5105-56
Solar Thermal Power Systems
Parabolic Dish Project
Research and Advanced Development

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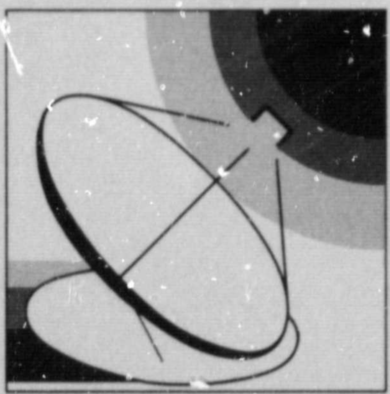
Criteria for Evaluation of Reflective Surfaces for Parabolic Dish Concentrators

F. Bouquet



July 15, 1980

Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration
by
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FOREWORD

The research described in this report was carried out at the Jet Propulsion Laboratory, California Institute of Technology, by the Applied Mechanics Technology Section for the Thermal Power Systems Project. This work was sponsored by the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

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ABSTRACT

A summary of the technology for evaluating reflective surfaces for parabolic solar dishes is presented in this report. Commercial, second-surface glass mirrors are emphasized, but aluminum and metallized polymeric films are also included. Criteria for sealing solar mirrors in order to prevent environmental degradation and criteria for bonding sagged or bent mirrors to substrate materials are described. An overview of the technical areas involved in evaluating small mirror samples, sections, and entire large gores is presented.

The objective of this document is to establish a <u>basis</u> for mirror criteria that eventually may become part of inspection and evaluation techniques for three-dimensional parabolic reflective surfaces. Concentrator support structure, optical tracking, gore alignment, and other important ancillary problems are omitted from this report.

A glossary and important references concerning optical criteria are included.

GLOSSARY

DEFINITION OF TERMS

Absorber	Component of a solar collector (generally metallic), the function of which is to collect and retain as much of the radiation from the sun as possible.
Air Mass	The length of the path through the earth's atmosphere transversed by the direct solar radiation, expressed as a multiple of the path length with the sun at the zenith (overhead).
Aluminosilicate Glass	A particular type of high transmittance glass that contains between 17 and 25.3% Al_2O_3.
Anneal	To prevent or remove objectional stresses in materials by controlled cooling from a suitable temperature.
Blank	See lite.
Blister	An imperfection; a relatively large bubble or gaseous inclusion.
Borosilicate Glass	Any silicate glass having at least 5% boron oxide (B_2O_3).
Bubbles	Gas inclusions in any glass.
Check	A surface crack or imperfection in glass surface.
Chemical Durability	The lasting quality (both physical and chemical) of a glass surface. It is frequently evaluated, after prolonged weathering or storing, in terms of chemical and physical changes in the glass surface, or in terms of changes in the contents of a vessel.
Collector	Any device for gathering the sun's rays and directing it in a useful way.
Collector Efficiency	The ratio of the energy collected by the solar collector to the radiant energy incident upon the collector area.
Collimated Light	Parallel rays of light, the direct or beam component of the solar radiation.

Concentrator	A solar collector that focuses or funnels solar radiation onto a relatively smaller absorber at a focal point or line.
Devitrification	Crystallization in glass.
Dice	The more or less cubical fracture of tempered glass.
Diffuse Radiation	Scattered radiation from the sun that falls on a plane of stated orientation; in the case of an inclined surface, ground reflected radiation is included.
Digs	Deep, short scratches.
Dispersion	Variation of the refractive index with the wavelength of light.
Figure Error	Variations of the mirror surface contour from its expected position of low spatial frequency, i.e. >1 cm.
Float Glass	Sheet glass made by floating the glass on a liquid metal during cooling.
Forming	The shaping of hot glass.
Gaseous Inclusions	Round or elongated bubbles in the glass.
Glass	A hard, brittle, noncrystalline, more or less transparent substance produced by fusion, consisting of mutually dissolved silica and silicates that also contain soda and lime.
Gore	A section of a parabolic concentrator.
Heat Treated	A term sometimes used for tempered glass. See "tempered glass."
Heliostat	A flat device (reflector) for directing the sun's radiation toward a fixed target.
Latitude	The angular distance north (+) or south (-) of the equator, measured in degrees.
Lite	A section of glass sold and/or handled separately such as a 0.61 m x 0.61 m (24 in. x 24 in.) section. Also called "blank" or "light."
Mirror	A reflective surface, orginally a polished metal but now usually made of glass with a silvery, metallic or amalgam backing.

Moiré Contouring	The use of Moiré fringe patterns to measure figure errors.
Mold	A form (usually metal) in which glass is shaped.
nm	Nanometers or 10^{-9} meters.
Near-UV	The wavelengths in the solar spectrum from 200 to 400 namometers in this report. See "Ultraviolet Radiation (UV)."
Normal	Mathematically, the Gaussian distribution.
Parabolic	The locus of a point moving in a plane so that its distances from a fixed point (focus) and a straight line (directrix) are equal; equation is $y = r^2/4f$ where f is the focal length, r the radius, and y the optic axis.
Photon	A quantum of electromagnetic energy; its energy, E, is defined by $E = h\nu$ where h is Plank's constant, and ν is the frequency.
Plate Glass	Flat glass formed by a rolling process, ground and polished on both sides, with surfaces essentially plane and parallel.
Pyrolysis	Decomposition of organic material into chemical constituents by the action of heat.
Ream	Inclusions within the glass, producing a wavy appearance.
Reflectance	The ratio of radiation reflected from a surface to that incident on the surface.
Reflectivity	The property of reflecting radiation possessed by all materials to varying extents.
Residual Stress	The average tensile stress remaining in the glass after manufacture.
Sagging	The process of forming glass either with heat (hot sagging) or without heat (cold sagging) until it conforms to the shape of the mold or form on which it rests.
Seam	To slightly grind the sharp edges of a piece of glass.
Seed	An extremely small gaseous inclusion in glass.

Shear Mark	A scar appearing in glassware, caused by the cooling action of the cutting shear.
Sheet Glass	Flat glass made by continuous drawing.
Slope Error	The error in the angle or position from its expected position, usually less than 1 cm period.
Solarization	Change in transmission of glass as a result of exposure to sunlight or other radiation.
Spectral Energy Distribution	A curve showing the variation of solar energy intensity with wavelength.
Spectral Irradiance	The monochromatic irradiance of a surface per unit bandwidth at a particular wavelength. Units are often watts per square meter per nanometer bandwidth.
Specular Reflectance	Ratio of the energy reflected from a plane surface in a given defined waveband to the energy incident in that waveband.
Specular Reflection	Mirror-like reflection in which the incident and reflected angles are equal.
Stability	(1) Resistance to devitrification; (2) chemical durability.
Stone	An imperfection or crystalline contamination in glass.
Strain	An elastic deformation due to stress.
Strain Point	The temperature at which the internal stresses are reduced to low values in 4 hours. At this viscosity the glass is substantially rigid.
Tempered Glass	Glass that has been rapidly cooled from near the softening point, under rigorous control, to increase its mechanical and thermal endurance. Some types of glass may be tempered chemically also.
Thermal Endurance	The relative ability of glassware to withstand thermal shock.
Total Solar Transmittance	The calculated transmittance of solar energy using the solar data for air mass 1.5 and incident upon a perpendicular surface.

Transmittance	The ratio of the radiant energy transmitted by a given material to the radiant energy incident upon the surface of the material.
Trough	A solar concentrator that has a single axis of curvature.
Ultraviolet Radiation (UV)	Radiation having wavelengths longer than those of X-rays but predominantly shorter than visible wavelengths, usually 100 angstroms to 4000 angstroms.
Vee-Chip	Deep "V" chip at glass edge.
Wave	Defects resulting from irregularities in the surface of glass, making the viewed objects appear wavy or bent.
Weathering	Attack of a glass surface by atmospheric elements.

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SECTION I

INTRODUCTION

Although solar reflective surfaces have existed for over 2000 years, parabolic dish concentrators have been used effectively during the last century (see References 1 through 5). With the present U.S. national goal of producing a significant part of U.S. energy from solar sources by 1990, an impetus to refine and improve reflector surface technology has evolved. A number of facts have emerged from this research thus far:

(1) A number of suitable types of solar reflector materials are currently available, exhibiting various efficiencies depending upon type of glass, glass thickness, and metallization.

(2) Commercial back-silvered glass mirrors have relatively high initial reflectances.

(3) All reflective surfaces undergo inherent degradation, however small, with exposure time in the environment.

(4) Man-made and natural phenomena, such as cleaning processes and dirt accumulation, can accelerate degradation unless adequate edge sealing is provided for the protection of the second-surface metallization.

The designer of large solar concentrators usually desires to know the characterization and environmental response of a particular selected reflective material. Although some limited data are available and many documents on reflective surfaces have been written, frequently the desired information is scarce, incomplete, or non-existent.

It is the purpose of this document to summarize, with a minimum of repetition of other pertinent documents in this field, the criteria for evaluation of reflectors specifically for parabolic dish concentrators. Although not exhaustive, this report gives an overview of the more important criteria from the layman's viewpoint.

The advanced concentrator parabolic dish system currently being designed for the Solar Energy Research Institute (SERI) by the Jet Propulsion Laboratory is shown in Figure 1-1 (artist's concept). The concentrator's diameter is large (11 m, 36.1 ft), and is composed of borosilicate glass on a cellular glass substrate. A detailed drawing of a typical outer gore is shown in Figure 1-2. Note the three-dimensional mirror surface.

Another design of a smaller test facet for the advanced concentrator is shown in Figure 1-3. The very slight surface curvature, which corresponds to a radius of curvature of 13.2 m (520 in.), is apparent. Two of the three attachment points are shown as well as the edge seal details.

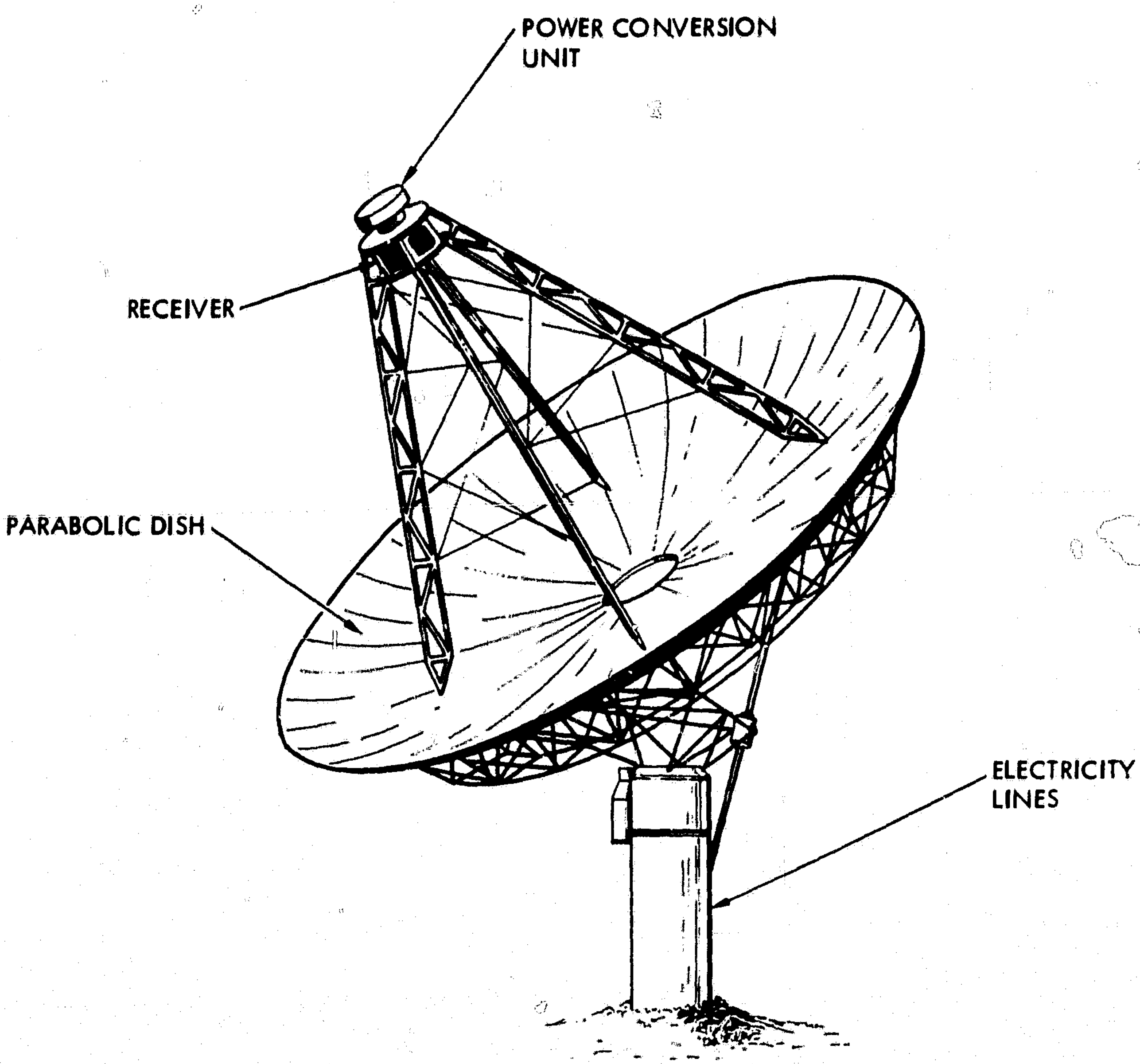

Figure 1-1. Advanced Concentrator Parabolic Dish System

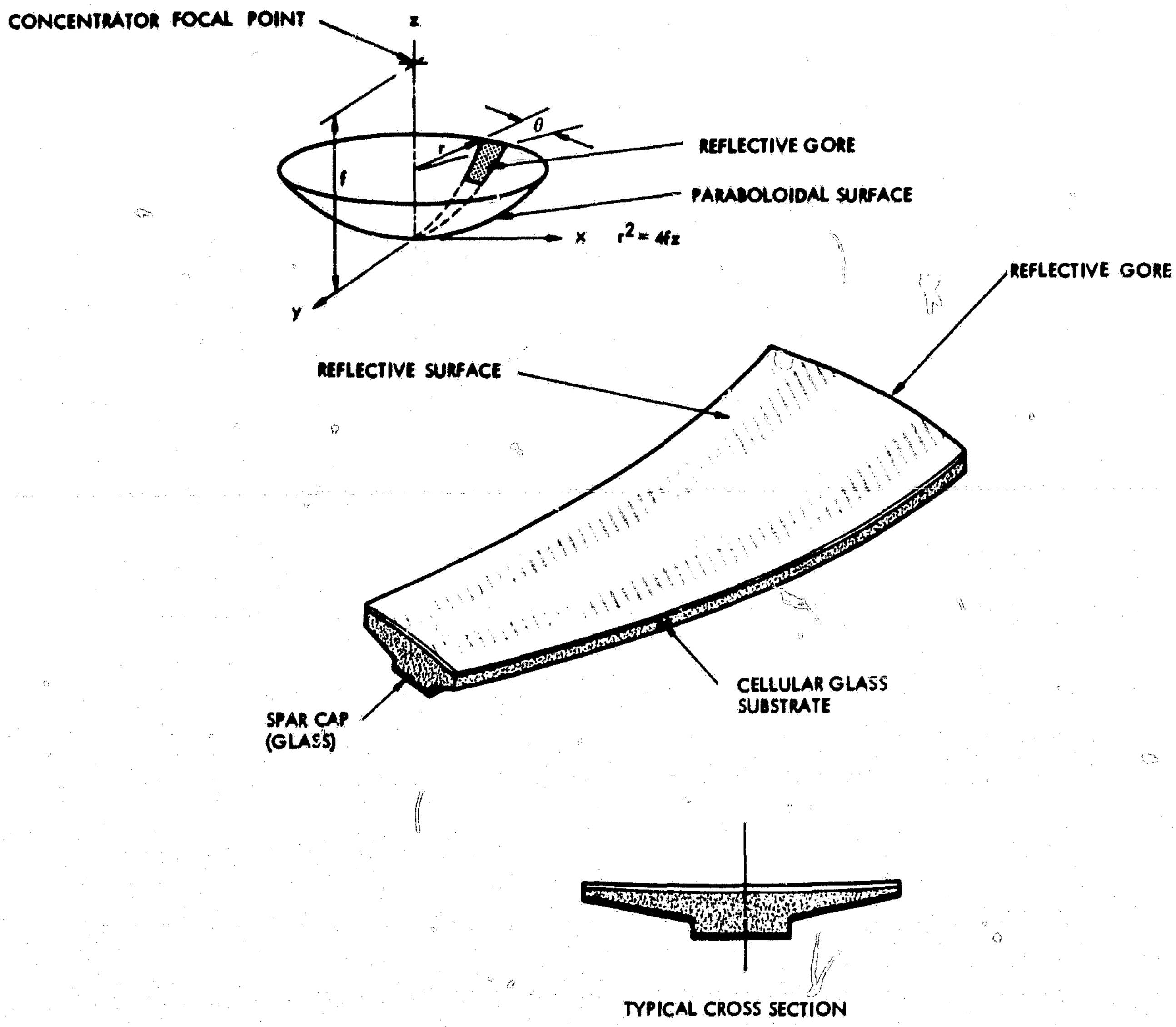

Figure 1-2. Cross Section of Advanced Concentrator Gore

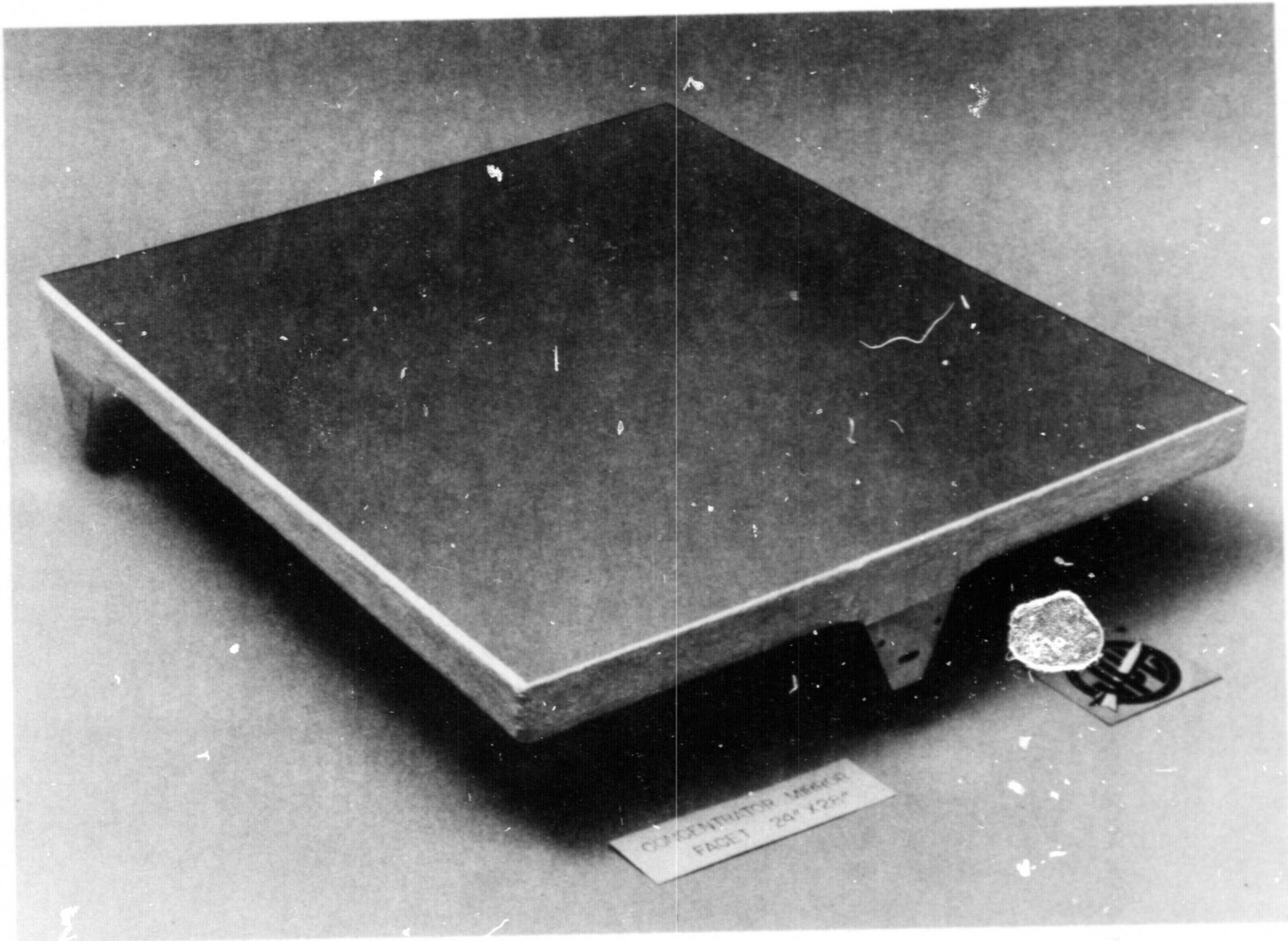

Figure 1-3. Mirror Facet for Test Bed Concentrator Showing Three-Dimensional Curvature

Section II identifies some general environmental design conditions that should be taken into consideration when establishing criteria for reflective surfaces for large parabolic concentrators.

General considerations for criteria are given in Section III, but the emphasis is on second-surface glass mirrors that are commercially available. Other types of mirrors, bonding, cleaning, and criteria for testing methods are discussed briefly. Section IV presents the study conclusions in terms of the technology status of reflective surface criteria for parabolic dishes.

SECTION II

DESIGN ENVIRONMENTS

The criteria for evaluation of reflective surfaces vary with environmental conditions. Some of the types of effects resulting from time-varying stress levels are shown schematically in Figure 2-1.

Because weather conditions in the United States differ with site location, the constructional design characteristics of parabolic dish concentrators tend to be regional and site-specific. As an example, the weather conditions for 19 major U.S. cities are shown in Table 2-1. The wide variation of rainfall and temperature is noted. Table 2-2 shows representative particulates that may be encountered. Figures 2-2 and 2-3 show hail effects on glass (Reference 6) and the U.S. hail distribution (Reference 7).

Estimations of solar energy and wind energy available in various U.S. cities are summarized in Reference 9. Also see Reference 10 for more details.

As implied above, the test criteria for evaluation of reflective surfaces must match the site environment conditions and the concentrator specifications. Section III discusses definitions and general criteria for the three major types of reflective surfaces.

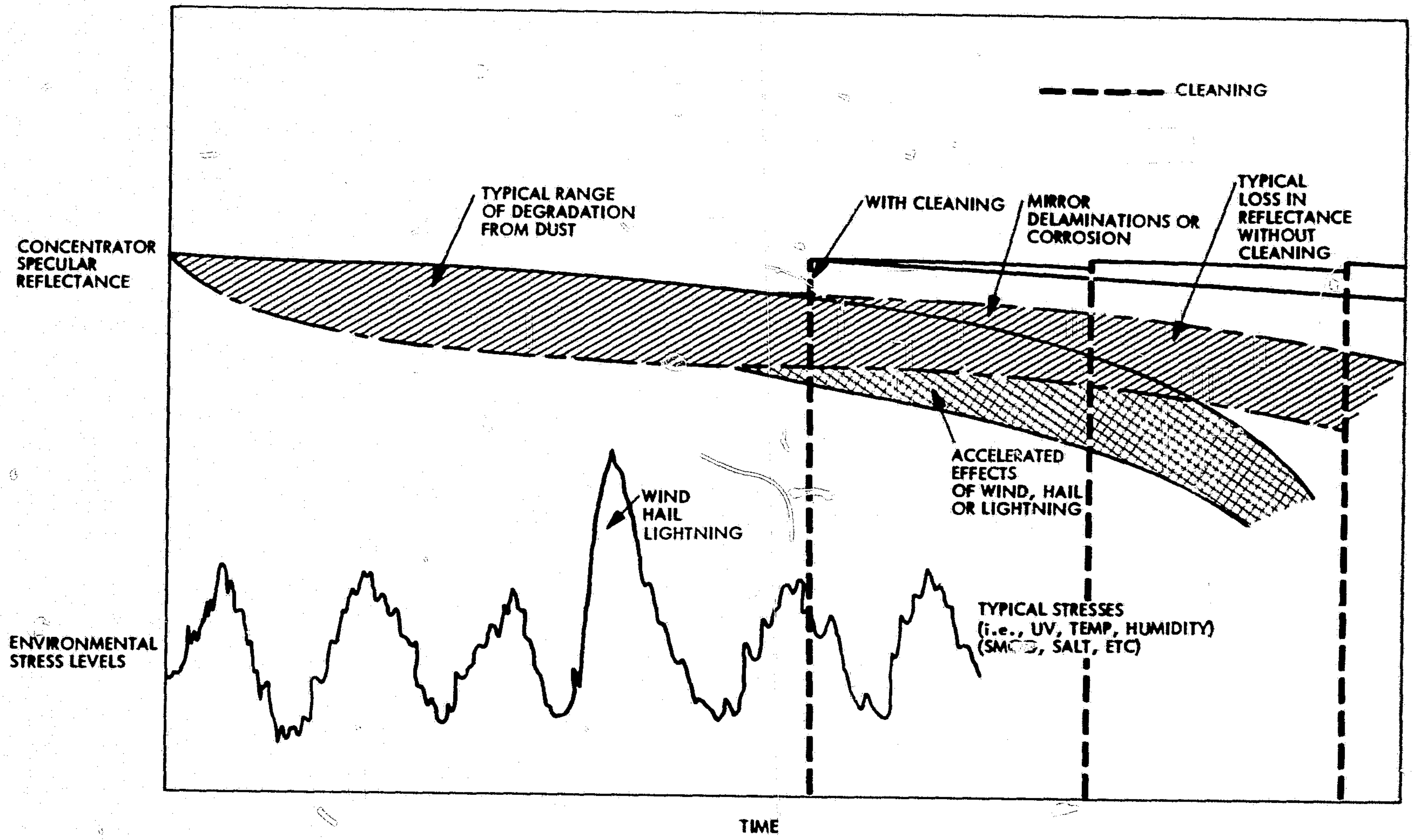

Figure 2-1. Typical Mirror Response to Cyclic Stress with and without Cleaning

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Table 2-1. Weather Data for Selected U.S. Cities

City	Location			Climate													
	Latitude deg.	Elevation m	(ft)	Sun %	Wind Avg. km/hr	(mi/hr)	Rain mm	(in.)	Precipitation, days	<0°C (32°F) days	Avg. Rel. Humidity, %	Temperature * °C	(°F)	S** °C	(°F)	Particulate µg/m
Mobile, AL	31	64.3	(211)	61	15.3	(9.5)	1727.2	(68)	123	21	71	[-13.3]	[(8)]	[38.9]	[(102)]	NA
Phoenix, AZ	34	341	(1117)	86	9.3	(5.8)	182.9	(7.2)	NA	16	44	1.11	(34)	23.9	(75)	123
Los Angeles, CA	34	95.1	(312)	73	11.7	(7.3)	320	(12.6)	36	-	69	6.67	(44)	20.6	(69)	104
Denver, CO	40	1610	(5283)	70	14.6	(9.1)	375.9	(14.8)	87	164	54	-16.1	(3)	17.2	(63)	135
Hartford, CT	42	4.6	(15)	57	14.6	(9.1)	1089.7	(42.9)	125	138	66	-15	(5)	23.3	(74)	69
Washington, DC	39	4.3	(14)	58	15.1	(9.4)	1041.4	(41)	111	82	62	-7.22	(19)	32.2	(90)	77
Miami, FL	26	2.1	(7)	66	14.5	(9.0)	1524	(60)	128	-	73	8.33	(47)	26.1	(79)	69
Honolulu, HI	21	2.1	(7)	69	18.5	(11.5)	533.4	(21)	101	-	72	16.7	(62)	22.8	(73)	42
Boise, ID	44	866	(2842)	67	14.5	(9.0)	289.6	(11.4)	90	127	61.5	-12.2	(10)	18.3	(65)	105
Wichita, KS	38	403	(1321)	65	20.6	(12.8)	721.4	(28.4)	83	112	68	[-24.2]	[(-12)]	[45]	[(113)]	67
New Orleans, LA	30	0.9	(3)	61	13.5	(8.4)	1419.9	(55.9)	112	12	76	1.67	(35)	26.1	(79)	75
Portland, ME	44	18.6	(61)	59	14.0	(8.7)	1089.7	(42.9)	126	162	70	-17.8	(0)	21.7	(71)	NA
Bismark, ND	47	502	(1647)	62	17.4	(10.8)	386.1	(15.2)	96	188	66	-28.3	(-19)	21.1	(70)	82
Omaha, NE	41	298.1	(978)	62	17.7	(11)	701	(27.6)	98	137	69	-18.3	(-1)	24.4	(76)	115
Albuquerque, NM	35	1618	(5310)	77	14.2	(8.8)	205.7	(8.1)	58	118	47	-8.33	(17)	17.8	(64)	NA
New York, NY	41	5.8	(19)	59	15.3	(9.5)	1066.8	(42)	121	82	64	-8.89	(16)	23.9	(75)	131
San Juan, PR	18	4	(13)	64	14.3	(8.9)	1625.6	(64)	205	-	74	16.1	(61)	35.6	(96)	NA
Dallas, TX	33	146.6	(481)	65	17.5	(10.9)	889	(35)	80	37	67	-4.44	(24)	25.6	(78)	84
Seattle, WA	48	4.3	(14)	45	15.3	(9.5)	990.6	(39)	161	32	80	0	(32)	17.8	(64)	61

( ) = English units
[ ] = Extremes for recent records
*Winter temperature exceeded 97.5% of the time
**Highest 1% wet bulb temperatures during warmest months
NA = Not Available

Table 2-2. Representative Percentages of Total Suspended Particulates in Urban Areas (Reference 8)

Constituents	Mass Quantity, %		Average Size, μm	
	Commercial Industrial Residential Areas	Undeveloped Areas	Mean	Range
Minerals	65	90	8	< 1-62
SiO_2 (Quartz)	29	32		
$CaCO_3$ (Calcite)	21	40		
Al Silicates	5	3		
Fe_2O_3 (Hematite)	10	15		
Other	< 1	< 1		
Combustion Products	25	8	5	< 1-58
Soot	17	7		
Fly Ash	8	1		
Miscellaneous	< 1	< 1		
Biological Material	3	1	24	5-82
Misc. (Mostly Rubber)	7	1	43	13-135

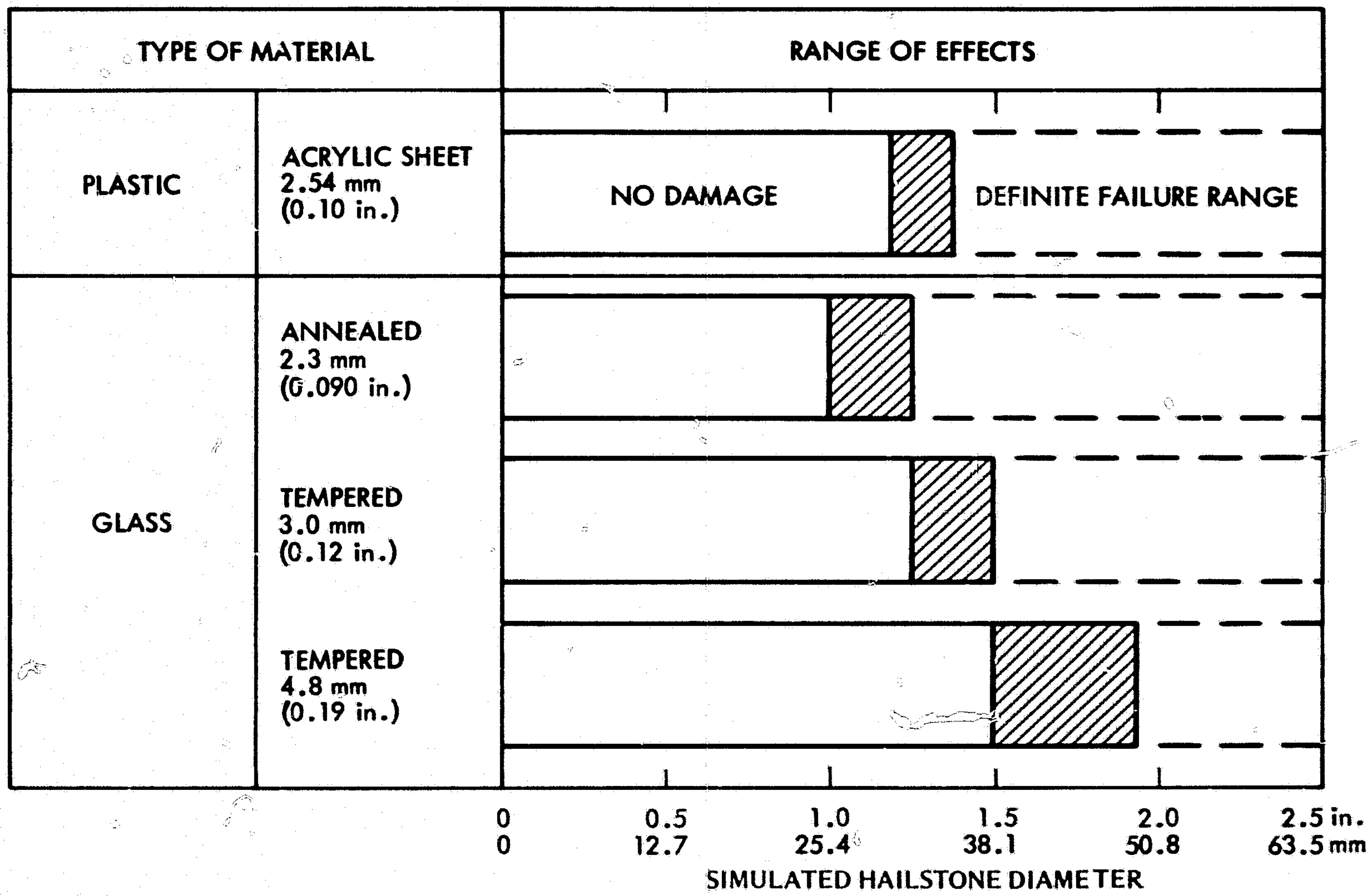

Figure 2-2. Failure Ranges for Glass of Various Thicknesses When Exposed to Simulated Hail

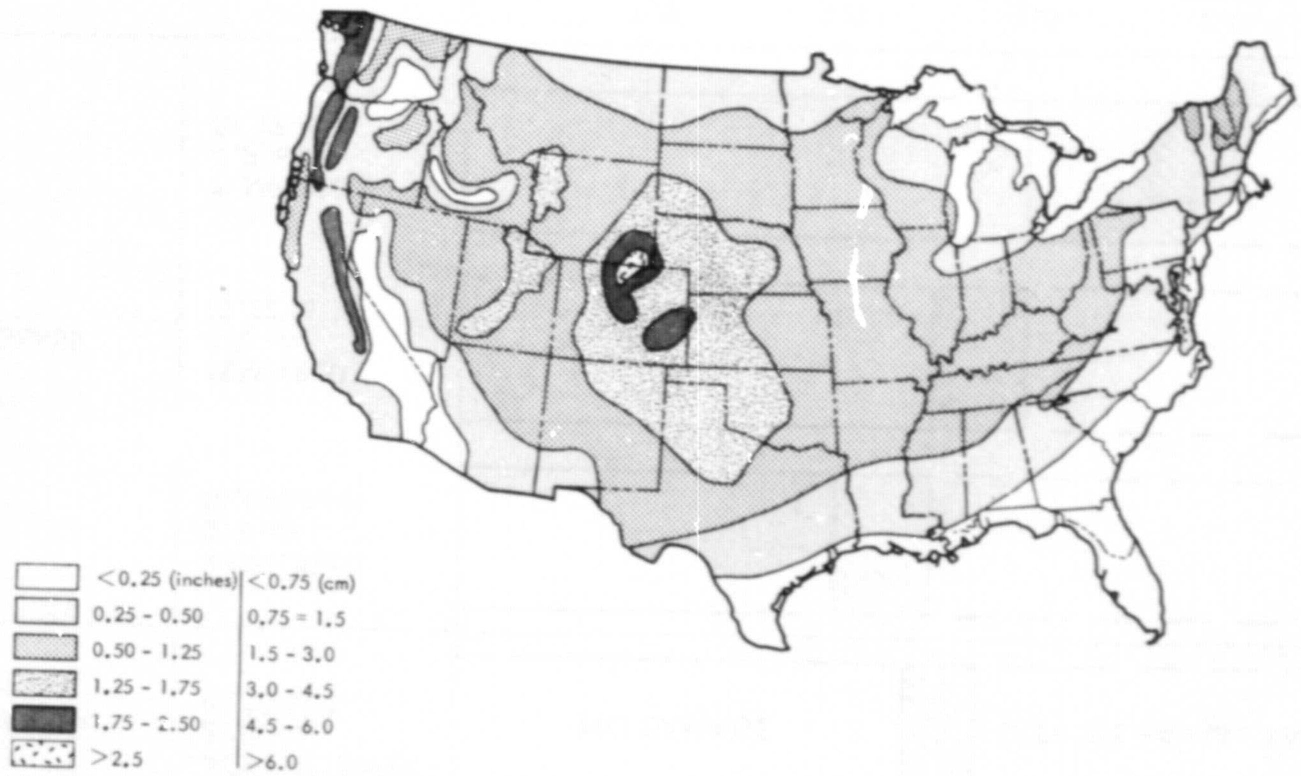

Figure 2-. . Geographical Distribution of Hail in the United States (Reference 7)

SECTION III

EVALUATION CRITERIA FOR PARABOLIC DISH REFLECTIVE SURFACES

A. DEFINITIONS AND REFLECTION RANGES

Second-surface silvered mirrors, aluminum mirrors, and metallized polymeric films can be generalized as shown schematically in Figure 3-1. Similarities are noted; however, the metallized polymers are classed as superstrate reflectors for obvious reasons. (See Reference 11.) Glass, when used as a hermetic barrier between the environment and the metallization, is classified as a substrate configuration. The technology behind the fabrication of silvered mirrors is relatively advanced, having been used for some 80 years. Although the criteria in this report are primarily directed toward silvered glass mirrors, the criteria are, in general, equally applicable to other types of reflective surfaces.

This report does not cover all existing advanced solar reflecting surfaces. For example, substitution of indium for silver has been investigated briefly by JPL. Although in initial samples the reflectance was found to be less than that of silver, the metal shows promise.

The criteria, terminology, and illustrations are derived from current JPL parabolic dish designs. Because of the dynamic nature of reflective surface technology, it is understood that the criteria presented herein may not be universally applicable to all concentrator designs, and other designs may require criteria not presented in this report.

Back-silvered glass mirrors obtained from commercial sources exhibit high solar hemispherical reflectance, i.e., 80-96%, along with high specularity. Examination of the reflectance data (Refs. 12 through 16) shows that many of the surfaces fall into arbitrary ranges, and these are generalized in Table 3-1 along with potential solar or non-solar applications.

A detailed examination of the specular characteristics of various solar reflective surfaces has been performed by Pettit of Sandia Laboratories using a bidirectional reflectometer. It was found that the reflected light from a material can be either a normal intensity distribution or the sum of two normal distributions. (See References 12 through 16.) This technique is invaluable for assessing the characteristics of solar reflective surfaces.

In summary, one criterion for establishing the reflectance of a parabolic dish concentrator is use of reflective surfaces having as high a specular reflectance as possible, unless cost trade-off calculations indicate otherwise. (See the following section, "Collector Performance Criteria.")

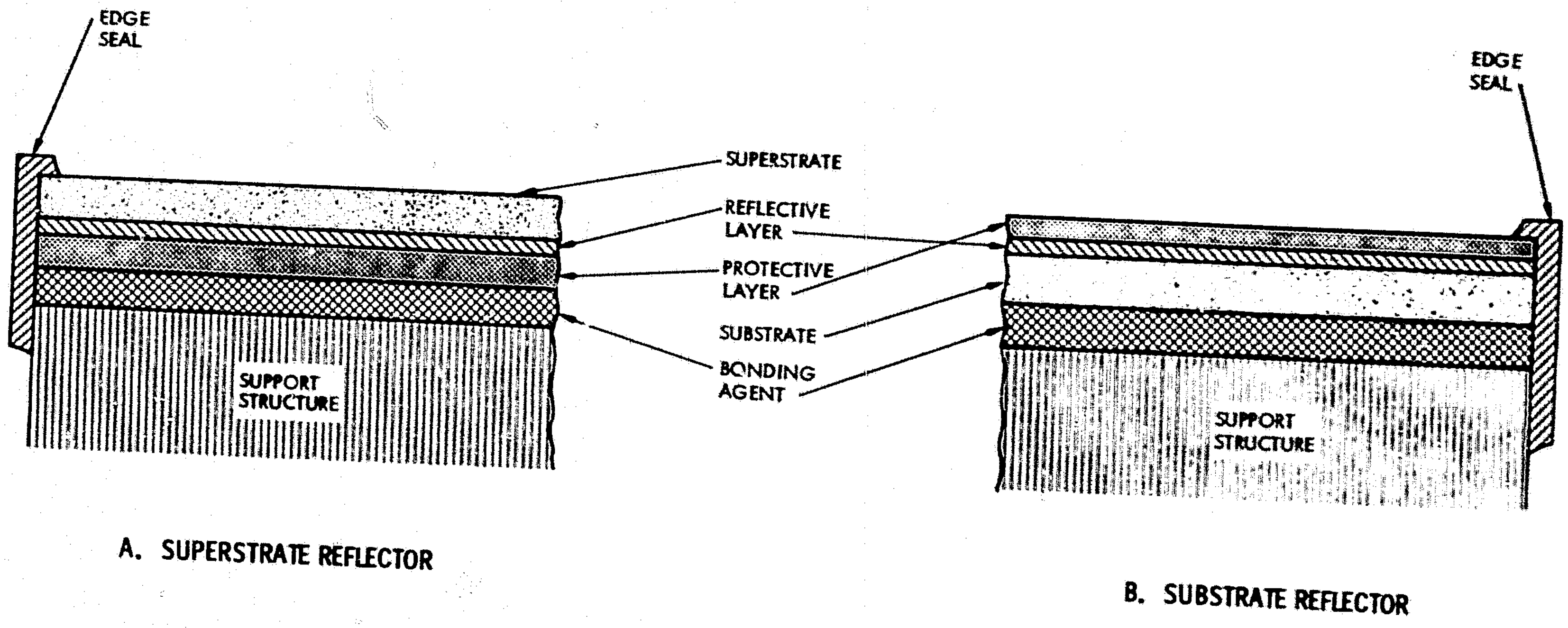

Figure 3-1. Examples of Typical Reflective Surfaces

Table 3-1. Proposed Arbitrary Ranges of Evaluation of Solar Total Reflectances

Step 1*

Solar Total Reflectance Level	Evaluation	Type	Application
0.90 - 1.00	Excellent	Solar	Parabolic Concentrators
0.80 - 0.90	Satisfactory	Solar	Low-Cost Concentrators
0.70 - 0.80	Marginal	Solar	Very Low-Cost Concentrators
0.0 - 0.70	Unacceptable	Non-Solar	General Applications

*When step 1 is completed, the surfaces must be further evaluated to ascertain if the specularity reflectance criteria are met.

B. COLLECTOR PERFORMANCE CRITERIA

General criteria for performance of a solar concentrator have been stated by Gupta (Ref. 17). (See Table 3-2.) The concentrator efficiency is the product of two terms representing relative receiver energy collection minus the relative heat losses. Therefore, increased efficiency is proportional to the specular reflectance, ρ, of the concentrator surface.

More definitive information concerning the criteria for reflective surfaces for parabolic dishes has resulted from JPL analyses. (See Reference 18.)

Optical data and sophistication of the reflective surface model required for accurate prediction of performance and optical/substrate interactions depend upon concentrator configuration and complexity. Generally, current analytical and experimental techniques for determining concentrator performance are adequate for investigating such interactions. When the structural characteristics and the mathematical model have been determined, interaction analyses can be conducted using a dynamic model.

Optimization. The solar concentrator should be designed so that reflective surfaces are compatible with other component structures. Undesirable interactions between component structures should be minimized. The goal is to optimize reflective surface/substrate interactions. Elements to be considered for back-silvered mirrors are the following:

(1) Mirror glass
(2) Silver metallization
(3) Copper metallization
(4) Backing paint
(5) Sealant
(6) Epoxy or bonding agent
(7) Substrate
(8) Substrate coating

In general, interactions can occur in many ways depending upon the characteristics of the above components. An undesired interaction, once identified, can be alleviated or circumvented by modification of the component.

Many interactions can be anticipated and potential problems solved in the design phase. With a cooperative effort between the structural and optical designers, an adequate model of the reflective surface can be established. In addition, this model should specify the uncertainties (tolerances) in the reflective structure.

Table 3-2. Collector Performance Criteria
(Reference 17)

$$\eta_T = (\rho\tau\alpha)_e \cdot F_T - \frac{(Q_1/A_R)}{C\ I_{DN_T}}$$

$$\eta_T = \frac{\text{Whole Day Total Heat Collection/Aperture}}{\text{Whole Day Total Direct Normal Insolation}}$$

$(\rho\tau\alpha)_e$ = Effective Product of Specular Reflectance, Transmittance and Absorptance Coefficients for All Optical Elements

F_T = Whole Day Average Tracking Efficiency (Includes, Cosine, Blocking, Shading Losses, etc.)

$\left(\frac{Q_1}{A_R}\right)_T$ = Whole Day Total Heat Loss/Receiver Area

C = Concentration Ratio = $\left(\frac{A_A}{A_R}\right)$

I_{DN_T} = Whole Day Total Direct Normal Insolation

C. SOLAR MIRROR CRITERIA

1. Second-Surface Glass Mirrors

a. Glass

Thickness and Composition Criteria. Criteria for the acceptability of solar glass/mirrors may be classed as being (a) independent of the design or (b) dependent upon the design of the mirror. It is the purpose of this report to present a list of specific criteria that can serve as a model for developing acceptance/ rejection criteria useful in future designs, independent of the detailed design.

Many types of glass are currently being used for solar applications including soda-lime and low-iron glass. Transmittance of the glass varies remarkably with thickness and composition. (See Figure 3-2.) Typical thicknesses of solar glass are identified by vertical lines. Note that most of the slanted lines shown at zero thickness of glass point to the high 90% range on the reflectance scale. The criterion for thickness selection is that the glass be as thin as possible for double transmission of the incident solar radiation over as wide a spectrum as possible and still withstand the strength specifications or other ground rules for a particular application.

The composition criterion is that the glass satisfy durability, transmittance, cost, and other requirements.

The physical properties of two types of high solar reflectance glass are shown in Table 3-3. The aluminosilicate and borosilicate glass are found to exhibit low coefficients of expansion and, hence, low stress corrosion. Using these data, one can make engineering estimates without performing time-consuming strength measurements. (See Reference 19.)

Glass Acceptance Criteria. An interim Federal specification on float glass was developed by the General Services Administration Federal Supply Service (Ref. 20). The specification treats glass classification, applicable government documents, military standards, glass surface requirements, quality assurance provisions, defects, and recommended wind load table.

A considerable amount of information on glass acceptance and testing can be found through ASTM (American Society of Testing Materials) sources (Ref. 21).

In order to reduce the probability of high degradation rates in the field, visual inspection should be performed to assure that the mirror surfaces are free from defects in workmanship. Inspection should be performed on all elements tested, namely, small samples, large sections, and the final gore. A list of the type of defects to be encountered are given in Reference 22 and the glossary (page v).

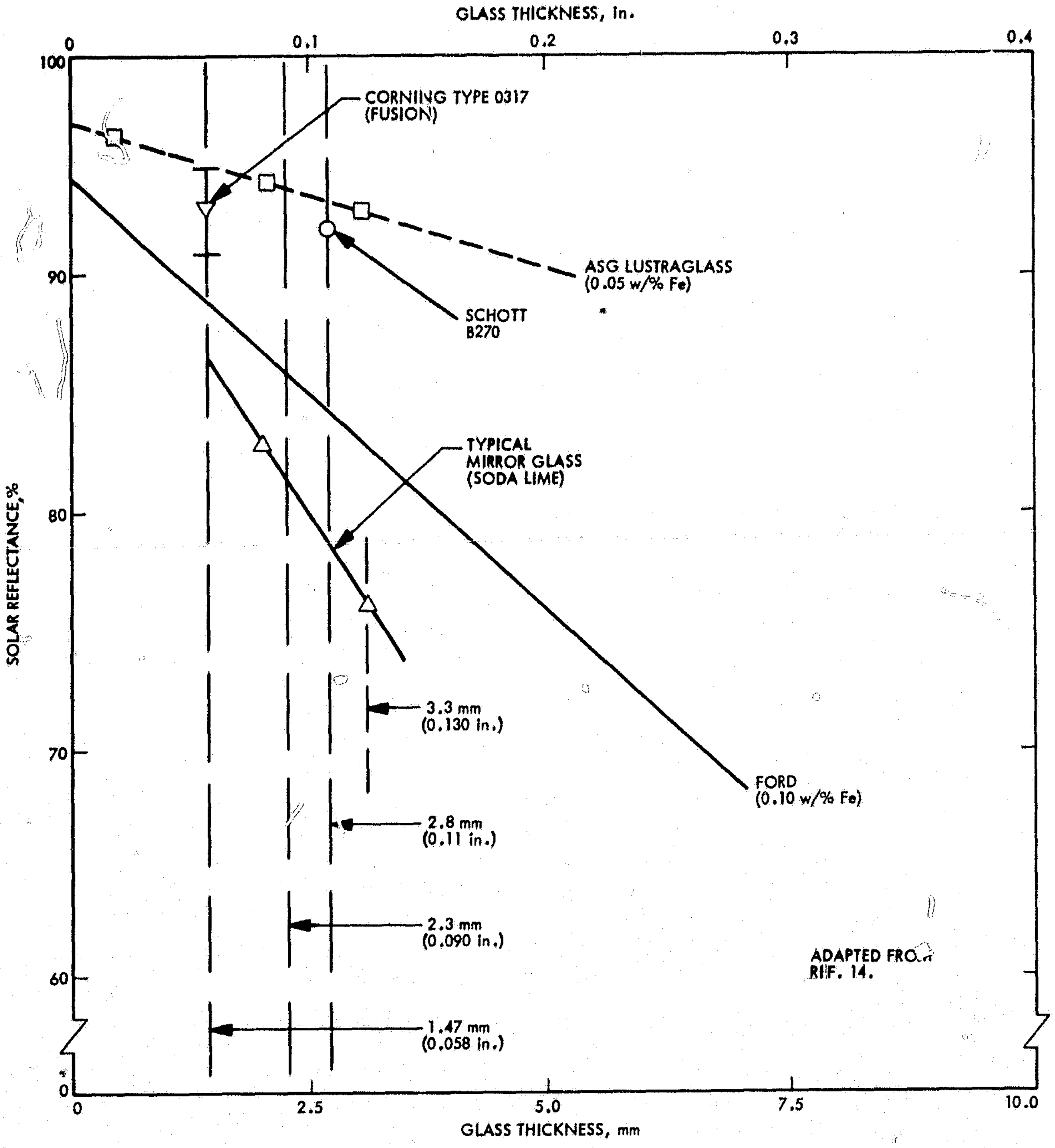

Figure 3-2. Solar Reflectance versus Glass Thickness for Typical Types of Glass

Table 3-3. Typical Solar Mirrors; Preliminary Properties of Corning 0317 and 7809 Glass [Thickness - 1.5 mm (0.060 in.)]*

Property	Type of Corning Glass	
	0317 (Aluminosilicate)	7809 (Borosilicate)
Density, g/cm^3	2.45	2.44
Index of Refraction	1.512	1.509
Solar Transmittance, %	90.0 (est.)	91.7 $\pm$ 2
Solar Reflectance, %		
(a) Vacuum-Deposited Silver	95 $\pm$ 1	95 (est.)
(b) Chemically-Deposited Silver	94 $\pm$ 1	94 (est.)
Weather, 20 years	Excellent	Excellent
Softening Point, ^oC	870	750
Annealing Point, ^oC	NA	569
Strain Point, ^oC	NA	529
Strengthening Capacity	Yes	No
Expansion Coefficient		
(a) 0-300^{o}C, $10^{-7}/^oC$	88	77
(b) -30- +50^{o}C, $10^{-7}/^oC$	81	72
Poisson's Ratio	0.22	0.20
Young's Modulus, GPa	68.94	76.52
(10^6 psi)	(10)	(11.1)

*Corning Glass Works, Corning, New York

In addition to the visual inspection criterion, optical instrument data on the characteristics of the mirror glass should be developed where cost, schedule, and program requirements permit. A detailed written record of the data is desirable.

Glass Strength Criteria. Measurement of flat glass strength has been treated by Lewis (Ref. 23). Multiple types of methods were used:

(1) Hertz fractures were produced by pressing a steel ball against the glass.

(2) The bending strength of circular glass plates was measured.

The latter test is found to be more reliable, considering the fact that the side of float glass next to the tin bath is observed to be weakest. Since the side opposite the time bath is silvered by the mirror industry, it follows that the glass side of the mirror is weakest.

One of the greatest limitations in using glass for parabolic dishes is its static fatigue, which can be described by the following equation:

$$t_f = K\sigma_f^{-n}$$

where

K,n = constants
t_f = time to failure
σ_f = the stress level causing failure

In recent studies, Tummala (Ref. 24) has shown n to be a function of the bulk glass composition. It changes little with the surface of the glass.

Also, experiments show that the stress corrosion resistance varies inversely with the thermal expansion coefficient over the 25 to 300°C range.

Slow crack growth in glass that can lead to failure frequently is initiated by edge cracks. Edge processing (beveling, polishing, or other treatments) can improve the useful life of glass.

During three-dimensional glass bending, glass has a tendency to spring back toward its original shape upon cooling. An initial effort is needed to ascertain the amount of spring-back allowable when selecting a new type of glass. A tentative criterion is less than a 1% dimensional spring-back along the smallest radii of curvature.

Sample Records Criterion. It is imperative that a systematic procedure be developed to code and characterize the glass/mirror types as received. Thickness tolerances should not be assumed since wide tolerances are sometimes used in glass production. This procedure will permit traceability of the glass/mirror samples and may prove valuable at later times.

Maintaining control samples (in a hermetic environment) of the glass and/or mirror being used for the development of a concentrator is desirable. The size criterion proposed is 930 cm^2 (1 ft^2) of glass or mirror.

b. Metallization Criteria.

Analysis. The criteria for evaluation of reflective surfaces can be derived by considering the incident solar spectrum at the concentrator location and the specular reflection distribution of the mirror. One possible approach is shown schematically in Figure 3-3. This type of analysis can lead to identification of a priority listing in terms of optical reflectance. When the reflectance analysis and experimental measurements cannot be performed at multi-wavelengths, 500 nm and a maximum total specular reflectance angle of 18 milliradians should be used.

Given the type of reflectance surface, supporting structure, and other system components, the mirror specifications can be written.

General Mirror Defects. Examples of the types of defects that can occur in the glass, metallization, or backing paint due to poor workmanship or other factors are listed in References 25 and 26. Table 3-4 lists some typical defects. In addition, other defects not considered here may occur in any particular mirror design.

Peak Temperature Criterion. The integrity of the metallization is dependent upon the environmental temperature ranges of operation. Feasible temperature limits should be obtained by laboratory testing. If the metallization is too thick, stress cracking may occur. If the temperature is too high, silver agglomeration may occur and with it a loss of reflectance. (See the environmental temperature ranges listed in Table 2-1.) Typical test temperatures used range from -15°C to +75°C.

Thermal Cycling Criterion. The thermal cycling test is conducted in an environment characteristic of eventual dish deployment. For example, a possible test would subject the mirrors to 50 cycles of temperature variation between -15°C and +75°C. The temperature variation should use a planned linear rate not exceeding 100°C per hour with a period not exceeding 6 hours per cycle.

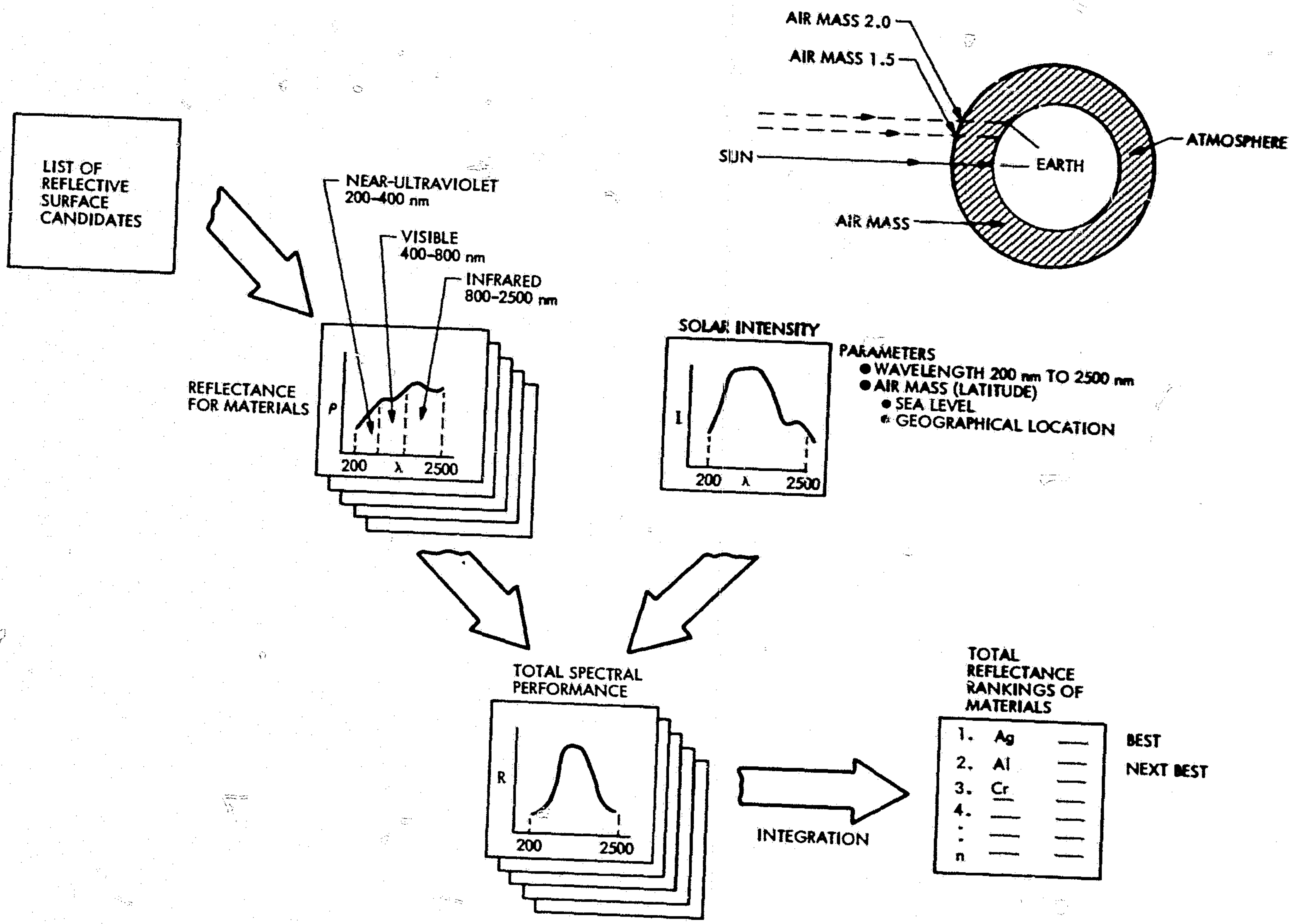

Figure 3-3. An Approach to the Analysis and Evaluation of Reflective Surfaces

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Table 3-4. Mirror Defects

Mirror Components	Defects
Glass	Broken edges Scratches Lines or bubbles Center cracks Surface blemishes Edge cracks
Metallization	Separation of metal and bonded elements Black spots in reflective surface Edge corrosion
Backing Paint	Uneven coverage Bubbles or blisters Cracks Delamination

Temperature Gradient Criterion. Parabolic dish concentrators frequently are designed to allow an undesirable temperature gradient to exist on the reflective surface. For example, receiver support struts could cast a shadow over the mirror surface with resulting damage to the reflective surface. It has been proposed that the following preliminary temperature gradient differentials be simulated over 1 mm dimension. (See Table 3-5.)

Table 3-5. Proposed Temperature Gradients

Mirror	Temperature Gradient ^oC (^oF)
Second-Surface silvered glass	38 (100) to 93 (200)
Anodized aluminum	149 (300) to 204 (400)
Metallized polymer	38 (100) to 93 (200)

Humidity Cycling Criterion. This environmental test requires that the mirror be subjected to a humidity regime. This test will vary with the particular concentrator design and site location. For example, possible test criteria would be as follows:

(1) Pre-dry at 54°C for 24 hours.

(2) Exposure to 50% relative humidity (RH) for 24 hours.

(3) Cycle at 90 to 95% RH for 16 hours per day at high temperature such as peak operating temperature of mirror followed by 8 hours at lower temperature corresponding to night operation.

(4) Continue humidity cycling for 6 cycles.

Edge Loss Criterion. Light losses from edge effects should be considered in optimizating the number of facets in a concentrator design. Measurement of the amount of edge loss should be performed during testing after sagging the mirror. A proposed tentative criterion is not more than 1% of the reflected light intensity lost through edge losses.

Edge Sealant Criterion. Edge sealant is required to prevent the reflective surface from undergoing chemical attack by atmospheric elements. The criteria for design and evaluation include

(1) providing an effective barrier to diffuse atmospheric contaminants, especially liquid water (Ref. 27), and

(2) providing resistance to degradation by the sunlight, especially the near-ultraviolet (UV) radiation. For this report near-UV refers to the range of wavelengths between 200 and 400 nanometers.

Bonding Criterion The quality and integrity of the bond of the reflective surface to the substrate should be tested. Pull tests in the range of 0 to 20.7 MPa (0 to 3000 psi) are needed. The delamination effect of the glass/metal interface should be evaluated. For example, recent pull tests by McDonnell Douglas Astronautics Company obtained approximately 11.0 MPa (1600 psi) for failure of one type of mirror while JPL tests produced 15.0 MPa (2180 psi) for another type (Ref. 28).

Backing Paint Criterion for Second Surface Mirrors. Since paint is a polymeric material, it undergoes various rates of degradation in the presence of sunlight. Outdoor plastics and paints have been subjected to extensive research. The near-ultraviolet component in sunlight is believed to be responsible for the degradation of these materials. (See Reference 29.)

The criteria for mirror backing paint are that it be (1) resistant to atmospheric radiation for the operational life of the mirror and (2) able to minimize diffusion of atmospheric contaminants. Quantitative data on the UV effects on materials are scarce although reports describing JPL's recent research in this area are available (Refs. 30 and 31). Further information on UV effects are given below.

Near-Ultraviolet Exposure Criterion. Experiments have shown that near-ultraviolet radiation can penetrate typical soda-lime-silicate glass used in commercial mirror production. (See Figure 3-4.) The amount of UV radiation penetrating the glass will vary with the iron content, metallization, and glass thickness. Therefore, a criterion for long-lived solar mirrors is that all elements behind the glass, such as the backing paint, bonding agent, sealants, and substrate be designed to resist degradation effects of UV. (For more details see Reference 29.)

If a reflective surface is thought to be susceptible to near-ultraviolet radiation, analysis and testing should be performed over the wavelengths present in the environment. For north latitudes characteristic of the continental U.S. and sea level locations, the UV cutoff is approximately 295 nanometers. For equatorial or mountain locations, shorter wavelengths can occur. As shown in Figure 3-4, a UV cutoff of 200 nm was arbitrarily selected for the analysis and evaluation approach.

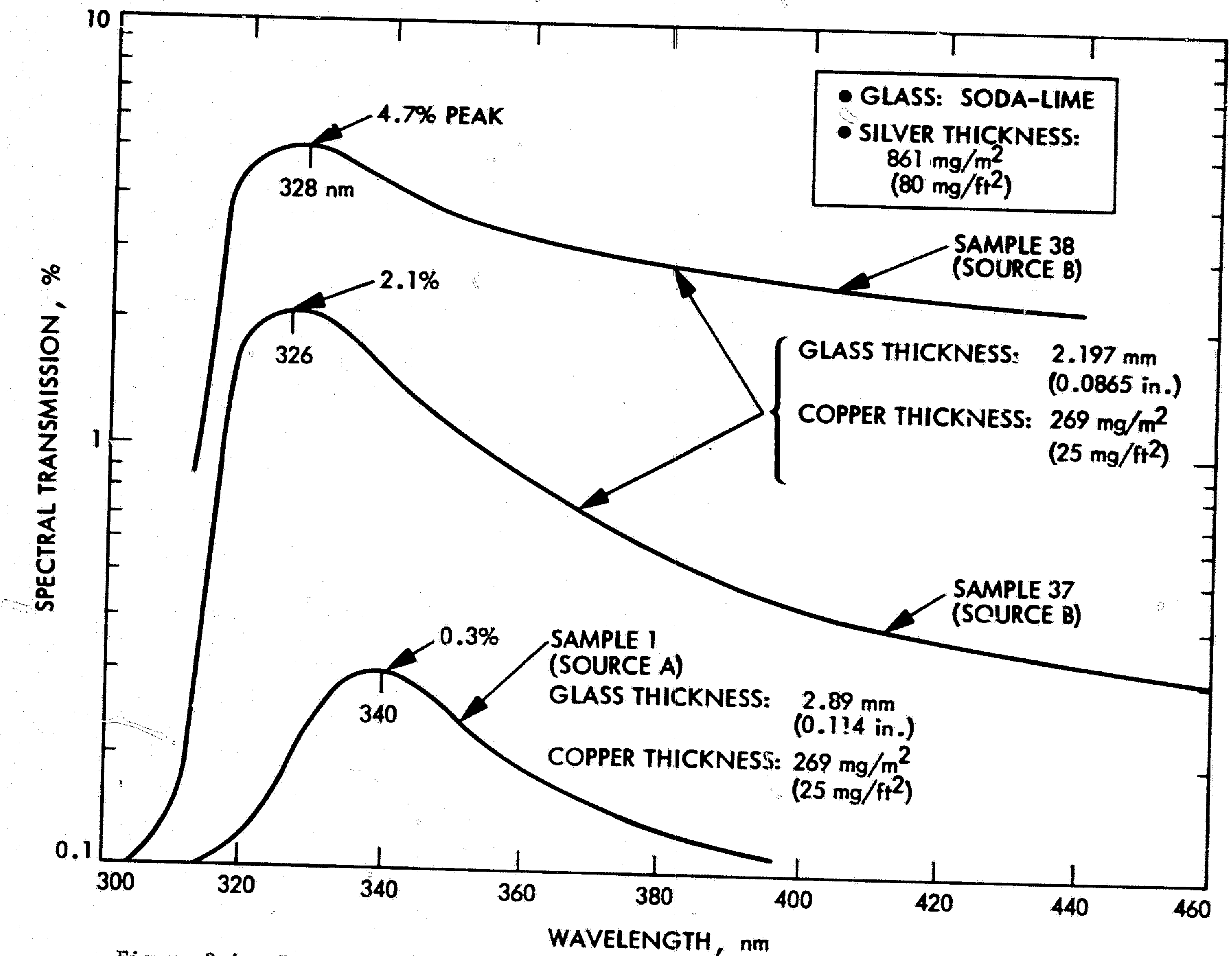

Figure 3-4. Percent Spectral Transmission of Ultraviolet Radiation through Commercial Second-Surface Glass Mirrors versus Wavelength (Reference 30)

2. Aluminum Mirrors

Aluminum reflective surfaces exhibit total hemispherical reflectances in the 80 to 91% range, which is less than that of good second-surface glass mirrors. Several types of bulk aluminum reflective surfaces are currently available. Two types that have been investigated are the following:

(1) Anodized aluminum (Kinglux)

(2) Chemically brightened aluminum (Coilzak)

Both of the above aluminum surfaces are viable candidates for large solar concentrators. In both cases substrates must be used that have small slope errors so that the optical quality of the light beam is not degraded. Detailed measurements of the specularity of bulk aluminum reflectors have been performed by Sandia Laboratories (Ref. 32).

Other types of aluminum surfaces, such as electroplate deposition, should be investigated.

The criterion for use of aluminum reflectors is that three-dimensional (3-D) bending procedures maintain minimum slope errors. The ultimate achievable slope errors for aluminum surfaces are yet to be determined. A tentative goal should be slope errors equivalent to second-surface silvered mirrors.

3. Metallized Polymeric Mirrors

Most of the technology described in the preceding sections on back-silvered glass mirrors and bulk aluminum is also applicable to metallized plastic mirrors. Usually, these commercial reflectors consist of back-aluminized polymers such as acrylics or polyesters. Two criteria are important: (a) the thin film should be less than 0.0127 cm (0.005 in.) thick in order to achieve high transmittance and (b) the metallization should be greater than 700-1000 angstroms for adequate reflectance.

If plastic films are used, operating temperatures must be maintained that are safe for the reflective surface. Surface deformation or melting could occur above 200°C (Ref. 33). Many methods exist for examination of the mechanical and other properties of thin films and coatings. (See References 34 and 35.)

Thermal analyses and tests should be performed to make sure that the polymeric film does not exceed its safe operating temperature.

Decomposition products from organic polymers are known to contain corrosive elements and, therefore, are capable of attacking the silver or other metallization on mirrors (Ref. 30). Contamination products, especially gaseous chlorine, have been found to be aggressive corrosive agents for silver. The effect of decomposition and contamination on the particular metallization used should be researched.

In summary, thin polymeric reflecting films are viable candidates for three-dimensional parabolic dish concentrators. They have many advantages including low cost and good reflectance. However, good reflectances (~80%) are achieved by the use of a precise contoured substrate along with a good method of film bonding. In addition to the previous criteria stated above, these last two criteria are of utmost importance.

D. BONDING CRITERIA

As stated previously, for second-surface glass mirrors, mirror system adhesives should be insensitive to radiation over the entire solar spectrum, especially the near-ultraviolet. For example, LTV-602 primer has darkened after exposure to near-UV after 1800 hours exposure. Fluorocarbons, polycarbonates, and polyesters are also very sensitive. The effect of UV radiation on the properties of epoxies has been summarized in Reference 29.

For bulk aluminum mirrors or other types of reflective surfaces that are opaque to UV, the UV problem, of course, is reduced. However, the bond line at the edge of the mirror will still be vulnerable to the sunlight.

Optimization of cure kinetics of the bonding agent is important because of the potential volume of concentrators planned for eventual production. Not only should time be minimized for curing with room-temperature cures desired, but a minimum amount of excess solvents should be used in order to prevent degradation of mirror reflectance through attack of the silver or other metallization by ionic diffusion.

Development of quality assurance tests are necessary for the identification and maintenance of highly reliable bonding systems. Since proprietary bonding systems are proposed for use in long-lived critical components, characterization of the bonding agents is recommended. Chemical analysis, particularly when coordinated with important functional properties, and analysis of the volatile condensable material can lead to cost reduction and increased reliability of the system. (See References 36 through 38.)

In summary, bonding system criteria are low vulnerability to adjacent chemicals and UV as well as emission of a minimum amount of chemically aggressive solvents.

E. CLEANING CRITERIA

At the present time, optimum cleaning materials, techniques, and frequencies for parabolic reflective surfaces have not been precisely defined. Further research is required in these areas. (See References 39 and 40.)

The criteria for cleaning parabolic reflective surfaces should be identical to that for flat heliostats and troughs made of the same materials. Attention must be given to chemical interactions between the cleaning liquid and the edge seal material.

Cleaning strategy depends upon the amount of degradation that the surface can withstand before the system power output is adversely affected. Recognizing that cleaning strategy technology is undergoing changes, tentative cleaning criteria are proposed in Table 3-6. A recent summary of the effects of soiling on solar mirrors and techniques for cleaning have been summarized by Sandia Laboratories (Ref. 41).

F. CORROSION EVALUATION

There are a number of ongoing efforts to develop corrosion data for glass mirrors (SERI, T. Coyle). Definitive corrosion criteria for long-lived mirrors are not currently available.

G. SUMMARY OF EVALUATION METHODS FOR REFLECTIVE SURFACES

1. Laboratory Criteria

A general approach to engineering evaluation of reflective surfaces and substrates is shown in Figure 3-5. This approach is equally applicable to evaluation of the glass, silvered glass, and protected mirror system.

As indicated in the previous sections, there are no preferred simple methods for a complete quantitative evaluation of the reflecting surface of a solar parabolic dish. However, a proposed laboratory procedure is as follows:

After an initial selection of mirror type, the surface may be evaluated in three separate steps:

(1) Screening evaluation of small flat glass samples

(2) Evaluation of moderately-sized (such as half-size) mirror sections on candidate substrate(s)

(3) Final evaluation of full-size gores

All applicable scientific and engineering tests mentioned in the previous sections should be utilized.

Figure 3-6 shows a schematic of one possible flow diagram leading to field deployment of solar mirrors. The important point in this figure is that flat silvered mirrors can be cut after silvering, but, in general, bent mirrors must be cut and bent before silvering.

Table 3-6. Proposed Cleaning Criteria (Preliminary)

Type of Reflective Surface	Cleaning Technique			Cleaning Frequency
	First Washing Agent	Second Washing Agent	Third Process	
Silvered Glass Mirrors	Mild Detergent	Deionized Water	Air Dry	Once/20-25 days
Aluminum	Mild Detergent	Deionized Water	None	Once/3 days
Metallized Polymeric Films	TBD	TBD	TBD	TBD

TBD = To Be Determined

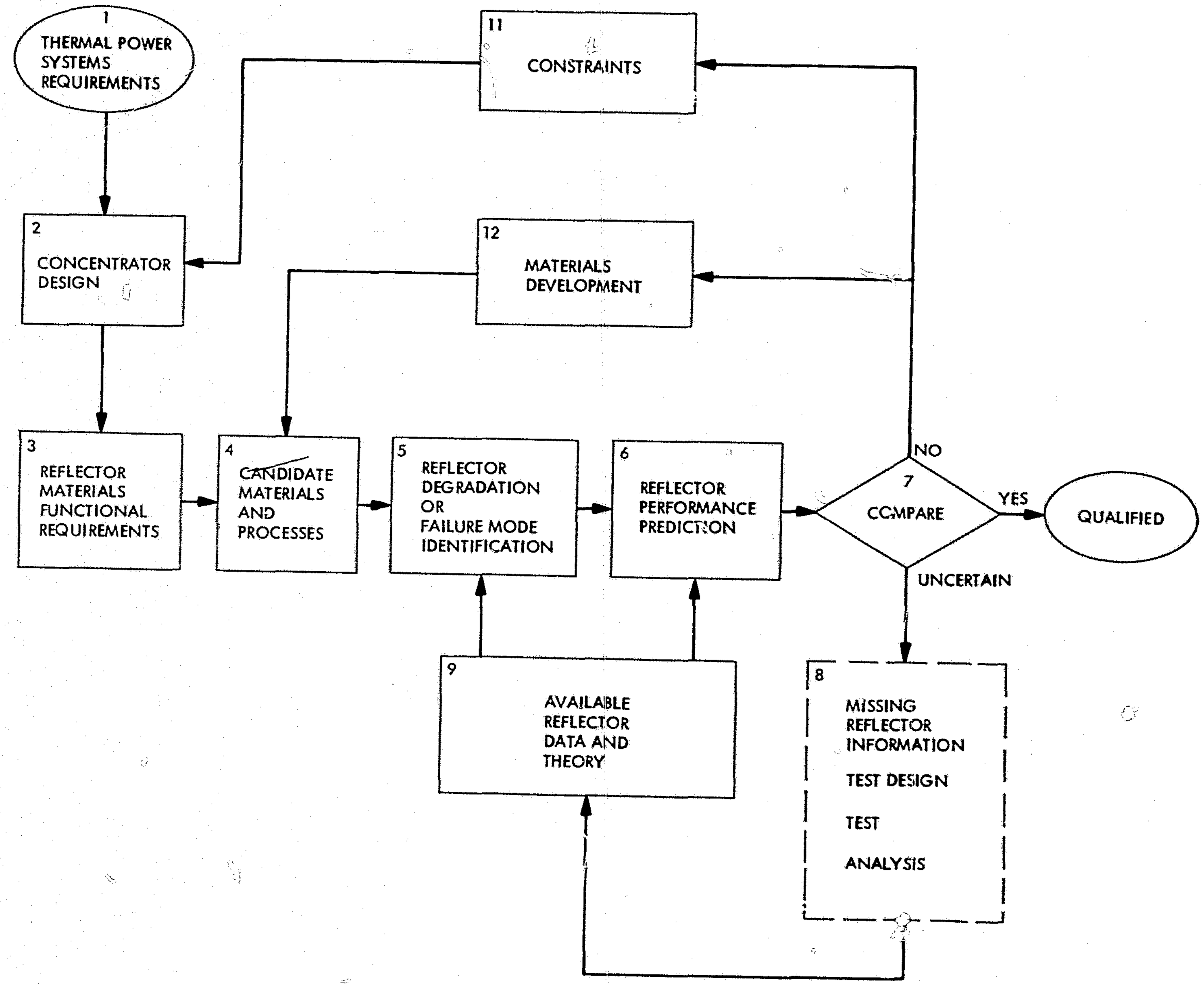

Figure 3-5. Approach to Engineering Evaluation of Reflective Surfaces

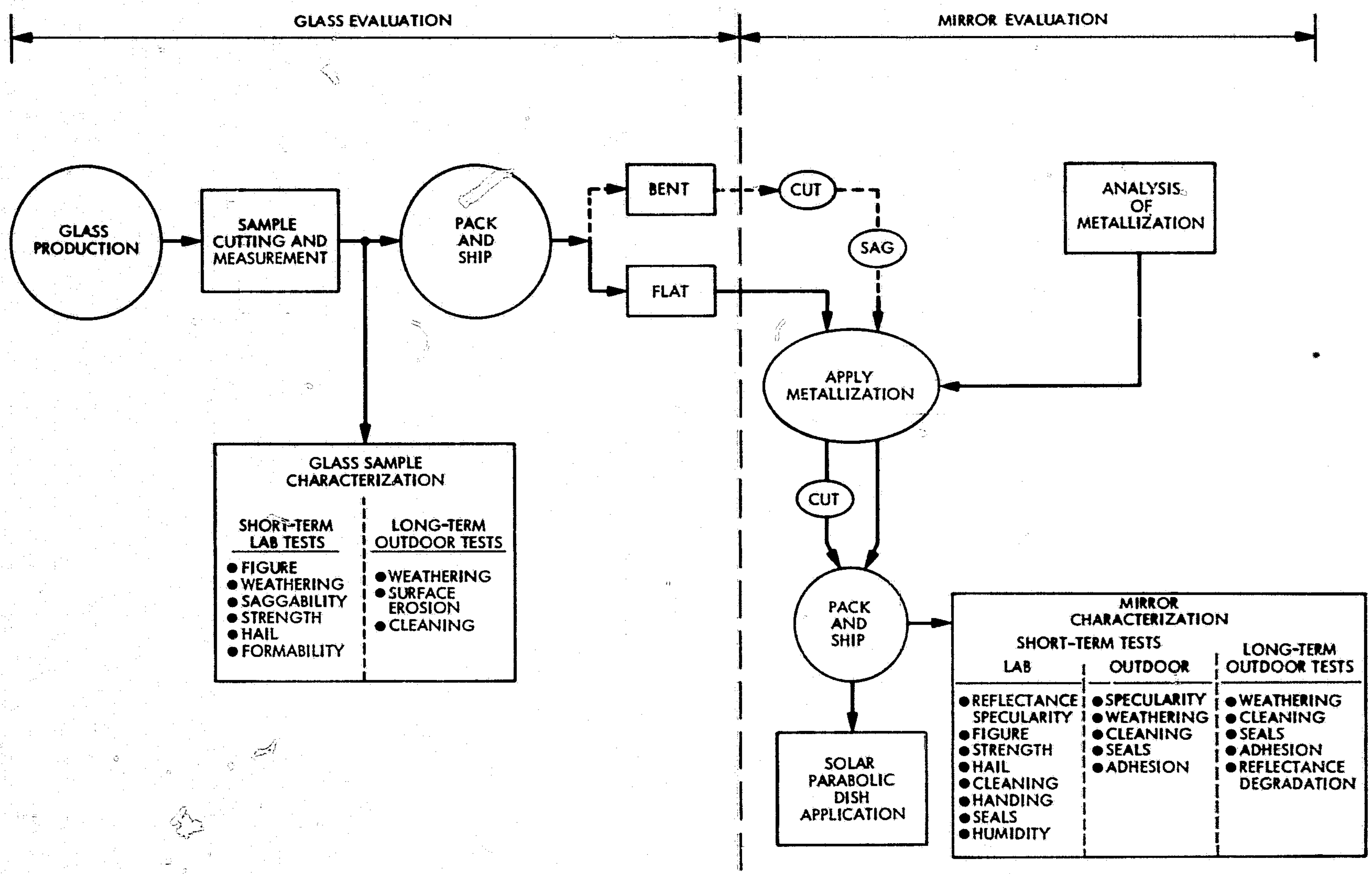

Figure 3-6. Flow Diagram for Field Deployment of Solar Mirrors

Table 3-7 summarizes the environmental and other criteria (depending on the particular concentrator requirements) to be considered in evaluating samples, sections, and entire gores in the laboratory.

a. Screening Evaluation of Mirror Figure. The techniques for detailed evaluation of mirror reflectivity, specularity, and figure have been treated by Griffin (Ref. 42). The Moiré method of fringe analysis for mirrors pioneered by Battelle Pacific Northwest Laboratories has been shown to be an effective technique for figure analysis of solar mirrors. The development of this method for evaluating large parabolic contours appears promising.

However, a simplified, low-cost technique has been used successfully to qualitatively evaluate solar mirrors for reflectance, specularity, and figure. The basic geometry can be arranged so that the light from the mirror under test can be compared to a standard (Figure 3-7). In this test, a visually defective mirror sample was selected and compared to a Corning Type 0317 light spot (shown on left in Figure 3-8). The dotted lines indicate the expected target area for the light image.

b. Screening Evaluation of Mirror Sections. A qualitative indication of the characteristics of a mirror section can be made by reflection of the light onto a smooth vertical surface. An example of a 0.61 m x 0.71 m (24 in. x 28 in.) mirror facet is shown in Figure 3-9 for morning conditions (10:00 a.m. on May 5, 1980). Of course, the fine structure of the light image in this case includes substrate effects.

Portable Reflectometer. With the development of a computerized portable reflectometer at Sandia Laboratory (J. Freeze, 1978), it is now possible to measure solar reflectances in the field. (See Figure 3-10.) This type of reflectometer is capable of measuring the reflectance of three-dimensional parabolic surfaces having relatively large radii of curvature.

The effects of time degradation and soiling should be measurable with the portable reflectometer under both laboratory and field conditions. Some modification of this instrument may be necessary for field use on relatively hot days. The price of the instrument depends upon the quantity produced, of course, but is reported to be in the range of 5 to 10$k.

Laser System. The use of a laser system to inspect and evaluate the figure error in large parabolic mirror facets has been proposed by Zakhidov, et al. (Ref. 43). The measurement sequence consists of recording the reflected beam profile and the

Table 3-7. Laboratory Criteria Test Areas

Reflectance:	Total Hemispherical Specular
Temperature Stability:	Peak Levels Thermal Cycling Gradient Effects
Impact:	Hail Abrasion Resistance
Aerodynamic Loads:	Vibration
Operating Life:	Dust Adherents Pollutants Water Optical Degradation Pressure Cycling Humidity Cycling Ultraviolet Flux

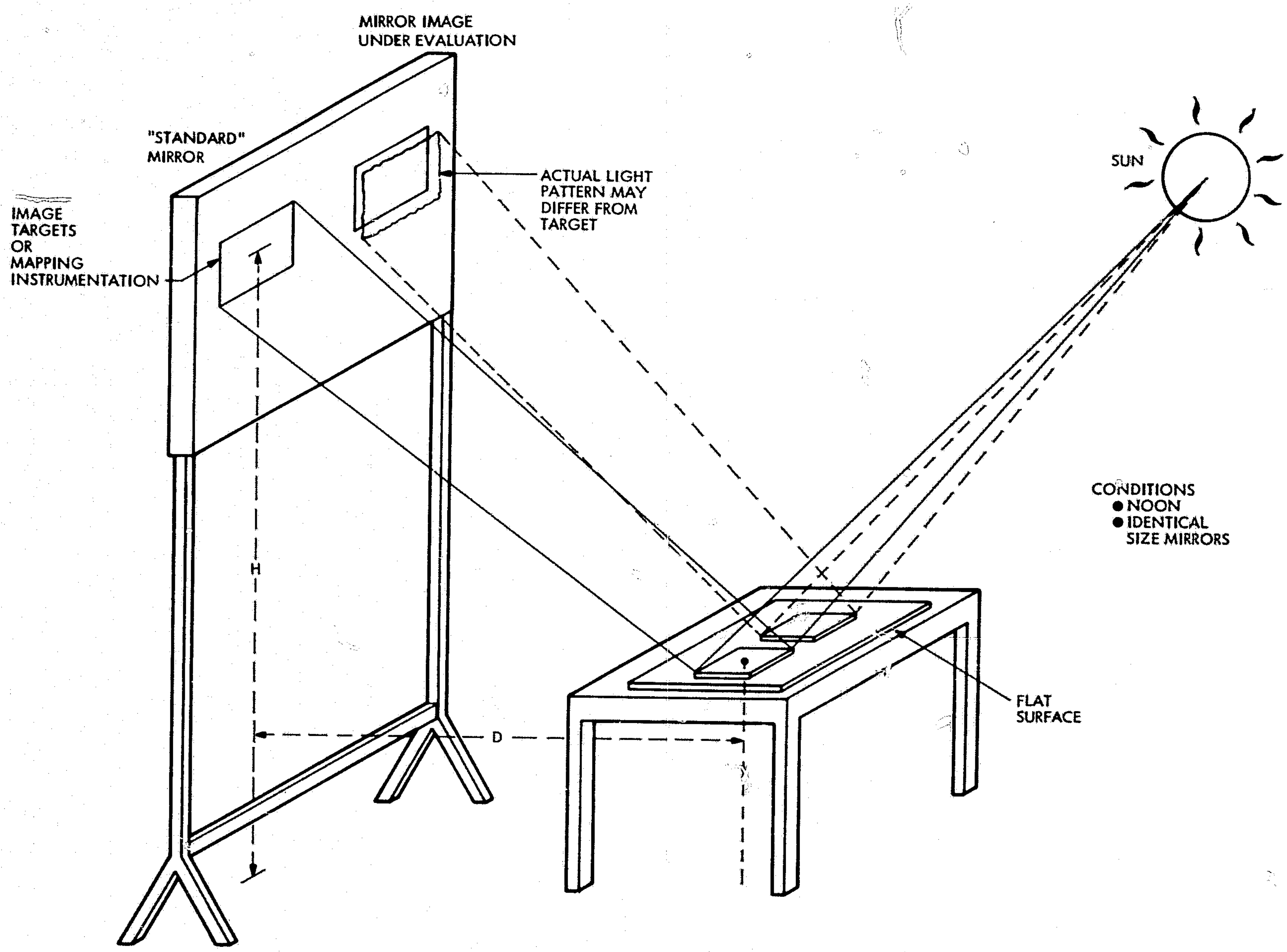

Figure 3-7. Simplified Screening Test Geometry

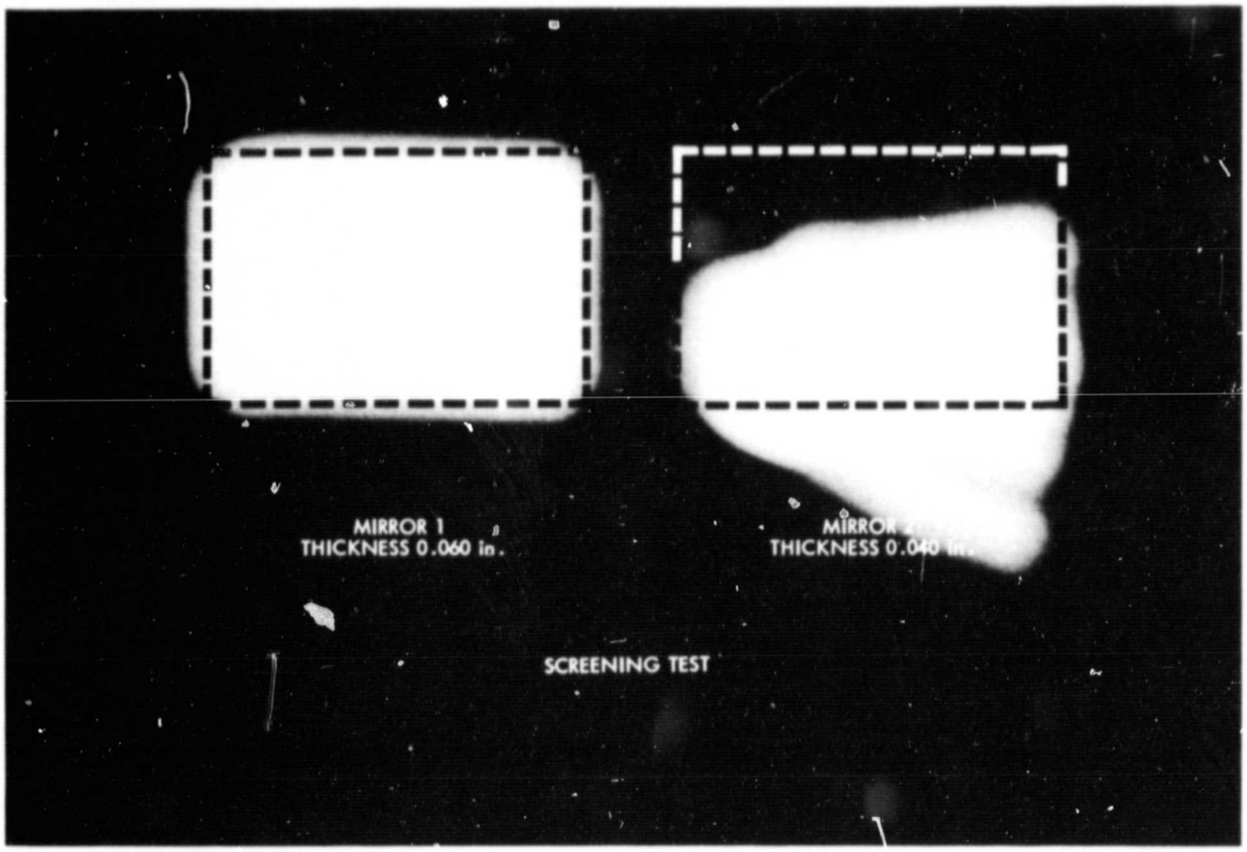

Figure 3-8. Screening Test

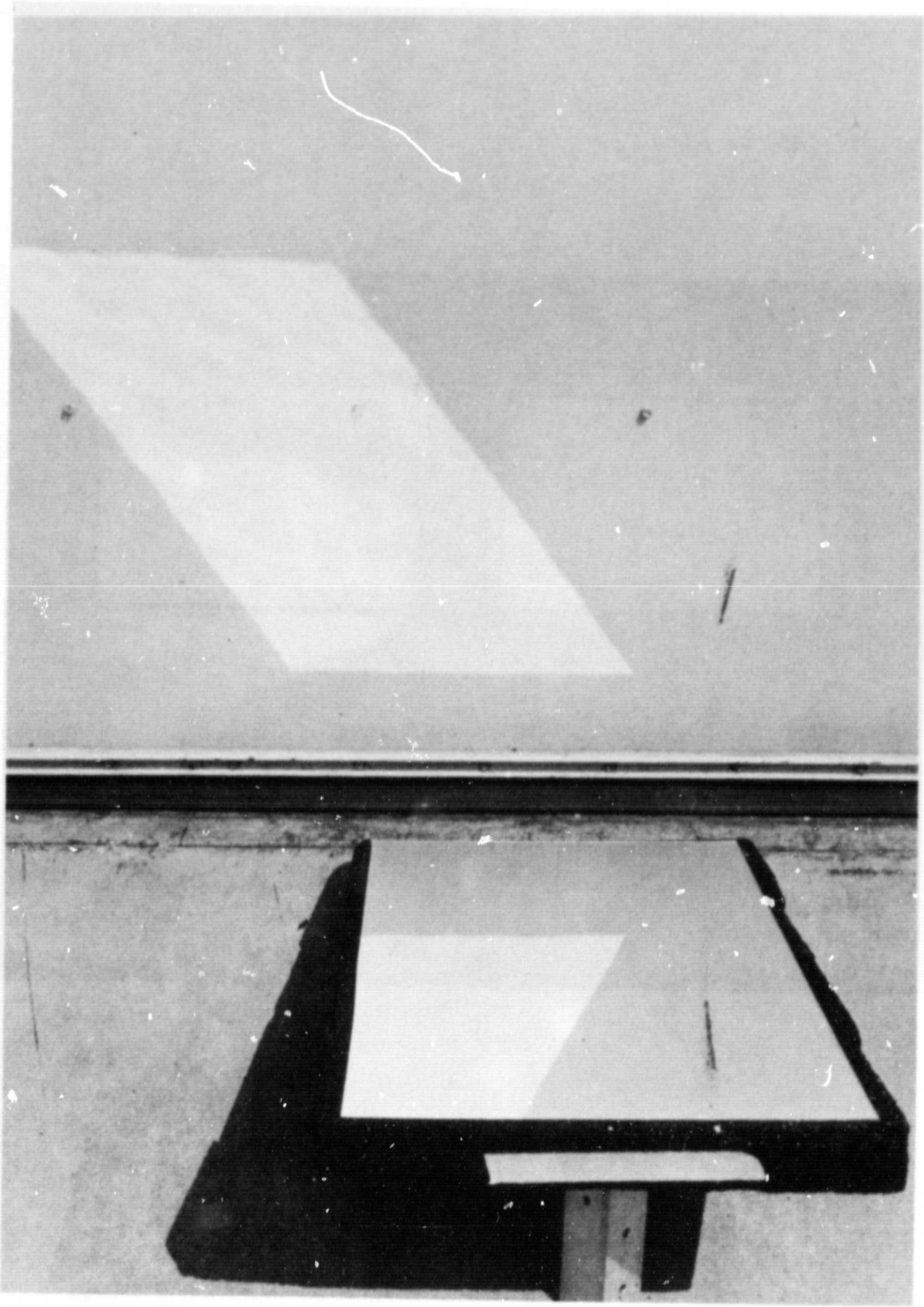

Figure 3-9. Reflected Solar Image from a Typical Mirror Section (Photo taken at Pasadena, California, at 10:00 a.m., May 5, 1980.)

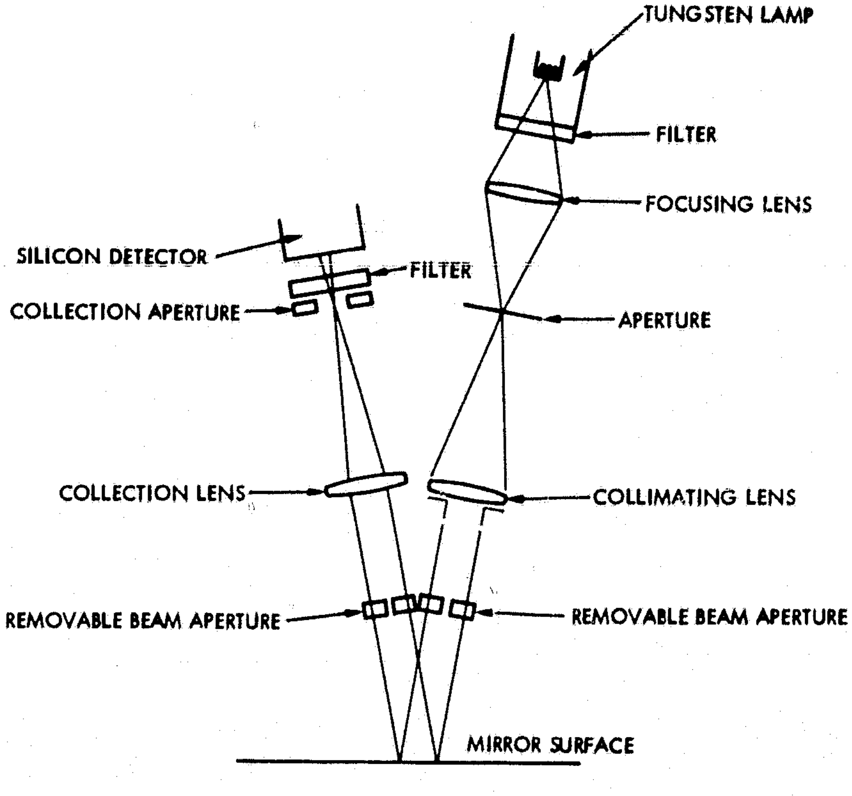

Figure 3-10. Schematic Diagram of Portable Reflectometer (Reference 42)

maximum brightness coordinate. (See Figure 3-11.) The laser mount is then moved to the next sequential position and the process repeated. With this method, the shape of the light spot indicates the figure error within a discrete area, while the position of the spot indicates the spatial figure inaccuracy across the entire mirror gore.

Thermograph. Thermograph techniques may be valuable for the evaluation of figure of three-dimensional concentrators. Further research is required to evaluate this technique and establish criteria for the thermograph technique applicable to 3-D gores.

Evaluation Using Photographic Techniques. JPL (M. Argoud, 1978) has built a light imaging system capable of evaluating the distribution of energy from moderately-sized mirror sections. Using photographic records, the figure of the mirrors can be characterized. The mirrors for the two test bed concentrators installed at JPL's Parabolic Dish Test Site, Edwards, California, have been calibrated using this technique. Further research is required to establish general criteria for its use with large parabolic gores.

c. Evaluation of Optical Distribution of Parabolic Gores. The evaluation of the figure of an entire gore could be performed using a test bed concept. The basic elements are shown in Figure 3-12. In this case, the mirror is fixed on a support in the position and attitude that it will assume on the finished concentrator. The light flux is mapped electronically to determine the spatial distribution of the reflected rays.

d. Evaluation of Optical Alignment. A unique method of evaluating the optical quality of focusing solar collectors applicable to both parabolic troughs and parabolic dishes has been worked out by SERI (P. Brendt, Ref. 44). On a clear day, this test can be carried out without a laser system and involves evaluation of the effect of concentrator misalignment with respect to the receiver. Using this technique, the total optical errors resulting from imperfect specularity and from inaccuracies in reflector position or slope can be characterized by an angular standard deviation of the rays from the design direction.

e. Mechanical Load Cycling Criterion. This test is designed to verify that mechanical wind loading will not result in malfunction of the mirror, bonding agent, and/or substrate. The mechanical loading tests of the entire system are defined by the mirror specifications and should include pressure tests, hail impact tests, and other tests.

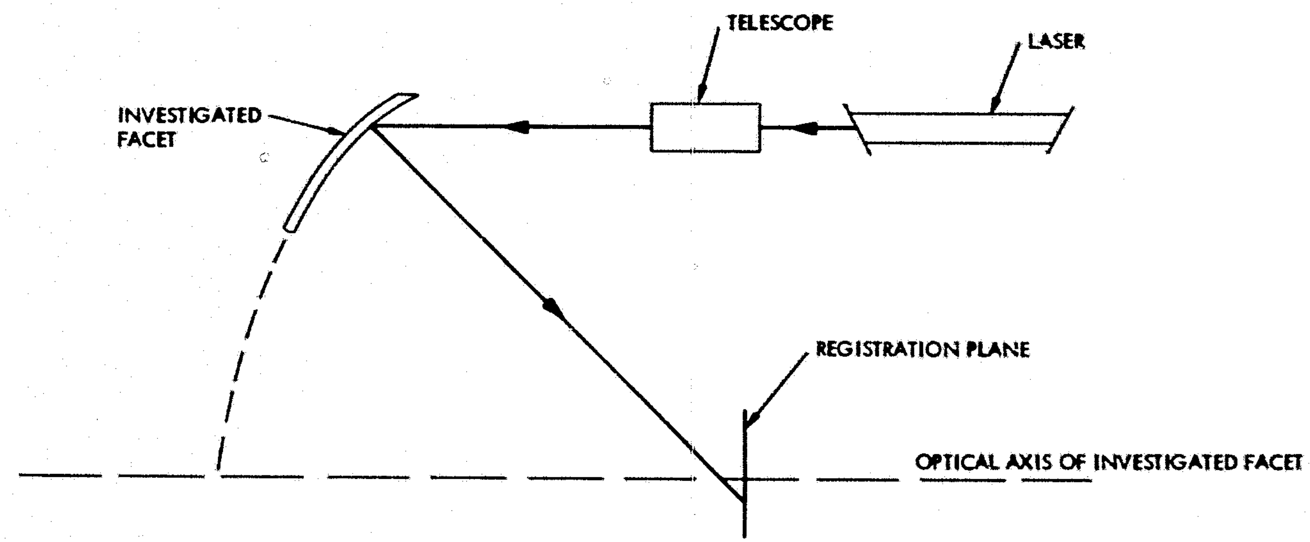

Figure 3-11. Laser Measurement Method for Parabolic Mirror Sections (Reference 43)

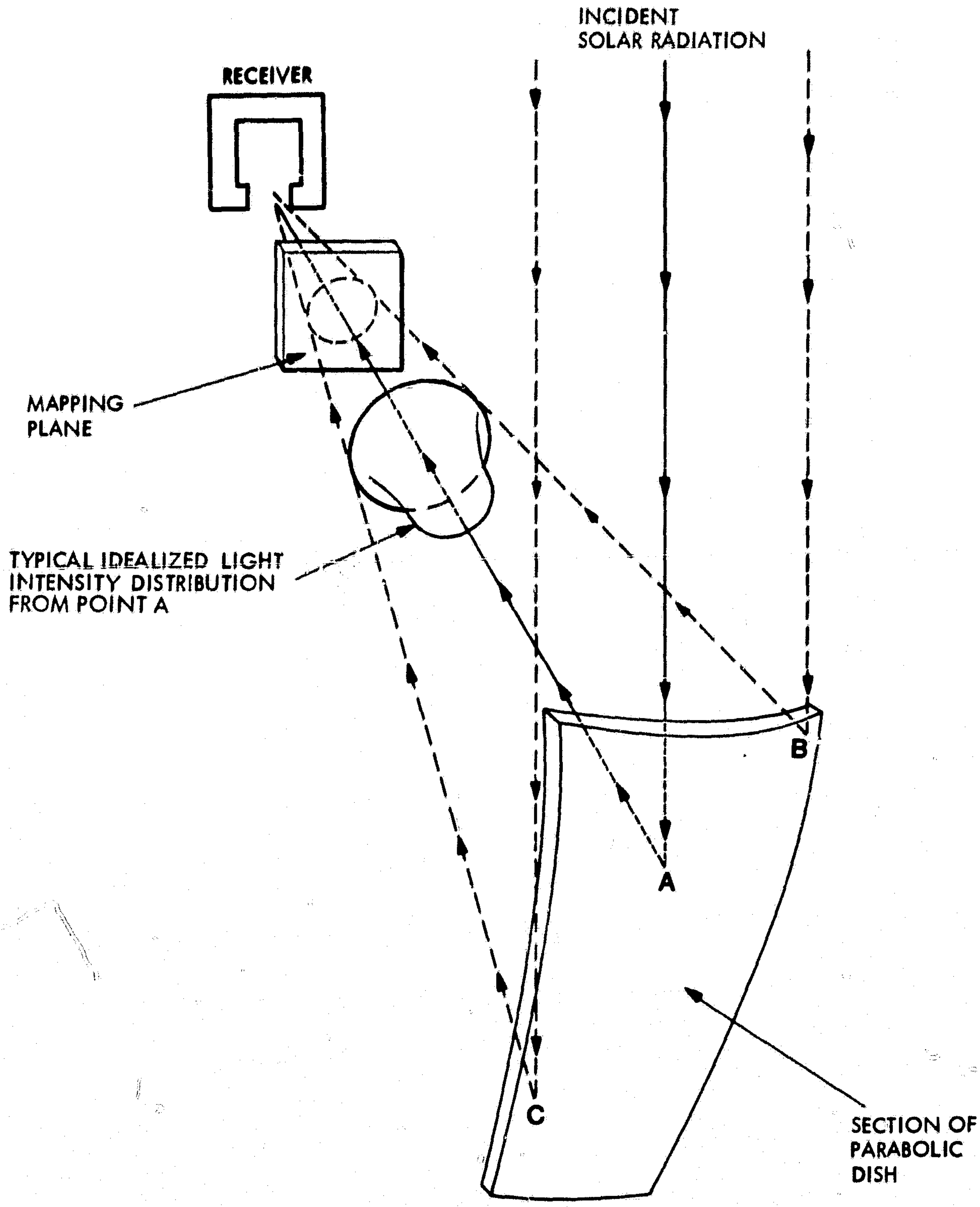

Figure 3-12. Proposed Optical Test for Large Parabolic Gore

f. Automated Evaluation Techniques. For eventual large-scale production of concentrator gores, the laboratory techniques need to be improved and applied to automated systems. High speed, automated techniques have been worked out for float glass in one-dimension (Ref. 45). These techniques are said to improve quality, efficiency and productivity. The extension of these techniques to large [$\geq$ 1.3 m x 3.1 m (4 ft x 10 ft)] bent glass sections is needed.

2. Outdoor Exposure Criteria

Samples of solar mirrors should be exposed to outdoor environments simultaneously with laboratory testing. External environments, preferably in the general location of concentrator deployment, can generate synergistic effects that cannot be simulated in the laboratory. In environmental testing, solar UV, temperature, environmental contaminants, and humidity, to mention a few, are all acting on the mirror at the same time. Also, seasonal degradation effects may be identified.

Data concerning reflectance degradation should be collected during at least a two-year time period in order to be meaningful. Figure 3-13 shows one of the JPL outdoor exposure racks in Pasadena containing over one hundred small samples, primarily mirrors. This rack incorporates special water run-off troughs between sample rows to prevent run-off from upper rows from contaminating the lower.

On other racks, samples larger than those shown [5.1 cm x 5.1 cm (2 in. x 2 in.)] are deployed. It is recommended that the largest mirrors feasible within program cost and schedule be deployed.

Figure 3-13. Outdoor Exposure Rack for Mirrors at JPL

SECTION IV

CONCLUSIONS

Parabolic dish mirrors differ from other types of solar concentrators, i.e., troughs and heliostats, because of their strong three-dimensional (3-D) curvature requirements. Therefore, criteria necessary for procurement, evaluation, and test are more complex.

In this report, an overview of the technology involved is directed primarily toward the layman or toward organizations preparing to fabricate three-dimensional parabolic concentrators. Therefore, practical considerations are emphasized throughout this document. The technical areas identified are not treated exhaustively but flagged as important areas. Keep in mind that the subject matter is dynamic, and new or improved reflective surfaces measured with improved techniques could appreciably modify the importance of some areas or negate others. Therefore, the concepts herein reflect proven, current state-of-the-art of the leading types of commercial reflective surfaces.

General conclusions of this report can be summarized as follows:

(1) Scientific instruments for measurement of reflectance, specularity, and figure of mirrors are expensive and, in general, unavailable.

(2) Commercial second-surface silvered glass mirrors, when adequately sealed, appear to combine the properties of high specularity and high durability. Also, aluminized plastic film and anodized aluminum mirrors exhibit properties that make them viable candidates for dish concentrators.

(3) Simplified techniques can be used to evaluate small samples of mirrors prior to commitment to a single type of reflecting surface. Subsequently, analysis, testing, and evaluation of larger mirror sections and complete gores should be conducted.

(4) Environmental field tests appear to be superior to laboratory simulation testing because more than one environmental parameter can be tested simultaneously. Although laboratory simulation tests can provide valuable data, interpretation problems exist. Accelerated testing of solar mirrors is not straightforward and should be formulated with care. Therefore, field evaluation testing is recommended where possible.

(5) Selection of a reflecting surface for a particular concentrator depends upon the specific system trade-off requirements.

(6) Tests are needed in order to categorize the long-term degradation properties of the reflective surfaces which may uncover subtle environmental and maintenance procedure responses that, in turn, may identify the "best" reflective surface for a particular application.

The conclusions are summarized further in the following tables in terms of special criteria for three-dimensional reflective surfaces, general mirror component criteria, and status of the underlying technology. A summary of the thickness ranges typically characteristic of parabolic point-focusing reflective surfaces and evaluation criteria that are specific to that type of concentrator are given in Table 4-1. General criteria for the reflective surface, bonding agent, and substrate are shown in Table 4-2.

Table 4-3 gives the criteria, some applicable evaluation techniques for the various sizes of mirror elements, in addition to the expected final specularity criteria.

A complete evaluation of parabolic dish reflective surfaces involves many areas. A summary list of criteria is given in Table 4-4 based upon the topics in this report. The circles indicate the amount of definitive technology that exists in the literature that is directly applicable to establishing hard, quantitative criteria for the design of dish concentrators. It should not be considered all-inclusive, but rather a reflection of important technical areas currently being researched at JPL. Further research is needed to define and quantify criteria for evaluation of solar reflective surfaces.

Table 4-1. Summary of Parabolic Dish Criteria for Leading Reflective Surfaces

Type of Mirror	Component	Thickness Criteria	Criteria Specific to Parabolic Dishes
Second-Surface Silvered Glass	Glass	0.7 - 6 mm (0.028 - 0.23 in.)	3-D formable or heat saggable
	Silver	700 - 1500 Å (70 - 150 mg/ft^2)	Withstand 3-D tension after bending
	Copper	216 - 600 Å (18 - 50 mg/ft^2)	Prevent corrosion over life with 3-D tension
	Backing Paint	0.003 - 0.010 cm (0.001 - 0004 in.)	Withstand 3-D stresses without cracking
	Bonding	--	Quick, room-temperature cured, flexible adhesive in 3-D
	Substrate	--	Low off-gassing; matching coefficient of expansion in 3-D
Aluminum	Anodized Aluminum	3 microns (0.0001 in.) (nominal)	Withstand 3-D bending without figure errors
	Bulk Aluminum	0.03 - 0.05 cm (0.012 - 0.020 in.) (nominal)	Withstand 3-D bending
Metallic Polymer	Polymer	0.0127 cm (0.005 in.) (nominal)	Laydown on 3-D surface without figure errors
	Metal	700 Å (nominal)	Withstand 3-D bending without stress cracks

Table 4-2. General Mirror Component Criteria

Component	General Criteria
Reflective Surfaces	. Withstand 3-D bending over system life . Minimize long-term spring-back (glass) . If sagged, heated, or bent, maintain specular reflectance
Bonding	. Flexible adhesive . Quick, room-temperature cure . Low-outgassing, non-corrosive gases . Withstand environmental effects
Substrate	. Matching coefficient of thermal expansion . Sealant required if cellular glass or other substrate is sensitive to external environmental effects . Low off-gassing material . Off-gassing products non-corrosive to reflective surface

Table 4-3. Summary of Criteria for Evaluation with Mirror Specularity

Mirror Element	Type of Criteria	Typical Criteria Evaluation Techniques	Average Criteria for Specularity of Element[1] (mrad)
Small test samples	General	. All tests . Screening tests	0.5 - 1
Medium section	Specific to Design[2]	. Specific with application . Laser scan . Tests without laser, i.e., Zakhidov[3]	0.5 - 2.0
Large gore	Specific to Design[2]	. Specific with application . Laser scan . Test bed mockup	2 - 4

(1) Expected criteria for "good" mirrors based upon current technology
(2) Depends upon the geometry of the concentrator and receiver
(3) Reference 43

Table 4-4. Summary of Technology Status of Criteria for Parabolic Dish Reflective Surfaces

Type of Reflector	Criteria									
	Temperature					Special Transportation Requirements		Optical Performance Screening Tests		Degradation and Cleaning
	Process Bending		Operating Levels	Gradient	Cycling					
	Hot	Cold				Handling	Shipping	Lab	Outdoor	
Silvered Glass Mirrors										
• Glass	●	○	○	⊕	○	⊕	⊕	⊕	⊕	⊕
Metallization										
• Silver			●	⊕	●	⊕	⊕	⊕	●	
• Copper			●	⊕	●	⊕	⊕	⊕	●	
• Paint			●		●	⊕	⊕	⊕	●	
Aluminum										
• Anodized Layer		⊕	⊕	○	●	○	○	⊕	●	●
• Bulk Aluminum		⊕								
Metal Film										
• Polymer		⊕	⊕	⊕	●	○	○	⊕	●	●
• Film		⊕	⊕	⊕	●	○	○	⊕	●	

○ Technology base exists
⊕ Partial technology base exists
● Technology is not well known

Table 4-4. **Summary of Technology Status of Criteria for Parabolic Dish Reflective Surfaces (Cont'd)**

Type of Reflector	Criteria				
	Components	Edge Polishing	Edge Sealing	Bonding	Near-UV Resistance
Second Surface Glass Mirror	Glass	⊕			○
	Silver		●		●
	Copper		●		●
	Paint		⊕	⊕	⊕
Aluminum Mirror	Anodized Aluminum Superstrate				○
	Bulk Aluminum			⊕	
Metallized Polymer Mirror	Superstrate Polymer		⊕		●
	Metal Film		●	●	●

○ Technology base exists
⊕ Partial technology base exists
● Technology is not well known

Table 4-4. Summary of Technology Status of Criteria for Parabolic Dish Reflective Surfaces (Cont'd)

Type of Reflector	Component	Corrosion Criteria Short-Term	Corrosion Criteria Long-Term
Second Surface Glass Mirror	Glass	○	⊕
	Silver	⊕	●
	Copper	⊕	●
	Paint	⊕	⊕
Aluminum Mirror	Anodized Aluminum Superstrate	⊕	●
	Bulk Aluminum		
Metallized Polymeric Film	Superstrate Polymer	⊕	●
	Metal Film	⊕	●

○ Technology base exists

⊕ Partial technology base exists

● Technology is not well known

REFERENCES

1. Hockok, F., Handbook of Solar and Wind Energy, Cahner Books, 1975.

2. Noll, E. M., Wind, Solar Energy, Howard W. Sams & Co., Inc., 1975.

3. Kreith, F. and J. F. Kreider, Principles of Solar Engineering, McGraw-Hill Book Co., New York, 1978.

4. Duffie, J. A., and W. A. Beckman, Solar Energy Thermal Processes, John Wiley & Sons, Inc., New York, 1974.

5. Considine, D. M., Energy Technology Handbook, McGraw-Hill Book Co., Inc., 1977.

6. Bouquet, F. L., "Glass for Low-Cost Photovoltaic Solar Arrays," JPL Internal Report 5101-147, February 1, 1978.

7. "Proceedings: 10th Project Integration Meeting, Low-Cost Solar Array Project," pp. 5-52, California Institute of Technology, Pasadena, California, August 16-17, 1978.

8. "National Assessment of the Urban Particulate Problem," EPA 450/3-76-024, July 1976.

9. Reed, J. W., "Wind Power Climatology of the U.S.," SAND 74-0348, 1975.

10. Jayadev, T. S., J. Henderson, and C. Bingham, "Conversion System Overview Assessment," Vol. II, Solar-Wind Hybrid Systems, SERI-TR-35-078, August 1979.

11. "Solar Optical Materials," Program Activity Committee, Progress Report for Period July 1, 1978 to January 31, 1979, SERI/PE-31-137, July 1979.

12. Butler, B. L., and R. B. Pettit, "Optical Evaluation Techniques for Reflecting Solar Concentrators," SPIE, Vol. 114, 1977.

13. Pettit, R. B., "Characterization of the Reflected Beam Profile of Solar Mirror Materials, Solar Energy, Vol. 19, pp. 733-41, 1977.

14. Taketani, H., et al., "Mirrors for Solar Energy Application," McDonnell Douglas Astro. Co., West, MDC G 7213, September 1977.

15. Taketani, H., and W. M. Arden, "Specular Mirrors for Solar Energy Applications," SAMPE Quarterly, pp. 54-63, October 1978.

16. Bouquet, F., "Glass for Solar Concentrator Application," JPL Internal Report 5102-105, April 1, 1979.

17. Gupta, Y., "Solar Electric Applications Requirements Solar Thermal Power Systems Project," Contractor Integration Meeting, JPL, December 4-5, 1979.

18. Adams, M., et al., "A Performance Model for Solar Energy Concentrators," a JPL paper being submitted for publication, 1980.

19. Tummala, R. R., "Stress Corrosion Resistance Compared with Thermal Expansion and Chemical Durability of Glasses," Glass Technology, Vol. 17, No. 4, pp. 145-146, August 1976.

20. New Interim Federal Specification, DD-001403, Glass, Plate (Float), Sheet, Figured and Spandrel (Heat Strengthened and Fully Tempered), PPG Industries Inc., August 1971. Source: PPG, One Gateway Center, Pittsburgh, Pennsylvania 15222.

21. "Selection of Geometric Conditions for Measurement of Reflectance and Transmittance," 1969 Book of Standards, American Society of Testing Materials, Part 30, No. 179-66, 1916 Race Street, Philadelphia 19103.

22. Lind, M. A., et al., "Heliostat Mirror Survey and Analysis," PNL-3194, September 1974.

23. Lewis, J. V. and H. Rawson, "Comparison of Measurements of the Strength of Flat Glass by Plate Bending and Hertz Fracture Methods," Glass Technology, Vol. 17, No. 4, pp. 128-135, August 1976.

24. Tummala, R. R., "Stress Corrosion Resistance Compared with Thermal Expansion and Chemical Durability of Glasses, Glass Technology," Vol. 17, No. 4, pp. 145-146, August 1976.

25. Nemura, H., and H. Tabuchi, "Characterization of Typical Knots in Window Glass," Proc. XII, Inter. Congress on Glass, North-Holland Publishing Co., New York, pp. 791-796, 1980.

26. Shelby, J. E. and J. Vitko, "Surface Characterization of Weathered Low-Iron Flat Glass," Proc. XII Inter. Congress on Glass, North-Holland Publishing Co., New York, pp. 631-636, 1980.

27. Burolla, V. P. and S. L. Roche, "Silver Deterioration in Second Surface Solar Mirrors," SAND 79-8276, January 1980.

28. Bouquet, F. L., T. Hasegawa, and E. L. Cleland, "UV Transmission, Visible Reflectance and Mechanical Properties of Commercial Solar Mirrors," paper presented at the 2nd Solar Reflective Surfaces Workshop, sponsored by SERI, San Francisco, California, February 13, 1980.

29. Carmichael, C. C., et al., "Review of World Experience and Properties for Encapsulation of Terrestrial Photovoltaic Arrays," Battelle-Columbus Laboratories, ERDA/JPL 954328-7614, July 21, 1976.

30. Bouquet, F. L., "UV Transmission through Glass of Commercial Mirrors," Solar Energy (in press).

31. Gupta, A., "Photodegradation of Polymeric Encapsulants of Solar Cell Modules," JPL Internal Report 5101-77, August 10, 1978.

32. Pettit, R. B. and E. P. Roth, "Solar Mirror Materials; Their Properties and Uses in Solar Concentrating Collectors," SAND 79-2190, June 1980.

33. Allen, J. et al., "Development of Lightweight Compound Parabolic Concentrators for Solar Thermal Electric and Process Heat Applications," Solar Thermal and Ocean Thermal Symposium, Vol. 5, pp. 232-241, 1979.

34. Poate, J. M. and T. King-Ning, "Analysis of Thin Films and Interfaces," Physics Today, Vol. 33, No. 5, pp. 34-38, 1980.

35. Bunshaw, R. F. and D. M. Mattox, "Applications of Metallurgical Coatings," Physics Today, Vol. 33, No. 5, pp. 50-55, 1980.

36. Skeist, I., Handbook of Adhesives, Second Edition, Van Nostrand Reinhold Co., New York, 1977.

37. Hasegawa, T., "Adhesive Bond of Parabolic Dish Solar Concentrators," SAMPE Technical Conference, 1981 (in preparation).

38. Eddy, S. R., et al., "Evaluating New Polymers as Structural Adhesives," Adhesives Age, Vol. 23, No. 2, pp. 18-25, February 1980.

39. Cuddihy, E. F., "Theoretical Considerations of Soil Retention, 2nd Solar Reflective Surfaces Workshop, San Francisco, California, February 13, 1980.

40. Call, P. J., "Summary of Solar Experience with the Soiling of Optical Surfaces," SERI/TP334-478, February 1980.

41. Roth, E. P. and R. B. Pettit, "The Effect of Soiling on Solar Mirrors and Techniques Used to Maintain High Reflectivity," SAND 79-2422, June 1980.

42. Griffin, J. W. et al., "Evaluation Techniques for Determining the Reflectivity, Specularity, and Figure of Solar Mirrors," Final Report, SERI/TR-98366-1, May 1980.

43. Zakhidov, A. A., et al., "Using Lasers to Inspect Solar Energy Reflectors," Geliotekhnika, Vol. B, No. 1, pp. 38-41, UDC 621.472.001.

44. Brendt, P., H. W. Gaul, and A. Rabl, "Determining the Optical Quality of Focusing Collectors without Laser Ray Tracing," Solar Energy Research Institute, SERI/TR-333-359, February 1980.

45. Branch, G. H., "Cold End Automation in the Glass Industry," Glass Technology, Vol. 17, No. 1, pp. 14-20, February 1976.