUSCEP-TIBLE SCRATCH-ING IF PROPER HANDLING NOT FOLLOWED	SEE SOLAR-IZATION	FUNGIS-TATIC	NO EFFECT OF 20% CONCENTRA-TION SALT SPRAY AT 95°F FOR 240 HR.	FOR PANELS REGULARLY CLEANED WITH 40-60 PSI DETERGENT AND WATER MIXTURE. FOR DIRTY PANELS, USE ECONOMIC LABS MAGNUS-728 OR EQUIVALENT AT 450 PSI AND WATER RINSE AT 750 PSI. USE COMPRESSED AIR FOR DRYING THE SURFACE.			
FEK-244 (3M)	MINNESOTA MINING AND MANUFACTURING (3M)	EC	84.2 APERTURE, ρ 2°, 84.2 1°, 84 1/2°, 48	SIMILAR TO ABOVE	HYDRO-PHOBIC	SAME AS ABOVE	-DO-	FUNGIS-TATIC	SAME AS ABOVE	SAME AS ABOVE			
FEK-244 (3M)	SOLAR KINETICS INC.	EC	83 TO 85% AT 1.5 MRAD.	ULTRA VIOLET LIGHT STABLE	LITTLE EFFECT	POOR RESISTANCE	11 YEARS	NONE	-	0.1% NON-IONIC SURFACTANT. USE HIGH-PRESSURE WATER AT 400-800 PSI AND C-910 MASBURY PRESSURE WASHER			
FEK-244 (3M)	DESERT RESEARCH INSTITUTE	EC	86%	GOOD SPEC-ULAR ρ=85%	GOOD	-	-	-	-	1% JOY SOLUTION. WASH IN JOY AND DISTILLED WATER			DATA SHOWS LOSS OF SPECULARITY IN ONE SAMPLE PLACED AT STAUFFER CHEMICAL COMPANY IN NEVADA. OTHER SAMPLES SHOWED NO DEGRADATION. SPECULARITY LOSS PER WEEK AS HIGH AS 15% DUE TO DUST CONTAMINATION.
LLUMAR (MARTIN PROCESSING)	GENERAL ELECTRIC	EC	88.7% $1\sigma<0.8$MRAD	-	-	-	-	-	-	-			FIRST SURFACE ALUMINIZED LLUMAR (POLYESTER FILM). JUST BEGUN WEATHER TESTING, NO DATA AVAILABLE NOW.
LLUMAR	GENERAL ELECTRIC	EC	82.3% $1\sigma<0.6$MRAD		-	-	-	-	-	-			

Table 3-4. Letter Survey Materials Data (concluded)

MATERIAL	SUPPLIER/USER, R & D ORGANIZATION	STATE OF DEVELOPMENT	REFLECTANCE AND SPECULARITY	SOLARIZATION	HUMIDITY	ABRASION RESISTANCE	REAL TIME EXPOSURE	BIO-ATTACK	OTHER	EASE OF CLEANABILITY	CLEANING SOLUTION	CLEANING PROCEDURE	GENERAL REMARKS
®COILZAK ALUMINUM LIGHTING SHEET	ALCOA	EC	.83% AND 78-80%	EXCELLENT	EXCELLENT	EXCELLENT	SEE COMMENTS	EXCELLENT	-	VERY EASILY CLEANED	MILD SOAP SOLUTION	USE WET SPONGE, CLOTH OR MILD ALKALINE SPRAY	SPECULARITY DECREASES IN 6 MONTHS TO 3 YEARS DEPENDING ON ENVIRONMENT. GOOD RETENTION OF TOTAL REFLECTANCE FOR 20 YEARS PROVIDED COATING THICKNESS APPROXIMATELY 3 MIL IS SPECIFIED. NORMAL COATING THICKNESS FOR INTERIOR APPLICATION IS APPROXIMATELY 1 MIL.
®COILZAK	MND-INC.	EC	-	-	-	-	-	-	-	-	MILD SOAP AND H_2O; NO ABRASIVES	-	-
®COILZAK (0.020-INCH ALUMINUM)	SUNHEET INC.	EC	83%	-	-	-	-	-	-	-	-	-	REFLECTOR ENCLOSED WITHIN COLLECTOR. THEREFORE, NO EXPOSURE
KINGLUX CAT. NO. CA	KINGSTON INDUSTRIES	EC	87.4% AND 84.6%	INERT	COATING NOT AFFECTED BY 95% EXPOSURES	RESISTS ABRASION	180,000 LANGLEYS; NO DEGRADATION	-	SALT SPRAY FOR 24 HOURS; NO FALL OFF	-	MILD DETERGENT SOLUTIONS	NORMAL DUSTING OR WASHING	-
KINGLUX	OAKRIDGE SOLAR ENGINEERING INC.	EC	-	-	-	-	-	-	-	-	CLEAN WITH WINDEX OR LIGHT SOAP AND WARM WATER	-	-
KINGLUX	BERRY SOLAR	EC	-	-	-	-	-	-	-	-	-	-	-
KINGLUX	AMERICAN SCIENCE AND ENGINEERING	EC	-	-	-	-	-	-	-	-	-	-	-

Table 3-5. Reflectance Histories for EEK Test Exposure

MATERIAL (SOURCE/SUPPLIES)	INITIAL REFLECTANCE	EXPOSURE TIME (WEEKS)	TOTAL LANGLEYS (IN 1000'S)	PREWASH REFLECTANCE	POSTWASH REFLECTANCE
ALUMINIZED ACRYLIC (3M COMPANY)	0.86	23 50 66 111 139	118 256 353 543 676	0.81 0.83 0.79 0.83 0.82	0.86 0.85 0.86 0.86 0.86
ALUMINIZED TEFLON (G.T. SHELDAHL)	0.78	9 39 58 103 135	46 202 301 491 624	0.71 0.79 0.74 0.77 0.76	0.78 0.82 0.82 0.82 0.80
SILVERED TEFLON (G.T. SHELDAHL)	0.86	9 39 58 103 135	46 202 301 491 624	0.79 0.83 0.72 0.82 0.80	0.88 0.87 0.88 0.86 0.87
ALUMINIZED FIBERGLASS WITH PROTECTIVE COATING (GENERAL DYNAMICS)	0.88	23 50 66 111	118 256 353 543	0.81 0.79 0.70 FAILED	0.85 0.76 0.69 FAILED
ALUMINIZED FIBERGLASS WITHOUT PROTECTIVE COATING (GENERAL DYNAMICS)	0.92	23 55 74 119	118 282 399 589	N/A N/A N/A N/A	0.87 0.82 0.76 FAILED
ALUMINIZED ACRYLIC PLEXIGLASS (RAM PRODUCTS)	0.80	9 39 58 103 135	46 202 301 491 624	0.66 0.71 0.69 0.70 0.70	0.75 0.78 0.72 0.73 0.72
ALUMINIZED GLASS (HONEYWELL)	0.76	9 44 63 108 140	46 225 325 512 645	0.75 0.76 0.69 0.70 0.70	0.76 0.76 0.76 0.75 0.75
SILVERED GLASS (HONEYWELL)	0.87 0.86	32 21	133 85	0.80 0.83	0.86 0.86
ANODIZED ALUMINUM (ALCOA)	0.82	43 75	180 310	N/A 0.78	0.84 0.83

made on some of the reflector samples is given in Table 3-6. The samples were exposed on EEK rack in Minnesota, Florida, and Arizona. Table 3-7 gives a summary of reflectance and transmittance data for material used for solar concentration. The data were extracted from Reference [19]. Figure 3-4 shows specular reflectance degradation, due to dust accumulation, of silvered glass mirrors mounted at different angles. Data on some of the plastics--which includes acrylics, polycarbonates, polystyrene and cellulosic FEP flouropolymers--are given in Table 3-8.

The data given includes cost, trade names, advantages and some of the notable limitations of these plastics being used for solar applications. However, some of the properties can be controlled by addition of different materials during formulation of a polymer. For example, incorporating acrylates or higher metacrylates lowers the deflection temperature and hardness and improves thermoformability at some loss in resistance to weathering. For outdoor polycarbonate applications, a strong UV stabilizer is used that reduces the transmittance by five percent. The process by which a polymer is formed also makes a difference. Table 3-9 gives exposure data for some of the plastics. Transmittance and Yellowness Index (YI) were measured before and after exposure for different trade name plastics. The exposure tests conducted included EMMAQUA, Carbon arc weatherometer and 1X exposure in Kentucky. Data on cast acrylic S-360, a specific formulation used by Swedlow in the Fresnel lens, is available in Reference [20]. Figure 3-5 gives real-time exposure data on cast acrylic [21].

Figure 3-6 shows the effects of natural cleaning on specular reflectance of glass mirrors. Several cleaning agents were evaluated for model heliostats. Tables 3-10 and 3-11 show the results of washing heliostats. Figure 3-7 shows the effects of cleaning cycle on specular reflectance of a silvered float glass mirror. The cleaning procedure used was a laboratory method that included placing the mirror in a beaker of distilled water and ultrasonically agitating it for 3 minutes and wiping it with soft tissue.

Table 3-6. Degradation Effects Caused by Test Site Variation

MATERIAL	ARIZONA 2-15 TO 7-10, 21 WEEKS EXPOSURE	FLORIDA 2-15 TO 7-10, 21 WEEKS EXPOSURE	MINNESOTA 2-15 TO 7-10, 21 WEEKS EXPOSURE
ALUMINIZED ACRYLIC (3M COMPANY)	NO DETERIORATION	FOGGING OVER ENTIRE SAMPLE; EDGE DETERIORATION	SLIGHT EDGE DETERIORATION; VERY SLIGHT FOGGING; NO VISIBLE DEGRADATION
ALUMINIZED TEFLON (G.T. SHELDAHL)	VERY DIRTY; SOME SMALL SCRATCHES	SMALL SURFACE SCRATCHES; EDGE DETERIORATION	NO DETERIORATION
SILVERED TEFLON (G.T. SHELDAHL)	VERY DIRTY; SOME SMALL SCRATCHES	SMALL SURFACE SCRATCHES; EDGE DETERIORATION BEGINNING TO MOVE INWARDS	NO DETERIORATION; ONE YELLOWISH BROWN SPOT ON UPPER PORTION OF SAMPLE NEAR PLACE WHERE SAMPLE WAS HELD DOWN
ALUMINIZED FIBERGLASS WITH PROTECTIVE COATING (GENERAL DYNAMICS)	NUMEROUS SMALL CRACKS; GREEN SPOTS SPREADING ACROSS SAMPLE	NO DATA	BAD EDGE DETERIORATION; GREEN SPOTS OVER LARGE PART OF SURFACE
ALUMINIZED FIBERGLASS WITHOUT COATING (GENERAL DYNAMICS)	GOLD-GREEN SPECKS; VERY SLIGHT VIOLET TINGE OVER ENTIRE SURFACE	NO DATA	NO DATA
ALUMINIZED ACRYLIC PLEXIGLASS (RAM PRODUCTS)	YELLOW-GREEN OVER ENTIRE SURFACE	NO DETERIORATION	NO DETERIORATION
ALUMINIZED GLASS (HONEYWELL)	VERY DIRTY; NO DETERIORATION	NO DETERIORATION	NO DETERIORATION

Table 3-7. Properties of Reflective Surfaces for Solar Concentrators [19]

No.	Producer/ Supplier	Material Type	Glass Thickness mm (in)	Hemispherical Solar Reflectance	Glass Thickness mm (in)	Solar Transmittance	Reflectance at 500 nm*				Coef. Thermal Expansion -cm/cm°C	Cost† $/Mft²	Remarks
							R_1	σ_1 (m rad)	R_2	σ_2 (m rad)			
1	Alcoa	Alzak	0	0.85	0	0	0.56 (505)	0.42	0.33	10.1	NA	NA	Aluminum
2	Alcoa	S460666	0	0.32	0	0	--	--	--	--	NA	NA	Aluminum
3	Alcoa	S460667	0	0.92	0	0	--	--	--	--	NA	NA	Aluminum
4	ISC	90-10	0	0.90	0	0	0.86	--	--	--	--	1.50	Silver plated brass
5	ISC	80-20	0	0.88	0	0	0.80	--	--	--	--	1.50	Requires overcoat Cu-Zn 80% Cu, 20% Zn
6	ISC	70-30	0	0.91	0	0	0.81	--	--	--	--	1.50	
7	3M	Scotchcal 5400	0	0.85	0	0	0.86	1.9	--	--	--	0.5 (E)	Estimated cost
8	Corning	Code 7806 (fusion)			1.14 (0.045)	0.88	--	--	--	--	70 (-7) (0-300°C)	1.40	>10 Mft², $0.45
9	Corning	Code 0317 (fusion)	--	--	2.29 (0.090)	0.910	--	--	--	--	88 (-7) (0-300°C)	0.65-0.80 1.10-1.80	Without metallization With metallization
10	Corning	Code 0317 (fusion)	--	--	1.52 (0.060)	0.909	--	--	--	--	88 (-7) (0-300°C)		
11	Corning	Code 0317 (fusion)	--	--	2.8 (0.110)	0.903	--	--	--	--	88 (-7) (0-300°C)		
12	Schott B270	B270 (Rolled)	--	--	3 (0.120)	0.913	--	--	--	--	NA	0.5-0.8	Without metallization
13	PPG Works	#6 (Float)	--	--	3.17 (0.125)	0.881	--	--	--	--	86 (-7) (25-300°C)	2.15	>10⁷ft², $0.60-0.65
14	ASG	(Float)	--	--	3.17 (0.125)	0.847	--	--	--	--	85 (-7) (0-300°C)	0.30	
15	Sheldahl	Aluminized Teflon	NA	0.87	--	--	0.80	1.3	0.07	30.9	NA	NA	
16	Kingston Ind.	Kingflux (Al)	0	< 0.85	0	0	0.65 (498)	0.37	0.23	16.1	NA	2.00	Similar to Alzak; JPL measurements, 85.4% small quantities
17	Corning	Microsheet Al	--	0.95	0	0	0.77 (550)	1.1	0.18	6.2	NA	NA	
18	Carolina Mirror Co.	2nd Surface Ag Glass	--	0.83	0	0	0.92	0.15	--	--	NA	NA	
19	Payne Co.	Microglass	0.15 (0.006)	0.94	--	--	--	--	--	--	NA	NA	
20	Payne Co.	Microglass	0.30 (0.012)	0.93	--	--	--	--	--	--	NA	NA	

* Measurements at other wavelengths are shown in parentheses. Data from R. B. Pettit.

† These costs are preliminary and are being updated.

Table 3-7. Properties of Reflective Surfaces for Solar Concentrators [19] (concluded)

No.	Producer/ Supplier	Material Type	Glass Thickness mm (in)	Hemispherical Solar Reflectance	Glass Thickness mm (in)	Solar Transmittance	Reflectance at 500 nm* R_1	σ_1 (m rad)	R_2	σ_2 (m rad)	Coef. Thermal Expansion -cm/cm°C	Cost† $/ft²	Remarks
21	GE	Glass (float) (Soda lime)	-- --	-- --	3.17 (0.125)	0.838	--	--	--	--	85 (-7) (0-300°C)	0.50	
22	Ford	Glass (float) (soda lime)	--	--	3.17 (0.125)	0.844	--	--	--	--	85 (-7) (0-300°C)	0.40	
23	Fourco	Glass (float) (Soda lime)	--	--	3.17 (0.125)	0.891	--	--	--	--	--	NA	
24	Liberty Mirrors	Cr coated front surface glass	3.17 (0.125)	0.65	--	--	--	--	--	--	32-93(-7) (20-300°C)	NA	Special measurements
25		Lead-sulfide front surface glass	3.17 (0.125)	0.25	--	--	--	--	--	--	32(-7) (20-300°C)	NA	Auto side mirrors applications only
26	Schott-Jena	Tempax (sheet)	--	--	--	--	--	--	--	--	32 (-7) (20-300°C)	NA	
27	Corning	Code 0317 (fusion low Fe)	1.47 (0.058)	0.95 ±1	--	--	--	--	--	--	88 (-7) (0-300°C)	*	Sandia data * see item #9 vacuum deposited silver
28	Corning	Code 0317 (fusion low Fe)	1.47 (0.058)	0.94 ±1	--	--	--	--	--	--	88 (-7) (0-300°C)	*	Sandia data * see item #9 chemically deposited silver
29	Corning	Code 0317 (fusion low Fe)	1.47 (0.058)	0.926	--	--	--	--	--	--	88 (-7) (0-300°C)	*	JPL measurements old glass. 12/1/73
30	3M	Metallized Polyester	0.07 (0.0028)	0.86	--	--	0.86 (E)	1.9 (E)	--	--	--	0.50	Measurements @AM2 20. degradation/7 yrs.
31	Flabeg Corp.	Crown Glass (float)	3.17 (0.125)	TBD	--	--	--	--	--	--	70 (-7) (0-300°C)	--	Resin and/or Mylar reverse side sealant
32	Corning	7806 (modified) (fusion)	0.050(E)	0.95 (E)	--	--	--	--	--	--	70 (-7) (0-300°C)	--	

* Measurements at other wavelengths are shown in parentheses. Data from R. B. Pettit.

† These costs are preliminary and are being updated.

E Estimated

Table 3-8. Properties of Plastic Materials for Solar Applications

MATERIALS (CHEMICAL NAME)	TRADENAMES (COST, ¢/CU. IN.)	ADVANTAGES	LIMITATIONS	REFRACTIVE INDEX	TRANSMITTANCE (TYPICAL)*
ACRYLICS (POLYMETHYL-METHACRYLATE)	PLEXIGLAS, SWEDCAST LUCITE-L POLYCAST (1.96-2.39)	• EXCELLENT OPTICAL PROPERTIES, INCLUDING HIGH TRANSPARENCY. • EXCELLENT LONG-TERM RESISTANCE TO SUNLIGHT AND WEATHERING.	• LOW SCRATCH RESISTANCE COMPARED TO GLASS. • LIMITED RESISTANCE TO ALKALIES AND SOLVENTS, ATTACKED BY KETONES, ESTERS, AND CHLORINATED AND AROMATIC HYDROCARBONS.	1.491	92 PERCENT
POLYCARBONATES	LEXAN, MERLON (3.25)	• GOOD OPTICAL PROPERTIES, INCLUDING TRANSPARENCY. • EXCELLENT TOUGHNESS. • HEAT RESISTANCE TO 250°F IN CONTINUOUS USE. • GOOD DIMENSIONAL STABILITY.	• LOW SCRATCH RESISTANCE. • ATTACKED BY OXIDIZING ACIDS. • POOR SOLVENT AND ALKALI RESISTANCE • CANNOT BE MACHINED EASILY. • FOR OUTDOOR APPLICATION, A STRONG ULTRAVIOLET STABILIZER IS REQUIRED WHICH REDUCES TRANSMITTANCE.	1.586	88 PERCENT
POLYSTYRENES	DURATRON, DYLENE, LUSTREX, STYRON FOSTARENE (0.52-0.89)	• HIGH HARDNESS AND RIGIDITY. • READILY MOLDED AND EXTRUDED. • LOW COST.	• BRITTLE. • LOW HEAT RESISTANCE. • ULTRAVIOLET LIGHT CAUSES YELLOWING. • NOT RESISTANT TO SOLVENTS. • ATTACKED BY OXIDIZING ACIDS.	1.590	89 PERCENT
CELLULOSICS (CELLULOSE ACETATE BUTYRATE)	UVEX (2.58-2.74)	• GOOD OPTICAL PROPERTIES, INCLUDING TRANSPARENCY. • GOOD TOUGHNESS. • GOOD WEATHER AND AGING RESISTANCE.	• LOW TENSILE STRENGTH. • NOT RESISTANT TO STRONG ACIDS AND SOLVENTS.	1.47	89 PERCENT
STYRENE ACRYLONITRILE	LUSTRAN, TYRIL, C-11, FOSTACRYL (0.85-0.89)	• GOOD CHEMICAL RESISTANCE. • RESISTANT TO ABOUT 185°F IN CONTINUOUS USE. • HIGH RIGIDITY AND HARDNESS	• BRITTLE. • LOW SCRATCH RESISTANCE. • ULTRAVIOLET LIGHT CAUSES YELLOWING. • NOT RESISTANT TO SOLVENTS.	1.567	88 PERCENT
FEP FLOUROPOLYMER	TEFLON (35-37)	• EXCELLENT CHEMICAL RESISTANCE EVEN AT HIGH TEMPERATURE. • EXCELLENT RESISTANCE TO SUNLIGHT AND WEATHERING. • RESISTANT TO TEMPERATURES AS HIGH AS 400°F IN CONTINUOUS USE.	• VERY HIGH COST. • LOW STRENGTH.		

*MAY NOT BE SPECTRAL TRANSMITTANCE

Table 3-9. Exposure Data for Plastics Used for Optical Applications [15]

TRADE NAME	COMMON NAME (MANUFACTURING PROCESS)	BEFORE EXPOSURE		AFTER EXPOSURE[1]				CHEMICAL NAME
				TEST 1[1]		TEST 2[2]	TEST 3	
		T[2]	YI[3]	T[2]	YI[3]	YI[3]	YI[3]	
SWEDCAST-300	CAST ACRYLIC (CONTINUOUS CAST)	93	2.26	92	2.71	2.68	2.55	POLYMETHYL METHACRYLATE
LUCITE-L	CAST ACRYLIC (CONTINUOUS CAST)	93	2.03	92	2.48	2.73	2.57	POLYMETHYL METHACRYLATE
PLEXIGLAS DR	IMPACT ACRYLIC (EXTRUDED)	90	1.16	87	19.74	8.02	5.73	POLYMETHYL METHACRYLATE
POLYCAST	CAST ACRYLIC (CONTINUOUS CAST)	92	1.05	91	3.50	3.95	3.25	POLYMETHYL METHACRYLATE
KALWALL SUNLITE	FIBERGLASS (CONTINUOUS LAYUP)	88	5.31	77	29.47	43.98	13.18	ACRYLIC-COATED POLYESTER GLASS LAMINATE
UVEX	BUTYRATE (EXTRUDED)	89	2.10	73	16.03	17.80	11.19	CELLULOSE ACETATE BUTYRATE
LEXAN S-100 (0.093")	POLYCARBONATE (EXTRUDED)	86	2.97	76	27.97	23.88	11.97	POLYCARBONATE

NOTES:

1. TEST 1: EXPOSED FOR 3000 HOURS IN CARBON ARC WEATHEROMETER
   TEST 2: EXPOSED FOR 1 YEAR; EMMAQUA IN ARIZONA
   TEST 3: EXPOSED FOR 2 YEARS; 45° SOUTH FLORENCE, KENTUCKY
2. TRANSMITTANCE
3. YELLOWNESS INDEX

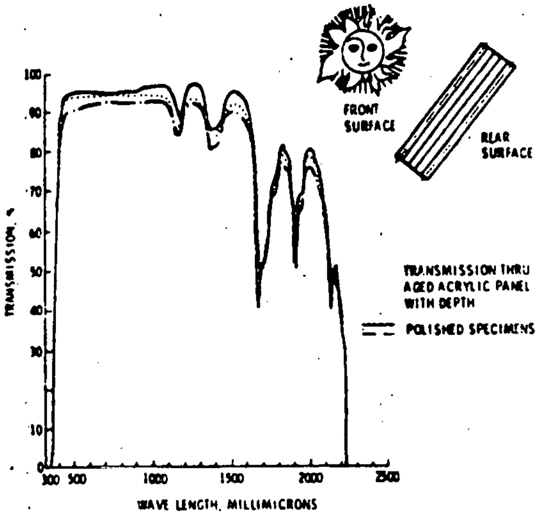


Figure 3-5. Transmission Through Aged Acrylic Specimens as Recovered, Compared with Polished Specimens [21]

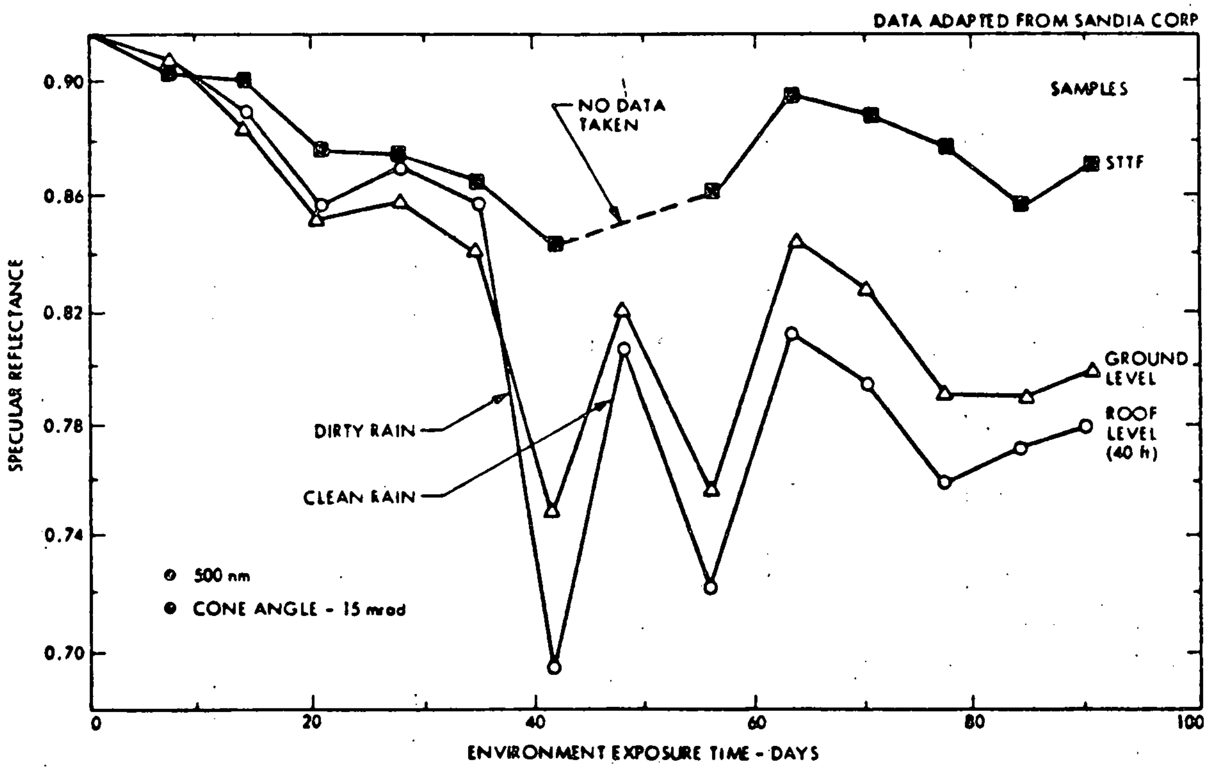


Figure 3-6. Glass Mirrors: Specular Reflectance Versus Environmental Exposure Time for Albuquerque, NM, 1978 [19]

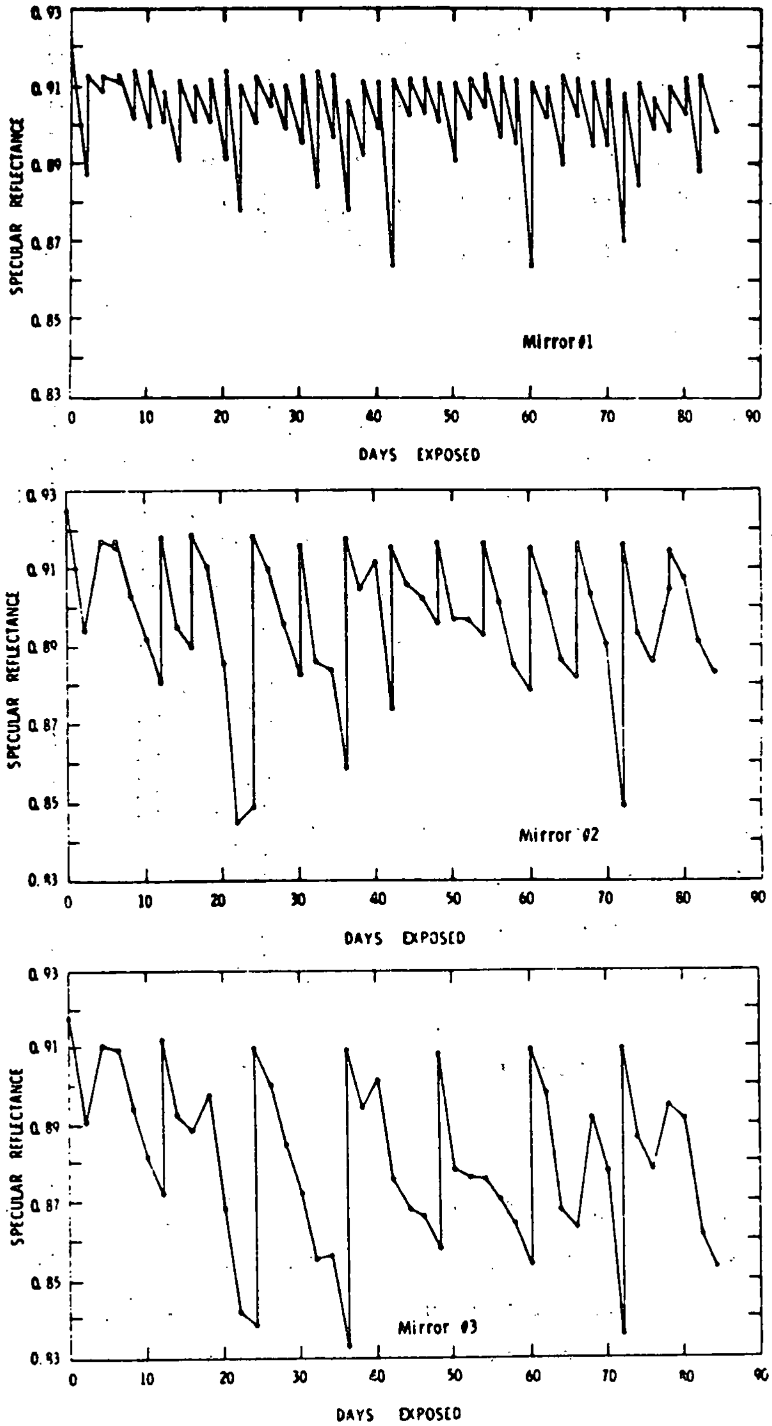
Table 3-10. Washing of Model Heliostat Using Different Washing Solutions [19]

Company	Exposure Time (days)	Reflectance Efficiency (%)		Washing Solution Application					Rinse Solution Application				Drying Time (min)
		Dirty	Clean	Pressure (psi)	Time	Quantity (gal.)	Nozzle	Dwell Time (sec)	Pressure (psi)	Time (sec)	Quantity (gal.)	Nozzle	
McGean	20	59.1	64.75	80	35 sec	0.83	80.10	30	80	90	3.2	65.16	20
Turco	29	56.52	63.54	40	3 min	2	80.04	60	50	105	4.0	90.20	20
TEC	39	N/A	N/A	150	80 sec	6	Graco Gun	60	150	145	5.0	Graco Gun	30

Table 3-11. Washing of SRE Heliostats Using McGlean Chemical's Washing Solution [19]

Heliostat No.*	Prewash Reflectance Efficiency (percent)	Postwash Reflectance Efficiency (percent)	Application Time		Solution Quantity		Solution Type		Nozzle Size	
			Wash (min)	Rinse (min)	Wash (gal.)	Rinse (gal.)	Wash	Rinse	Wash (gpm)	Rinse (gpm)
H_1	65.9	78.2	1.0	5.0	1.50	14.0	A69M	Deionized Water	1	5
H_2	56.1	76.5	1.0	3.7	1.25	8.75	A69M	Deionized Water	1	5
H_3	69.2	87.5	1.0	3.0	0.75	8.0	A69M	Deionized Water	1	5
H_4	73.3	84.0	1.0	2.0	1.25	5.75	CB120	Deionized Water	1	5
IH1	76.8 / 72.2	85.1 / 86.6	1.4	2.8	1.60	7.75	CB120	Deionized Water	1	5

* H_1, H_2, H_3 = Acrylic first surface mirrors, H_4 = Laminated mirror, IH1 = 3/32 mirror bonded to foam core laminated mirror



a. 2-Day Cycle

b. 6-Day Cycle

c. 12-Day Cycle

Figure 3-7. Cleaning Cycles for a Mirror: Specular Reflectance Changes over an 84-Day Period [18]

Table 3-12 gives reflectance degradation as function of wavelength for ASG Lustra sheet mirrors before and after cleaning. Figure 3-8 shows the reflectance of a Kinglux aluminum reflector before and after cleaning. The samples for measurements were taken from a parabolic panel which was exposed for 3 months between January and April of 1979.

CONCLUSIONS

Although the sources of data seemed extensive as we entered this project, the available hard facts which permit definition of maintenance and operating procedures are few. Data are abundant, as evidenced by the multitude of tables in the data base. Unfortunately, the conclusions we have reached in regard to the data are characterized by a lack of information that could lead to a maintenance requirements definition.

What we can conclude is that real-time one-sun and accelerated-exposure test data, for desert conditions and for most of the state-of-the-art optical materials used for solar collectors, are available. However, due to lack of standard tests for weatherability and lack of correlation between accelerated and real-time exposure testing, there is large variability in data for some of the materials. Also, data for environmental conditions other than the desert is lacking.

In addition, we note that extensive studies have been conducted on UV degradation of PMMA (polymethyl metacrylate: acrylic) and on discoloration of polymers when exposed to sunlight. Some of the mechanical effects have also been evaluated. Literature references and data from these references for these materials are cited in this report.

Table 3-12. Reflectance Degradation as a Function of Wavelength for Desert-Soiled Mirrors [19]

Specimen Number	Mirror Glass	Mirror Condition	Instrument	Specularity	Solar Reflectance Efficiency at the Following Wavelengths in Nanometers										Average Value Over Solar Spectrum
					426	498	561	623	691	774	860	1008	1208	1594	
65.16	ASG Ind Lustra Sheet 3.2 mm (0.125)	Dirty	Beckman	125	92.5	95.5	96.5	96.0	94.5	92.0	90.5	89.5	89.5	92.0	92.9
			Specular Spectro Photometer	16	83.6	87.7	89.4	88.5	92.2	86.8	85.4	83.9	84.7	89.9	87.0
				8	83.6	87.7	89.4	88.5	90.1	86.8	85.4	83.9	84.7	89.2	87.0
				4	79.6	81.7	81.7	82.1	82.8	82.4	81.2	79.2	77.9	73.0	80.0
			Specular Photometer	16			96.5								
				8			96.0								
				4			95.5								
		Clean	Beckman	125	94.0	96.5	98.0	97.0	96.5	94.5	92.0	90.5	90.5	93.5	94.3
			Specular Spectro Photometer	16	90.9	93.7	94.5	93.7	95.2	91.7	90.5	89.8	89.5	94.6	92.0
				8	91.1	93.7	95.6	94.4	92.5	90.0	89.4	80.2	89.5	93.8	93.0
				4	89.1	93.1	94.0	93.8	94.3	80.0	83.8	82.6	80.5	79.6	87.0
			Specular Photometer	16			95.0								
				8			95.0								
				4			94.0								

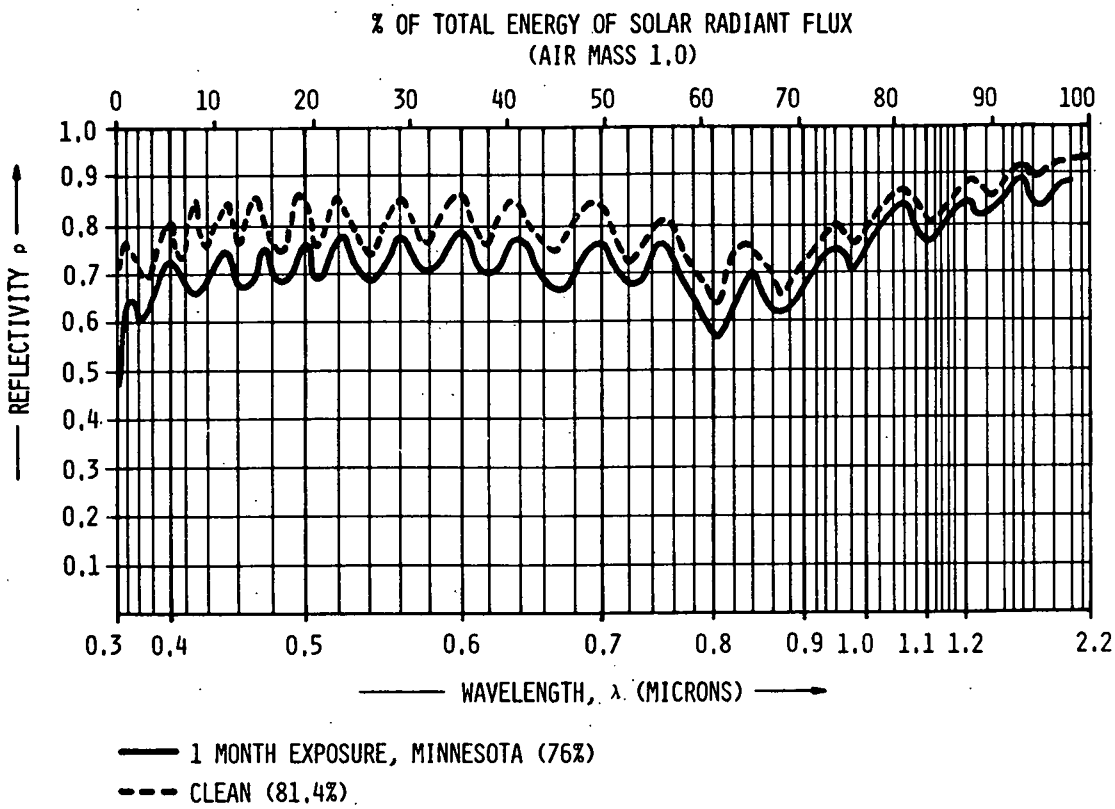


Figure 3-8. Kinglux™ Reflectance Data (Parallel Orientation)

What we can cite as other weak spots are the minimal efforts to characterize both the individual and a synergistic effects of degradation due to humidity, temperature, sunlight and weathering parameters. Furthermore, the available data on maintenance and degradation control is nearly nonexistent at this time. Studies on degradation mechanisms to define degradation control requirements have been initiated but results were not available at the time of our efforts.

Other comments include the fact that transmittance data reported for most of the polymers in handbooks are not spectral trasmittance and caution should be exercised in using that data. Most of the authors reporting data have not labeled or have failed to describe the optical material with respect to composition or procurement data or part number. Technological development in the material field may have outdated the results. This could be confusing for the materials whose brand name was preserved and changes made to suit solar applications.

The summary thus indicates a lack of optical standards for materials and materials testing. We strongly recommend that standards be established and used.

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APPENDIX A

SAMPLE OF LETTER SURVEY

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WAS INTENTIONALLY

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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,

Anoop Mathur

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

   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 PROCEUDRE ____________________

OTHER ____________________

ACKOWLEDGEMENT

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:

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