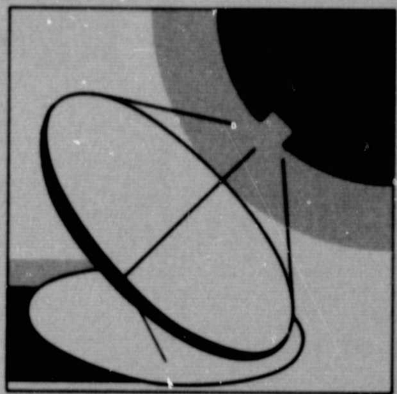
5105-67
Solar Thermal Power Systems
Parabolic Dish Project
Research and Advanced Development

DOE/JPL-1060-40
Distribution Category UC-62b

Cost / Performance of Solar 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
Jet Propulsion Laboratory
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The JPL Solar Thermal Power Systems Project is sponsored by the U.S. Department of Energy and forms a part of the Solar Thermal Program to develop low-cost solar thermal and electric power plants.

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 Solar Thermal Power Systems Parabolic Dish 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

Materials for highly reflective surfaces for use in parabolic dish solar concentrators are discussed in this report. Some important factors concerning performance of the mirrors are summarized, and typical costs are treated briefly. Although much of the data given are general and applicable to flat or curved solar reflectors, capital investment cost/performance ratios for various materials are computed specifically for the double curvature parabolic concentrators using a mathematical model.

The results are given in terms of initial investment cost for reflective surfaces per thermal kilowatt delivered to the receiver cavity for various operating temperatures from 400 to 1400°C. Although second-surface glass mirrors are emphasized, first-surface, chemically brightened and anodized aluminum surfaces as well as second-surface, metallized polymeric films are treated. Conventional glass mirrors have the lowest cost/performance ratios, followed closely by aluminum reflectors. Also, ranges in the data due to uncertainties in cost and mirror reflectance factors are given.

ACKNOWLEDGMENT

Contributions to this study were made by a number of individuals in both industry and the U.S. Government without whose assistance the report would not have been possible. Special recognition is given to R. B. Pettit, B. Stiefeld, and S. Thrunborg of Sandia National Laboratories, and Dr. H. Taketani of McDonnell-Douglas Astronautics Corporation. The following individuals in the glass/mirror industry were helpful in furnishing/interpreting mirror price data: A. Shoemaker (Corning Glass Works), J. Schrauth (Schott-America), B. Walker (Binswanger Mirror Products), J. Bolton (Artistic Glass Products), S. Nickols (Flexible Mirrors), L. P. Oldham (Martin Marietta Corporation), M. Sherwood (Kingston Industries), J. Kesling (Eagle Convex Glass), R. Carter (AFG Industries), L. Brown (Buchmin Industries), and A. Schottland (Standard Bent Glass).

This work was performed for the Solar Thermal Power Systems Parabolic Dish Project under the direction of Materials Subtask Leader, E. L. Cleland, and Materials Task Manager, Dr. M. A. Adams. The review by members of the Materials Science and Applications Group was appreciated.

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 silicate glass that contains between 17 and 25.3% of Al_2O_3.
Blank	See lite.
Borosilicate Glass	Any silicate glass having at least 5% boron oxide (B_2O_3).
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	A concentrator plus a receiver.
Collector Efficiency	The ratio of the energy collected by the solar collector to the radiant energy incident upon the collector.
Collimated Light	Parallel rays of light, the direct or beam component of the solar radiation.
Concentrator	Any device for gathering the sun's rays and directing them in a useful way.
Cost	The actual or estimated amount of money required to produce an item. Frequently in this report, cost is used interchangeably with price in that cost is assumed to include manufacturer's profit.
Diffuse Radiation	Scattered radiation from the sun that falls upon a plane of stated orientation; in the case of an inclined surface, ground reflected radiation is included.
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.
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.
Heliostat	A flat device (reflector) for directing the sun's radiation toward a fixed receiver.
Lite	A section of glass sold and/or handled separately such as a 0.61-mm x 0.61-mm (24-in. x 24-in.) section. Also called "blank" or "light."
Mirror	A reflective surface, originally a polished metal but now usually made of glass with a silvery, metallic or amalgam backing. It may also consist of laminated glass or polymer layers.
Near-UV	The wavelengths in the solar spectrum from 200 to 400 nanometers in this report. See UV.
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.
Plastic	See polymer.
Polymer	A large molecule made up of many small repeating units or mers. Most plastic materials are polymers. The term plastic and polymer are used interchangeably in this report.
Price	The money needed to purchase an item. Price is equal to the basic cost of production plus the manufacturer's profit.
Reflectance	The ratio of radiation reflected from a surface to that incident upon the surface.

Reflectivity	The property of reflecting radiation possessed by all materials to varying extents.
Sagging	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 upon which it rests.
SERI	Solar Energy Research Institute, Golden, Colorado.
Slope Error	The error in the angle or position from its expected position, usually less than 1 cm period.
Spectral 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 of each ray are equal.
Tempered Glass	Glass that has been rapidly cooled from near the softening point, under rigorous control, in order to increase its mechanical and thermal endurance (physical tempering). It also may be tempered chemically.
Total Solar Transmittance	The calculated transmittance of solar energy using the solar data for a given air mass 1.5 or 2.0 and incident upon a perpendicular surface.
Transmittance	The ratio of radiant energy which passes through a material to the radiant energy incident upon the surface of the material.
Ultraviolet Radiation (UV)	Radiation having wavelengths longer than those of X-rays but predominantly shorter than visible wavelengths, usually 100 to 4000 angstroms.

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SECTION I

INTRODUCTION

The purpose of this report is to provide information on the selection and evaluation of materials for mirror components of parabolic dish concentrators. Cost/performance ratios for various operating conditions are discussed in general. The data in this report are based primarily upon (a) recent publications on solar reflective surfaces (Refs. 1 and 2), (b) previous background reports (Refs. 3 through 11), and (c) recent JPL analysis, evaluation, and test results (Refs. 12 through 15).

Cost/performance data are extremely important for large solar concentrator systems for utility use as well as other applications. An example of a large system with an 11-meter diameter dish is shown in Figure 1-1. These test bed concentrators (TBCs) have been developed by JPL as part of the U.S. Department of Energy funded Solar Thermal Power Systems Parabolic Dish Project and are used to evaluate and test various types of receivers and engines. Their rugged construction allows the handling of relatively heavy electrical and process heat conversion systems. Typical advanced solar collector systems are considerably lighter and somewhat smaller than the TBCs, which have been calibrated at 65 to 66 kilowatts of thermal power (normalized to 800 watts/m^2) with clean mirrors. The receiver used in initial testing was a cold water cavity calorimeter, 53 cm (21 in.) in diameter.

Three typical mirror gores of the type used on solar concentrators are shown in Figure 1-2. The straight lines of the building structure are reflected in these experimental borosilicate glass mirrors. The waviness is due to local slope errors in the glass as well as specularity effects.

The primary candidate reflective surface for the JPL advanced parabolic dish concentrator is a silvered, second-surface glass mirror with a cellular glass structural substrate. The functional elements (hermetic top seal (glass), silver metallization with protective copper overcoat, edge sealant, backing paint, bonding agent, and support substrate) and the thickness ranges being evaluated are shown in Figure 1-3. Further detailed information on this system is given in Reference 1.

While soda-lime-silicate glass is less expensive, aluminosilicate and borosilicate glasses have been observed to be extremely resistant to corrosive atmospheric components. Although other types of reflectors are treated in this report, the glass mirrors are emphasized because of their use by hardware developers, their availability, low dust accumulation characteristics, and reports of favorable field experience to date.

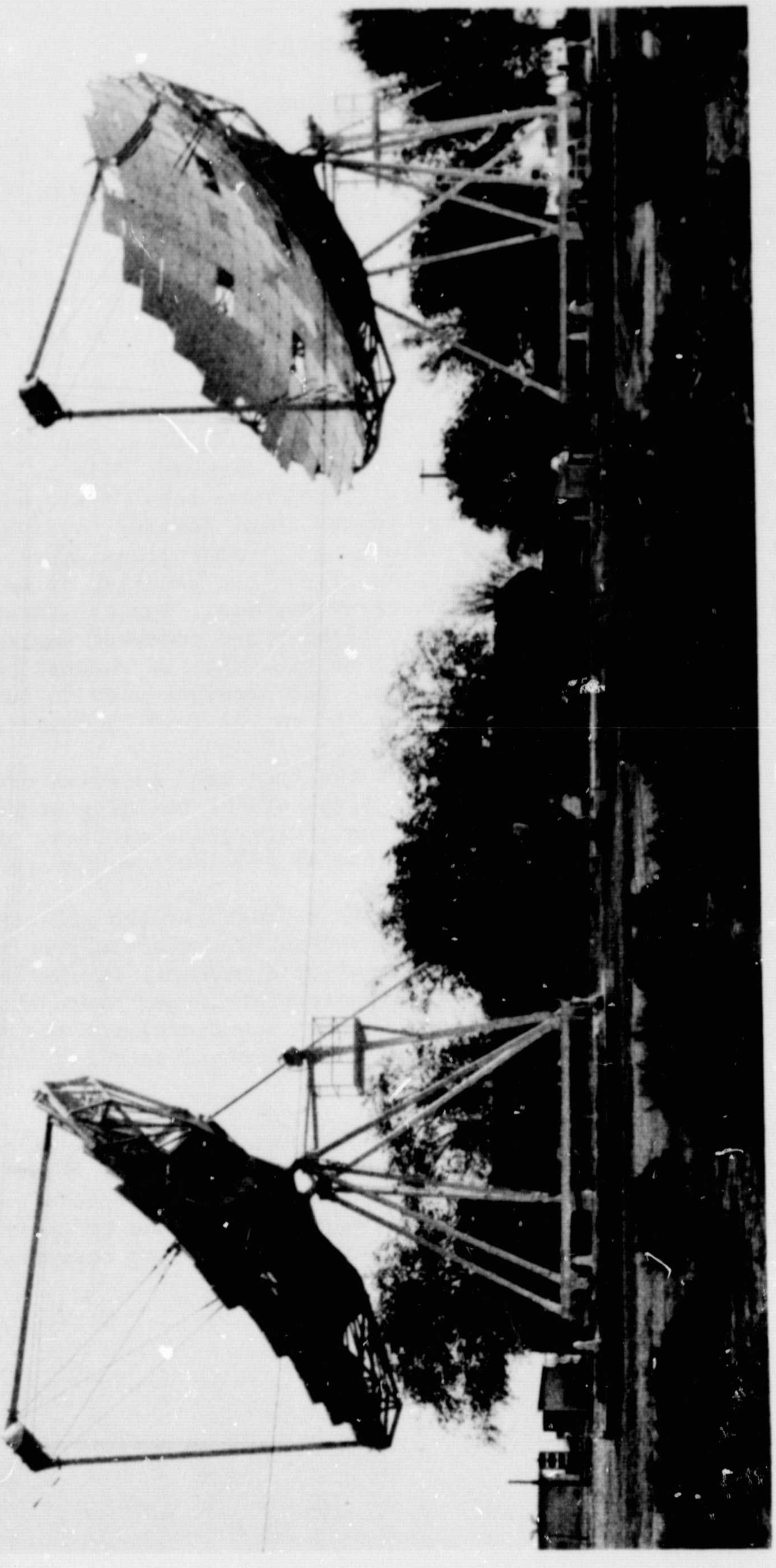

Figure 1-1. Two Test Bed Concentrators at JPL's Parabolic Dish Test Site

SECTION II

PERFORMANCE OF REFLECTIVE SURFACES

A. GENERAL

Identification and characterization of the type of reflective surfaces to be used are necessary for the determination of the cost/performance ratios of specific parabolic dish concentrators. Therefore, characterization, evaluation, and testing of available commercial solar reflectors must be undertaken. Mirror type (i.e., first- or second-surface mirrors), ease of bending into three-dimensional parabolic shape, and slope errors are among those factors that should be addressed. Figure 2-1 illustrates the optical characteristics of first- and second-surface reflectors. Reflectance characteristics of flat mirrors have been obtained by R. B. Pettit of Sandia National Laboratories using a bidirectional reflectometer for both types of surfaces (Ref. 5). The reflected beam distribution for a second-surface glass mirror (Figure 2-1a) can be described by a single distribution shown as a single cone, while second-surface polymeric films and bulk aluminum surfaces usually require a multiple beam profile (Figure 2-1b) for adequate description (depending upon whether or not the surface is viewed in the across or with-roll direction).

The use of reflecting materials to concentrate solar energy requires (1) high solar reflectance and (2) good specular reflectance properties. For the complete characterization of the performance of a specific system, beam spreading due to the reflecting materials should be combined with other sources of beam spreading such as size of the sun, mirror figure errors, or tracking errors.

B. HEMISPHERICAL REFLECTANCE

Evaluation criteria for each of the functional elements making up the solar mirror system have been described in detail by JPL (Refs. 1 through 4). Of prime importance is the use of low-iron glass in order to obtain high specular reflectance. Also, the thinner the glass, the higher the transmittance of the light rays through the glass into the receiver. This effect is illustrated in Figure 2-2.

The data for measured normal hemispherical solar reflectances for silver and aluminum surfaces obtained from a number of sources are compared with theoretical values in Figures 2-3a and 2-3b for air mass 2.0 conditions. Measurements by Sandia Laboratories found second-surface, silvered glass mirrors to have the highest specularity (Ref. 5).

Information on the reflectance and transmittance of various mirror surfaces is summarized in Table 2-1. The measured reflectances from many sources, including data from Sandia Laboratories (Refs. 5 through 8) and McDonnell Douglas Astronautics (Refs. 10 and 11), as well as recently measured values from JPL are tabulated. Because precise reflectance standards have not yet been available, the data should be regarded as preliminary. Nonetheless, trends in the data are evident. For further detailed information

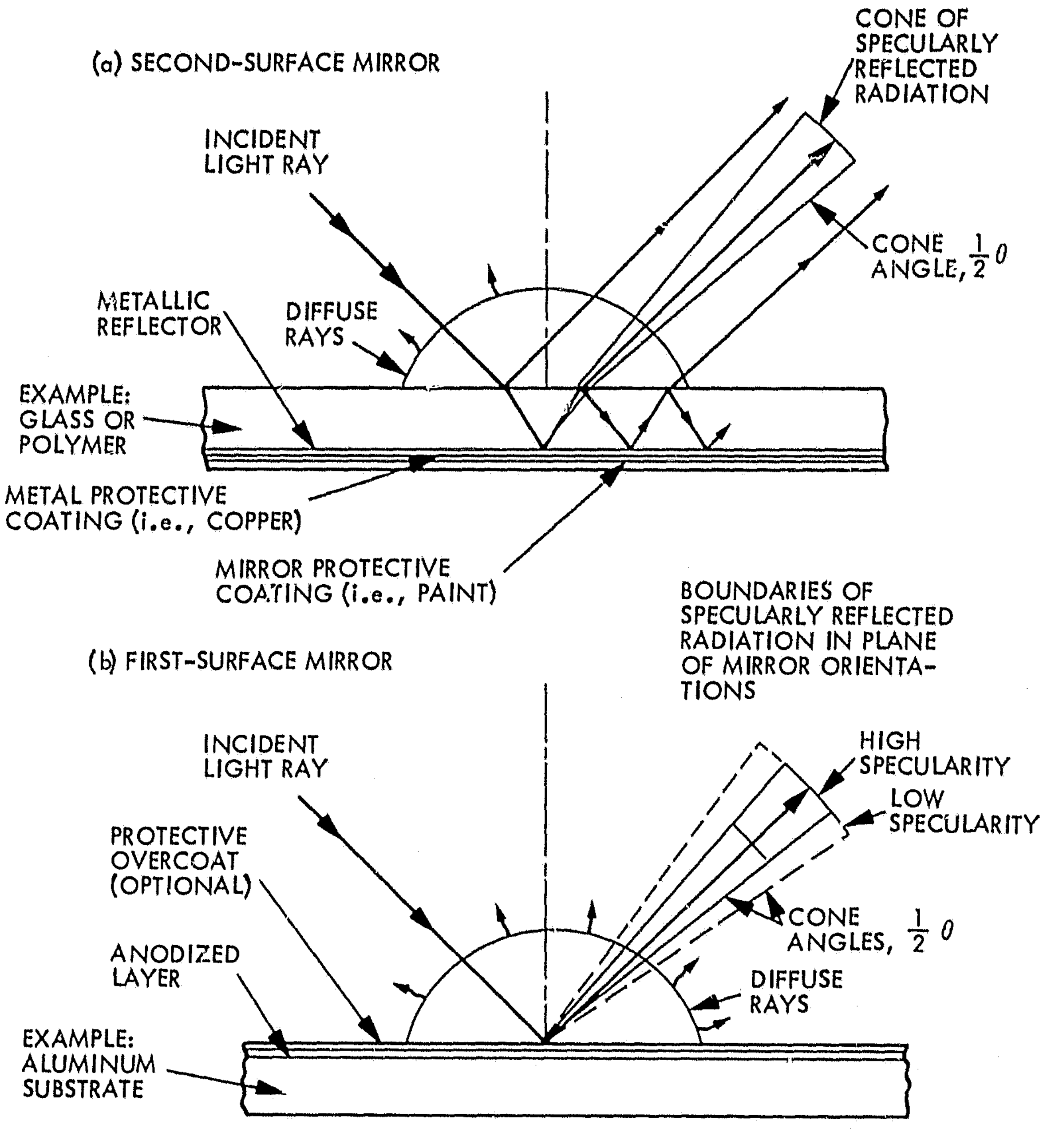

Figure 2-1. Reflection Characteristics of Second- and First-Surface Mirrors

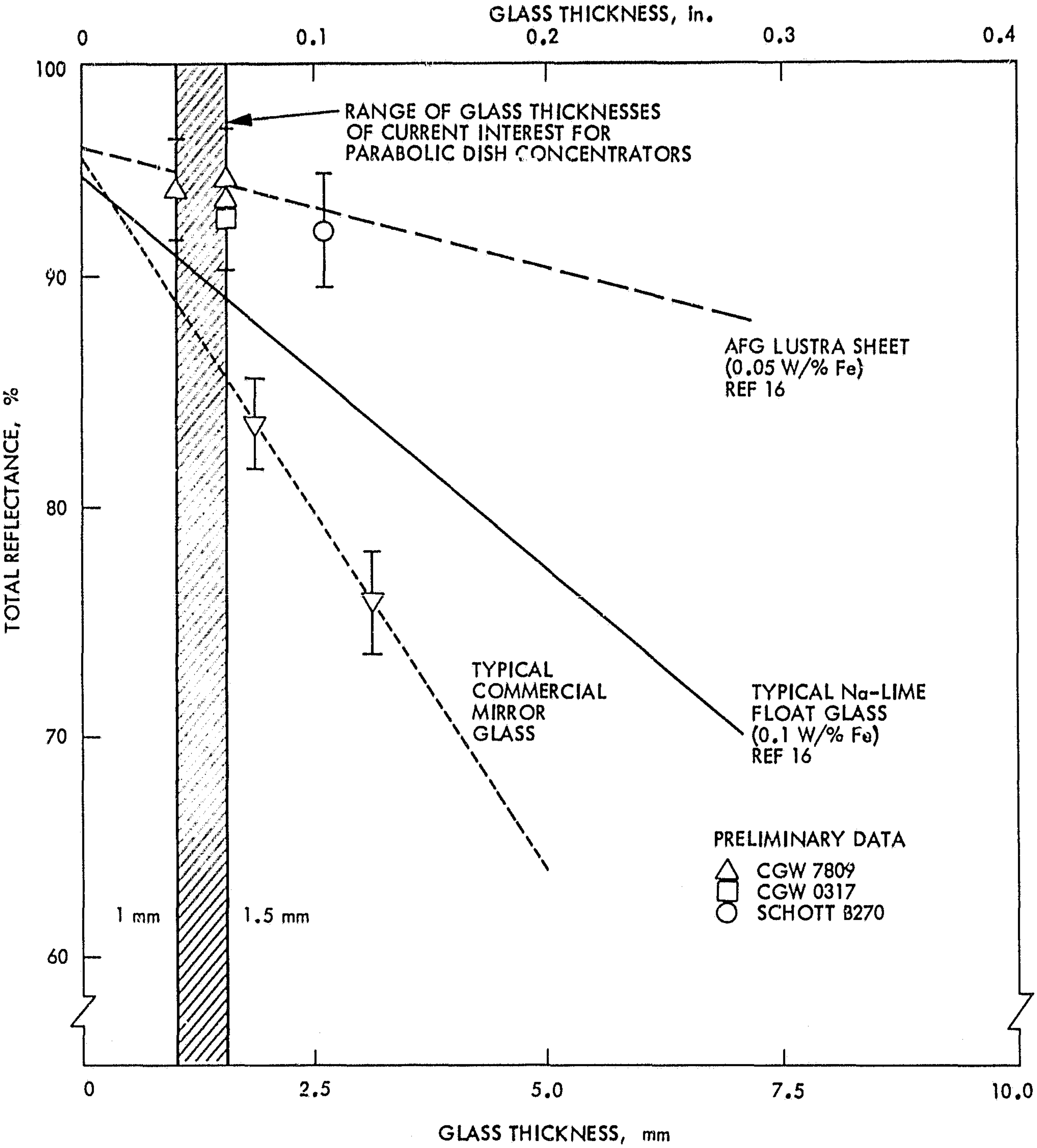

Figure 2-2. Total Reflectance versus Glass Thickness for Various Types of Mirrors

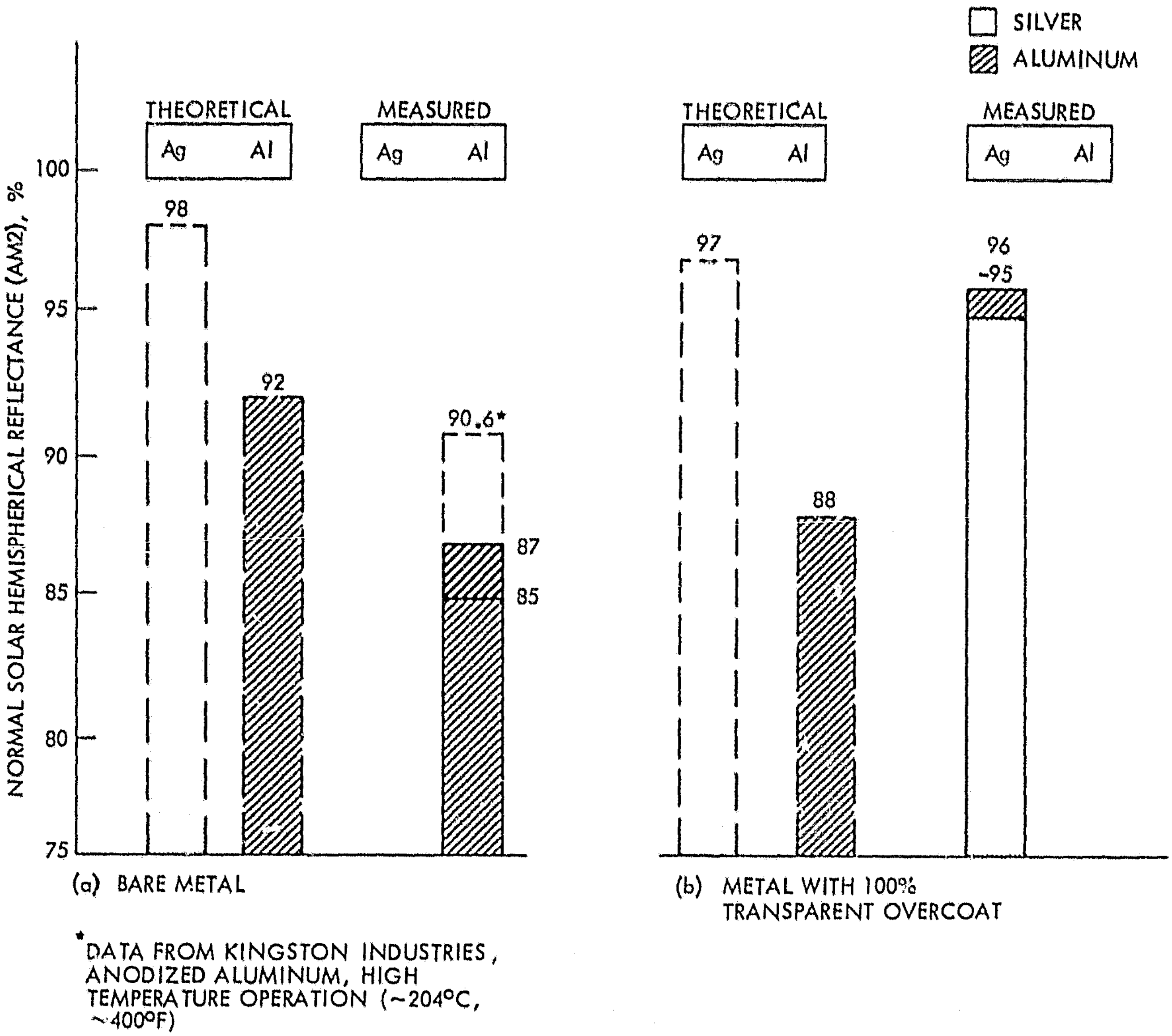

Figure 2-3. Normal Solar Hemispherical Reflectance for Theoretical and Measured Silver and Aluminized Surfaces

Table 2-1. Summary of Reflective Surfaces for Solar Concentrators (Refs. 5, 11, and 12)

(a) Non-Glass Reflectors

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 mrad	R_2	σ_2 mrad	Remarks
1	Alcoa	Aluminum Alzak	0	0.85	0	0	0.56 (505)	0.42	0.33	10.1	Wavelength: 505 nm Perpendicular to roll marks
							0.62 (505)	0.29	0.27	7.1	Parallel to roll marks
2	Kingston Ind.	Aluminum Kinglux	0	0.85	0	0	0.65 (498)	0.37	0.23	16.1	Similar to Alzak; JPL measurements, 85.4% in small quantities. Wavelength: 498 nm Perpendicular to roll marks
							0.67 (498)	0.43	0.21	18.5	Parallel to roll marks
3	Metal Fabr.			0.84	0	0	0.44 (550)	1.4	0.43	10.3	
4	Alcoa	S460667	0	0.92	0	0	--	--	--	--	Aluminum
5	ISC	90-10	0	0.90	0	0	0.86	--	--	--	Silver plated brass Requires overcoat Cu-Zn, 80% Cu, 20% Zn
6	ISC	80-20	0	0.88	0	0	0.80	--	--	--	
7	ISC	70-30	0	0.91	0	0	0.81	--	--	--	
8	3M	Scotchcal 5400	0	0.85	0	0	0.86	1.9	--	--	Aluminized Acrylic film
9	3M	FEK-163	0	0.85	0	0	0.86	0.90	--	--	Aluminized Acrylic film
10	Sheldahl	Aluminized Teflon	NA*	0.87	0	0	0.80	1.3	0.07	30.9	

*Measurements at other wavelengths are shown in parentheses.

Table 2-1. Summary of Reflective Surfaces for Solar Concentrators (Contd) (Refs. 5, 11, and 12)

(b) Glass Reflectors

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 mrad	R_2	σ_2 mrad	Remarks
11	CE	Glass (float) (Soda lime)	-- --	-- --	3.17 (0.125)	0.838	--	--	--	--	
12	Ford	Glass (float) (Soda lime)	--	--	3.17 (0.125)	0.844	--	--	--	--	
13	Fourco	Glass (float) (Soda lime)	--	--	3.17 (0.125)	0.891	--	--	--	--	
14	Liberty Mirrors	Cr coated front surface glass	3.17 (0.125)	0.65	--	--	--	--	--	--	Special measurements
15	Corning	Code 7806 (fusion)			1.14 (0.045)	0.88	--	--	--	--	Preliminary
16	Corning	Code 0317 (fusion)	--	--	2.29 (0.090)	0.910	--	--	--	--	
17	Corning	Code 0317 (fusion)	--	--	1.52 (0.060)	0.909	--	--	--	--	
18	Corning	Code 0317 (fusion)	--	--	2.8 (0.110)	0.903	--	--	--	--	
19	Schott B270	B270 (Drawn)	--	--	3 (0.120)	0.913	--	--	--	--	
20	PPG Works	#6 (float)	--	--	3.17 (0.125)	0.881	--	--	--	--	
21	AFG*	Low-Fe (Float)	--	--	3.17 (0.125)	0.847	--	--	--	--	
22	Corning	Code 0317 (fusion low Fe)	1.47 (0.058)	0.95	--	--	--	--	--	--	Sandia data vacuum deposited silver
23	Corning	Code 0317 (fusion low Fe)	1.47 (0.058)	0.94	--	--	--	--	--	--	Sandia data chemically deposited silver
24	Corning	Code 0317 (fusion low Fe)	1.47 (0.058)	0.926	--	--	--	--	--	--	JPL measurements old glass
25	NA	Pb - sulfide	varies	0.25	--	--	--	--	--	--	Auto side mirrors only
26	Corning/ Keim	Indium	1.47 (0.958)	0.35	--	--	--	--	--	--	Experimental mirror

*Formerly ASG Industries

Table 2-1. Summary of Reflective Surfaces for Solar Concentrators (Contd) (Refs. 5, 11, and 12)

(b) Glass Reflectors (continued)

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 mrad	R_2	σ_2 mrad	Remarks
27	Corning	2nd-Surface Microsheet	114 μm, 0.0045	0.95	0	0	0.77 (550)	1.1	0.18	6.2	
28	Carolina Mirror Co.	2nd-Surface Ag Glass	--	0.83	0	0	0.92	0.15	--	--	
29	Payne Co.	Microglass	0.15, 0.006	0.94	--	--	--	--	--	--	
30	Payne Co.	Microglass	0.30, 0.012	0.93	--	--	--	--	--	--	
31	Flabeg Corp.	Crown Glass (float)	3.17, 0.125	TBD**	--	--	--	--	--	--	Resin and/or Mylar reverse side sealant
32	Corning	7806 (fusion)	0.050	0.95	--	--	--	--	--	--	Preliminary

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

$R_t(\Delta\theta) \alpha R_1 \exp[-\Delta\theta^2/2\sigma_1^2] + R_2 \exp[-\Delta\theta^2/2\sigma_2^2]$ for a given intercept angle $\Delta\theta$

**TBD = To be determined

on total or specular reflectance, the reader is referred to the measurements of Sandia Labs, particularly References 5, 7, and 8.

C. SPECULAR REFLECTANCE

Specular effects are especially important for any high temperature system, including heliostats and dish systems. Sandia has measured the specular reflectance of various surfaces as a function of circular detector aperture size (Figure 2-4). The superior performance of the second-surface, silvered glass mirrors (Curve a) is apparent (Ref. 5).

As mentioned above, the energy distribution of the reflected beam profile of second-surface mirrors may be described in terms of a single normal distribution; however, many front-surface mirrors require a convolution of two normal distributions to adequately describe them. The reflectance coefficients for the reflectance equation are tabulated in Table 2-1.

D. RESULTS OF RECENT MEASUREMENTS OF REFLECTANCE

Screening tests for a number of commercial mirrors have been performed at JPL to determine (1) relative reflectance performance characteristics for the mirrors, (2) an initial assessment of degradation effects, and (3) the approximate slope or figure errors due to manufacturing differences.

The results of total and wide angle (~2°) reflectance data for silvered mirrors, aluminum, and stainless steel surfaces are shown in Table 2-2 as a function of incident wavelength. When the mirror glass is relatively thick (i.e., 3 mm), there is an appreciable reduction in reflectance.

An example of recent measurements performed on a selected sample of a high-transmittance glass mirror is shown in Figure 2-5. The particular sample (Figure 2-5a) is Corning Code 7809 glass of 1.0-mm (0.040-in.) thickness supplied by the Solar Energy Research Institute (SERI). High reflectance over the entire spectrum is noted. The peak intensity in the near-ultraviolet region (300 to 400 nanometers) is possibly due to glass fluorescence.

E. REFLECTANCE DEGRADATION

Efforts to further define and understand the subtle mechanisms of mirror degradation have been initiated by Battelle-PNL (Pacific Northwest Laboratory), Sandia National Laboratories, and JPL. A number of research directions are being pursued. Battelle is investigating mirror life expectancy through the use of lanthanide doping in the silver deposition process (Ref. 9) while Sandia is evaluating the role of water in silver degradation processes (Ref. 6).

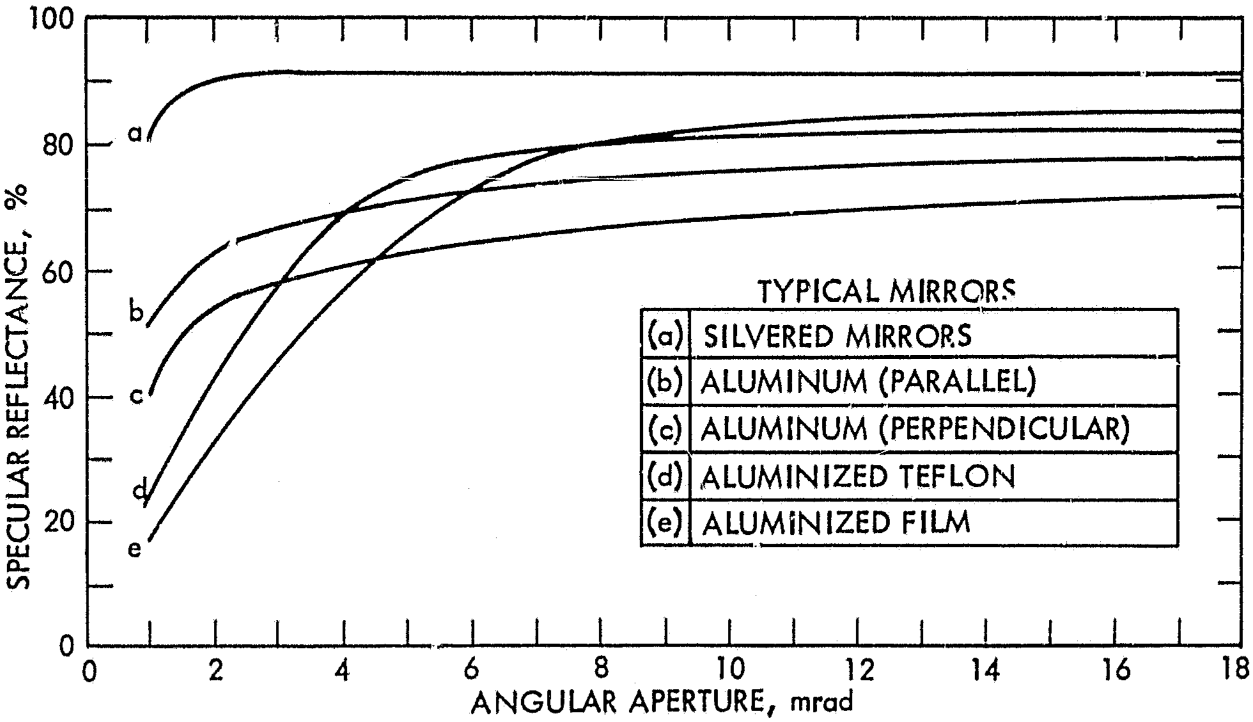

Figure 2-4. Specular Reflectance as a Function of Angular Aperture for Several Reflector Materials (Ref. 5)

Table 2-2. Total and Wide Angle Reflectances for Selected Surfaces

Type of Mirror[1]	Thickness mm (in.)	Wide Angle[2] Reflectance, % Wavelength, nm 400	500	600	800	Total Reflectance, % Wavelength, nm 400	500	600	800
1. Standard ($MgCO_3$)	———	-	-	-	-	100	100	100	100
2. Source A (Glass, CGW-0317)	1.5 (0.060)	92	95	95	100	97	98	98	100
3. Source B_1 (Glass)	3.0 (0.118)	91	95	94	89	96	98	97	88
4. Source B_2 (Glass)	5.0 (0.197)	88	93	91	78	91	93	89.5	74
5. Source B_3 (Glass)	6.0 (0.236)	90	92	89	75	90	90	86	69
6. Source C_1 (Glass)	2.13 (0.084)	76	80	80	75	98	99	98	90
7. Source C_2 (Glass)	3.25 (0.128)	72	78	77	66	92	95	93	80
8. Source C_3 (Glass)	3.3 (0.130)	75	79	77	66	94	96	94	80
9. Source C_4 (Glass)	3.3 (0.130)	88	79	77	67	94	95	93.5	80
10. Source D_1 (Glass)	3.2 (0.125)	76	79	77	66	96	97	94	80
11. Source D_2 (Glass)[3]	3.2 (0.125)	72	77	75	64	92	96	93	77
12. Source E (Aluminum)	———	75	71	72	63	99	95	92	86
13. Source F (Stainless Steel)	———	32	38	36	48	65	67	70	75

[1] With the exception of mirrors 1, 12, and 13, all are second-surface.

[2] Two degree half angle with incident angle of 51°.

[3] Second-surface aluminized glass.

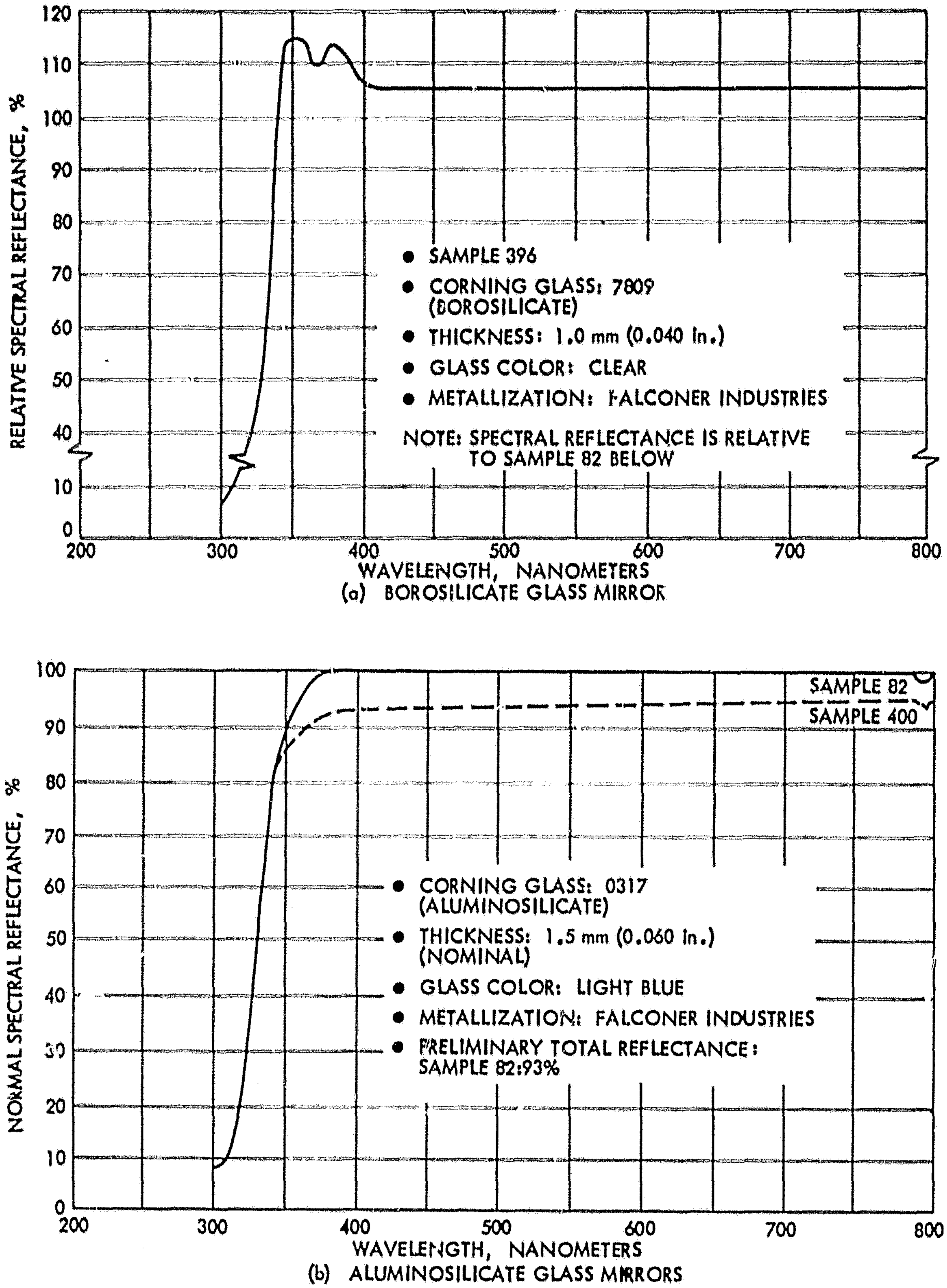

Figure 2-5. Spectral Reflectance versus Wavelength for Borosilicate and Aluminosilicate Glass Mirrors

Since March 1980, JPL has been involved in limited outdoor testing of mirrors at Pasadena, California, and at the Goldstone Test Site, Barstow, California. This testing is being performed in conjunction with the JPL Low-Cost (Photovoltaic) Solar Array Project. The goal is to identify seasonal and other effects of dust pileup and mirror corrosion.

In addition, a study of the composition and thickness of the silver/copper metallization on second-surface mirrors has been undertaken by Wittenberg College under JPL direction. The objective of this study is to determine the feasibility of using X-ray fluorescence and neutron activation to characterize the metallization and/or foreign corrosion agents. (See the Appendix for a further statement of this effort.)

Preliminary data on degradation in harsh outdoor test conditions at DSET Laboratories, Inc., Phoenix, Arizona, have been compiled by Rausch. (See Table 2-3, Reference 16.) His results show that the silvered glass mirrors exhibited only 3% degradation when cleaned after 32 weeks exposure. These data are indicative of the type of test results that can be obtained by accelerated testing. (For further details, the reader is referred to Reference 16.)

F. PERFORMANCE EVALUATION

Performance evaluation and testing have been extensively documented in recent solar energy literature. (See References 17 through 26.)

In summary, the complete evaluation of mirrors for solar thermal applications involves several areas in addition to that of optical properties (Table 2-4), including primarily mirror degradation mechanisms.

Performance of entire mirror sections during JPL ice ball impact tests has been determined to be dependent upon (1) the type and thickness of the bonding layer and (2) the elastic properties of the substrate (Refs. 27 and 28).

Atmospheric contamination (i.e., dust, dirt, and mud) can have an important effect on solar concentrator design, deployment, and cleaning operations. In a recent JPL study, different types of concentrators were evaluated using the latest (1979) dust degradation rates. The results are summarized in Table 2-5. Three types of solar concentrators were compared to the primary candidate: second-surface, silvered glass mirror concentrator, 11 meters in diameter.

Cleaning was assumed to take place once a month. More recent data (Ref. 29) have indicated that for plastic film the 15% per month average degradation rate due to dust accumulation may be pessimistic. It then follows that for the same power output and receiver configuration, aluminum, plastic, and Fresnel lens systems have to be 21, 37, and 25% larger, respectively, than the 11-meter diameter dish. Although these results are preliminary, they emphasize the effects of dust accumulation and beam spreading phenomena on the size of parabolic dish reflective surfaces.

Table 2-3. Summary of EMMAQUA Test Exposures (Ref. 16)*

Type of Reflective Surface	Material	ρ_o Original Average Reflectance	ρ_e Cleaned Surface Reflectance	Exposure Time, weeks	Reflectance Change** %
Second-Surface	Silvered Glass	0.86	0.84	32	-3
Second-Surface	Aluminized Fiberglass with Protective Coating	0.87	0.75	52	-14
			0.69	97	-21
			0.52	129	-40
Second-Surface	Aluminized Glass	0.76	0.76	52	0
			0.70	97	-8
			0.69	129	-9
First-Surface	Anodized Aluminum	0.82	0.77	52	-6
			0.79	97	-4
			0.74	129	-10
Second-Surface	Aluminized Acrylic Plastic	0.86	0.81	52	-5
			0.73	97	-14
			0.69	129	-19
Second-Surface	Aluminized Teflon	0.79	0.81	52	+3
			0.80	97	+1
			0.80	129	+1

*A DSET Laboratories, Inc., accelerated testing device that exposes sample to a water spray.

**Defined as $\frac{\text{clean reflectance - dirty reflectance}}{\text{original reflectance}}$

Table 2-4. Areas for Mirror Evaluation

- o Operating Life
  - o Temperature Stability

    Maximum operating temperature
    Gradient effects (shock)
    Cycling (fatigue)

  - o Chemical Stability
  - o Structural Stiffness with Respect to Total Operating Load Spectrum

    Body forces
    Mechanical forces
    Aerodynamic forces

  - o Fabrication

    Bondability

  - o Repairability
- o Degradation Mechanisms
  - o Effect of Adherent Dust on Reflective Surfaces
  - o Impact and Abrasion Resistance (Hail and Sand)
  - o Effects of UV Radiation on Mirror Components

Table 2-5. Solar Thermal Dust Assumptions (Ref. 28)

	Type of Concentrator Surface	Reflectance %	Average Reflectance Degradation Due to Soiling	Dish Radii m (ft)	Effective Area m^2 (ft^2)	Relative Dish Size Required*
1.	Second-Surface Silvered Glass	94	3	5.5 (18)	100 (1076)	1.0
2.	First-Surface Anodized Aluminum	86	3	6 (19.7)	121 (1308)	1.21
3.	Second-Surface Metallized Plastic Film	85	15	6.4 (21.0)	137 (1472)	1.37
4.	Fresnel Lens	83.5**	6	6.3 (20.7)	125 (1342)	1.25

*Relative to second-surface silvered glass mirrors. Each reflective surface was designed to produce the same average installed power capability. Monthly cleaning was assumed. The larger sizes are required as a result of (1) different reflective (transmittance) surface characteristics and (2) different reflectance (transmittance) degradation due to soiling. Receiver reradiation effects are not included.

**Since the Fresnel lens was assumed to be clear acrylic plastic, this value is for transmittance. Soiling is assumed to occur on both sides of the plastic lens.

Many areas still must be researched in order to adequately quantify indoor mirror technology for outdoor solar applications. In addition to the dust accumulation effects mentioned above, the nature and causes of various types of infrequently observed silver corrosion need to be investigated.

Mirror performance, including degradation effects, greatly influences cost, both maintenance costs and capital investment. The latter is treated briefly in the following section.

SECTION III

COSTS

A. GENERAL

The particular aspects of costs of reflective surfaces discussed in this Section reflect current purchase prices (August 1980, in dollars) for commercial reflective surfaces. These data, when used in conjunction with the performance data in Section II provide the basis for computing the cost/performance ratios for solar parabolic dish concentrators in Section IV. Prototype prices are largely omitted herein, and prices of concentrators in the range of 100 to 100,000 units per year are emphasized where information is available. Most data given are "price" data which were obtained from the manufacturer. Glass and mirror manufacturing sources are given in References 15 and 9, respectively. "Cost" data herein are assumptions, since cost data are, in general, considered proprietary by the manufacturer. "Price" data include basic costs plus the manufacturer's profit.

Production of a large number of concentrators implies that costs may be reduced through production efficiencies, yet this is not necessarily the case, especially for patented, proprietary reflectors. The reduction in price achievable in very large quantity mirror procurements is omitted from this report. All three commercial reflective surfaces treated herein are produced by relatively mature technologies, and a quantum reduction in price is not envisioned for the near future.

B. COST EQUATIONS

A simplified, general model of the basic cost equations for solar concentrators is given below. The total cost is the sum of three cost quantities, namely:

$$C_t = \sum_{i=1}^{13} C_i + \sum_{j=14}^{15} C_j + \sum_{k=16}^{17} C_k$$

where

C_t = Total Cost

C_i = Initial Production Costs

C_j = Maintenance Costs

C_k = Replacement Costs

where

Fabrication

C_1 = Cost of reflective surface application

C_2 = Cost of basic mirror material

C_3 = Cost of bending the reflective surface into parabolic shape

C_4 = Cost of cutting mirror to shape

C_5 = Cost of edge sealant for mirror

C_6 = Cost of packaging and handling

C_7 = Cost of shipping

C_8 = Cost of substrate

C_9 = Cost of mating mirror and substrate

C_{10} = Cost of bonding agent

C_{11} = Cost of bonding mirror to substrate (labor)

C_{12} = Cost of support structure, if any

C_{13} = Cost of assembly of concentrator mirror plus reflective surface with support structure

Maintenance

C_{14} = Cost of cleaning liquids (or dry air system)

C_{15} = Cost of washing (labor)

Replacement

C_{16} = Cost of replacing reflective surfaces

C_{17} = Cost of replacement (labor)

Some terms, of course, will not be applicable to specific reflective surfaces because the equations refer to glass mirrors. In those cases, other equivalent terms may need to be substituted. Although all of the above cost factors are not used explicitly in the analysis, they are nonetheless important.

Costs resulting from improvement of a specific type of reflective surface will, in general, increase with improved requirements for reflectance characteristics and mirror durability. Examples are (1) increase of silver and copper thicknesses for improved reflectance and (2) increase of thickness, composition, or choice of paints for metallization protection. This relationship is illustrated in Figure 3-1.

In certain cases, transportation costs can become appreciable, especially in the case of low-cost reflective surfaces and long transportation distances. As an example, consider 1000 ft^2 of mirror glass priced at 0.7 $\$/ft^2$ with 2 ft x 5 ft dimensions. The material cost would be \$700 per unit, but the shipping cost would add an additional \$250 or 35% to the cost at a shipping distance of 2500 miles.

Detailed information on prices of commercial reflective surfaces is given below.

C. TYPICAL PRICES OF COMMERCIAL REFLECTIVE SURFACES

1. Glass Mirrors

Commercial reflective surfaces are available from a large number of manufacturers in both the United States and Europe. A few illustrative examples are shown in this section. The general subject of glass prices has been treated extensively in References 12 and 15. Prices vary widely and are dependent upon the thickness, type, processed state, maximum length dimension, and other complex factors.

The basic price (1980 dollars) for West Coast delivered mirrors is in the general range of 7.5 to 8.3 $\$/m^2$ (0.70 to 0.77 $\$/ft^2$) for single strength 2.5-mm (0.125-in.) glass in moderate quantities. (See Figure 3-2 and Table 3-1 for two typical industry sources.) These data represent maximum prices. Very large quantities would presumably lower the cost per square meter.

Very thin-film glass mirrors, 0.7-mm (0.028-in.) thick are reported to cost less, e.g., 5.4 $\$/m^2$ (0.50 $\$/ft^2$). However, breakage during shipment and handling may increase the real cost. Clearly, a trade-off is required between initial inexpensive mirror costs versus expensive transportation costs necessary to deliver a given number of mirrors to the fabrication site as well as breakage costs during gore fabrication. Likewise, the extremely thin glass may be unsatisfactory due to high replacement costs in certain environments (i.e., hail or vandalism).

Commercial mirrors requiring special processing, such as "flexible" mirrors (Figure 1-4), are presently more expensive than the basic mirror price range shown above. Flexible mirrors in 2.54-cm (1.0-in.) squares, for example, retail in the 43-86 $\$/m^2$ (4-8 $\$/ft^2$) range. Of course, cutting, bonding, and plastic backing protection are included in these numbers. With larger squares designed specifically for larger power systems, the cutting costs may be appreciably reduced through automated techniques.

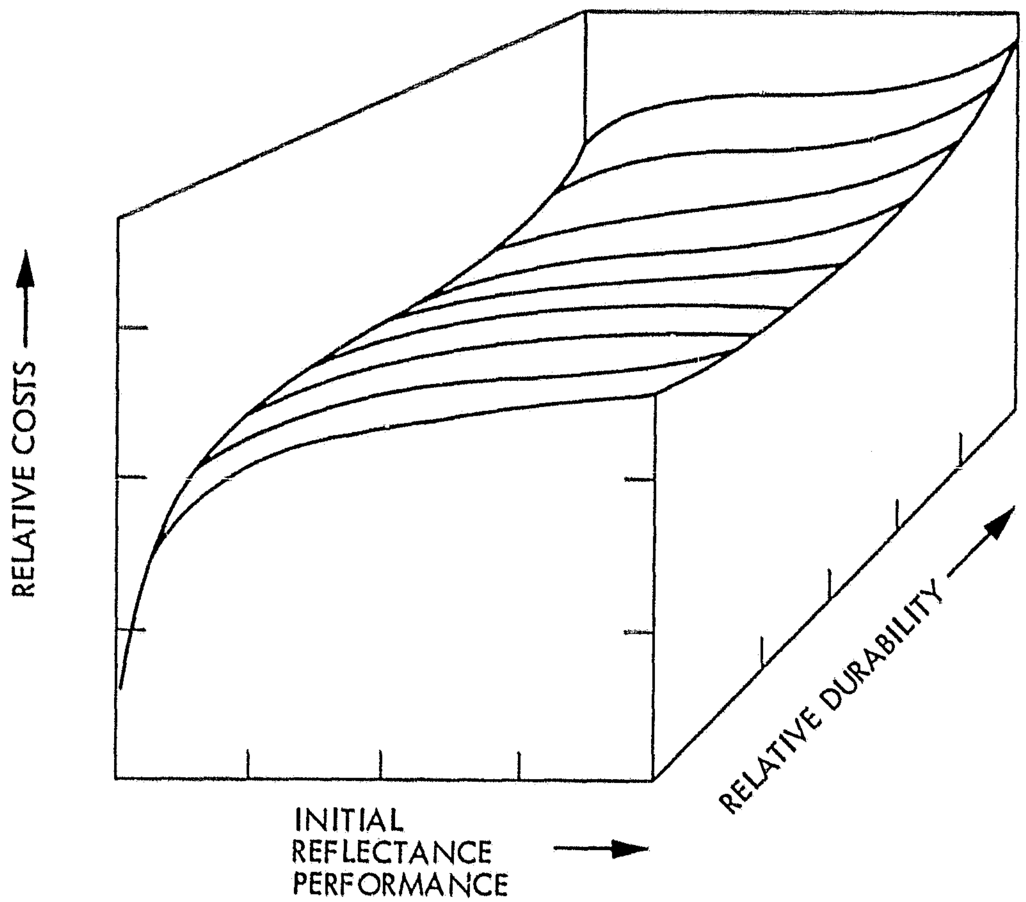

Figure 3-1. Relative Costs versus Initial Reflectance Performance and Relative Durability

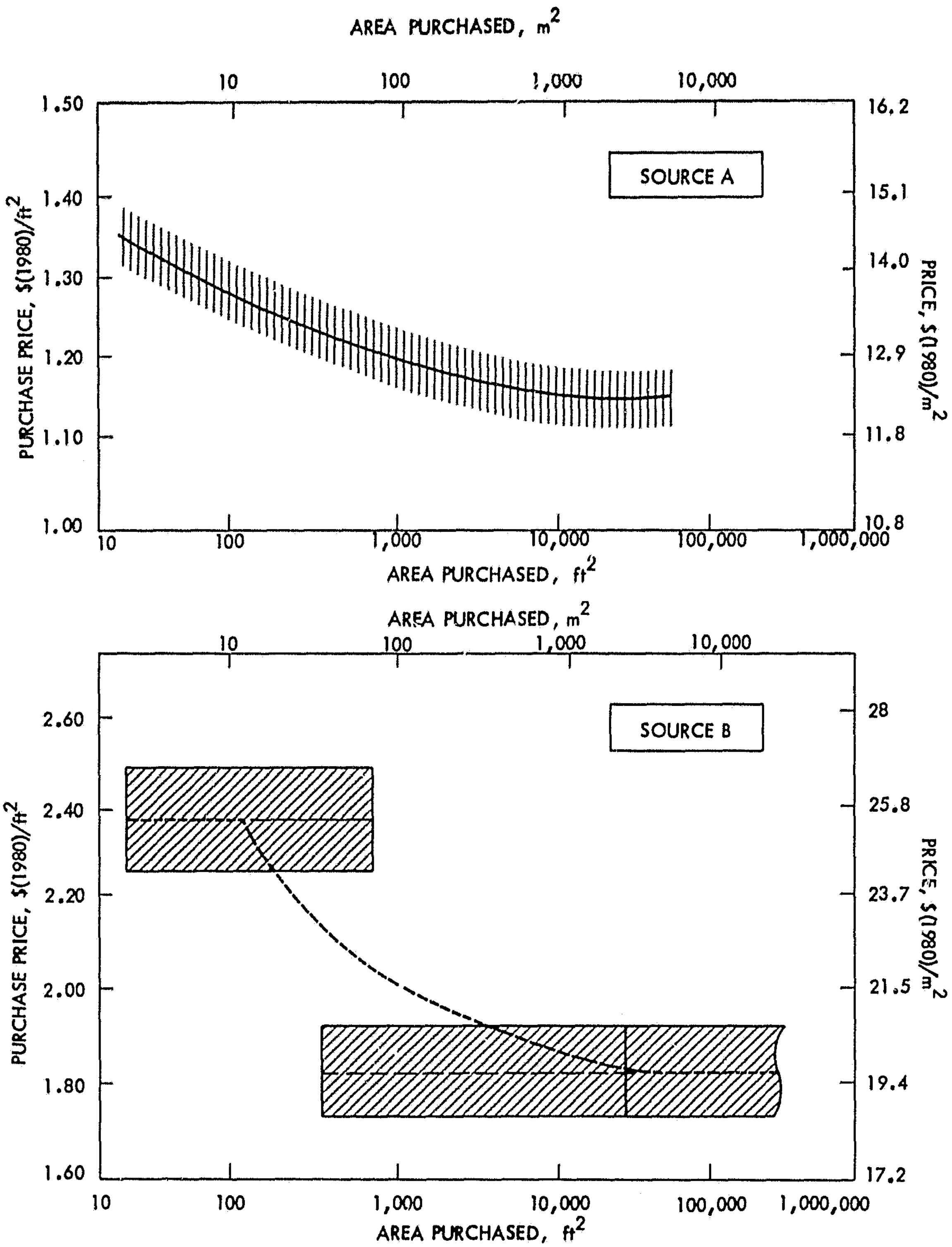

Figure 3-4. Typical Prices of Surface Processed Bulk Aluminum Reflectors

3-5 to 3-8

Table 3-2. Typical Prices of Aluminized Acrylic Film for Solar Mirrors

Area Purchased		Price (1980$) per Unit Area	
m^2	ft^2	$\$/m^2$	$\$/ft^2$
0.93	10	18	1.67
9.3	10^2	18	1.67
93	10^3	15	1.39
930	10^4	13.23	1.23
9,300	10^5	13.23	1.23
93,000	10^6	13.23	1.23

SECTION IV

COST/PERFORMANCE

Evaluation of the type of reflective surface to be used involves a cost/performance ratio, which is the ratio of dollars expended to the amount of energy delivered to the receiver system.

Extensive analyses have been performed at JPL on solar parabolic dish concentrators. (See References 1 through 4.) Concentrator cost goals of 40 to 100 $\$/m^2$ (3.7 to 9.3 $\$/ft^2$) have been proposed. In this investigation, it has been shown that reflective surfaces in large volumes may be priced initially between 7.5 and 23 $\$/m^2$ (0.70 and 2.15 $\$/ft^2$). With the exception of bent glass technology, the reflective surface contributes a small fraction of total concentrator cost. Substrate costs are yet to be determined and are the subject of a concurrent JPL report (Ref. 2). Although costs for cutting large mirrors have been found to be small and, hence, negligible, bonding and sealing costs during fabrication may be significant. These factors will be addressed in future studies of complete gore fabrication.

Nevertheless, the range of usefulness of the three different reflector systems (silvered glass, aluminum, and plastic film) can be determined using recent JPL analysis techniques (Figure 4-1). These analyses result in estimates of the useful power delivered to the receiver (Table 4-1) along with capital costs. Figure 4-2 shows the initial costs of the reflective surface per kilowatt of thermal energy delivered to the receiver as a function of receiver operating temperature.

For purchases of large mirrors, i.e., greater than 930 m^2 (10,000 ft^2), total concentrator prices of 100, 60, and 40 $\$/m^2$ are assumed for second-surface silvered glass, anodized aluminum, and metallized plastic film, respectively.

This investigation shows that commercial glass mirrors are the single most economical system, from an initial capital investment standpoint, across the temperature range of 400 to 1400°C. Likewise, this investigation shows that from a capital investment standpoint, aluminized metallic film is the second most cost effective below a receiver temperature of 600°C, while aluminum mirror is the second most cost effective from 600 to 1400°C (the highest temperature studied). (See Figure 4-2.)

The borosilicate glass mirrors are found to be lower priced than metallized polymeric film, and the hot-formed, high-transmittance glass reflector the most expensive of the systems studied.

The preceding two figures have been recalculated assuming (1) an uncertainty band of +10% on the power delivered to the receiver due to various effects (Figure 4-3) and (2) price ranges of reflective surfaces from available commercial price lists. The results are shown in Figures 4-4 and 4-5 for glass and non-glass mirrors, respectively. The ranges of overlap are apparent, and conventional glass mirrors exhibit the narrowest uncertainty band.

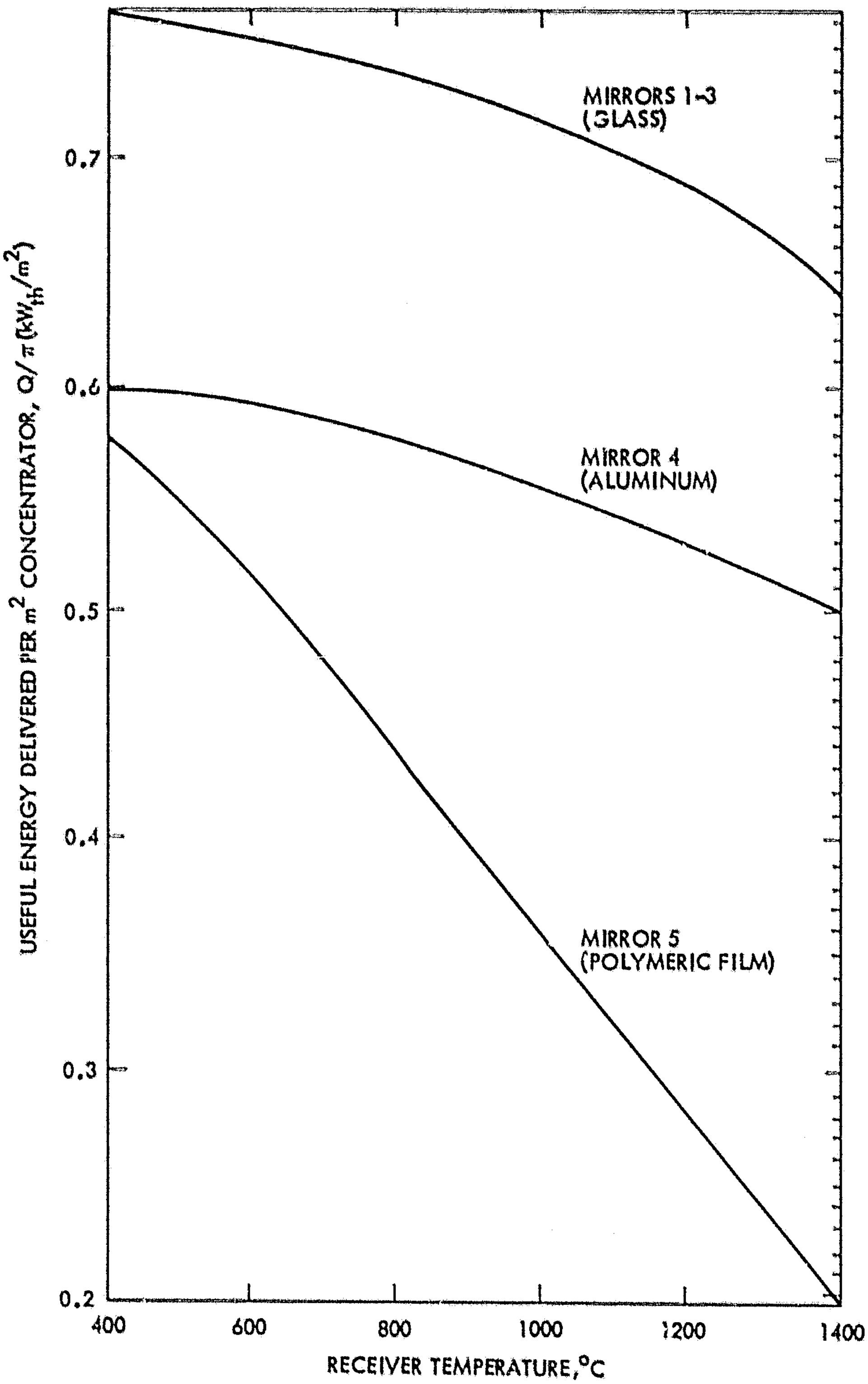

Figure 4-1. Useful Energy Delivered to the Receiver versus Receiver Temperature

Table 4-1. Initial Cost for Various Reflective Surfaces for Parabolic Dish Concentrators

	Mirror Construction*	Receiver Operating Temperature, °C					
		400	600	800	1000	1200	1400
Energy Delivered $\frac{kW_{th}}{m^2}$	A_{gh}	0.76	0.752	0.735	0.715	0.69	0.64
	A_{ga}	0.76	0.752	0.735	0.715	0.69	0.64
	A_{gc}	0.76	0.752	0.735	0.715	0.69	0.64
	A_{ℓ}	0.6	0.592	0.575	0.552	0.525	0.5
	A_f	0.58	0.51	0.435	0.355	0.28	0.19
Price $\frac{\$(1980)}{m^2}$	A_{gh}	48.42	48.42	48.42	48.42	48.42	48.42
	A_{ga}	23.13	23.13	23.13	23.13	23.13	23.13
	A_{gc}	7.53	7.53	7.53	7.53	7.53	7.53
	A_{ℓ}	15.49	15.49	15.49	15.49	15.49	15.49
	A_f	13.23	13.23	13.23	13.23	13.23	13.23
Ratio $\frac{P(\$1980)}{kW_{th}}$	A_{gh}	63.71	64.39	65.88	67.72	70.17	75.66
	A_{ga}	30.43	30.76	31.47	32.35	33.52	36.14
	A_{gc}	9.91	10.01	10.24	10.53	10.91	11.77
	A_{ℓ}	25.82	26.17	26.9	28.06	29.5	30.98
	A_f	22.81	25.94	30.41	37.26	47.25	69.63

Legend:
A_{gh} - second-surface glass, hot-formed
A_{ga} - second-surface glass, high-transmittance, sagged
A_{gc} - second-surface glass, conventional
A_{ℓ} - first-surface aluminum
A_f - second-surface aluminized polymeric film

*Insolation = 850 W/m^2

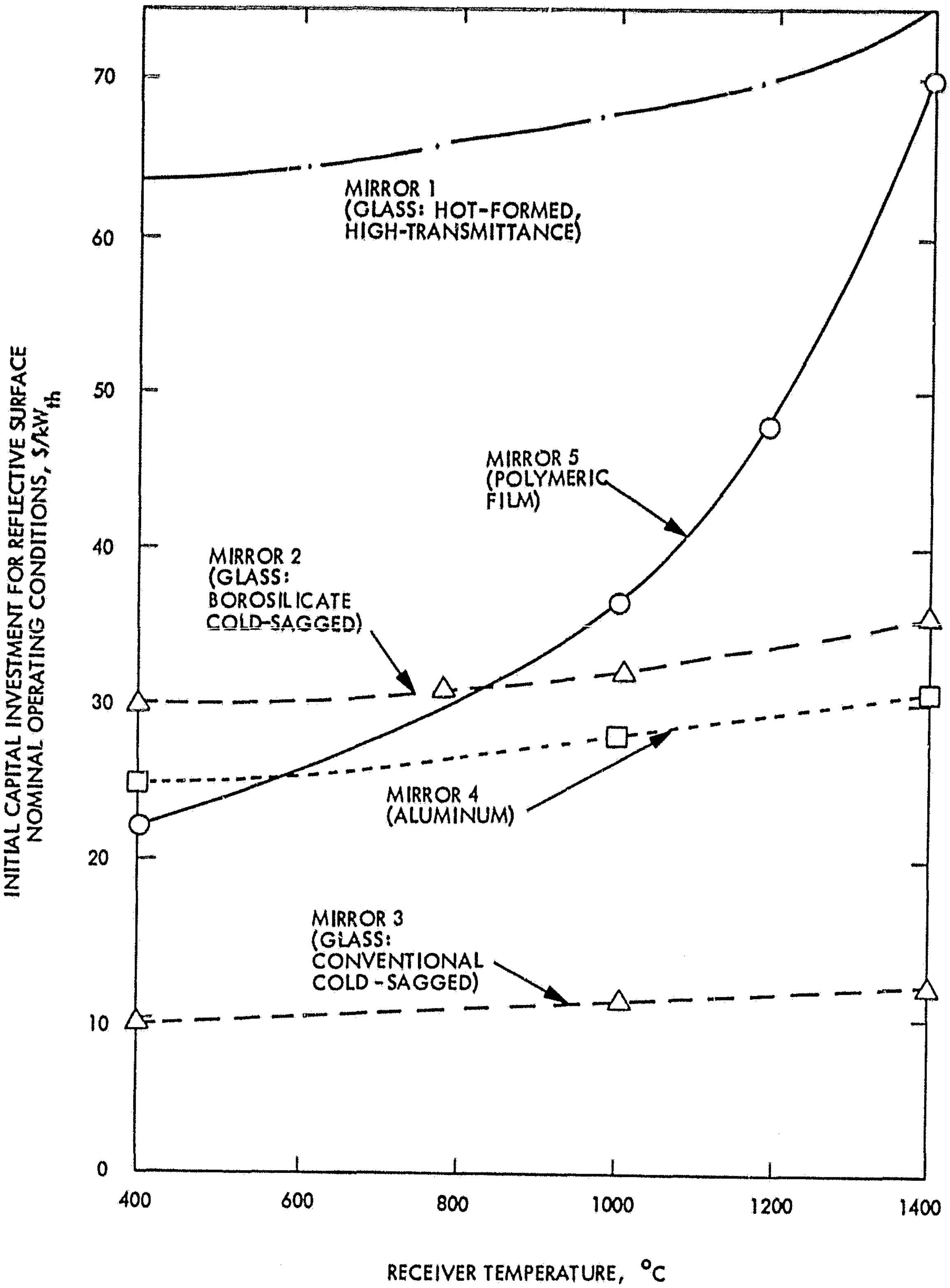

Figure 4-2. Initial Capital Investment for Reflective Surfaces for Nominal Operating Conditions

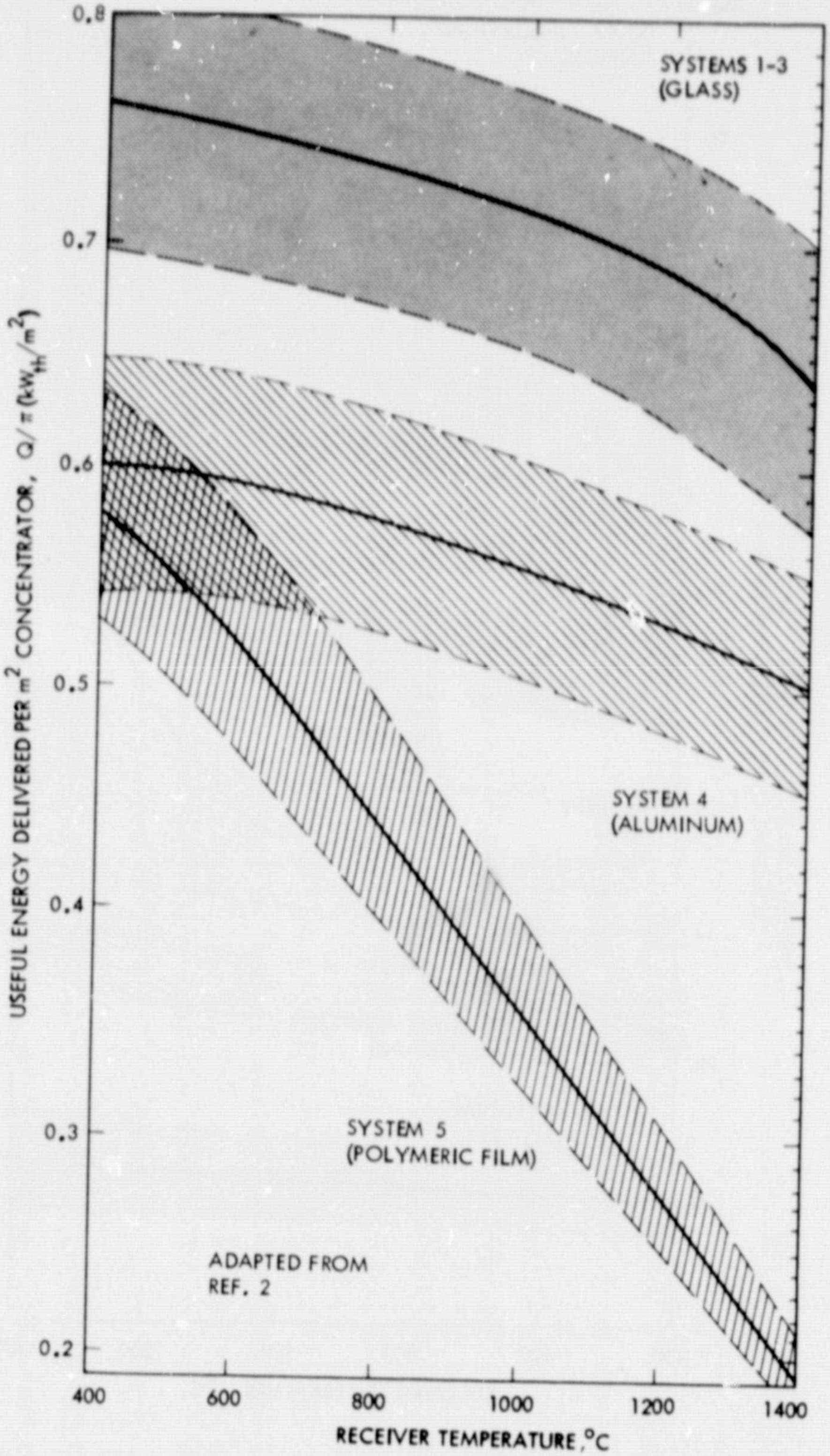

Figure 4-3. Useful Energy Delivered to Receiver versus Operating Temperature Showing Plus and Minus 10% Uncertainty Bands

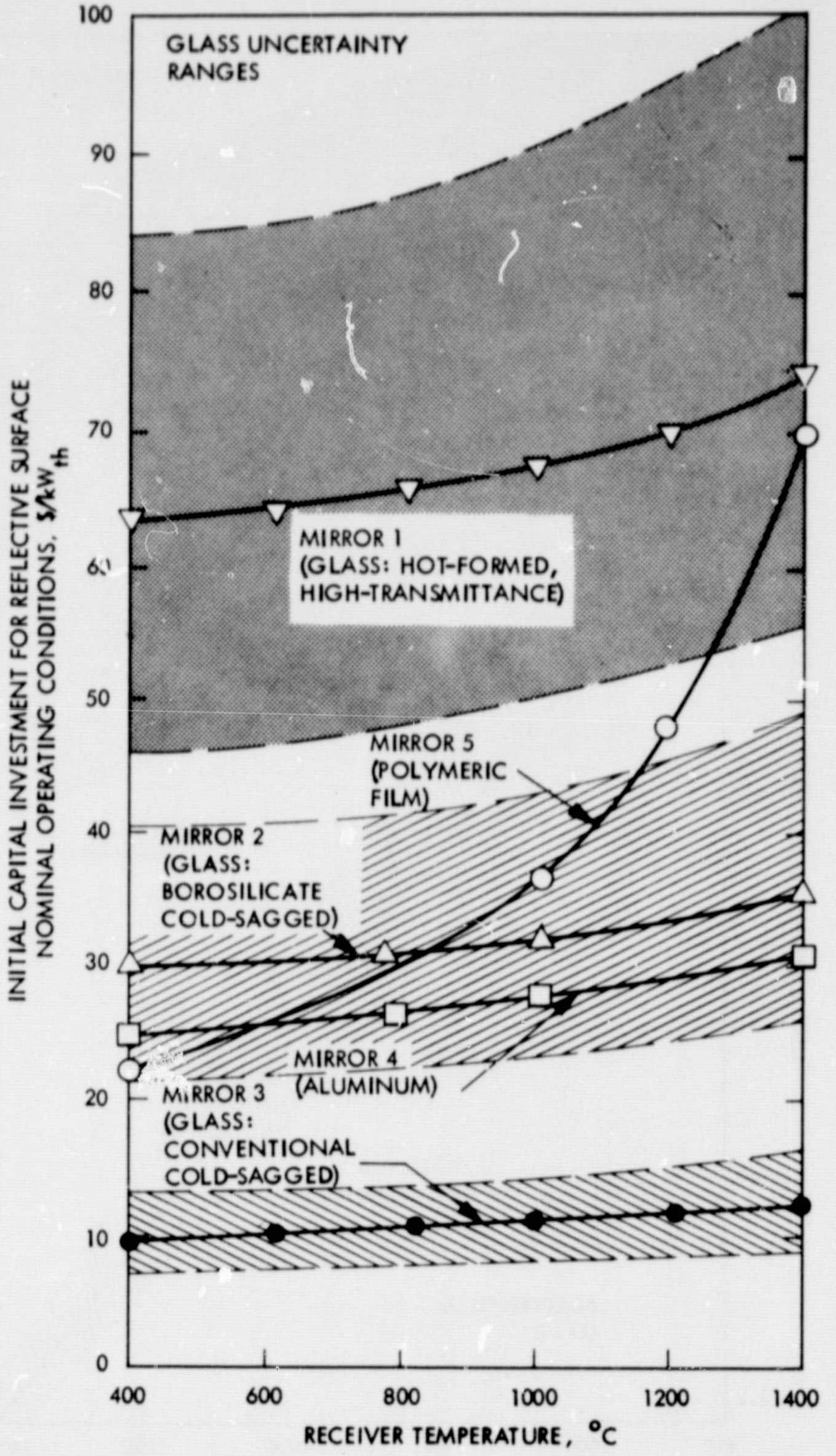

Figure 4-4. Ranges of Initial Capital Investment for Glass Mirrors versus Receiver Temperature

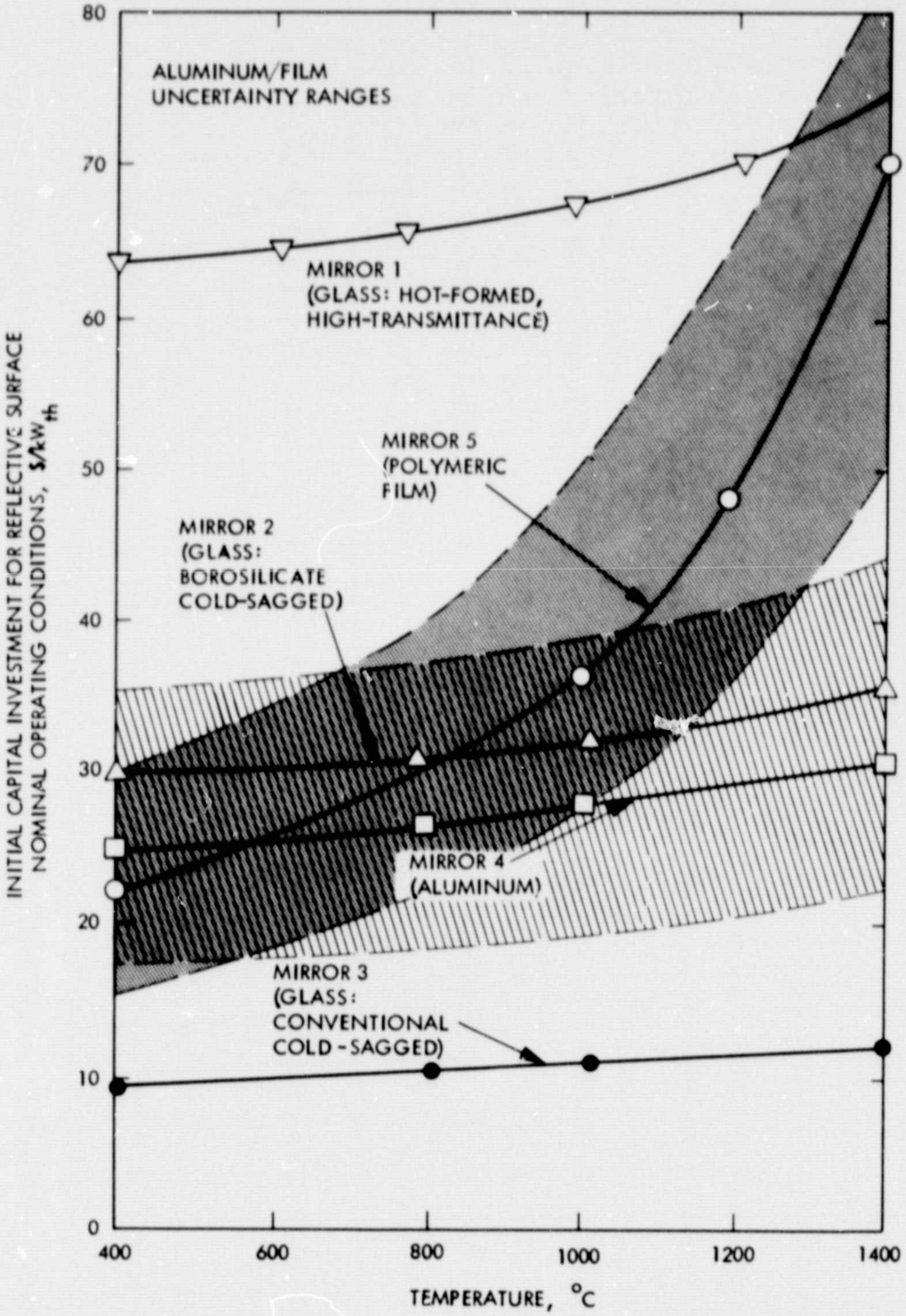

Figure 4-5. Ranges of Initial Capital Investment for Aluminum Surfaces and Metallized Polymeric Films

SECTION V

SUMMARY

This report is a summary of the cost, performance, and cost/performance ratios for reflective surfaces for solar parabolic dish concentrators. The performance data have been obtained primarily from the work of Sandia National Laboratories supplemented by limited reflectance data performed by JPL and industry. The cost information for both limited and mass-production quantities has been obtained for various glass and mirror manufacturers in the United States and Europe.

The lack of an organized data base for use in cost/performance analyses of parabolic solar collectors formed the impetus for this report. It is an introduction which highlights the major considerations and trade-off/sensitivity analysis necessary to develop a complete cost/performance characterization.

Capital investment costs are treated in this initial study. Development of life-cycle costs reflecting longevity of the various construction materials is the next step. As techniques for cleaning the various types of mirrors become available, their costs should be included. In addition, the inclusion of recent soiling models, mirror degradation models, and models of better specular performance of alternative (non-glass) mirror technology could significantly improve the usefulness of the results.

The conclusions of this report concerning performance, costs, and cost/performance ratios are summarized as follows:

(1) In general, the reflective properties of parabolic solar commercial mirrors can be divided into three general types: second-surface silvered (or aluminized) glass, anodized aluminum, and aluminized polymeric film. All three types of mirrors remain potential candidates for use as reflective surfaces for parabolic dish concentrators. The ultimate selection depends upon the system requirements and further developments in the respective mirror technologies.

(2) The cost of hot forming glass into parabolic shapes is appreciably higher than cold forming. A major contributing factor is the lack of industrial sources for production of large thin glass sheets required for solar applications.

(3) For nominal receiver cavity operating temperatures of 400 to 1400°C, cold-sagged, commercial second-surface metallized glass mirrors require the lowest initial capital investment per thermal kilowatt delivered to the receiver.

(4) With the exception of conventional glass mirrors, the model shows that aluminum reflector surfaces have the second lowest cost for receiver cavity temperatures above 600°C. However, cold-sagged borosilicate glass reflectors are only 20% higher.

(5) For receiver cavity temperatures below 600°C, the energy delivered by an aluminized polymeric film reflective surface appears lower in cost than either aluminum or borosilicate glass reflectors.

(6) There are relatively large uncertainty bands about the cost performance values due mainly to a lack of definitive cost information.

The data presented herein are the results of a relatively limited cost/performance analysis based upon a simple concentrator mathematical model and available data. This preliminary assessment should be expanded to include other glasses, metals, and films available for reflective surfaces including advanced surfaces such as those produced by ion implantation.

Only partial costs are given, namely for the reflective surface of the solar collector. As information on substrate costs becomes available, generation of similar curves for reflective surface/substrate combinations is planned. Life-cycle costs including the effects of maintenance and inflation factors are needed. In the meantime, these curves should be useful for indicating general trends.

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APPENDIX

ABSTRACT OF MIRROR GAUGING STUDY

A contract has been let by JPL to the Board of Directors of Wittenberg College, Springfield, Ohio, to study the thickness and composition of metallic films on second-surface glass mirrors. The approach is to use X-ray fluorescence and neutron activation techniques to perform characterization of the metallization, i.e., especially silver and copper. The goal is to determine the feasibility and limitations of non-destructive techniques for evaluation of the thickness, uniformity and composition of various types of reflective surfaces. Samples with and without corrosion are being studied. The contract is scheduled for completion by December 30, 1980.