GEORGIA INSTITUTE OF TECHNOLOGY | OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[x] ORIGINAL
[ ] REVISION NO. ____

Project No. A-2916 | DATE: 5/2/81

Project Director: Ken Maddox | XXXXXX/Lab TAL/ECD

Sponsor: U. S. Department of Energy; Albuquerque, NM 87115

Type Agreement: Contract DE-AC04-81AL16306

Award Period: From 3/16/81 To ~~9/16/81~~ 12/31/81 (Performance) 10/16/81 (Reports)

Sponsor Amount: $58,623 | Contracted through:

Cost Sharing: N/A | GTRI/XXX

Title: Durability of Reflecting Surfaces Used in Solar Heliostats

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ADMINISTRATIVE DATA | OCA CONTACT Leamon R. Scott

1) Sponsor Technical Contact: Mr. Jerry E. Zimmerman (COR); Department of Energy; Albuquerque Operations Office; P. O. Box 5400; Albuquerque, NM 87115 Phone 505-844-5230

2) Sponsor Admin./Contractual Contact: Laverne Scott; Off-Site Contracts Administration Branch; Contracts & Procurement Division; Department of Energy; P. O. Box 5400; Albuquerque, NM 87115; Phone 505-844-7202

Reports: See Deliverable Schedule | Security Classification: N/A

Defense Priority Rating: N/A

RESTRICTIONS

See Attached Government Supplemental Information Sheet for Additional Requirement

Travel: Foreign travel must have prior approval - Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with None proposed

COMMENTS:

COPIES TO:

Administrative Coordinator	Research Security Services	EES Research Public Relations
Research Property Management	Reports Coordinator (OCA)	Project File (OCA)
Accounting Office	Legal Services (OCA)	Other: ____
Procurement Office	Library, Technical Reports	

GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION SHEET

Date 3/4/82

Project Title: Durability of Reflecting Surfaces Used in Solar Heliostats

Project No: A-2916

Project Director: Ken Maddox

Sponsor: US DOE

Effective Termination Date: 12/31/81

Clearance of Accounting Charges: 12/31/81

Grant/Contract Closeout Actions Remaining:

- [x] Final Invoice ~~and Closing Documents~~
- [ ] Final Fiscal Report
- [x] Final Report of Inventions
- [x] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ______

Assigned to: TAL/ECD (~~School~~/Laboratory)

COPIES TO:

Administrative Coordinator	Research Security Services	EES Public Relations (2)
Research Property Management	Reports Coordinator (OCA)	Computer Input
Accounting	Legal Services (OCA)	Project File
Procurement/EES Supply Services	Library	Other ______

FORM OCA 10:781

LIBRARY DOES NOT HAVE

Project Status Report No. 1   March 16, 1981 to April 16, 1981

June 12, 1981

Project Status Report No. 2

Report Period: April 16, 1981-
May 15, 1981

CONTRACT TITLE AND NUMBER:

Durability of Reflecting Surfaces Used in Solar Heliostats

DE-AC04-81AL16306

EES Project A-2916

CONTRACTOR NAME: Georgia Institute of Technology
Engineering Experiment Station
Technology Applications Laboratory
Atlanta, Georgia 30332

CONTRACT PERIOD: March 16, 1981 through September 16, 1981

1. Contract Objective: No Change.

2. Technical Approach Changes: No Change.

3. Contract Tasks:

Task 4.1 - Data gathering - literature review continued as did contacts with industry and the military (old mirrors).

Task 4.3 - Conference - The conference date has been rescheduled to July 29 and 30, 1981 to suit the schedule of those attendees from Europe. The conference location has been changed from Atlanta to Washington, D.C. at the request of DOE. This appears to be a change in scope and may cause additional travel expenses to be incurred. Invitations to the conference are being provided to people after they are interviewed and determined to be of benefit to the conference.

4. Open Items: None.

5. Summary Assessment and Forecast:

Contacts with individuals and companies involved in the solar field continue to be positive and it appears that good support and a large turnout can be expected for the conference.

Kenneth P. Maddox, Ph.D

Principal Investigator

June 30, 1981

Project Status Report No. 3

Report Period: May 16, 1981-
June 15, 1981

CONTRACT TITLE AND NUMBER

Durability of Reflecting Surfaces Used in Solar Heliostats

DE-AC04-81AL16306

EES Project A-2916

CONTRACTOR NAME: Georgia Institute of Technology
Enginerring Experiment Station
Technology Applications Laboratory
Atlanta, Georgia 30332

CONTRACT PERIOD: March 16, 1981 through September 16, 1981

1. Contract Objective: No Change.

2. Technical Approach Changes: No Change.

3. Contract Tasks:

Task 4.1 - Data gathering - Visits have been made to the following industries:

Gardner Mirror

Carolina Mirror

Hilemn Laboratories

Desert Sunshine Exposure Testing

Solar Energy Research Institute

Libby Owens Ford

Solar Devices

A number of other telephone contacts have been made, and several other site visits are scheduled for the week of June 15-19, 1981.

Task 4.2 - Position paper - Preliminary outline of the paper has begun, based on the results of the literature review, site visits, and telephone conversations.

Task 4.3 - Conference - Invitations are being distributed to the appropriate people for the conference to be held in Washington, D.C., July 29-30, 1981. The Washington, D.C. location is proving to be inconvenient, as it is difficult to book space during the summer tourist season.

4. Open Items: None.

5. Summary Assessment and Forecast:

All site visits outside the Atlanta area should be completed by June 19, 1981. A varied and quite knowledgeable list of conference attendees has been developed and it is expected that a beneficial conference will result.

Kenneth P. Maddox, Ph. D.
Principal Investigator

August 1, 1981
Project Status Report No. 4
Report Period: June 16, 1981 -
July 15, 1981

CONTRACT TITLE AND NUMBER:
Durability of Reflecting Surfaces Used in Solar Heliostats
DE-AC04-81AL16306
EES Project A-2916

CONTRACTOR NAME: Georgia Institute of Technology
Engineering Experiment Station
Technology Applications Laboratory
Atlanta, Georgia 30332

CONTRACT PERIOD: March 16, 1981 through September 16, 1981

1. Contract Objective: No Change

2. Technical Approach Changes: No Change

3. Contract Tasks:
Task 4.1 - Mirror review - Contact has been made, both in person and by telephone, with a large number of manufacturers of mirrors, heliostat system integrators, testing laboratories, and foreign researchers. Site visits have included Gardner Mirror, Carolina Mirror, Binswanger Mirror, Falconer Glass, Buchmin Industries, and Hoyne Industries, all mirror manufacturers, and chemical suppliers London Laboratories and Hilemn Laboratories. System integrators visited were Martin Marietta, McDonnell Douglas, Arco Power Systems, and Acurex. Test installations included DSET, SERI, Barstow, and the Central Receiver Test Facility. Foreign contacts have been made with Glaverbel, CETHEL, AMN Spa, and Hitachi.

Task 4.2 - The dicussion paper was being prepared during the reporting period and will be released before the conference is held. It will be in four basic sections: mirror manufacturing considerations for reliability, paints and coatings, testing, and heliostat experience.

Task 4.3 - conference - The conference is scheduled for July 29-30, 1981 at Arlington, Virginia. About 20 industry representatives are expected to attend.

4. Open Items: None

5. Summary Assessment and Forecast:
Contact has been made with all of the appropriate industry representatives and a well-attended conference is expected.

Kenneth P. Maddox, Ph.D.
Principal Investigator

August 18, 1981
Project Status Report No. 5
Report Period: July 16, 1981 - August 15, 1981

CONTRACT TITLE AND NUMBER
Durability of Reflecting Surfaces Used in Solar Heliostats
DE-AC04-81AL16306
EES Project A-2916

CONTRACTOR NAME: Georgia Institute of Technology
Engineering Experiment Station
Technology Applications Laboratory
Atlanta, Georgia 30332

CONTRACT PERIOD: March 16, 1981 through September 16, 1981

1. Contract Objective: No Change.

2. Technical Approach Changes. No Change.

3. Contract Tasks:

   Task 4.1 - Mirror review - Preliminary contacts with industry and researchers were completed during the report period.

   Task 4.2 - Discussion paper - The paper was completed and released during the reporting period.

   Task 4.3 - Conference Planning - Planning and arrangements for the conference, including space, luncheons, and facilities, were completed during the reporting period.

   Task 4.4 - Conference - The project conference was held July 29-30, 1981 at Arlington, Virginia. The conference was well-attended, as nearly all invited industries were represented. The moderated forum proved to be productive in eliciting responses from the participants. The conference went as planned, and it is hoped that the results will be beneficial to the DOE Solar Thermal Program.

   Task 4.5 - Final Report - Documentation of the conference proceedings was begun during this reporting period.

4. Open Items:

   A no-cost extension to December 31, 1981 has been requested. This extension will enable follow-up tasks, identified at the workshop, to be performed. One such task is the characterization of mirrors used in European heliostats, as a continued effort on Task 4.1, mirror review. It appears that there are sufficient funds remaining in the contract. A request of foreign travel is also an open item as is authorization to pay for the conference space, luncheons, and coffee breaks.

5. Summary Assessment and Forecast:

   The conference was a success in terms of attendance and participation as well as technical content. Further work is now planned or under way to document the conference and follow-up several new areas which were identified during the conference.

Kenneth P. Maddox, Ph.D.
Principal Investigator

December 15, 1981
Project Status Report No. 6
Report Period: August 16, 1981 - September 15, 1981

CONTRACT TITLE AND NUMBER

Durability of Reflecting Surfaces Used in Solar Heliostats
DE-AC04-81AL16306
EES Project A-2916

CONTRACTOR NAME: Georgia Institute of Technology
Engineering Experiment Station
Technology Applications Laboratory
Atlanta, Georgia 30332

CONTRACT PERIOD: March 16, 1981 through December 31, 1981

1. Contract Objective: No Change.

2. Technical Approach Changes. No Change.

3. Contract Tasks:

Task 4.1--Mirror review--Preliminary contacts with industry and researchers were made prior to August. Follow-up contacts continued during the reporting period.

Task 4.2--Discussion paper--The discussion paper for the conference was completed and released in July.

Task 4.3--Conference planning--The conference planning was completed in July.

Task 4.4--Conference--The conference was held July 29-30, 1981 at Arlington, Virginia.

Task 4.5--Final Report--Work on the conference proceedings (final report) for the project began the first of August and continued during the reporting period.

4. Open Items:

A no-cost extension to December 31, 1981 has been granted.

5. Summary Assessment and Forecast:

Work continues on documenting the project conference and on follow-up work, such as characterizing the old French heliostat mirrors. A visit to France is planned by Tech personnel, in conjunction with another project, and efforts will be made to obtain a sample of an Odeillo mirror at that time.

Kenneth P. Maddox, Ph.D.
Principal Investigator

December 15, 1981
Project Status Report No. 7
Report Period: September 16, 1981 - October 15, 1981

CONTRACT TITLE AND NUMBER

Durability of Reflecting Surfaces Used in Solar Heliostats
DE-AC04-81AL16306
EES Project A-2916

CONTRACTOR NAME: Georgia Institute of Technology
Engineering Experiment Station
Technology Applications Laboratory
Atlanta, Georgia 30332

CONTRACT PERIOD: March 16, 1981 through December 31, 1981

1. Contract Objective: No Change.

2. Technical Approach Changes. No Change.

3. Contract Tasks:

Task 4.1--Mirror review--Follow-up contacts with London Laboratories continued during this reporting period. London has offered to become extensively involved in work directed towards the development of more durable mirrors, specifically through improvements in the backing paint. London has at its facility a research mirror production line which can be used to make test runs to simulate mirror production. These runs could be carefully controlled with the key independent parameters varied, including copper thickness, paint type, glass type, and others.

Task 4.2--Discussion paper--The discussion paper was completed and released in July 1981.

Task 4.3--Conference planning--The conference planning was completed in July 1981.

Task 4.4--Conference--The conference was held July 29-30, 1981 at Arlington, Virginia.

Task 4.5--Final Report--Work on the conference proceedings (final report) for the project continued during the reporting period.

4. Open Items: None.

5. Summary Assessment and Forecast:

Work continues on the preparation of the conference proceedings. Copies of the proceedings will be released during the next reporting period. Contacts with industry (such as London Labs), which could be helpful to the Department of Energy in the development of superior mirrors for heliostat applications, will continue.

Kenneth P. Maddox, Ph.D.
Principal Investigator

December 15, 1981
Project Status Report No. 8
Report Period: October 16, 1981 - November 15, 1981

CONTRACT TITLE AND NUMBER

Durability of Reflecting Surfaces Used in Solar Heliostats
DE-AC04-81AL16306
EES Project A-2916

CONTRACTOR NAME: Georgia Institute of Technology
Engineering Experiment Station
Technology Applications Laboratory
Atlanta, Georgia 30332

CONTRACT PERIOD: March 16, 1981 through December 31, 1981

1. Contract Objective: No Change.

2. Technical Approach Changes. No Change.

3. Contract Tasks:

   Task 4.1--Mirror review--Follow-up contacts with Sandia, SERI, and CNRS continued during this reporting period. Sandia was contacted and their efforts to develop a mirror backing paint development program (together with PPG Industries) were discussed. The test matrix program was reviewed with SERI, including the use of photomicrography as an evaluation criterion. A letter was received from Hitachi Energy Research Laboratory describing tests that had been run on mirrors for the IMW Nio plant. Laminated mirrors were selected for that facility. A request was made to CNRS (France) personnel for a sample of one of the mirrors used at Odeillo. M. Claude Royiere declined to provide a sample; he said he had already given one to Sandia Livermore for analysis some time ago and had heard no results.

   Task 4.2--Discussion paper--The discussion paper was completed and released in July 1981.

   Task 4.3--Conference planning--The conference planning was completed in July 1981.

   Task 4.4--Conference--The conference was held July 29-30, 1981 at Arlington, Virginia

   Task 4.5--Final Report--The conference proceedings were released during the reporting period.

4. Open Items: None

5. Summary Assessment and Forecast:

   The workshop proceedings were mailed, thereby completing this portion of the contract. Analysis of a sample of one of the Mont Louis mirrors, obtained by Mr. J. D. Walton of Georgia Tech, will proceed during the next reporting period.

Kenneth P. Maddox, Ph.D.
Principal Investigator

December 15, 1981
Project Status Report No. 9
Report Period: November 16, 1981 - December 31, 1981

CONTRACT TITLE AND NUMBER
Durability of Reflecting Surfaces Used in Solar Heliostats
DE-AC04-81AL16306
EES Project A-2916

CONTRACTOR NAME: Georgia Institute of Technology
Engineering Experiment Station
Technology Applications Laboratory
Atlanta, Georgia 30332

CONTRACT PERIOD: March 16, 1981 through December 31, 1981

1. Contract Objective: No Change.

2. Technical Approach Changes. No Change.

3. Contract Tasks:

Task 4.1--Mirror Review--Analysis of the Mont Louis mirror sample, in an effort to characterize it for use as a standard, was in progress during the reporting period. Attempts to photograph the edge of the sample, using a scanning electron microscope, have been unsuccessful in discerning the individual layers. A sample is now being mounted and polished in a metallurgical mount, however the polishing procedure is difficult because of the need to preserve the fragile interface between the hard glass and the (relatively) soft metallic layers.

Task 4.2--Discussion paper--The discussion paper was completed and released in July 1981.

Task 4.3--Conference planning--The conference planning was completed in July 1981.

Task 4.4--Conference--The conference was held July 29-30, 1981 at Arlington, Virginia

Task 4.5--Final Report--Work on the project final report was in progress during the reporting period.

4. Open Items: None

5. Summary Assessment and Forecast:

Composition of the final report is in progress and the report should be released by the contract termination date. Also the analysis of the Mont Louis sample, if successful, should be completed by that time.

Kenneth P. Maddox, Ph.D.
Principal Investigator

PROCEEDINGS

DURABILITY OF REFLECTING SURFACES USED IN SOLAR HELIOSTATS

A Workshop Held
July 29-30, 1981
Washington, D.C.

Sponsored by

U.S. Department of Energy
Division of Solar Thermal

Under Contract
DE-AC04-81AL16306
EES Project A-2916

Conducted by

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia
October, 1981

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Department of Energy
Washington, D.C. 20585

OCT 2 1 1981

Dr. Ken Maddox
Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Dear Dr. Maddox:

Reflecting surfaces are major elements of almost all solar thermal systems. The development of durable, high-performance mirrors is important to the progress of the solar thermal program and is a crucial part of establishing the technical feasibility of central receiver systems.

This publication is a summary of the papers presented and the discussions that occurred at the "Durability of Reflecting Surfaces Used in Solar Heliostats" workshop which was held in Washington, D.C. on July 28-29, 1981. Two issues framed the discussion at this workshop sponsored by the DOE Division of Solar Thermal Technology: (1) whether a durable 30-year mirror can be made in mass production; and (2) whether reliable tests exist to determine how mirrors will react to long-term outdoor exposure. The workshop was attended by those groups most familiar with mirror durability questions, namely, mirror manufacturers, glass makers, paint and chemical suppliers and testing laboratories.

The mirror durability workshop provided an unprecedented opportunity for direct communication between mirroring experts and the Department of Energy. The meetings provided a forum for industry opinion and resulted in informative and useful discussions. As a result of the workshop, the Division of Solar Thermal Technology has a much clearer understanding of the practical side of mirroring and mirror testing. The mirror industry appears capable of meeting the technical challenges posed by the Solar Thermal program and producing durable mirrors.

The existence of durable high-performance mirrors is an essential prerequisite to establishing the technical feasibility of central receiver systems and other solar thermal technologies. The information contained in this document will make an important contribution to the development of mirrors that are compatible with solar thermal applications.

Sincerely,

James E. Rannels, Chief
Research and Technology Branch
Division of Solar Thermal Technology

Preface

The workshop reported in this document was supported by the Department of Energy (DOE) under Contract No. DE-AC04-81AL16306 through the Albuquerque Operations Office. Technical monitor in that office is Jerry Zimmerman; J. Rannels and K. Cherian of DOE's Solar Thermal Technology Division have responsibility for the programs to which this project pertains. Their advice encouragement, and support have been invaluable in guiding the project team.

Team members for the project are Steve Bomar, David Keith, Kenneth Maddox, and J. D. Walton; and they are the authors of these proceedings. Dr. Bomar wrote Section 3.5 on Heliostats. Mr. Keith authored Sections 1 and 2 and Section 3.3 on Mirror Manufacture. He also prepared Section 4. Dr. Maddox is responsible for Section 3.4, and Mr. Walton is the author of Section 3.2 and of Section 3.6, Mirror Testing.

Correspondence

All correspondance with regard to these proceedings should reference EES Project A-2916 and be addressed to:

Director
Technology Applications Laboratory
Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

1.0 Introduction

A workshop was held in Washington D.C. on July 29-30, 1981 to gather manufacturers of products related to reflecting surfaces used in solar heliostats to discuss the reliability of solar mirrors. This workshop was sponsored by the U.S. Department of Energy and was conducted by the Engineering Experiment Station at the Georgia Institute of Technology. A discussion paper was released to the participants in advance of the workshop in order to stimulate and direct conversation. The goal of the workshop was to present a base of information and to develop industry positions on several key topics related to solar mirror durability.

The proceedings that follow are divided into several sections. First a brief summary of the workshop is presented. Next, the discussion paper, which served as a basis of the workshop deliberations, is included, with slight revisions and clarifications which resulted from the workshop. Finally, a transcript of the workshop discussions is provided, including names and addresses of the participants.

2.0 Workshop Summary

A workshop was held in Washington, D.C., on July 29-30, 1981 to discuss the reliability of solar mirrors from the manufacturers' viewpoints. The workshop was sponsored by the U.S. Department of Energy. Representatives of several major industry groups were in attendance:

Mirror Manufacturers

Binswanger Mirror Products
Buchmin Industries
Carolina Mirror
Falconer Glass
Gardner Mirror
Glaverbel (Belgium)

Glass Manufacturers

General Glass
Glaverbel
Schott America

Manufacturers of Coatings

Hilemn Laboratories

London Laboratories Ltd.

PPG Industries

Outdoor Exposure Testing Laboratory

DSET (Desert Sunshine Exposure Testing Laboratories)

Heliostat Manufacturers

ARCO Power Systems

Martin Marietta Aerospace

McDonnell Douglas Astronautics

Also attending the workshop were representatives of the Solar Thermal division DOE Washington and its consultants from Meridian Corp. and PRC. Personnel from the Engineering Experiment Station at Georgia Tech conducted the workshop.

2.1 Introductory Session

The workshop began with an overiew of the DOE Solar Thermal organization and programs, presented by Dr. Jim Rannels, to introduce the industry representatives to the status and direction of the central receiver power station program. Dr. Rannels stressed the importance of mirror reliability as a determining factor in assessing the feasibility of such projects, and expressed keen interest in the proceedings of the workshop.

The results of preliminary visits to the various manufacturers and solar installation sites were then reviewed by the Georgia Tech project staff. Mr. David Keith described the manufacturing processes used in the production of mirrors. Dr. Ken Maddox reviewed the materials and chemicals used in applying the metallic films, paint coatings, and laminate backing sheets to the mirror. Dr. Steve Bomar presented the history of heliostat application experience, focussing on observed mirror corrosion problems. Mr. J. D. Walton spoke on mirror testing and evaluation, describing the types of tests used and their apparent validity to the solar heliostat application. These sessions gave all participants a common base upon which to add the benefit of their own experience in the moderated forum sessions which followed.

2.2 Moderated Forum

An open forum was established for interaction between the industry representatives and was moderated by Dr. Ken Maddox of Georgia Tech. A paraphrased transcript of the discussion is included as part of this report (Section 4). A summary of the results of the forum, with regard to selected topics, follows.

2.2.1 Laminated Mirrors

It was the general opinion that laminated mirrors provide the highest degree of reliability in expected service lifetimes of 30 years. Laminated mirrors are essentially impervious to water, chemicals, or atmospheric contaminants attacking from the back. Edge corrosion may occur in some environments, although it is unlikely to be severe. Thermal cycling and physical stress are other factors that can lead to cracking damage, which may or may not degrade the mirror's optical figure significantly.

Workshop participants in the main associated heliostats featuring laminated mirrors with higher costs than those for heliostats employing painted back mirrors. There were reports from some attendees that the economics of heliostats incorporating laminated mirrors vary greatly with system design, and to the extent that structural properties of laminates can be usefully employed in heliostat design, there is opportunity to mitigate initially higher costs for the mirrors. It was agreed that the important economic choices involved the total heliostat systems rather than solely the mirror components, but generally the group indicated that mirror reliability gained through use of laminated mirrors was likely to entail added costs.

The intermediate coating and bonding agents used between the mirror and the backing sheet are areas that could merit further investigation. Polyvinyl butyril (PVB) is commonly used in laminated sheet glass and has been generally used in laminated mirrors with glass backing sheets. PVB is a hygroscopic material, and improper handling may lead to the ingestion of water which could interact with the mirror backing paint. Steel backing sheets have been attached by means of acrylic double-stick tape and silicone grease (slip-plane). These adhesives could also contain chemicals which might interact with the backing paint, so it seems that the development of a paint formulation intended for use in laminated mirrors could be worthwhile.

2.2.2 Painted-back Mirrors

There was general agreement that a painted-back mirror would be more desirable than a laminated mirror, if not only in terms of cost then in simplicity, ease of handling and compatibility with mirror production lines. The degree of confidence expressed in the reliability of the painted mirror was less than that for the laminated mirror, although it was felt that a new coating could be developed to improve the reliability.

Dissatisfaction was expressed with the design applications of mirrors in some of the heliostat designs. The mirrors are essentially designed for indoor domestic use, but (in certain heliostats) they have been exposed to sulfur-compound adhesives, foam glass backing with bubbles of hydrogen sulfide gas, or trapped standing water. These conditions represent applications in which the mirror is not being used as it was intended, and very severe degradation has occurred in some cases. In some instances, the mirror manufacturers were not aware of the final configuration or application of their products.

The development of a new paint coating for solar heliostats was an area receiving favorable response. Because indoor mirrors are often made in large stock sheets for subsequent cutting (postfabrication), the paint formula is one that will break cleanly along the glass cut line. The resulting formulation is pigment-rich and has poor water-resistance. In the case of heliostats, the postfabrication requirement is not necessary, so an entirely new paint compromise can be made to make the paint impermeable to water. One consideration in developing a paint for long-term outdoor exposure would be resistance to ultraviolet radiation degradation. Another important design goal is that the paint itself be free of residual contaminants, particularly sulfur and chlorine, which may be present as a result of pigment-extraction chemical processes. For greatest compatibility with American mirror lines, a single paint coat is desirable, although the development may lead to the conclusion that two coats are necessary.

The application of additional thicknesses of copper in the mirror backing is another alternative that appears to warrant testing. Presumably copper acts as a sacrificial buffer which must be penetrated before attack on the silver begins. If the copper thickness is increased, then the time and/or quantity of water or concentration of contaminants should also have to increase before the silver layer is reached. Today's galvanic methods of copper application results in loss of adhesion of the silver layer to the glass when thick copper layers are applied. However, a disproportionate copper solution has been developed which does not appear to lead to such a loss of adhesion. Should outdoor exposure testing correlate copper thickness to lifetime, such an increase in copper thickness could be a cost-effective means to greater reliability.

2.2.3 Testing

A good portion of the workshop forum was spent in deliberating testing, but no definite conclusions could be drawn. Presently there is no test nor battery of tests which has proven validity to the outdoor exposure application. At best, the tests are relative screening tools for making comparisons between two or more mirrors.

The industry standard is the salt spray test. In Belgium, this test is used to evaluate edge corrosion, but a humidity test is used to determine surface corrosion. Optimally, from the manufacturers standpoint, a short duration test would enable a bad lot of mirrors to be detected prior to shipment. Such a test does not now exist.

There was general agreement that a series of tests, in addition to salt spray, having the following parameters should be useful in evaluating mirrors for outdoor applications.

1. The presence of liquid water - perhaps through humidity and condensation cycles.
2. Thermal cycling - to simulate diurnal variations, perhaps in conjunction with (1).
3. Radiation - particularly in relation to paints, perhaps using back-illumination.
4. Materials compatibility - especially with regard to any adhesives contemplated in the heliostat design.

Combinations of these parameters, particularly 1, 2, and 3 should be considered in order to identify any possible synergistic effects. The correlation of the test results to actual long term exposure conditions will only be made by real time experience, therefore the development of a truly valid test will take many years. One problem is that an actual application may be highly correlated to site-specific microenvironments.

An important consideration in any testing program is data handling, including documentation and dissemination of results. The description of the mirror, how it was made, and how it was tested all need to be completely documented, and considered in the analysis. Following the tests, or as they proceed in the case of long-term exposure, the results need to be disseminated in an organized program. In some cases, results have not been made available to the manufacturers who supplied mirror samples to the testing labs.

2.2.4 Old Mirrors

It was generally agreed that better data are needed regarding the manufacture of old mirrors used in outdoor applications. In particular, the mirrors used at the two French installations, Mont Louis and Odeillo, should be analyzed, if possible, to determine the formulations of the paint coatings used and the thicknesses of the silver and copper films. This would provide a baseline, with a known degree of success in outdoor applications, against which modern mirrors could be compared.

2.2.5 Glass

The point was raised that the freshness of the glass influences the mirror quality. This had not been observed by the U.S. mirror manufacturers, who purchase glass from the glass manufacturers. In Japan and Europe, the industries are vertically integrated so that the best glass can be reserved for mirroring and it can be silvered soon after it is crated. U.S. manufacturers have a consent agreement with the government not to vertically integrate, so the mirror manufacturers have little or no control over the glass.

Glass cleaning has changed over the years. Formerly, the glass was blocked; that is, felt pads under heavy blocks were used with red rouge as a polishing agent. This may have prepared the surface better than today's scrubbing brushes, but the blocking machines have been abandoned because of problems with contaminants becoming imbedded in the felt pads.

Float glass has been specified and used in all heliostats but the iron content of the glass reduces its transmissivity. This has led to the specification of very thin (down to 0.6 mm) glass, in some cases, for the mirrors. This thin glass is difficult to clean before silvering, as it tends to move under the action of the polishing brushes. One alternative is to use very low-iron sheet glass. This glass has higher transmissivity, so very thin lites are not required to achieve the same overall mirror reflectivity.

2.2.6 Solar Market and Designs

At present, the solar market for heliostat glass is made up of just a few orders, totalling about 1 million square feet. In order to represent a sizable market for which mirror manufacturers could justify substantial research and development investments, the market must be much larger, perhaps 100 million square feet per year.

One possible design trade-off discussed is the tailoring of the design to suit the market. For example, if the heliostat is to be mounted in the Southwest desert region, perhaps water resistance is not a large problem and present designs may be an overkill. However if the heliostats are to be placed in Florida or the Caribbean, greater moisture protection may be required. This tailoring could reduce overall system costs, making the solar thermal power stations more economically attractive.

2.2.7 Design Interaction

It was recommended by several of the mirror manufacturers that they be consulted during the heliostat design phase. There was some feeling that at least some of the problems encountered could have been avoided if the heliostat designers had a better understanding of mirrors (for example, the use of hydrogen sulfide in foam glass mirror backing structures). The reliability of the reflecting surface depends not only on the mirror itself but also on the methods used to mount it. Questions such as materials compatibility with adhesives should be potential topics for discussion between the heliostat manufacturers and their mirror suppliers.

2.2.8 Workshop Overview

The reliability of heliostat reflecting surfaces has been a subject of concern since corrosion began occurring in field installations. In order for solar thermal power installations to be technically and economically competitive with fossil and nuclear plants, the reflecting surfaces must be durable enough to approach a 30-year lifetime.

The workshop "Durability of Reflecting Surfaces Used in Solar Heliostats;" held July 29-30, 1981 established an important dialog between the U.S. Department of Energy and industry. The entire spectrum of industries which produces for the solar heliostat market was well represented, including glass manufacturers, painted-back and laminated mirror manufacturers, metallic film and chemical solution manufacturers, backing paint manufacturers, heliostat system manufacturers, and testing laboratories. The workshop will have been a success if the interchange which was established and the interactive efforts which may follow as a result of this dialog lead to the development of a mirror better suited to the environment in which heliostats must perform.

3.0 Discussion Paper

3.1 Preface

The discussion paper presented here as Section 3 of the workshop proceedings was originally a preliminary report based on personal, face-to-face contacts with members of the U.S. mirroring industry, some overseas companies, heliostat manufacturers and other solar mirror users, and test facility operators. Its purpose was to stimulate exchanges of experience and ideas on the steps necessary to consistently supply mirrors that can endure without serious degradation for 20 to 30 years of outdoor exposure. The discussion paper was distributed in advance to attendees of the workshop held July 29 and 30, 1981, in Washington, D.C. It was used in preparation for that workshop and formed the background for summary presentations during the first session. Some changes have been incorporated as a consequence of comments and suggestions by workshop participants.

Special appreciation is extended to the representatives of the following companies for their time and effort spent in meeting with the project staff and in freely sharing their extensive experience concerning mirror reliability:

Acurex Corporation
AMN Spa (Italy)
ARCO Ventures Inc.
Binswanger Mirror Products
Buchmin Industries
Carolina Mirror Corporation
CETHEL (France)
Desert Sunshine Exposure Testing Laboratories
Falconer Glass Industries
Gardner Mirror Corporation
Glaverbel Ltd. (Belgium)
Hilemn Laboratories
Hoyne Industries
Libbey Owens Ford
London Laboratories Ltd.
Martin Marietta Aerospace
McDonnell Douglas Astronautics
PPG Industries

3.2 Introduction

A principal objective of the DOE Solar Thermal Program is to develop solar thermal power systems utilizing heliostats with reflective surfaces that will provide a service life of 20 to 30 years. Based on current technology and knowledge of materials, the most promising materials with the potential of meeting this life expectancy are second surface, silvered glass mirrors; and presently all the heliostats being used in existing solar thermal power systems and being evaluated as second generation prototypes use silvered glass mirrors. The issue of mirror durability is thus a question of how well the glass/silver system will last in outdoor environments.

Historically, the U.S. mirror industry has produced mirrors for use in indoor applications. For these applications the mirrors are protected from direct exposure to such severe weather conditions as rain, snow, sleet, sunshine, and extreme variations in temperature. Therefore, the industrial wet process for producing second surface silver mirrors, including the backing paint, was developed and optimized to provide a high quality mirror for indoor use at a competitive price. M. A. Lind, et al., have published an excellent review of the development of the current state of technology as practiced by the mirror industry (1).

It is instructive to consider those factors that limit mirror lifetime. The single component of a silvered glass mirror that is most crucial to its performance as a reflector and at the same time the most susceptible to corrosion when exposed to the atmosphere is the reflective silver film itself. Since corrosion of the silver directly reduces the performance of the reflective surface, it is imperative that the silver be protected from those environmental elements which produce corrosion in silver. It is, of course, to protect the silver that the copper layer is used in the mirroring process. The copper serves to protect the silver either directly as a barrier to corrosive elements or as a sacrifical layer and to provide better adhesion between the silver and paint layers. To provide still further protection a mirror paint or varnish is used as a final coating over the copper.

In addition to chemical corrosion, adverse mechanical, or thermal conditions can act to degrade silvered mirrors through such mechanisms as bond failure between the silver and the glass, agglomeration of the silver, or interaction between the silver and the copper. Also, when mirrors are put into service, other materials such as adhesives, backing materials, frames and other supporting structures can reduce mirror lifetime by degrading the protective coatings through abrasion, reaction or penetration leading to deterioration of the silver. Therefore, compatibility of the mirror components with other materials and structures is important in determining the lifetime of a mirror in its final configuration. Also important is the indirect influence that outdoor exposure conditions can have on the ultimate performance of the finished mirror. For example, mechanical stresses can be imposed on the mirror as a result of differential thermal expansion between the mirror glass and a supporting or containment structure. In the presence of water, galvanic corrosion of the reflective film can result if an electrically conductive path is provided between associated exposed metal components and the reflective film of the mirror.

Hampton and Lind have identified the most commonly used stress parameters which may effect the ultimate performance of a given material; these are temperature, moisture and UV radiation (2). Other parameters which also may be important are ozone, sulfates and other atmospheric pollutants. In addition, other factors such as biological attack and the effects of abrasion and mechanical stress also can degrade certain materials. They also pointed out that these stress factors may degrade the material alone or they may act in combination with other parameters to change the rate character of the degradation.

From this brief discussion of a few of the environmental, material, and construction parameters which can influence the lifetime of mirrors exposed to outdoor conditions, it is clear that a multiplicity of factors can interact in a variety of ways to contribute to mirror degradation. Thus it is not surprising that there is no known accelerated test capable of predicting mirror lifetime for heliostat applications. However, given the excellent weatherability of glass, if those factors which are most important in determining the durability and performance of the reflective silver film can be identified, and the end-use hardware designed in such a way as to optimize these factors, then it should be possible to produce a mirror with a 20-30 year life expectancy using existing technology and materials.

Since no single test currently predicts mirror service lifetime under outdoor conditions, and since all factors which contribute to mirror degradation cannot be evaluated simultaneously, it is important to concentrate on those parameters which are the most fundamental to the behavior of the basic mirror element and over which significant process parameters can be controlled. For second surface glass mirrors this suggests that tests should concentrate on standard production type silvered mirrors to optimize service lifetime in outdoor environments.

Mirror manufacturers who were contacted during the course of this project were in agreement that protecting the silver surface from corrosive elements was essential to a long service life. Water is particularly detrimental, and mounting or supporting techniques should be used which minimize the possibility for trapping water behind the mirror and should also provide means for free circulation of air in the event that water reaches that surface.

It should be pointed out that present mirror backing paints were designed to be used on a stock mirror product which would later be cut to custom sizes and shapes. This paint was formulated to provide the property of breaking cleanly and in exact conformity with the cut glass edge. A paint high in extender pigments was found to provide this particular characteristic. Unfortunately, such paints are relatively porous and thus are not suited for outdoor exposure, particularly in the presence of accumulated water. For heliostat applications it would be expected that glass would be pre-cut to the proper size before being silvered. Therefore, the backing paint need not have the physical characteristics required for stock mirrors. Thus a paint optimized for outdoor exposure might be used directly over the copper. Alternatively a second, weather resistant paint can be used directly over the currently used backing paint to improve weatherability.

Regardless of what type of final protective coating is used, careful attention must be given to designing supporting structures which will minimize potential detrimental synergistic effects. For example, when developing heliostats for the solar furnaces at Mont Louis and Odeillo in France, Professor Trombe insisted that mirrors be supported in such a way that any motion between the frame/support and the mirror element resulting from differential thermal expansion or mechanical movement would be free to take place without distorting the mirror or changing its alignment on the heliostat. He avoided the use of adhesives, minimized the number of contact points between the mirrors and the support frame and provided for complete air circulation behind the mirrors. During the operation of both of these systems, mirror degradation could be traced to the deterioration of the backing paint. In the case of the Mont Louis solar furnace an aluminum backing paint was used. This paint provided sufficient protection of the silver from the corrosive effects of the weather so that the facility remained operational for more than 20 years with only minor mirror degradation. A single mirror element about 15 x 16 cm x 2 mm thick taken from the site in 1973, showed only a limited number of isolated spots where the silver film had corroded. The three largest spots were only 2 mm in diameter and most of the others were less than one millimeter in diameter. At the larger spots, the backing paint was completely gone, exposing clear glass. Eight of these spots corresponded to points where the ends of mounting posts contacted the back of the mirror. Visual examination revealed that less than 1% of the surface showed visible degradation after more than 20 years exposure to the harsh outdoor environment in the eastern Pyrenees of France, and the solar reflectance of this mirror measured with a pyroheliometer was 90%.

In contrast to the Mont Louis experience, the heliostat mirrors at Odeillo (about 5 miles west of Mont Louis) exhibited extensive silver degradation in about 5 years. In this case a conventional mirror backing paint was used which was dark, grayish black in color. At certain locations, along the outside edge of heliostat, mirrors degraded more rapidly than those near the center. This appeared to be due to the fact that the backs of these mirrors were illuminated by heliostats behind them. These mirrors showed significant degradation in less than 5 years and had to be replaced. It was felt that the poor weathering resistance of this paint together with its relatively dark color (high solar absorptivity) were responsible for this extremely short lifetime. By 1978 all of the heliostat mirrors (11,340 each 50-50 cm) had to be removed, stripped, resilvered and remounted, only nine years after the heliostats were installed. In both of these cases the service life of the mirrors appeared to be determined by the degree of protection provided the silver by the backing paint.

From this discussion it can be inferred that there are several problems to designing a reliable 30-year mirror. However, based on some successful experience with outdoor applications, and much more experience with silvered glass mirrors generally, the mirroring industry is confident that engineering solutions can be developed quickly to meet the increasing demands of experimental and commercial solar installations.

The chapters which follow develop in more detail the factors that influence mirror durability and the issues that must be addressed to achieve successful and reliable engineering solutions. A brief review of mirror manufacturing in the next section examines how mirrors are currently made and raises several technical and practical issues. Section 3.4 on mirrror coatings contains suggested alternatives for heliostat applications to the standard mirror coating sequence and gives initial estimates of some engineering and economic compromises that must be considered.

Section 3.5 is a review of experience to date with mirrors in heliostats; it is a broad but not exhaustive survey of several alternative mounting and protective systems for outdoor mirror use. The final Section 3.6 deals with mirror testing and the categories of useful testing procedures that might identify long-lived mirrors and mirror components.

3.3 Mirror Manufacturing

3.3.1 Production Sequence

Today's mirror manufacturing process is a continuous operation. Handling of the glass is achieved by a conveyor line, usually with motorized rollers. This line automatically feeds the glass through several stations for deposition of the metallic films and coatings.

Glass is loaded from crates, as received from the glass company, onto the conveyor line. This is usually performed manually, although some manufacturers have automated (vacuum-cup) material handling equipment which may be used for handling large lites. Experience with such equipment has often been less than satisfactory. In silvering float glass, the untinned, or air, side of the glass is always silvered, to ensure good film adhesion. Wherever possible, glass is received paper-packed from the glass factory in order to avoid cleaning problems associated with powder-packed glass.

Upon loading onto the line, the first step in the mirroring process is glass cleaning. Scrubbing units used by most manufacturers consist of several parallel rows of rotating circular brushes. These brushes scrub the surface with a cleaning agent, which is usually a slurry of cerium oxide in a tap water medium. The brushes not only rotate but also oscillate in the lateral direction across the glass as it passes transversely, to assure total cleaning. In the past, glass was usually polished by "blocking." In this case, felt pads attached to heavy blocks were moved across the glass, again together with an abrasive slurrry. Most manufacturers have abandoned this method, primarily because contaminant particles can become imbedded in the felt pad and scratch the glass.

After scrubbing, the slurry is rinsed off the surface of the glass with water nozzles. Deionized water is used in this and all subsequent rinsing operations to prevent contamination of the coating solutions.

Before silvering, the glass is sprayed with a sensitizing solution, usually stannous chloride ($SnCl_2$). The sensitizer acts to increase the silver deposition rate and improve the adhesion of the silver to the glass. The solution is rinsed from the glass following application, again using deionized water.

The silvering solutions are next sprayed onto the sensitized glass. Three solutions (silver, caustic, and reducer) are applied by three separate spray nozzles. When the solutions mix on the glass surface, pure silver molecules are precipitated out of the silver solution and are deposited on the glass surface. The three spray nozzles traverse laterally across the glass surface, and multiple sets of nozzles are used longitudinally to increase the silver layer thickness and to insure multiple spraying to each spot for uniformity. The silver reaction occurs very quickly. Following silvering, the surface is rinsed to terminate the reaction, which has by this point built up a layer of the desired thickness, and to remove residual chemicals which may interfere with the deposition of the next layer (copper).

The copper application is carried out with two spray nozzles, which apply the copper solution and a slurry of iron filings, which acts as a reducing agent. A coating of iron slurry is first applied without copper to ensure that sufficient reaction sites exist before the copper solution and additional iron slurry are sprayed. As in the case of the silver solutions, mutliple sets of spray mechanisms are used to achieve a uniform coating of the prescribed thickness. Residual solutions are thoroughly rinsed, following the reaction, using deionized water.

An air jet drier, or "air knife," is used to blow the rinsing water off the copper surface. This removes all standing water or droplets. Next the mirror is heated using infrared lamps to partially cure the metallic films. The lamps are placed under the mirror, so that the radiation is directed to the glass side. This tends to heat the mirror evenly and to drive water from the silver/glass interface outward.

Following the metallic film drying, paint is applied to the copper backing. The most common method of application is known as a "curtain coater." This applicator sets up a thin sheet of paint which falls across the conveyor line. A reservoir with a knife edge drain at the top is continuously filled with paint, and excess paint collected below is filtered and recirculated. The mirror is accellerated by power rollers to a speed much greater than the rest of the line before entry into the paint curtain (about 180 ft/min as compared to typical line speeds of 5-10 ft/min). This assures the proper thickness of paint coating.

Following painting, the mirror is slowed to the normal line speed and enters a vent hood. Here air is blown across the mirror and paint solvents are removed, the fumes being exhausted. Heated air is used by some manufacturers to achieve "preheat" before the mirror enters the paint dryer.

An infrared dryer section is used to dry the mirror paint. The section is fairly long, and mirrors require several minutes to traverse it, achieving temperatures on the order of 250°F.

Following drying, several cleaning or wash-off steps may be used. Chemical solutions may be sprayed on the glass side to remove any metal film that may have been deposited by overspray. The top and bottom surfaces may be cleaned by water spray or rotating brushes, following which an air knife blower is used to dry the surface.

Manual inspection follows the production sequence, with pinhole or blemish defects being criteria for rejection.

Upon removal from the line, the mirrors are usually repacked into the original glass shipping crates. This handling is generally done manually, although automatic equipment is available for large mirrors. Small felt pad spacers are used between the mirrors in packing to prevent shipping damage.

3.3.2 Lamination

In the case of laminated mirrors, the completed second surface glass mirror is bonded to a backing sheet. This may be another sheet of glass, or a sheet of metal. Even plywood and masonite have been used as backing sheets. Lamination to glass is achieved by the same process as is used in the manufacture of laminated window glass, for example as used in automobiles.

The laminated glass process takes the completed mirror and bonds it to another sheet of glass, using an intermediate bonding material. The mirror is placed on a conveyor line, glass side down. Another plain glass sheet, of the same size (although perhaps different thickness), is then placed on the line. These sheets then pass into the environmentally-controlled lay-up room. Here a sheet of the bonding material is manually layed over the mirror back, and the glass backing sheet is placed on the top (also manually).

The customary bonding material used is polyvinyl butyril (PVB), as is used in automotive laminated glass. This material is hygroscopic, and must be stored under controlled conditions of temperature and humidity, hence the requirement for the dehumidified, air conditioned room.

Upon leaving the lay-up room, the laminate is run through an initial roller which presses the sandwich together to achieve a preliminary bond. The flash PVB is cut away manually, using a razor knife. The sandwich then passes through a heated high pressure roller to achieve a better bond.

After being set by the rollers, the laminated mirrors are stacked onto carts. The mirrors are loaded in a near-vertical position, with small spacers between them. Once full, the cart is wheeled into an autoclave for final curing. Upon removal from the autoclave, the laminated mirror is complete, and ready for shipment.

One alternative to the glass laminate which is used by at least one mirror manufacturer is a steel backing sheet. This sheet is attached to the mirror backing using an intermediate acrylic peel-off adhesive. This adhesive sheet is similar to a double-stick, two-sided tape. Some problems with delamination have occurred in applications in which the subsequent mirror is formed for use in parabolic, line-focus, troughs. As a result, experimentation with other adhesives is under way.

3.3.3 Quality Control

During the course of the study, plant visits were made to six different mirror manufacturers in order to observe their operations and to solicit experience and opinions on mirror durability in outdoor and other active environments. Based on these visits, a general concensus has been drawn, although not all manufacturers mentioned each of the same areas. The important issues in how to make a reliable mirror fall under several general categories related to the manufacturing process.

3.3.3.1 Glass

The glass must be thoroughly cleaned before silvering. Generally, the industry views powder-packed glass as undesirable because of the likelihood of stains occurring should the glass crate get wet. These stains are quite difficult to remove. Some degree of Lucor powder is usually present in glass received in paper-packed form, indicating some use of powder at the glass plant. The size of glass is a consideration as well. The use of very thin glass makes cleaning difficult, as the glass moves laterally under the abrasive brushes. The specification of large lites of glass, such as used in the Barstow project, introduces increased costs due to a higher percentage of breakage, the inherent safety hazard of handling large lites, and diversion of the mirror line from normal operations.

3.3.3.2 Silvering

The application of the stannous chloride (tin) sensitizer is particularly important to ensure good adhesion of the silver film to the glass. The temperatures of the glass and the solutions influence the rate of reaction, which proceeds faster as temperature increases. Water quality is particularly critical to the process, and deionized water of high purity is preferred. The thickness of the silver layer, for reflectivity and opacity purposes, need not be much heavier than 60 mg/sq. ft. However, to ensure uniformity of coating, a layer 15-40% heavier than this is usually specified. For reliability, especially in the solar heliostat application, an even heavier layer may be of benefit. Some overspray of silver usually occurs onto the edges of the glass. At least one heliostat mirror specification requires the overspray to be removed. This was done with steel wool and is thought to be an unwarranted operation, as the backing paint may be scratched in doing so.

3.3.3.3 Copper

The layer of copper over the silver film is required to ensure adhesion of the paint and presumably to act as a sacrificial buffer to delay corrosion of the silver. A layer of copper which is too thick can cause the silver to delaminate from the glass surface, however. A new type of copper (disproportionate) solution may permit thicker layers to be deposited.

3.3.3.4 Paint

The most critical factor influencing the reliability of a mirror is the backing paint. The type of paint selected will determine how vulnerable the metal films are to attack by moisture, ultraviolet radiation, and abrasion. The standard mirror backing paints are relatively brittle and porous, since they were developed mainly to permit mirror cutting after fabrication. Therefore, a different formulation may be better suited for solar heliostats. The system used for the Solar One (Barstow) pilot plant, consisting of an acrylic top coat, is an example of such a formulation. The method of application of the paint influences the uniformity and thickness of the coating, with curtain coating preferred for a consistent finish. Filtering of the recirculating paint in the curtain coater is necessary to prevent the introduction of contaminants that may provide sites for corrosion. The paint drying process is quite critical. Sufficient preheating of the mirror is required so that curing can begin to occur adjacent to the copper layer. After application of the paint, the curing process must be carried out over a long enough time and with sufficient heat to ensure that all detectable solvent has been driven off. The problem of solvent retention is especially critical if the mirror is to be laminated.

3.3.3.5 Installation and Further Treatment

The eventual application in which the mirror is used can largely determine its reliability. Extreme care must be taken in selecting adhesives and bonding techniques to prevent chemical attack and abrasion. The mirror can perform well if the backing is allowed to dry out and not be exposed to standing water. In the short term, until better paints and mounting designs are developed, a laminated mirror appears to offer the greatest reliability. However, the laminated mirror has high production costs and weight, and is susceptible to fairly high rejection rates in initial quality control inspections because of the occurrence of bubbles from solvent retention or trapped air. Also, care must be taken in selecting the combination of mirror backing paint and laminating adhesive material for compatibility. Sealing the edges of the laminated mirror is probably not necessary, as the laminating adhesive does this to a certain extent.

3.3.3.6 Testing

The industry standard reliability test is the DD-M-00411b (federal) salt spray test of 95^{o}F, 100% humidity, 20% salt by weight, 150 hours minimum duration. This test is not thought to have a particularly good correlation to outdoor exposure, but it does provide a basis of comparison from batch to batch as a quality control device. The Northern Michigan test, developed for automotive mirrors, may also be useful for certain applications, as it exposes the mirror to extreme conditions of both hot and cold temperatures, humidity, salt spray, and thermal cycling. In-plant quality control tests include titration tests to determine the weight of the copper and silver layers being applied as well as adhesion tests (Scotch tape) to ensure good bonding to the glass.

3.3.4 Failure Mechanisms

The primary pathway of mirror failure is through the backing paint. As such, the sustained presence of water on the backing paint is the single most damaging factor. The water can seep through the relatively porous paint layer and serve to dissolve, agglomerate, or otherwise attack the copper and silver paint films. Handling of the mirror is also another potentially aggravating circumstance, as perspiration salts, other chemicals, or greases can attack through the paint layer. Airborne pollutants and "acid rain" are factors that can damage the paint layer. It is also well known that ultraviolet radiation can rapidly deteriorate a paint finish.

3.3.5 Industrial Considerations

The mirror industry is geared to the fabrication of mirrors for indoor applications, particularly for the building construction and furnishings applications. In this particular market, price differentials of just a few cents per square foot can make or break a manufacturer. For example, the market is so large, that an order such as Solar One (nearly 1 million square feet) represents substantially less than 10% of a typical manufacturer's annual production. The manufacturers are generally interested in the potential solar market but are somewhat disappointed that it has not grown at the rate DOE, and its affiliated agencies, have been claiming for the past several years. As a result, most manufacturers are reluctant to do much in-house research and development for solar, and many do not bid what they consider to be small solar jobs. Furthermore, the manufacturers do not feel that the benefit of their expertise has been utilized in developing the solar mirror specifications. Moreover, those manufacturers that have developed special products or processes are concerned that their R & D costs will not be recovered if the proprietary design is included in a specification for open bidding which is subsequently awarded to the lowest bidder. The general position of the manufacturers, however, is that a high-reliability mirror with a 20-30 years service life can be developed for solar applications, especially if the once-promised market is realized, and the manufacturers are excited about the potential to address that market.

3.4. Coatings and Backings

3.4.1 Introduction

The manufacture of modern glass/silver mirrors includes a series of engineering compromises designed to meet demands from today's major market: indoor utility and decorative installations. The coatings currently used in mirrors and the methods used to apply them demonstrate well-engineered attempts to produce high quality mirrors and to maintain low costs. High quality for the major market of indoor applications is defined in aesthetic terms: a pleasing, (generally) optically flat image without noticeable flaws that will last indoors for extended periods of time. Economic factors require use of modern production techniques: automated lines, large volume, postfabrication, efficient use of production (including pieces from larger flawed or broken sheets), high productivity from personnel and capital equipment. Engineering efforts to achieve these cost and quality goals have resulted in an active, highly competitive market characterized by widespread demand and general satisfaction with indoor products.

Solar applications of glass/silver mirrors carry different criteria from those for inside applications. For example, total reflectivity of solar mirrors is a high priority, while aesthetic considerations are minimal. Indeed, solar mirrors are often stressed to focus incoming radiation to a target area, producing an image that is far different from the optically flat one generally required of standard mirrors. Durability is a major criterion for solar mirrors, since replacement of mirrors in major portions of a reflector field entails large costs that adversely affect economic viability. The lifetime (vis-a-vis initial) cost can be much more important for solar mirrors than for indoor uses. A third set of considerations arises from the part solar mirrors play in overall systems. For instance, mirror designs directly impact total weight, which in turn influences the design of support structures and their operation. The mirror is a component of a large interactive system and as such must meet different design objectives than those expected from mirrors in normal indoor applications.

Obviously, the outdoor environment is different from that of interiors where mirrors are now commonly used. Moisture and airborne pollutants vary, as do temperature conditions, the incidence of sunlight, stresses from wind loadings and mechanical operations, and near-by sources of contaminants. These factors affect how mirrors will have to perform in successful solar applications.

According to representatives of the mirror industry, new criteria for mirror performance and different environmental stresses may indicate the need for new thinking on the set of compromises designed into today's mirror coatings. The coatings and coating techniques developed for the mass market may require modification for solar uses. In fact, some examples of such modification already exist in the laminated mirrors installed in the U.S. and overseas and in new coating paints, double coats, and altered formulations currently being investigated. Further changes may also be warranted.

The following discussion reviews coating designs now employed by the mirror industry and notes some of the areas where apparent trade-offs occur. It is based on results from discussions with the mirroring industry, including mirror manufacturers, chemical suppliers, and paint suppliers.

3.4.2 Background: Standard Coatings on Modern Mirrors

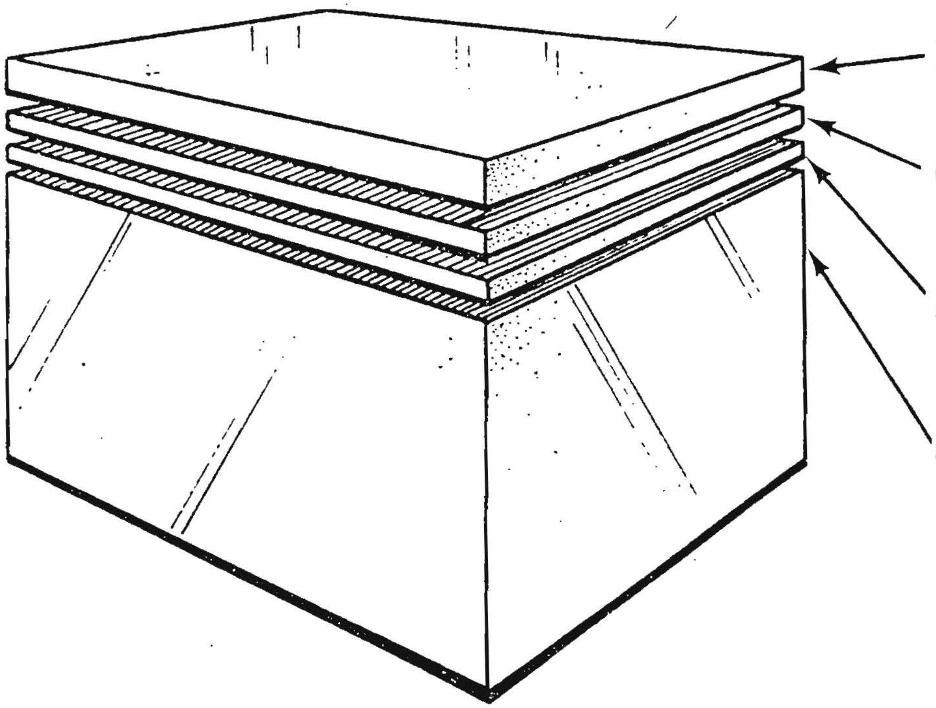
Conventional production mirrors in the U.S. are made with three successive coatings on glass (Figure 3.4.1). The first layer is silver, overlaid by copper, and then finished with a backing paint. The silver layer provides reflectivity; while the copper protects the silver layer in three possible ways: galvanic sacrifice, stress relief, and better bonding to the backing paint. The paint coat protects both copper and silver from abrasion and from contamination and exposure to the environment.

The silver layer is laid about 60 to 90 mg/ft^2, roughly 600 to 900 Å thick. A nominal value of 70 mg/ft^2 is generally thought to be sufficient to assure uniform reflectivity by allowing for variation in the coating thickness. The copper layer is approximately one-third the silver one, 15 to 30 mg/ft^2, generally with a margin that assures adequate thickness over all areas of the silver coat. Paint is applied at six to 10 g/ft^2.

3.4.3 Alternatives for Solar Mirrors

Alternatives to the standard coatings include three types: varying the thickness of existing coatings, substituting for one or more of the coatings, and adding backing or backing coats.

Increases in the thicknesses of metal and paint layers are thought by some industry representatives to provide greater protection against degradation of the reflective silver layer. Substitute materials also may offer enhanced resistance to



MATERIAL	QUANTITY (EST. TYPICAL VALUE)	
PAINT	6-10 g/ft²	∽0.001″
COPPER	25 mg/ft²	∽300 Å
SILVER	70 mg/ft²	∽700 Å
GLASS	THICKNESS	> 0.060″

Figure 3.4.1. Schematic of a Typical Glass/Silver, Second-Surface Mirror

<u>Source:</u> Lind, M. A. et al, "Heliostat Mirror Survey and Analysis," PNL-3149, Battelle, Pacific Northwest Laboratory, September 1979.

corrosion, and additional backing is still another method of excluding moisture and contamination that can result in mirror degradation.

The silver coatings of today's U.S. mirrors have as little as one-third the thickness of older mirrors and of some European products. Current silver thickness is largely a compromise with cost. Although the amount of silver in a 70 mg/ft^2 coating (assuming silver cost of $9/troy oz.) represents only about 4¢/ft^2, the relatively high price of silver and the highly competitive market tend to reduce silver use to an adequate minimum.

There are mixed opinions within the industry concerning the value of thick silver coatings. Some members believe that thicker silver produces better mirrors, providing more resistance to manufacturing flaws and to corrosive attack. Others have pointed out that reliance on thicker silver to retard degradation is unlikely to result in significant improvements in lifetime, since once corrosion begins it is a relatively rapidly progressing phenomenon. According to this thinking, thicker silver by itself does not add significantly to mirror lifetime.

A second issue with regard to the silver coating is its adhesion to glass. Several failure mechanisms apparently feature irregular bonding between silver and glass. The sensitization step is designed to reduce glass-silver separation and seems generally to work quite well. However, voids and silver islands still indicate that bonding is less than completely uniform. Alternative sensitization methods have been suggested, and one substitute has been examined (3), but to date no process generally accepted as better than the standard sensitization method has been found.

In the copper coating, the thickness of the copper layer may offer increased inhibition to mirror degradation. Thick copper might be expected to improve mirror lifetime, especially if it acted sacrifically and was thick enough to form a water barrier. Copper is much less expensive than silver, and its cost per se does not appear to present an inhibition to applications thicker than the present 15-30 mg/ft^2. If the copper layer could be laid thickly and avoid negative effects on silver, it might produce advantages in mirror lifetime.

However, thicker applications of copper using galvanic wet chemistry lead to damage to the silver. The thick galvanic copper is reported by industry personnel to lift silver from the glass, thereby degrading the mirror. This reaction is thought to be due to low pH (acidic attack) and the evolution of hydrogen atoms forming gaseous hydrogen at the interface.

Two processes other than the galvanic process are capable of applying a thick, stable copper layer. Electrolytic deposition is an old method that permits the build-up of copper to almost any desired thickness, and it might be applicable to special mirror applications. However, it is not readily compatible with modern mirroring lines, a disadvantage implying significantly higher costs and possibly limiting its utility.

A second method is disproportionate copper, a wet process that is compatible with standard mirroring techniques. The disproportionate copper process operates at pH of either 3-4 or 6-7, considerably higher than galvanic copper (typically pH less than 1.0). Copper layers of 700 mg/ft^2, 35 times standard thicknesses, have been deposited, and early results indicate improved protection of silver. A layer of 200 mg/ft^2 is also expected to yield good protection, though it has not yet been tested. One disadvantage to the process is deposition efficiency of only 10 to 12 percent, which requires copper recovery to be environmentally viable. The economics of the process with copper recovery are open to question at the present time.

Evaluations of substitute metal layers to protect the reflective silver layer are being conducted. For example, chrome forms a protective oxide resistant to water and to corrosive attack and is being investigated as a possible substitute for copper. Alternatively, it might be used as a third coat over copper and silver. Nickel is another metal mentioned for the same application. The advantages of such impermeable coatings are clear, but it has not yet been shown whether chrome or nickel or any similar material is compatible with the other coatings of the mirror system. Introduction of a new metal coating appears to require further investigative steps; this remains a potentially attractive but not yet thoroughly examined option.

While underlying layers offer opportunities for possible improvement in mirror durability, the paint layer in standard mirrors is most widely perceived as critical to longer lifetimes. Paint backing for standard mirrors has been developed for indoor applications and to suit the needs of modern fabrication techniques. It is rich in pigment and extenders such as talc, clay, and silicates; and it is "vehicle starved." The resulting brittleness allows cutting and other fabrication from stock sheet but also provides only modest resistance to water penetration, a factor that is thought to be primary in outdoor mirror failures (4-6).

A paint substitute exclusively for heliostat mirror applications could be developed on a very different basis. Heliostat glass to date has not been cut following mirror manufacture, and so the fabrication properties (brittleness) of current formulations are not necessary. Rather, requirements for a new backing paint for solar reflectors would include compatibility and bonding to the underlying copper layer, resistance to moisture and corrosive attack, longevity, and compatability with adhesive or other mounting systems that might be used in a heliostat. The series of engineering compromises specified for such paint would likely lead to an entirely different product. As an example, the Barstow top-coat is based on an automotive refinishing paint. Unlike normal mirror paint, it is low in pigment, glossy, with good water resistance and the promise of long lifetime. Modifications of industrial paints might provide still better results, as these paints are designed to last 20 years and more in highly active environments.

Paint for heliostat mirrors must also have properties that enable it to form part of the heliostat system. There have been several examples of corrosive attack due to adhesives and backings used in past applications. Ideally, a paint coating would be impervious to such other parts of the system. At the same time, the paint might be required to bond by adhesive to the support structure, which implies a degree of mechanical stress from adhesive to paint and from paint to the underlying metal layers. Thus, along with impermeability to moisture penetration, backing paint for a heliostat mirror must have good resistance to corrosion from chemicals of nearby heliostat components and to mechanical loadings.

Sealing surfaces to corrosion has long been and is still one of the chief purposes for painted coatings. This fact leads many members of the mirror industry to believe that a formulation for mirror backing with appropriate protective and mechanical properties can be developed. However, to date there has been only a modest incentive for the industry to investigate new paints, since only a small and uncertain market exists, and forecasts of future potential are tentative. Development of a successful paint is expected to follow a clearly defined need for it; or, alternatively, to result from investment outside the industry.

Paint has been used to seal mirror edges as well as mirror backs, especially in installations where extraordinary conditions are anticipated. Some manufacturers, for instance, edge seal mirrors for the coastal Florida market. The edge seal is an intuitive response to mirror failures in the salt spray test and to problems observed in the field. Mirror edges are known to be weak points for corrosive attack, whether due to disruption from the postfabrication step or simply to exposure of the silver and copper.

The industry seems divided on the effectiveness of edge paint in retarding corrosion. Some members attribute observed problems to microscopic disruption of the mirror coatings from cutting, handling, and other fabrication after the mirror surfaces have been deposited. They point out that edge paint will normally be thinnest on the edge corner between glass and paint backing, just where protection is most needed. As a consequence they believe current edge sealing is of little value. On the other hand, those manufacturers applying edge seals reason that they will be somewhat (even if not wholly) effective and that the extra protection is worth a small additional cost.

A painting technique widely used in the automotive industry, with possible solar mirror applications, is electro-deposition. In this technique, points and edges preferentially attract paint droplets, so that defects are filled and paint is thickest at the most vulnerable locations. Edge seals might be particularly effective were electro-deposition used; indeed better coverage over the entire mirror back, including point defects such as inclusions and pinhole voids, would also be expected. An electro-deposited paint might be effective in sealing mirror backs. However, compatibility with current mirroring techniques is an open question awaiting further investigation.

An additional backing that has been used in heliostats and in domestic installations where mirror wear was expected to be heavy is a laminate. As examples, laminated mirrors have formed components of heliostats at the Central Receiver Test Facility (CRTF), been installed as shower doors, and been used on shipboard (largely for safety reasons). Experiences with the laminated mirrors have been very positive, leading some industry representatives to state strongly that if long mirror lifetimes are to be guaranteed, lamination is the surest available method.

Laminate systems include standard mirrors laminated to backing sheets of glass, metal, and acrylic. Others feature use of thin glass, while several experiments are being run on changing or omitting the paint backing for use in a laminate structure. It has been suggested that even the copper layer might be omitted, because its functions (galvanic sacrifice, stress relief, and paint bonding) might not be required in a laminated mirror. The laminate systems, by excluding moisture and the atmosphere, are expected to isolate the silver reflective material from degradation almost indefinitely.

3.4.4 Economic Considerations

As with any engineering effort, production of a long-lived mirror must incorporate economic compromises. Standard mirrors are reported to cost from 70 to 90 cents per square foot. Table 3.4.1, copied from Heliostat Mirror Survey and Analysis by Lind et al (1), shows the approximate distribution of these costs. It also contains an estimate for laminated mirrors of the type used in the CRTF. Recent estimates from industry sources are in the same range, allowing for inflation and price fluctuations (especially for silver) since the 1979 Lind report.

Table 3.4.1

MIRROR PRODUCTION COSTS/SQ FT
(Estimated)

	1/8 in. glass	1/4 in. glass
Commercial Production		
Materials		
Glass	$ 0.35	$0.55
Coatings	0.06	0.06
Labor & Overhead	0.30	0.30
Total Production Cost	$ 0.71	$0.91
Laminated Mirror Production		
Materials		
Glass (2 at 1/8 in.)	$ 0.70	
PVB Layer	0.35	
Coatings	0.06	
Labor & Overhead	0.50-0.60	
Total Production Cost	$ 1.65	

Source: Heliostat Mirror Survey and Analysis, Battelle Memorial Institute, Richland, Washington, September 1979.

Cost effects of some of the alternatives suggested by industry can be estimated, as well, and are listed in Table 3.4.2. The cost of the silver layer rises linearly with thickness, so that application of thick silver coats of, for example, three times current practice would cause three-fold silver cost increases. It is currently estimated that 70 mg/ft^2 silver (at \$9 per troy ounce) costs four cents per square foot. Silver at 210 mg/ft^2 would therefore be 12 cents per square foot, an additional cost of eight cents per square foot.

Table 3.4.2
INCREMENTAL COSTS FOR VARIOUS MIRROR COATING ALTERNATIVES

Alternative	Incremental Cost/ Square Foot
Thicker Silver (200 mg/ft^2)	\$0.08
Thicker Copper (Disproportionate: 200 mg/ft^2)	0.04
High-Durability Paint	0.05
Lamination (High-Volume, Glass-Backed)	1.00
Lamination (High-Volume, Steel-Backed)	3.00

Note: Based on estimates. Figures are rounded to one-place accuracy.

The disproportionate copper process itself would cost about four cents per square foot for a 200 mg/ft^2 coating, adding more than 3.5 cents per square foot to current costs. The costs of greater or lesser thicknesses vary linearly. Environmental clean-up costs are not included in this estimate.

Mirror backing paint currently costs about 2.5 cents per square foot. Preliminary estimates of cost for a highly durable backing paint designed for outdoor mirror applications are seven to eight cents per square foot, or an increment of approximately five cents per square foot over present paint costs.

Laminated mirrors were estimated to cost around $1.65 per square foot, according to Table 3.4.1. Recent estimates from industry range from $2.00 per square foot for large-volume production runs of glass-backed laminates to more than $3.00 per square foot for special runs of the glass-backed system and about $3.70 for a steel-backed laminate. These costs represent increments of $0.70 to $3.00 per square foot over standard mirror costs.

Table 3.4.2 lists incremental costs associated with modifications to the standard production run mirror. As discussed, changes to coatings of the existing system result in relatively modest cost increases, while lamination represents a relatively large price jump. This is not to say, however, that overall system costs might not be less with the higher initial investment in laminated mirror systems, or that the relative measures presented in Table 3.4.2 would retain equal prominence when considered as part of the complete heliostat field system. As industry representatives have pointed out, failure of the mirror requires replacement which leads to duplication in mirroring, shipping, and installing costs as well as downtime losses. Still others have argued, for example, that the laminated mirror forms a superior structural component that permits compensating cost reductions in the heliostat design. Incremental initial costs must therefore be evaluated vis-a-vis effectiveness in improving mirror lifetimes, and in forming parts of the heliostat system.

3.4.5 Conclusions

Central issues regarding mirror coatings for long-life outdoor applications include both technical and economic considerations. Technically, the relative feasibility and effectiveness of varying, substituting, and adding coatings and backings have not been fully established, though industry representatives generally place confidence in two alternatives: lamination and improved backing paint. These areas are perceived as fruitful for improving durability in outdoor solar applications.

Economic issues are twofold. First, the market for solar mirrors is the primary stimulus for industrial development of improved coatings and backings. As the market expands, efforts supported by industry are likely to follow. Second, selection of the best techniques for protecting glass/silver mirrors from degradation is dependent on the costs of alternatives and on how they affect system costs. Lamination is currently a more expensive process than paint but may pay for itself through improved lifetime and structural strength. Development and comparison of alternatives are related to overall heliostat design and use.

The industry generally expresses confidence that a "30-year" mirror can be made. Clear directions on how to make the necessary trade-offs technically and economically remain to be resolved, but there appear to be several options worthy of attention. In pursuit of those options, design of a long-lived outdoor mirror will necessarily incorporate industry experience and draw on existing expertise that has successfully provided a good system for the current market. The challenge of developing a reliable 30-year mirror is one for which it is hoped there will continue to be widespread industry participation in identifying, creating, evaluating, and ultimately producing new alternatives.

3.5 Experience with Mirror Glass in Heliostats

3.5.1 Introduction

The economic viability of solar thermal power systems depends upon the development of reflector systems and heliostats which have reliable service lives of 20 to 30 years. The currently favored reflecting material is silvered glass, with metallic silver deposited on the back, or second, surface of the glass substrate. Back-silvered glass has several advantages over other mirror systems which have been applied in focusing solar thermal apparatus:

1. The manufacturing technology for the glass and for the silver and protective films is mature; these materials are produced in commercial quantities for uses which are not too far removed from heliostat applications,
2. The glass substrates survive weathering very well as evidenced by many examples of window glass exposed for a hundred years or more,
3. Metallic silver has the highest reflectivity in the solar spectrum of any material available.

For these reasons, back-silvered glass mirrors have been selected for all large central receiver and solar furnace installations with two exceptions: the U.S. Army Solar Furnace at White Sands Missile Range and the Tohoku University Solar Furnace at Sendai, Japan use first surface aluminum films on glass substrates which have been ground to obtain surface curvature.

This study has been restricted to back-silvered glass mirrors because this class of reflective material is currently recognized as the primary candidate for heliostats in solar thermal power systems. This paper reviews the methods which have been used for mounting glass mirrors on heliostat structures and subsequent experience with deterioration of the reflecting silver films. In the course of assembling information on experience with mirrors used in outdoor arrays, such as heliostats, an apparent correlation between mounting method and silver deterioration appeared. Thus, the paper is arranged according to mounting method and examples of representative mirror performance are given for each mounting concept. Some heliostat programs in the U.S. and those in Europe have not been included, but the objective of the paper is to trace a representative history of heliostat experience.

3.5.2 Background

By far, the largest fraction of the back-silvered mirror glass manufactured is intended for use indoors. The mirror manufacturing process has evolved to meet the requirements of this market. In the U.S., viewing quality mirrors (as opposed to decorative mirrors) are made from high quality glass having good flatness and thickness uniformity. The glass is chemically plated with about 700 Å of silver and 300 Å of copper, then coated with mirror backing paint, which dries to a thickness of about 1 mil (0.001 inch). When mounted properly, with provision for air circulating behind the mirror to prevent moisture buildup, good quality mirrors will last for 50 years or more in an indoor environment in most areas of the country. (Occasional failures still occur in southeast Florida and in the Caribbean.)

Up to now, heliostat developers have used variations of this "standard" mirror glass in most installations because it is readily available. Heliostat experience exists with mirrors installed so that (1) the back surface is exposed to the atmosphere, (2) the back surface is laminated to another sheet of glass, (3) the back surface is bonded to various types of enclosed boxes, and (4) the back surface is bonded to foam materials made of glass or plastic. In many of these installations, noticeable deterioration of the silver surface has occurred within a few months.

It must be presumed that each heliostat builder arrived at his design through careful engineering tradeoffs on the appropriate technical and economic issues. For example, each heliostat at the CNRS 1000 kW Solar Furnace is equipped with 180 mirror facets, each 50 centimeters on a side. From the beginning, heliostat builders in the U.S. adopted designs using much larger facets in order to reduce labor required to align mirrors in the field. While this choice can undoubtedly be supported on economic grounds, it has caused an accompanying set of new technical problems in mounting mirror glass on the heliostats. The following sections of this paper summarize the existing experience with mirror glass mounted on heliostats, with emphasis on gross phenomena which indicate mirror deterioration or failure.

3.5.3 Mechanical Mountings with Protective Paint Exposed

3.5.3.1 CNRS Solar Furnace at Mont Louis, France

The solar furnace became operational about 1952. Small mirror facets, on the order of 15 cm square and 2 mm thick, were supported by a system of metal rods and clips on the concentrator. Mirror facets 50 cm square and 6 mm thick, supported by metal clips, were used on the heliostat. These systems allowed for relative motion between the mirror facets and metal structures to accommodate thermal expansion and permitted free circulation of air on both sides of the mirrors. A protective paint containing aluminum pigment was used at Mont Louis; it is reported that at the time the Mont Louis solar furnace was constructed, mirror manufacturers in France applied orange-flake shellac directly over the silver, followed by a paint consisting of aluminum pigment in linseed oil.

By 1973, the solar furnace was no longer in use but a mirror facet taken from the site showed deterioration only on a limited number of spots. The three largest spots were about 2 mm in diameter and the others less than 1 mm. Eight of the spots corresponded to points where mounting posts had rested on the back of the mirror, and this particular mirror was typical of all those in the facility. Visual examination showed that less than 1% of the surface showed visible degradation after more than 20 years of exposure, and measurement revealed a solar reflectance of 90%.

3.5.3.2 CNRS 1000 kW Solar Furnace at Odeillo, France

The heliostat field was installed by 1969 and the solar furnace became operational about 1970. The mirror facets on the heliostats are 50 cm square and about 5 mm thick, supported by three spring-loaded clips at the top and bottom edges to permit facet alignment. The facets on the concentrator are 45 cm square and about 5 mm thick; four holes are drilled near the center of each concentrator facet and they are supported by a central pull plate and eight point-loading screws around the perimeter so that they can be mechanically curved. Both types of mount provide for thermal expansion and permit free flow of air behind the mirrors. Details of the original protective paint formulation are not known, but it was bluish-gray in color, presumably similar to the gray mirror backing paint used in the U.S. In 1974-75, after extensive chalking was evident, CNRS sprayed the backs of the facets with a protective varnish; also, at about this time some facets were replaced with mirrors having a gold-colored pigment containing copper powder.

Figure 3.5.1 is a photograph made in 1976 which shows the back side of several heliostats. It can be seen that the facets around the perimeter of some heliostats are illuminated at times from behind and that some new facets with light-colored backing paint have been installed. Figure 3.5.2 is

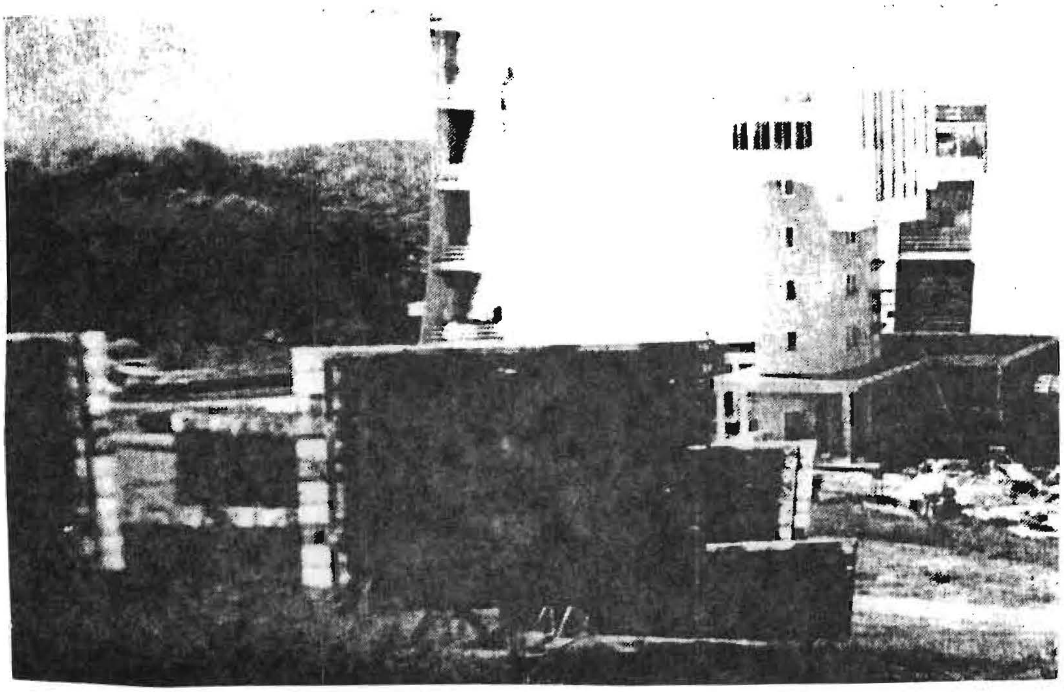


Figure 3.5.1. CNRS 1000 kW Solar Furnace, Showing Backs of Heliostats in 1976.

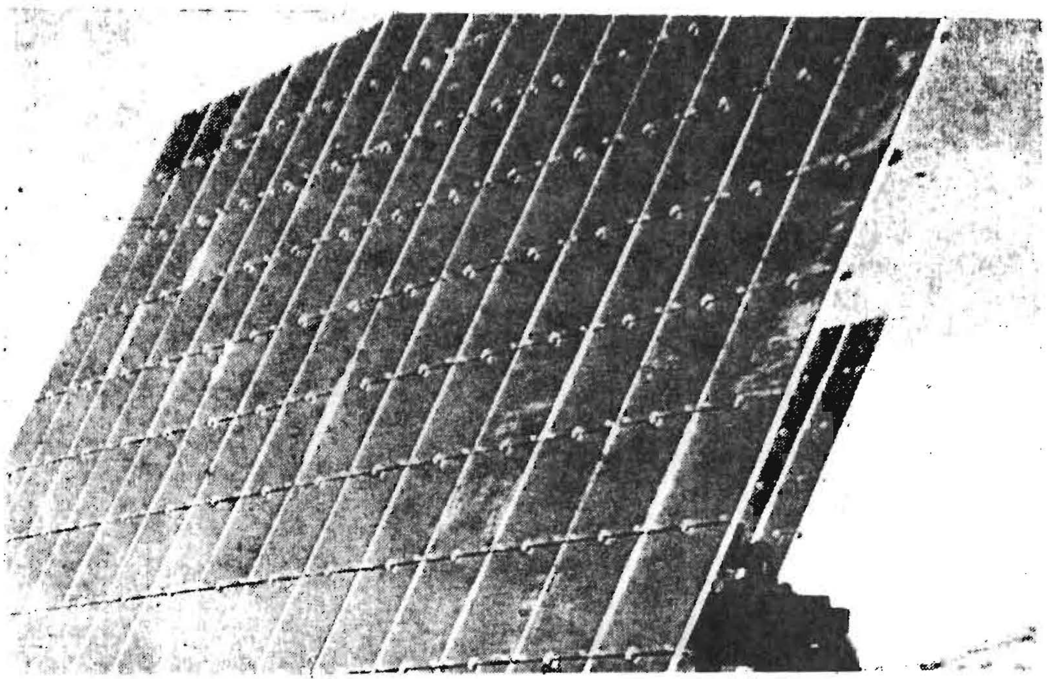


Figure 3.5.2. One Heliostat at CNRS 1000 kW Solar Furnace, Showing Deterioration of Reflective Surfaces in 1976.

also a photograph made in 1976 and illustrates the deterioration of several facets as seen from the front of a heliostat. The failure mode appeared to be weathering of the protective paint followed by washing away of the metal films when the paint had been penetrated; there was little staining or other evidence of reflectivity loss before the affected areas became transparent.

By 1978 the performance of the facility was degraded to a level that replacement of the heliostat facets was deemed necessary. Since the original mirrors had been made with polished plate glass, which was thought to have better surface flatness than float glass, the original heliostat mirrors were removed, stripped, resilvered, and remounted.

The original concentrator mirrors have not required replacement, presumably because they are somewhat sheltered by the building on which they are mounted and because their back surfaces are not illuminated by direct or reflected sunlight. Facets in isolated areas of the concentrator are showing deterioration, but these appear to be areas where rainwater sometimes drips on the mirror backs.

3.5.3.3 Advanced Components Test Facility at Georgia Tech

This heliostat field was installed and the facility became operational in 1977. The mirrors are 111 cm in diameter and 3 mm thick, supported by a 12-cm diameter pull plate at the center and a 1-m diameter ring near the perimeter. The mirrors were manufactured by Gardner Mirror Corporation and use the standard gray mirror backing paint made by PPG Industries, Inc. The pull plate is bonded to the mirror back with General Electric RTV-560 (use of the corresponding primer is necessary to get adhesion between the mirror paint and the rubber adhesive), and the mirror is held against the supporting ring by tension on the pull plate to achieve a curved surface. The mirror can move with respect to the support ring to accommodate thermal expansion and the mirror backs are exposed except in the central area where the plate is bonded.

In the early morning and late afternoon, the backs of some mirrors can be illuminated by reflected sunlight as a result of heliostat blocking and some can be illuminated by direct sunlight in certain mirror field parking positions. After four years, the mirror paint is showing a tendency toward chalking, but the overwhelming majority of the 550 mirrors are in good condition. About 15

After four years, the mirror paint is showing a tendency toward chalking, but the overwhelming majority of the 550 mirrors are in good condition. About 15 mirrors, which were washed with an experimental detergent formulation during trials of a high pressure spraying device, are exhibiting visible deterioration of their reflective films except at the area in the center protected by the pull plate adhesive. There are occasional small pinholes in the reflective films where the protective paint has been scratched by rubbing against the supporting rings, but otherwise there is no general degradation of the reflective surfaces up to the present time.

3.5.4 Mechanical Mountings with Laminated Mirror Glass

3.5.4.1 Central Receiver Test Facility at Albuquerque

The heliostats were installed in late 1977 and the facility became operational in 1978. The mirror modules are 1.2 m square (4 ft. square) and each mirror consists of two sheets of 3.2 mm thick double strength float glass, one of which is silvered, and a polyvinyl butyral (PVB) laminate. The silvered glass has the usual layers of chemically deposited copper and gray mirror backing paint, placed over the silver during the mirror manufacturing process. Gardner Mirror Corporation and Binswanger Mirror Products supplied mirrored glass in two separate procurements and all of the CRTF mirrors were laminated by Guardian Industries.

Each mirror is mounted on a steel warping structure to achieve proper focusing. This assembly, shown in Figure 3.5.3, uses a 1.17 m diameter steel hoop bonded to the back of the laminated mirror with an elastic adhesive, a planar strut assembly composed of two square tubes welded to the hoop, and a pullplate bonded to the center of the mirror. Warping forces are applied at the mirror centerline through threaded studs connecting the plate and the "cross" frame and at the corners by corner-push studs. The backs of most of the mirrors in the heliostat field have been painted white to reduce solar absorptivity, but some mirrors have no provision to prevent absorption of radiant energy at the lamination plane.

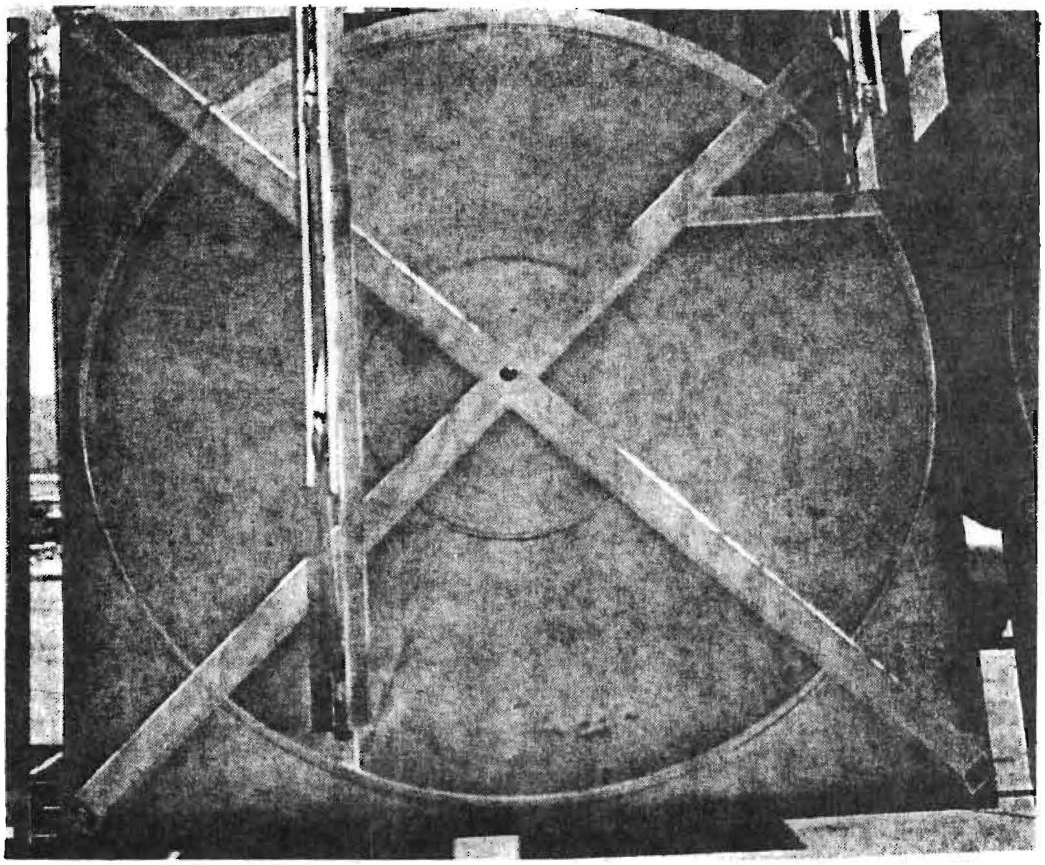


Figure 3.5.3. CRTF Mirror and Mounting Assembly.

The optical quality of all the mirrors in the CRTF heliostat field remains good after exposure times of 3 to 4 years. About 1% have developed cracks in the front glass (between 50 and 60 mirrors out of 5,500), but there is no visible degradation of the metallic films adjacent to the cracks. The cracks tend to "wander" around the mirror surface, often not touching the edge of the mirror glass, as shown in Figure 3.5.4. A recent inspection of several hundred of the mirrors revealed no spots on reflective surfaces or edge degradation.

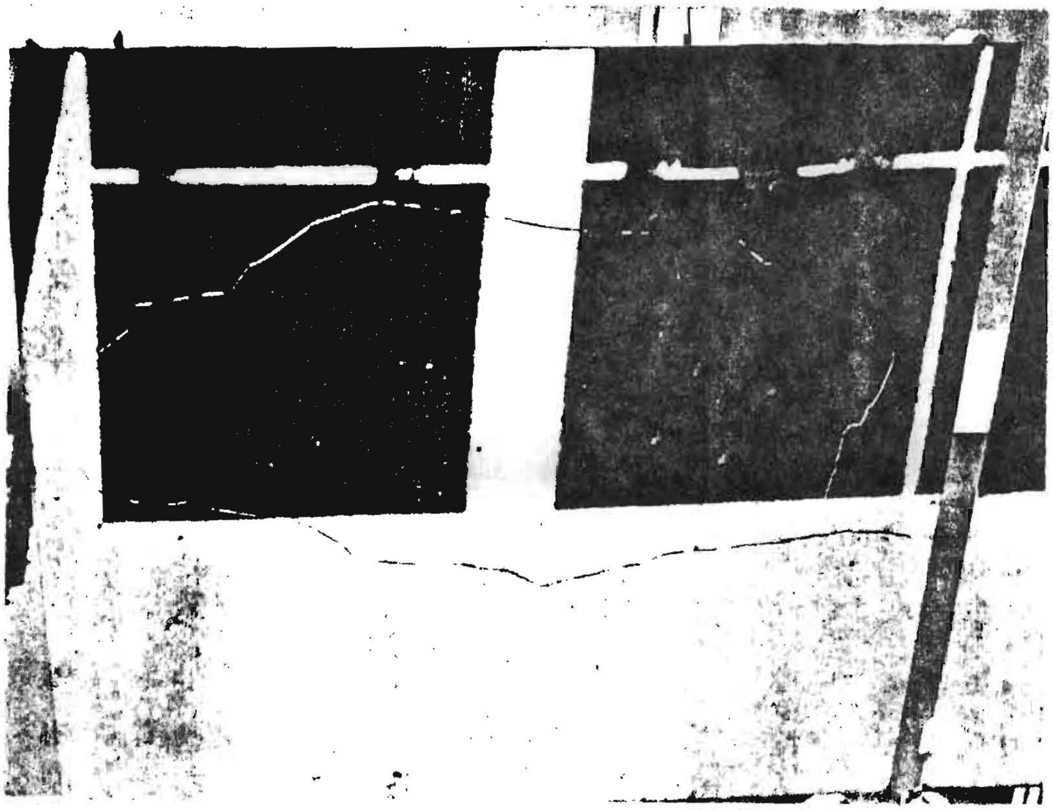


Figure 3.5.4. Typical Crack in Front Layer of CRTF Mirror Glass

3.5.4.2 McDonnell-Douglas Pre-Production Heliostats

MDAC used laminated mirror glass on its early octagonal heliostat about 1974 and on Subsystem Research Experiment heliostats in 1976. Problems with the laminated mirrors caused a switch to a core panel mounting design in 1977-1978, but the company returned to laminated mirrors for its second generation heliostats in 1979.

The first abandonment of laminated mirrors was attributed to four factors: (1) bubbles and delamination, (2) cracking due to backlighting, (3) weight, and (4) high cost. Difficulties with bubbles and delamination were experienced by Martin Marietta Corporation and its subcontractors during the development of CRTF heliostats in 1976-1977. It is reported that the first organization which attempted to laminate CRTF heliostat mirrors found that reactions occurred between the mirror backing paint and the PVB laminating sheets during and after autoclaving; another organization was able to laminate successfully. Likewise, a substantial number of mirrors furnished to Martin Marietta during this period for qualification tests suffered bubbles and delamination. Although glass cracking has occurred at the CRTF, it appears not to have caused degradation of mirror performance. Thus, it seems that some manufacturers were able to make satisfactory laminated mirrors during the mid-1970s and others were not; also, experience at the CRTF currently suggests that cracking of some mirrors may be tolerable since optical performance is apparently not affected.

3.5.4.3 McDonnell-Douglas Second Generation Heliostat

After beginning second generation heliostat development with a core panel design (which is described later in this paper), MDAC readopted laminated mirrors late in 1979. Rectangular mirror modules 1.22 m by 3.35 m (4 ft by 11 ft) are made up from a 2.4 mm thick float glass mirror laminated to a 4.8 mm thick float glass backing sheet. A white backing paint is used on the mirror to reduce solar absorption at the lamination plane and the two glass sheets are laminated with conventional PVB by pinch rolling and autoclaving. The color seen from the rear of the mirror is a light beige shade.

The edges of the mirror assembly are sealed by a rolled galvanized steel strip and silicone sealant. The mirror module is supported by two galvanized steel hat section stringers, bonded onto the back of the module in the direction of the longer axis. To reduce light absorption in the front glass, a 1.5 mm thick fusion glass mirror will be substituted for the 2.4 mm mirror when the thinner glass is available. Figure 3.5.5 shows details of the mirror module.

A test heliostat installed at the CRTF late in 1980 was exhibiting no visible deterioration or cracking of mirrors after seven months of exposure.

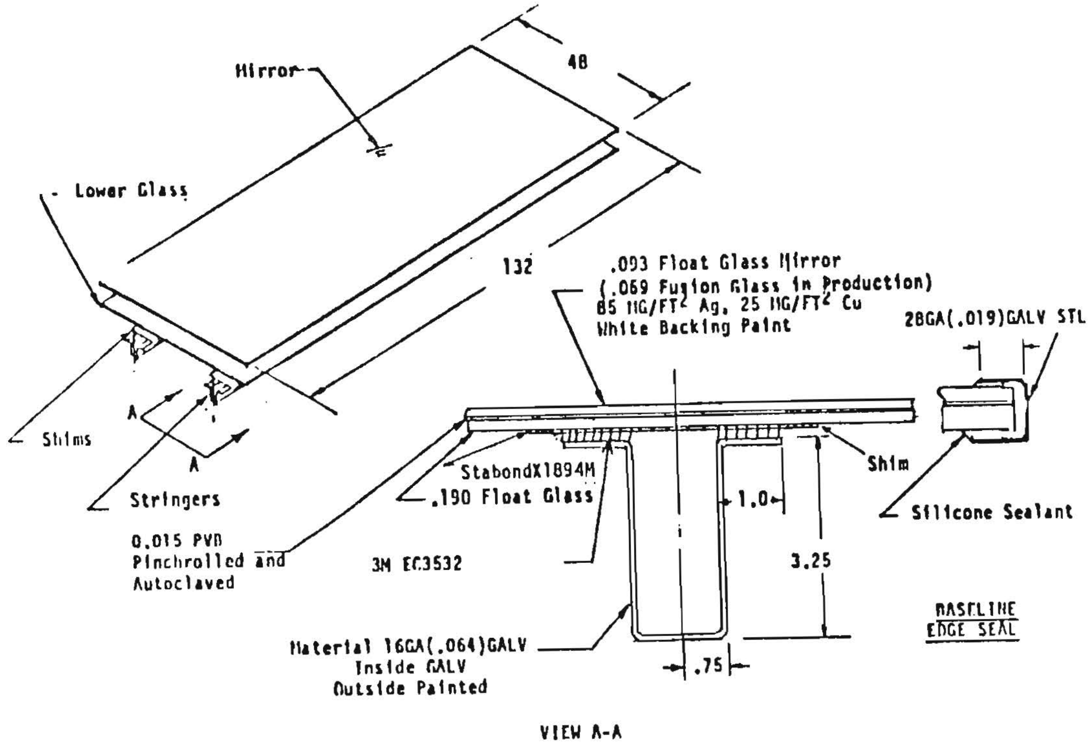


Figure 3.5.5. McDonnell-Douglas Second Generation Mirror Module

3.5.5 Mirror Glass Bonded to Box-Type Supporting Structures

3.5.5.1 Martin Marietta Pre-Production Heliostat for 10 MW Pilot Plant

In the course of developing heliostats for the Barstow Pilot Plant, Martin Marietta Corporation built and tested a mirror module having the configuration shown in Figure 3.5.6. The mirrors were 2.13 m square (7 ft square), bonded

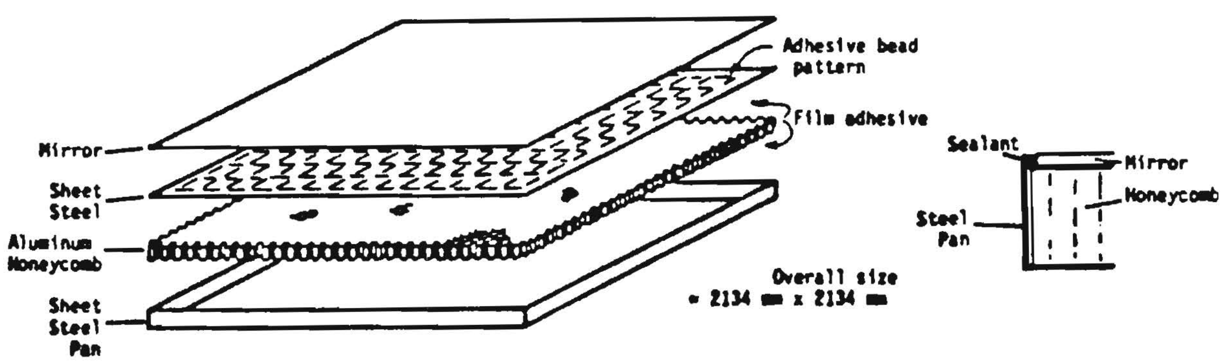


Figure 3.5.6. Martin Marietta Pre-Production Mirror Module

to a steel sheet, which in turn was bonded to an aluminum honeycomb enclosed in a steel pan. Modules with mirrors made from low-iron float glass and silvered by a commercial mirror manufacturer were exposed to weather outdoors at Livermore, California for eight months during 1978. Similar modules, made by a different mirror company, using different paint and adhesives, were tested at Baltimore, Maryland during the same time period. All the modules are reported to have been assembled at Baltimore.

Significant deterioration of the Livermore modules was evident after the eight-month exposure period. Examination revealed substantial quantities of water wherever the adhesive between the steel sheet and the mirror back did not form a continuous barrier to water penetration. There was very gross corrosion of the steel sheet and obvious blistering of the mirror backing paint where water had been trapped. Areas under the blistered paint were found to be devoid of silver and copper.

After about one year of exposure in a moderately polluted environment, the Baltimore modules showed no detectable deterioration.

3.5.5.2 Martin Marietta Production Heliostat for 10 MW Pilot Plant

The Martin Marietta mirror module design for the Barstow Pilot Plant was revised to eliminate the bonding of mirrors to steel in 1979. The revised design, shown in Figure 3.5.7, used rectangular mirror modules 1.22 m by 2.74 m (4 ft by 9 ft) and replaced the steel sheet bonded to the mirror with a coarsely woven fiberglass scrim cloth, to prevent the sharp edges of the aluminum honeycomb from cutting the mirror backing paint. An aluminum tape was added around the edges to prevent bonding of the honeycomb to the mirror edges and possible edge cracking. The mirrors were silvered by the standard process and used conventional gray mirror backing paint.

After about one year of exposure at the CRTF, these mirror modules are showing visible edge corrosion and a honeycomb pattern of darkened silver in certain areas, as shown in Figure 3.5.8. This degradation implies penetration of the backing paint by water or corrosive materials in the adhesive.

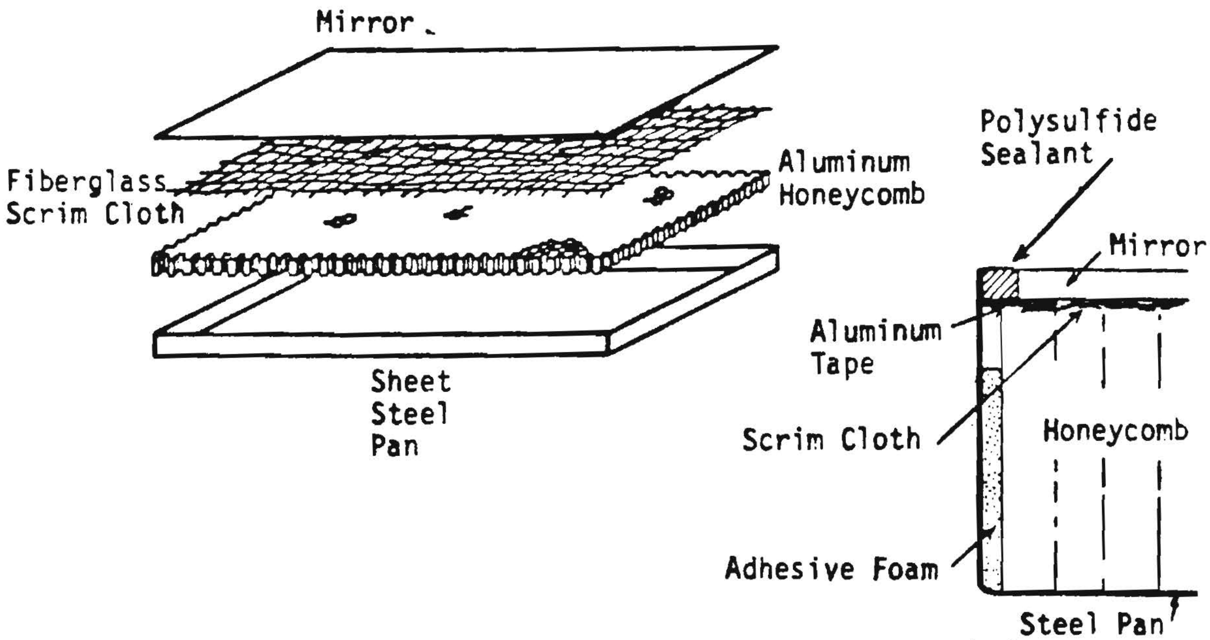


Figure 3.5.7. Martin Marietta Production Mirror Module for 10 MW Pilot Plant.

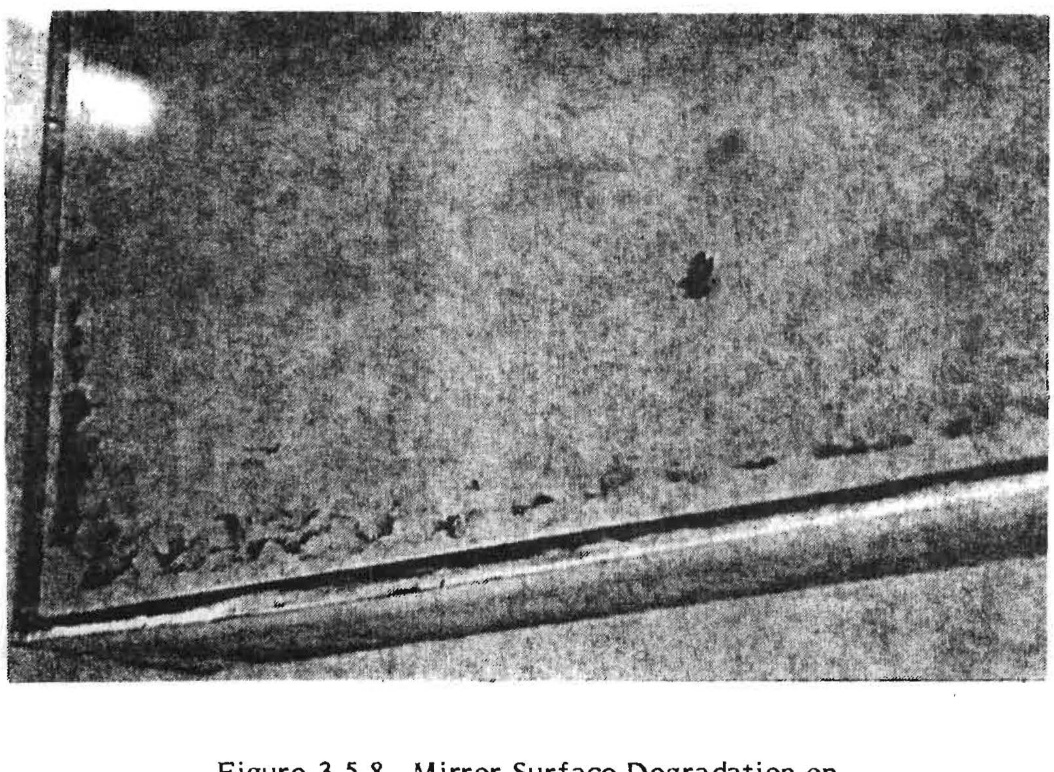


Figure 3.5.8. Mirror Surface Degradation on Martin Marietta Test Module for 10 MW Pilot Plant

Further modifications have been made for the production heliostats being installed at Barstow and at Almeria, Spain. Gardner Mirror Corporation, the mirror manufacturer, is applying a white acrylic paint over the gray mirror backing paint; the white acrylic is believed to be far more impervious to water penetration than the gray paint. Also, the steel box surrounding the honeycomb has been sealed to prevent the intrusion of water and a small "breathing tube" provided to accommodate changes in atmospheric pressure. It is reported that Martin Marietta has tested both breathing and sealed boxes with acrylic-coated mirrors, and that good results were obtained with both types in both coupons and full scale modules.

A prototype unit of the final Barstow heliostat design is in place at the CRTF for testing. No deterioration of the mirrors was evident after exposure of about two months.

3.5.5.3 Martin Marietta Second Generation Heliostat

This heliostat uses mirror modules incorporating two mirror lites approximately 1.5 m by 1.8 m (5 ft by 6 ft) for the full size mirror assemblies and half-width mirrors for the half-sized mirror assembly, as shown in Figure 3.5.9.

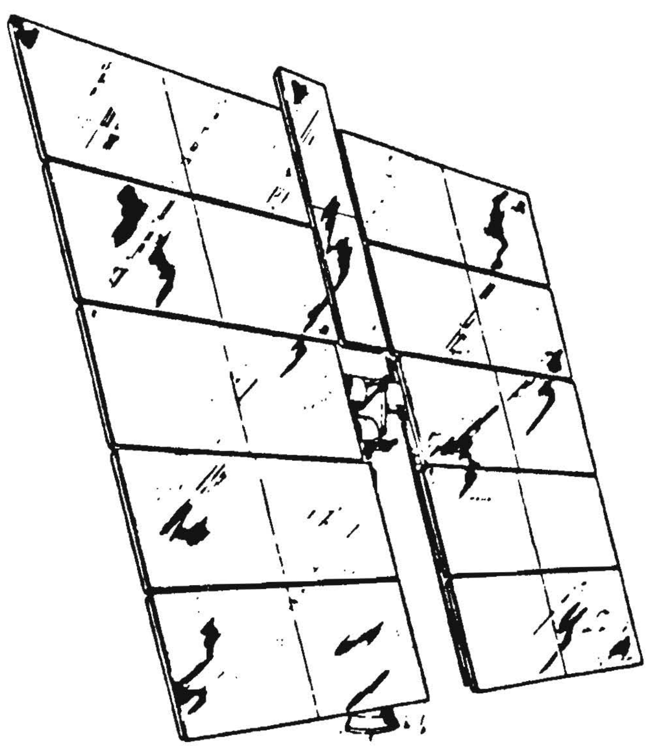


Figure 3.5.9. Mirror Modules on Martin Marietta Second Generation Heliostat

The modules are designed to use 1.5 mm thick second surface mirrors of either fusion glass or low-iron float glass. The mirrors are supported on a steel/honeycomb/steel sandwich structure. The honeycomb is phenolic-impregnated paper. The mirror is bonded to a sheet of butyl rubber to prevent water penetration of the backing paint.

A prototype unit is installed at the CRTF for testing. It is reported that water leaks into the box during rainstorms; very tenacious water streaks have formed on the surface of the mirror glass, presumably containing materials leached from the paper honeycomb by rainwater. One piece of mirror glass is cracked and visible rust has formed on the corners of the steel boxes after about three months of exposore. The cracked glass and water streaks are shown in Figure 3.5.10.

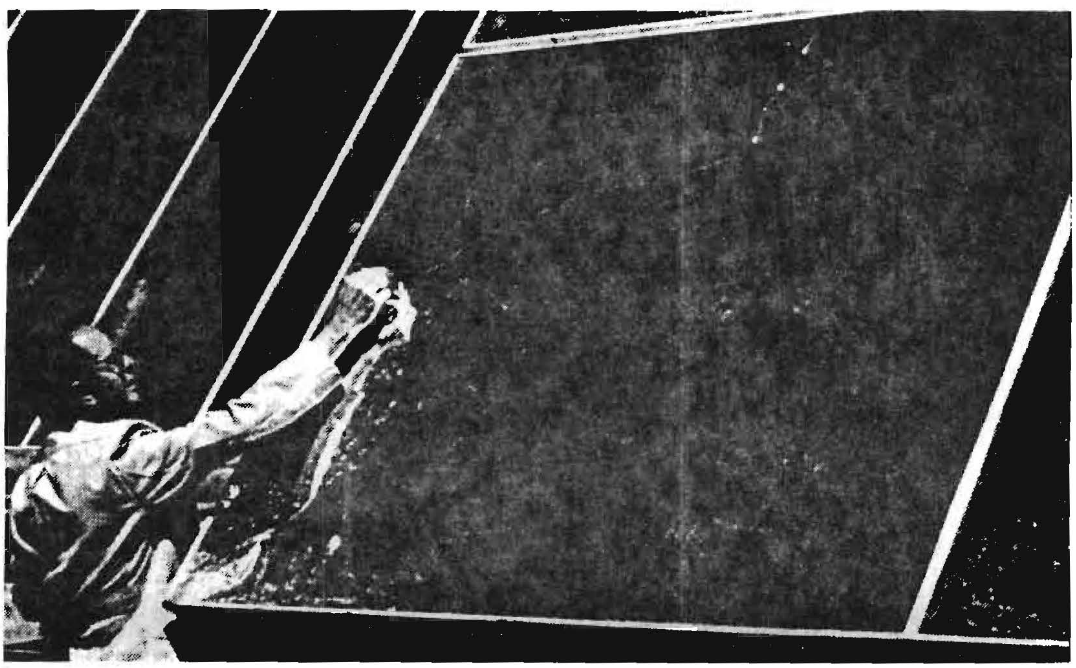


Figure 3.5.10. Water Streaks and Cracked Mirror on Martin Marietta Second Generation Heliostat

3.5.5.4 ARCO (Northrup) Second Generation Heliostat

This heliostat uses mirror modules incorporating two mirror facets 1.22 m by 1.83 m (4 ft by 6 ft). The 4 ft by 12 ft mirror modules are mounted on a fabricated steel box with internal rolled steel stiffening members. The second surface glass mirrors are attached to the box with a film of silicone grease to maintain contact with the box and prevent water from reaching the mirror paint. Since the silicone grease does not provide support in the mirror plane, the facets are held in place by edge moldings. The silicone grease accommodates thermal expansion differences between the steel box and glass mirrors.

A prototype unit is installed at the CRTF for testing. The mirrors show no visible signs of deterioration after about six months of exposure.

3.5.6 Mirror Glass Bonded to Structural Foam Materials

3.5.6.1 McDonnell-Douglas and Sandia-Livermore Modules with Polystyrene Foams

MDAC's initial mirror module design for its second generation heliostat used mirrors bonded to polystyrene foam. Exposure tests on this design and a Sandia modified version of this design were begun at Sandia-Livermore Laboratories in 1978. The mirrors were 1.08 m by 2.91 m (3.5 ft by 9.5 ft), bonded to styrofoam blocks contained within a steel box as detailed in Figure 3.5.11. The differences between the basic MDAC module and the Sandia modified version were in edge sealing details.

After eight months exposure at Sandia-Livermore, deterioration of the reflective surfaces was observed. A typical degradation pattern is shown in Figure 3.5.12, where it is evident that initial silver attack occurred near the edges of the module and along joints in the foam core. Examination of the modules revealed that noticeable amounts of water had accumulated in the vicinity of the degraded mirror areas.

New exposure tests were begun in 1979 on revised mirror module designs. As shown in Figure 3.5.13, the foam core was made in one piece rather than four pieces cemented together and the sealing components were upgraded. This revised module depended heavily on the experience of the thermal pane window industry. Of 15 modules made in 1979 using one-piece polystyrene foam panels and polyisobutylene sealant, about two are reported to have

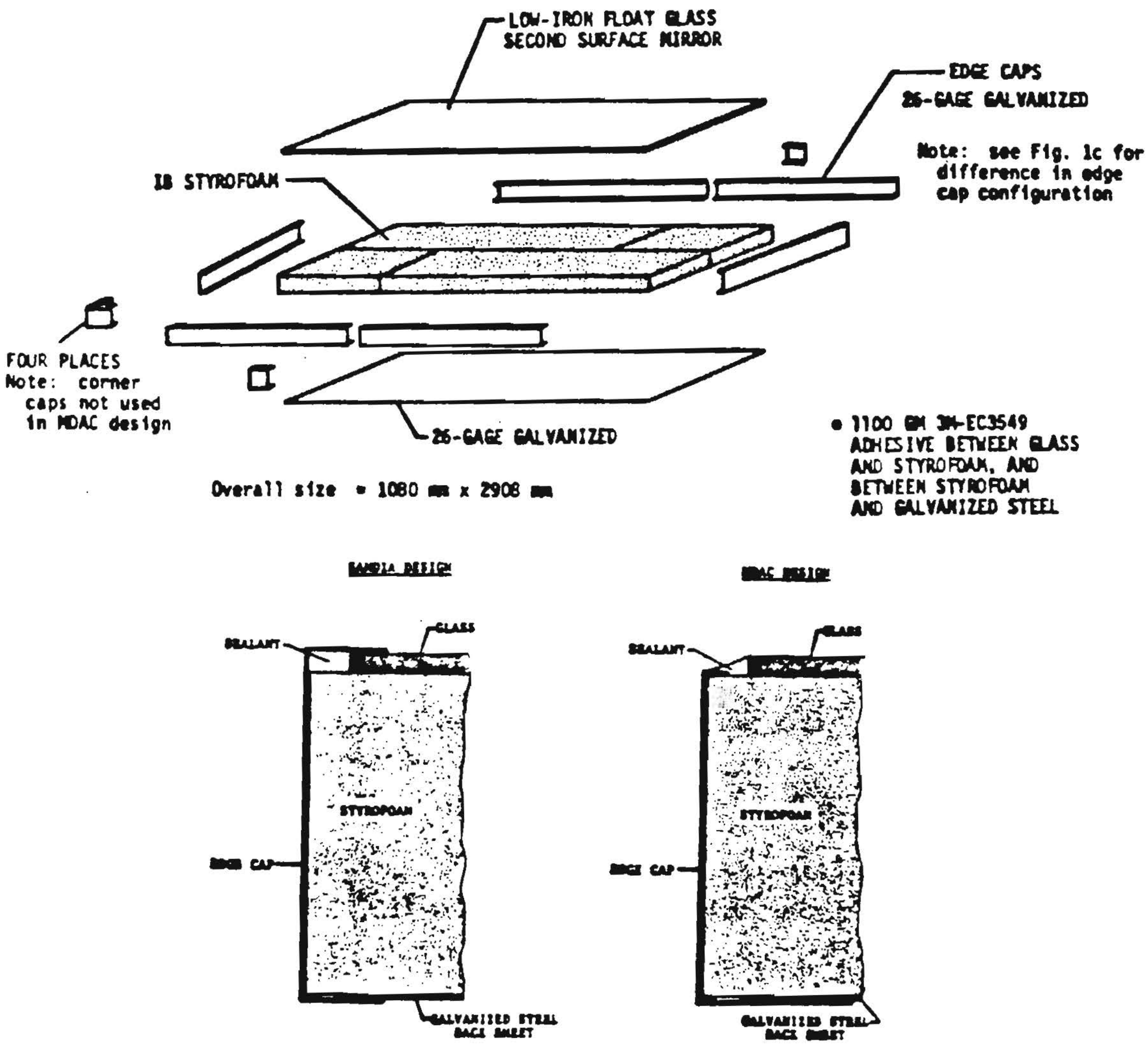


Figure 3.5.11. McDonnell-Douglas and Sandia-Livermore Mirror Modules with Polystyrene Foam Core.

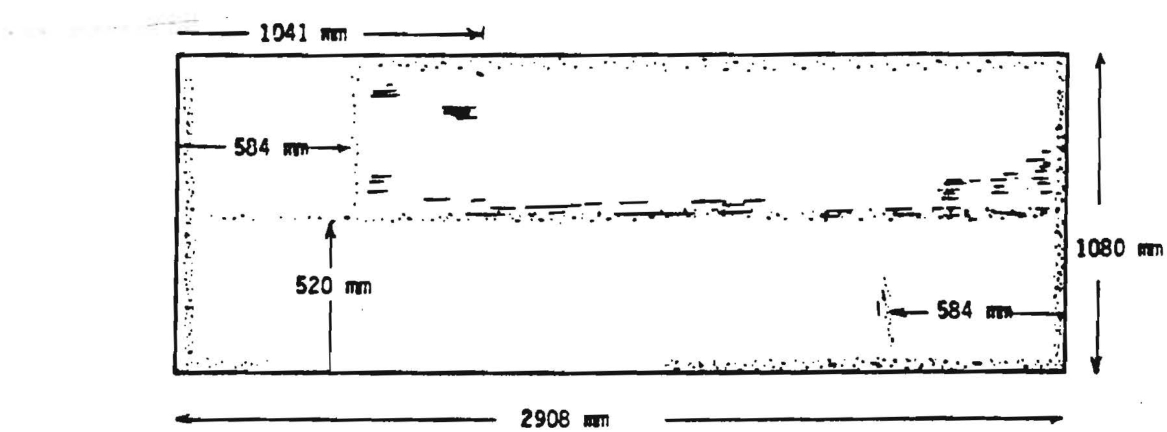


Figure 3.5.12. Deterioration Patterns on Mirror Module with Polystyrene Foam Core

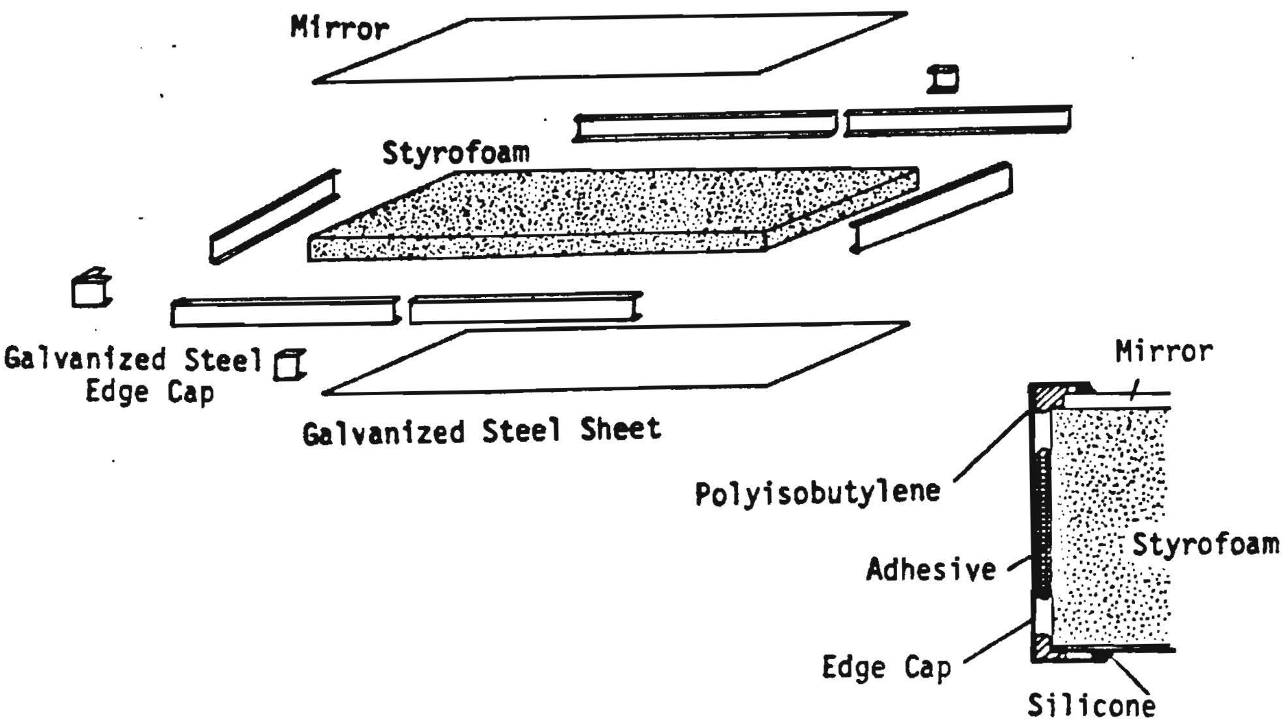


Figure 3.5.13. Revised McDonnell-Douglas Mirror Module
With Polystyrene Foam Core

leaked and the others remain in good condition after two years. MDAC returned to laminated mirrors late in 1979 for its second generation heliostat because of cost considerations.

3.5.6.2 Northrup Pre-Production Heliostat for 10 MW Pilot Plant

During heliostat development for the Barstow Pilot Plant, Northrup also developed a mirror module using polystyrene foam cores. The standard silvered glass with gray backing paint was sprayed with a white acrylic enamel in an effort to reduce the likelihood of water penetration into the mirror backing. The acrylic paint was then bonded to a styrofoam substructure.

After exposure to weather at Sandia-Livermore, it was reported that the foam soaked up a great deal of water. The reflective surfaces are reported to be in good condition after three years, however, presumably protected from water by the sprayed acrylic enamel. This use of acrylic enamel formed the basis for adoption of a similar coating by Martin Marietta for the Barstow production heliostats. The current acrylic paint is applied by the mirror manufacturer using a curtain coating process on the mirror manufacturing line.

Northrup subsequently adopted a mirror module design using a steel box substrate for its second generation heliostat.

3.5.6.3 Boeing Second Generation Heliostat Using Glass Foam Sandwich

The Boeing second generation heliostat uses a glass sandwich construction with front and back skins of borosilicate glass (Corning Fusion glass) and a borosilicate cellular glass core (Foamsil 75, made by Pittsburgh Corning). Panel sizes planned for the production design are 1.22 m by 3.35 m (4 ft by 11 ft), although the panels for the prototype heliostats are 4 ft by 10 ft (available glass size). The glass skins are 1.5 mm thick.

The cellular glass matches the coefficient of thermal expansion of the fusion glass skins and the closed cell characteristics of the cellular glass are said to prevent diurnal pumping of moisture into the panel core. The rear glass skin is painted white.

A prototype unit is installed at the CRTF for testing. It was showing spot corrosion of the reflective metal films after about seven months of exposure, as shown in Figure 3.5.14.

3.5.7 Conclusion

A rather large variety of mirror module designs have been constructed and exposed to outdoor environments for limited periods of time; the number exposed for extended periods (4 years or longer) is quite limited, including only free standing glass and laminated glass.

Present heliostat experience suggests that it is possible to produce mirrors which will have lifetimes of 20 to 30 years in an outdoor environment, but that substantially improved backing paints will have to be adopted. The commonly used mirror backing paints were developed for indoor applications and experience shows that these will deteriorate, with accompanying loss of metallic reflecting films, within five to ten years in an outdoor environment, especially if they are exposed to illumination by sunlight.

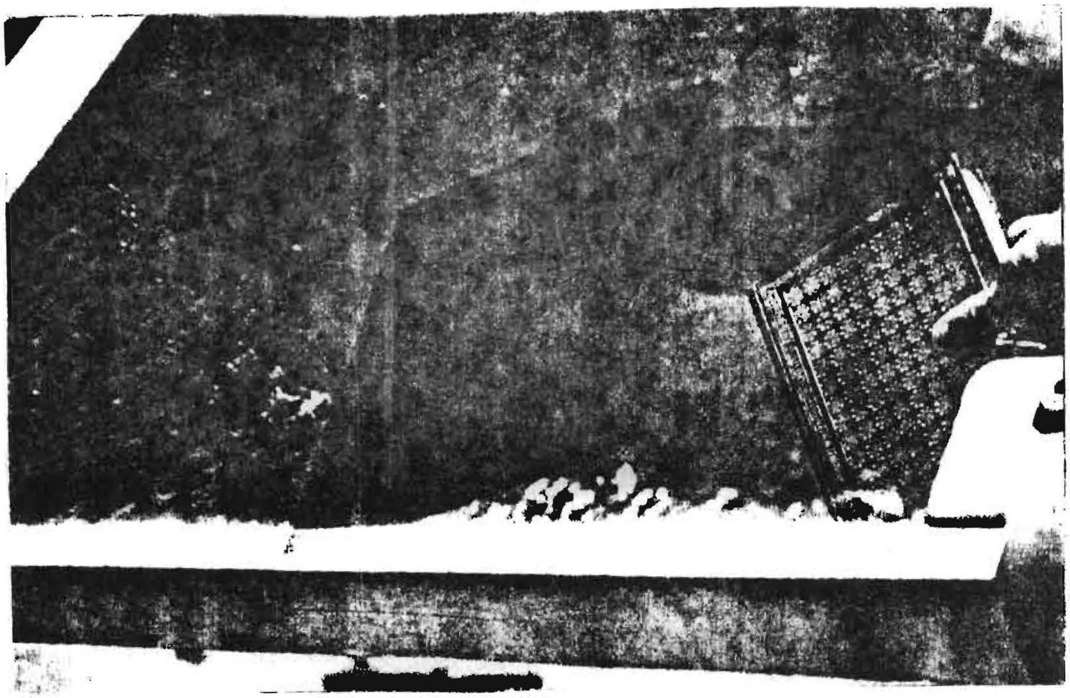


Figure 3.5.14. Boeing Mirror Module, Showing Spot Corrosion.

Protection of the metallic reflecting films from exposure to water is essential. Almost every early mirror failure can be correlated with the presence of liquid water penetrating the layer of protective paint behind the metallic films.

Up to the present time, experience with open mounting structures has been better than experience with the various box-type mirror supporting substrates. The abandonment of box-type substrates in favor of open structures cannot yet be unconditionally recommended, however. As substrate designs have evolved, it appears that continuing improvement in mirror lifetime has been achieved. The economic and manufacturing advantages associated with the box-type substrates may justify their continued use if improved sealing techniques, such as butyl rubber, silicone grease, and acrylic enamel, are proved to be successful.

3.6 Mirror Testing

Testing of mirrors to assess their durability under harsh environmental conditions can be considered to be of five types:

1. Tests of Protective Coatings: to determine the degree of protection provided to the silver by backing paints or other types of protective systems. These tests are primarily of the salt spray type where the temperature and humidity are maintained constant and penetration of the protective system results in corrosion of the silver/copper layers.

2. Tests of the Copper/Silver Films: to evaluate the inherent capability of the silver/copper films to withstand exposure to corrosive chemicals. These tests are designed to evaluate the quality of silver-glass bond as provided by the wet silvering process. They consist of direct exposure of the copper/silver film to a corrosive environment or to induced galvanic action. They may also be used as a quality control tool, as a means of optimizing processing parameters to obtain production silver/copper films with improved inherent corrosion resistance, and to provide information that will help understand the mechanism of silver/copper corrosion on glass and aid in formulating possible solutions to the problem of mirror degradation.

3. Tests Using Thermal Cycles: to determine the combined effect of humidity, temperature and temperature cycling on the performance of mirrors and mirror systems designed for outdoor exposure. These tests impose the effects of mechanical strain imposed on the various metallic and paint films resulting from differential thermal expansion together with the chemical effect of corrosion under low and high temperature and humidity conditions. This combination of chemical, mechanical and thermal effects is expected to provide data which should be more useful in determining useful lifetime in the outdoor environment than exposure to chemical or galvanic actions alone.

4. Accelerated Outdoor Weather Tests: to evaluate the performance of mirrors under intensified sunlight exposure combined with high and low humidity and cyclic temperature effects. These tests are intended to

accelerate the effects of outdoor exposure as related to solar radiation and thermal cycling. Chemical and other environment effects are not necessarily intensified in these tests. However, the effects of exposure to accelerated thermal cycling and corrosive atmospheres on the protection provided by the backing paints or the inherent corrosion resistance of the copper/silver films can be determined using either of the other types of tests designed for that purpose.

5. Tests for Material Compatibility: to evaluate the compatibility of adhesives, laminating films and other materials which might be used to provide additional protection for the finished mirror or to incorporate the mirror into the heliostat mirror module.

3.6.1 Tests of Protective Coatings

As pointed out earlier, the service lifetime of a mirror in an outdoor environment will be determined primarily by the degree to which the silver can be protected from the degrading elements of that environment. Since water and aqueous solutions of salts and acids are particularly corrosive to silver, the type of test selected should evaluate the performance of a finished mirror when exposed to an environment containing such corrosive elements. This test would aid in determining the ability of the backing paint to protect the copper and silver from the corrosive environment. It was basically for this purpose that the mirror industry adopted a modified salt spray test developed for evaluating paints, vanishes, lacquers and related products. This test is based on ASTM Standard B117-73, but modified to use a 20% by weight salt solution rather than the 5% specified in the ASTM Standard. This modification was specified in Federal Specification DD-M-411, updated in May 1967 as DD-M-00411a GSA-FSS. The temperature is maintained at 95° F with a relative humidity of 95-98 percent. The duration of the test is 150 hours with at least one manufacturer using 300 hours. Samples are inspected daily. The size, number and time of appearance of defects are reported in the test results. The Federal Specification specifies less than 9 spots in 150 hours.

A more aggressive test has been reported to be used in Europe (7). This is ASTM Standard B368-68, Copper-Accelerated Acetic Acid-Salt Spray Testing (CASS Test). A 120 hour CASS test is reported to be equivalent to 600 hours of the regular salt spray test. This test provides a more acid condition (pH 3.3-3.1) as compared to the salt spray (pH 6.5-7.2) and is thus more corrosive with respect to the silver. This test was developed for testing "decorative copper-nickel-chromium or nickel-chromium coatings on steel and zinc-base die castings designed for relatively severe service." The salt content is 5% and the temperature is 95^{o}F.

Another low pH type salt spray test developed for testing paints is ASTM Standard B287-74 "Acetic Acid Salt Spray Testing." This test also provides a pH of 3.1 to 3.3 with a salt content of 5% by weight and a temperature of 95^{o}F.

A test which is particularly aggressive toward the copper layer is a ferric chloride test (1). The test solution contains 5% by weight ferric chloride in water. Freshly cut test coupons 3 x 6 inches are placed in the solution at 70^{o}-80^{o} F for one and a half hours. This is thought to be equivalent to 150 hour salt spray test. Mirror degradation of less than 150 um along the freshly cut mirror edge is considered acceptable.

As a rapid test of the permeability of the backing paint PPG has suggested the use of an electrical resistance test (8). In this test the resistance to the passage of electrical current is measured on selected areas of the backing paint at the start and end of a one hour period. A simple ohmmeter is used to make the measurement. The test involves attaching one lead of the ohmmeter to the copper surface at a point where a portion of the backing paint has been removed. A cotton ball wet with a simple electrolyte solution provides the other contact point through a platinum electrode to the mirror backing. Four random spots on the mirror back are selected, usually at the four quadrants of the mirror. The four ohmmeter readings before and after one hour are averaged. Resistance readings above 19,000 ohms have correlated to mirrors passing a 300 hour salt spray test. Those with readings of 1,900 ohms correlate with failing mirrors. When initial readings are in the 1,900 or lower range, porosity pinholes, scratches, etc. are present in the backing. A drop off or marked lowering in the readings at the end of the one hour period indicates the probability of thin films, partial holidays, weak areas, or other causes of insufficient protection.

3.6.2 Test of the Copper/Silver Films

Two types of tests have been developed recently to evaluate the inherent corrosion resistance of the copper/silver films deposited on glass using the wet mirroring process. These are a boiling water test at PNL and an electrochemical test at SERI. Since it is generally thought that water plays an important role in the degradation process, Lind developed a tentative test to evaluate the integrity of the copper/silver layer in chemically silvered second surface mirrors (9). In this test a mirror with no paint backing is placed in boiling deionized water for 3 hours. A commercial mirror subjected to this test exhibited peeling of the copper/silver layer leaving the glass surface exposed. This test was designed to yield information that would help to better understand the degradation process and lead to the development of improved silvering process that will inhibit the degradation at the silver-glass interface. Such a process would thus improve the inherent resistance of the silver to outdoor exposure. One such effort at PNL has resulted in the development of mirrors that have withstood 8 hours in boiling deionized water without significant degradation.

Another test which is designed to evaluate directly the inherent corrosion resistance of the copper/silver films is the electrochemical scratch test developed at SERI (10). This test was developed not only to evaluate the corrosion resistance of the copper/silver film, but to provide data that will help in understanding the electrolytic corrosion processes. In this test the painted surface and reflective films of a finished mirror are penetrated with a scratch so that the protective effect of the paint is eliminated. The galvanic current is then measured between the mirror surface and the specimen holder when the scratched surface is exposed to a synthetic sea water solution. The data provided by this test showed a correlation between the electrochemical ranking of a number of specimens and corrosion resistance data obtained from a modified salt spray test. The advantage of the electrochemical test was the fact that it required only a few minutes to complete compared to hundreds of hours for the salt spray tests. It is possible that this test could be used as a rapid quality assurance test.

3.6.3 Tests Using Thermal Cycles

Since heliostat mirrors will be exposed to extreme variations in temperature as well as variations in humidity several tests have been developed which combine the effects of high and low temperatures, thermal cycling and a corrosive atmosphere. The primary effect of thermal cycling is the mechanical stress imposed at the interface of dissimilar materials which result from differences in coefficients of thermal expansion. These effects are particularly important at the silver-glass interface and at the bond line of any attached supporting structure. Thus, such tests are useful in locating weaknesses in interfacial bond areas and susceptibility to corrosion which may occur as a result of accompanying strain and temperature effects.

At Sandia Laboratories/Albuquerque work is underway to develop an accelerated mirror environmental chamber test (11). The experimental matrix currently being run consists of three tests: (1) continuous exposure at 160°F at high relative humidity, (2) continuous exposure at 160° F at low relative humidity, and (3) cycling temperatures from -20 to +55° F and from +55 to +120° F at about 50% relative humidity. The cycle is 2 hours rise, 1 hour hold, 2 hours down, 1 hour hold; four cycles between the lower temperature limits are completed in a 24 hour period, then four cycles between the higher limits are completed, then the lower cycle is repeated, etc. No conclusions concerning correlations between these tests and real time outdoor exposure can be made at this time.

In Europe thermocycling tests are used to evaluate mirrors for use by the automotive industry (12). These tests typically are run in cycles that include high temperature and humidity and low temperature typically four hours at 190°F, four hours at 100°F, both at 95 to 100 percent humidity and 16 hours at minus 40°F.

The "Cleveland Tester" (1) is a commercial test chamber for cyclic environmental testing. A temperature controlled tray of water is provided at the bottom of the chamber. Test samples form portions of the chamber roof with the coated surfaces inside the chamber. Under high temperature conditions, the chamber geometry causes condensate, on the coated mirror surfaces, to drip down the mirrors and back into the reservoir. With this system samples can be exposed to varying conditions of temperature and humidity and water that is not stagnant.

3.6.4 Accelerated Outdoor Weather Testing

Accelerated outdoor weather tests have been used for many years to evaluate various plastic, paints, finishes, glass, etc. One of the leading facilities in providing accelerated outdoor exposure testing is DSET, Phoenix, Arizona (13). The apparatus that they have developed are of two types: EMMA - Equatorial Mount with Mirrors for Acceleration, and EMMAQUA - Equitorial Mount with Mirrors for Acceleration plus Water Spray. The EMMAQUA was developed to simulate areas with high relative humidity. The target area for both EMMA and EMMAQUA systems is 5 inches wide by 55 inches long. Each machine has 10 mirrors (electropolished aluminum) 5 x 55 inches, that focus on the target area. The increased radiant flux provided by the 10 reflective slats plus the two axis tracking, which gives normal (direct) exposure to the sun throughout the day, provide a solar radiation acceleration factor of between 2 and 13 compared to conventional exposure. In order to minimize thermal effects the samples are air cooled essentially to the temperature that would be provided by one sun. The results of tests with these devices have shown good agreement between the accelerated tests and conventional exposure. However, it has been pointed out that each material required analysis before an exact acceleration factor can be determined. Although many plastic and other types of reflective films have been evaluated using these devices, only one known sample of second surface silver glass mirror has been exposed to these accelerated tests. This was a mirror prepared as part of the McDonnell Douglas heliostat program. After 32 weeks exposure the reflectance of this mirror was within 3% of the value before exposure (14).

"Weatherometers" provide a sample exposure system with a wide range of environmental parameters (1). These systems allow samples to be exposed to different parameters by moving them to different positions inside the chamber. These environmental parameters can include simulated solar radiation (from Xenon arc lamps), temperature, humidity, water and salt spray, and specialized chemical pollutant gases (H_2S etc.). No data have been found for silvered glass mirrors exposed to these devices

3.6.5 Tests for Material Compatibility

During the fabrication and evaluation of early prototype heliostat mirror modules it became evident that certain adhesive and sealing agents either directly reacted with or penetrated the backing paint and were the source of corrosion in the copper/silver film or acted in a way to reduce the protection provided by the backing paint thus accelerating the corrosion when exposed to the outdoor environment. Examples of the corrosion problem associated with the use of these materials are described by Burolla and Roche (15) and in the Section 3.5 of this paper. In order to study the compatibility problem with sealants and adhesives and to be able to screen candidate materials for these applications an accelerated deterioration test was developed. In this test an inverted plastic cup was bonded to the back of the mirror on which strips of adhesive had been placed. Distilled water was then inserted through a hole in the bottom of the cup. The assembly was then placed in an oven at $60^{o}C$. From these tests it was found that adhesives containing amines and sulfides would greatly accelerate the deterioration caused by the presence of water. This test also could be used to screen backing paints for use with particular adhesives.

3.6.6 Conclusions

From this brief overview of the various tests used to evaluate mirrors it is obvious that an accelerated weathering test does not exist which will establish the useful lifetime of heliostat mirrors. However, from the visits to mirror industries, mirror material suppliers, heliostat manufacturers and laboratories involved in testing mirrors, as well as a review of the literature some conclusions can be drawn concerning those factors which are most critical in determining the useful lifetime of heliostat mirrors. Very simply these can be divided into three categories: 1. the basic second surface silver glass mirror, 2. the structure, adhesives, sealants, etc. that come into contact with the mirror and which influence the micro-environment around the mirror, and 3. the thermal, mechanical and chemical environment in which the mirror must function. This environment results from a complex interaction between the external environment and the various materials and the way in which they are used in constructing the final hardware making up the mirror module.

Having an appreciation for each of these areas and their interaction it should then be possible to develop a test or series of tests for each of these categories.

The Sandia Mirror Deterioration Committee considered basically this same approach in isolating the various factors that contributed to the short time mirror deterioration observed in some of the first heliostat mirror modules exposed to the outdoor environment at Livermore, California (15). After a careful consideration of each of the factors which contributed to the observed deterioration, it was possible to develop tests to recreate field deterioration which were very successful in screening out potentially incompatible adhesives or potentially poor backing paints. From results of this work the committee concluded that design solutions, using current technology are available that could provide a minimum of 15 years service life with no significant deterioration. These designs employ the use of superior mirror backing paints and more compatible adhesives. There is every possibility that refinement of this technology could extend the life to 30 years or more.

Clearly laboratory tests will be required to screen or aid in the development of materials to be used in advanced heliostat designs, particularly for the selection of compatible adhesives and superior backing paints. Also, tests are needed to help better understand the silvering process and/or identify those process parameters that provide a silver/copper film with optimum corrosion resistance. Finally, accelerated outdoor exposure tests will be needed to evaluate mirror system designs and identify synergistic effects that may result from these designs and the interaction of the materials used.

3.7 References

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4.0 Workshop Proceedings

4.1 List of Attendees

Floyd Blake	ARCO Power Systems
Ross Cook	Binswanger Mirror Products
Sam Lamensdorf	Binswanger Mirror Products
Tom Coffin	Buchmin Industries
Dwight Royall	Carolina Mirror
Sonny Cherian	DOE Washington
Bill Hochheiser	DOE Washington
Jim Rannels	DOE Washington
Tom Anderson	DSET
R. H. Turner	Falconer Glass
Rolf Dieter-Pohl	Gardner Mirror
David Balik	General Glass
Steve Bomar	Georgia Tech
David Keith	Georgia Tech
Ken Maddox	Georgia Tech
J. D. Walton	Georgia Tech
Francois Toussaint	Glaverbel
Paul Potter	Hilemn Laboratories
Steve Wald	Hilemn Laboratories
Harry Bahls	London Laboratories
Tim Heard	London Laboratories
Joe Soltys	London Laboratories
Paul Brown	Martin Marietta
Ken Kordes	Martin Marietta
Lloyd Oldham	Martin Marietta
Charles Smith	McDonnell Douglas
Don Steinmeyer	McDonnell Douglas
Larry Delaney	Meridian
Brad Macaler	Meridian
Jo Meglen	Meridian
Red Mutzberg	PPG Industries
Dinesh Kumar	PRC
Joe Schrauth	Schott America

4.2 Transcript of Moderated Forum

WEDNESDAY, JULY 29, 1981

I. Morning Session

Review of DOE Solar Thermal Program - Jim Rannels
Mirror manufacturing - David Keith
Paints and coatings - Ken Maddox
Heliostat experience - Steve Bomar
Testing - J.D. Walton

II. Afternoon Session - Minutes, First Session (paraphrased)

MADDOX - Let's open by asking, can a mirror to last 30 years in a solar heliostat be developed? Or does it already exist?

MUTZBERG - We have evidence that it does exist, but from this morning's presentation I am hearing new conditions, such as adhesives, imposed on the mirror. We don't have the mirror needs clearly defined. So the answer was yes but now, not sure.

MADDOX - So it is a system consideration - design the mirror first then the heliostat, or the reverse?

DIETER-POHL - The need must be there, the market must be there. If so, it will be done.

MADDOX - What size market, one million square feet per year?

LAMENSDORF - Need much more, more like 100 million. We need to know the return so we can allocate resources.

MADDOX - How many resources will you need?

LAMENSDORF - Depends on the market.

RANNELS - Now the only market is Barstow. If it is successful, then the market will evolve. Southern California Edison is committed to build a 300 MW plant (alternatively 600 MW) like Barstow.

LAMENSDORF - Suppose we have a mirror that lasts 30 years, then where is the market?

RANNELS - It is not a federal market. There are probably a couple of years to go. We don't want to make technical errors. We must have demonstrated a technical success for the power companies to develop the market.

COOK - Success specifically means the Barstow project?

RANNELS - Yes, we must demonstrate technical feasibility, then it will be 9 months before DOE turns the plant over to Southern California Edison. They plan an early decision for 100 MW installed by 1985. If we have a technical success we can rationalize the economics but not the reverse.

COOK - What do you mean by that?

RANNELS - Each person will have to make the decision on an individual basis. Barstow is economical for DOE but 10 times too high cost for a utility. Take out the design and technical development costs, then we're down to 3-5 times too high. This could be rationalized as a first of a kind and could compare well to nuclear. On the other hand, if the plant is a technical failure, nobody will buy it.

COOK - What percentage of the cost of Barstow, or a commercial plant, is mirrors?

RANNELS - Heliostats are 30-50% of the total system cost, and mirrors are a large fraction of that.

STEINMEYER - Could be as high as 20% of the mirror module.

BLAKE - About 20% of the heliostat cost.

COOK - What about the relative cost of two 15-year mirrors for example. Is 30-years the right question?

RANNELS - DOE has looked at low-cost heliostats, mylar for example. Conclusion is that the lifetime does not justify replacement after 7-10 years. Also there is the labor cost and nuisance value to the utility.

COOK - That could influence the design.

SMITH - The French design looks easier to replace.

SOLTYS - The question about the market is solved - there is a market. It is the normal flat mirror industry. We need to improve because our reputation relative to Japanese and European mirrors is low. Any improvement will help in the real market.

RANNELS - I agree about the possible spin-offs.

SOLTYS - For example, Barstow uses a double paint coat; the Japanese and Europeans have been doing it for years. It shows how North American industry has stagnated, with respect to changes, over the last 10 years. All lines here have one applicator and one oven; two in Europe and Japan. So they can choose two entirely different paints.

LAMENSDORF - I'd like to hear what Red Mutzberg has to say about this.

MUTZBERG - I would defend American mirrors as meeting the current needs. What are the new needs?

BAHLS - The Europeans and Japanese sell in a market like Florida. Why couldn't American manufacturers do this and sell in Florida?

TURNER - They get a better price.

TOUSSAINT - In Europe, we use two different coatings and have two different tests. We have a humidity, or damp, test as well as salt spray. Certain paints are best for each.

TURNER - So you have different paints, depending on the application.

MADDOX - I wonder what were the coatings used at Odeillo?

DIETER-POHL - There were several types. One was orange, I guess it had copper dust in it. Some were grey. None performed as well as the 1952 mirrors.

SOLTYS - I don't want to leave the impression that we can't make good mirrors in North America. Actually the Japanese and Europeans have learned from us, except they take a different approach on the backing.

TOUSSAINT - All steps are important, of course, but you have said nothing about the glass itself. The mirror begins with the glass. The glass contains soda, and you may have sodium compounds leaching out. When you first make glass, the surface molecules are in a compact layer; this layer becomes less compact with time. For mirrors, you must use freshly ground glass because when the silica layer expands, the texture of the silver layer and its adherence becomes quite different. At Glaverbel, we never use glass more than one month old.

MADDOX - Again regarding the market and competition from Europe and Japan; are manufacturers worried about this competition - is there a need for further development?

COFFIN - This is the world's biggest market and everybody wants a piece of it.

LAMENSDORF - We salt spray test our mirrors and our competitors', and I believe we make as good a mirror as the Japanese and Europeans. One difference is the glass, because they select higher quality glass and use it expressly for mirrors.

COFFIN - I agree, but I do think that Japan has a better reputation in high humidity areas.

LAMENSDORF - We can't correlate salt spray results, but their mirrors are no better in salt spray.

TOUSSAINT - Salt spray is not a good test, humidity is a good test.

MADDOX - Is there a test you have confidence in?

SCHRAUTH - Sandia in 1977 put Schott no-iron B-270 silver mirror in a test chamber, and stated that test, 1977 to Sept. 1980, was more severe than solar; they privately said it was worth about 36 years. Again it's a matter of glass and coating techniques. The automotive field has had a wide range of experience although U.S. manufacturers have changed to front-surface chrome mirrors. The vertical integration of European glass/mirror manufacturers results in a good product.

DIETER-POHL - The US government in 1937 got a consent agreement from the glass companies not to vertically integrate. PPG was active in mirrors and also controlled prices at that time.

MADDOX - Is there any age criterion for glass used in U.S. mirrors?

LAMENSDORF - You want to silver as quickly as you can, but I can't believe that glass quality has anything to do with mirror degradation.

MADDOX - No better bonding?

COFFIN - What about Schott regarding borasilicate glass?

SCHRAUTH - No, it is a soda lime glass.

COFFIN - Are you saying it has better adhesion?

SCHRAUTH - I agree with Mr. Toussaint that glass is influencing the product. I know one outfit that spent $40,000 on cleaning glass, which verifies that yes there is sodium leaching. It has also been shown on glass watch crystals.

MADDOX - Now what about other opinions on mirror lifetime besides the silver/glass interface. Are there opinions on the principal degradation mechanisms?

SOLTYS - I don't think pure water is the culprit alone. Consider the carbon black in pigments, it is made from hydrocarbons and you can't wash out all the sulfur. Titanium is made from titanium chloride and you can't wash out all the chlorine. So you can't buy a perfect pigment, you're making a paint with the two worst things for silver - sulfur and chlorine, which react with water to make sulfuric and hydrochloric acids. This is why the humidity test is the best tool to determine how compatible a paint is with metallic coatings. Paint is very corrosive, especially if you remove the sacrificial copper layer. There are basically no coatings that can be applied on silver without corrosion. Excluding water may not be the whole answer either, you need a total system analysis. For example, the environment is basically acidic today.

COFFIN - Why do domestic paint manufacturers make a grey colored backing? International manufacturers use other colors.

MUTZBERG - It is basically style. We try to standardize on just one color to eliminate problems. If each mirror manufacturer wanted a separate color, we would have a horrendous problem. In spite of what Dr. Soltys says, the pigments are inherently inert compared to colored pigments.

MADDOX - What is happening in this problem with adhesives and contaminants?

MUTZBERG - Need to exclude sulfur and chlorine, which is what the paint is designed to do. There are a lot of corrosive compounds occurring naturally. I was shocked to learn that the voids in foam glass contained H_2S. I would naturally avoid this.

SCHRAUTH - There are two methods of getting the glass into bubbles, one is hydrogen sulfide.

MUTZBERG - If you know this up front, then you use another way.

SCHRAUTH - They indicated that when the glass was cut, you could smell it. The paint used was a double coating, the first coat being red; looked like red lead. Black was used on top. For further protection, other layers have been used on top of those; and they seal the edges.

MUTZBERG - I would defend the paint industry in general. The current backing meets the current needs of the industry. We can't be running our business on an exception basis. I am sure a much better paint can be devised to meet exterior needs. Again we need to narrow the field so we can spend research dollars to develop paint to fill the need. I see 6-7 different heliostat types; somebody needs to decide on one before the mirror industry can develop a better mirror. We can double coat like Barstow, this system should be much better than the standard mirror.

MADDOX - Let's deal with testing, what about the ferric chloride test?

SOLTYS - No, this is not the answer. Ferric chloride is a one-hour test and is just a fast salt spray. You are measuring edge penetration. We don't know the significance of this test. It is a quickie test used as a QA tool to ensure consistency. Couldn't possibly signify the life of the mirror.

WALTON - Following up on what is in the paint and its reaction with metallic films, maybe we need to rethink heliostats. The Caribbean and humid climates represent one market maybe, but perhaps we should look at different paints. We don't cut the mirror edges for heliostats, so why use the same paint if contaminants could be a problem. We don't necessarily need research, PPG could give us a paint for copper that doesn't have the postfabrication requirement, then it can be tested. But quick tests aren't going to tell us.

ANDERSON - Why does the paint have to be pigmented at all?

MUTZBERG - We use pigments so that the paint will break clean rather than hinge. We are talking about a total mirror system, and the glass is a factor, we are still trying to find out, with any test, how the total system will perform in 30 years. I don't feel that anybody can say with a fast test. I'll criticize salt spray till the cows come home but defend it against any other test. Any test is a tool but it must be interpreted and its validity considered. You have some evidence that these 1952 French mirrors held up and they were "standard best quality." You have that data, but some of these encapsulation methods are making it tougher. Also, are your expectations higher today?

SOLTYS - Baking or curing is a factor as well, as is the paint formulation of pigments. Paints age with time and their chemistry changes.

MUTZBERG - All vehicles degrade, and most all paint films shrink with age. This produces stress on the system, again if you have a poor bond then you have lack of adhesion of the silver to the glass. The whole mirror system is a compromise of the needs. We can improve some properties if others are sacrificed. I am hearing that you don't need postfabrication, so now maybe we can exclude water better.

MADDOX - Let's try, in general, to speak about types of tests that apply and what effects they may have. Perhaps we can reach our goal of some concensus on how best to proceed from here: new mirror, new heliostat, or new tests.

TURNER - I had spoken to you about submarine mirrors, we had coated mirrors with pitch, and a copper screen to hold it, I recall it was softened with heat. We coated an ordinary mirror with mastik and laminated it to masonite. No way could it be spoiled. We also had such an installation in a storefront. Why can't we use a pitch or compatible mastik that is impervious?

WALTON - This is a good example of the interface between mirror design and heliostat design. I recognize there are compromises. Can you make a 30 year mirror - yes, but. Silicone grease as used in the Northrop heliostat is another similar example.

III. Second Afternoon Session

MADDOX - Let's direct the meeting to a review of testing. We want to work toward the identification of a test or test series that might give qualitative indication of mirror lifetime.

BROWN - I didn't hear comments on what might have been observed on parabolic troughs.

KEITH - Up until only recently, glass mirrors were not used on troughs. Acurex has recently started using thin glass Glaverbel mirrors and they have experienced some problems with adhesives.

SCHRAUTH - You should have 50,000 sq. ft. of 3mm glass mirrors in use in parabolic line focus applications very soon, specifically the Georgia Power-Shenandoah job, Home Laundry in Pasadena, and the Alberquerque V.A. hospital. Some have been installed for two years, but not full operation, without serious degradation. I emphasize the edge sealing requirement. We had 5-6 years exposure at Sandia with no problem.

BROWN - It looks like maybe we have a 5 or 6 year exposure test result here we somehow missed.

SCHRAUTH - Another application is railroad crossing signal lights, which is a second surface glass outdoor exposure. There was only one supplier until recently when Schott got into it.

MADDOX - The difficulty is finding exactly what was done and in tracing the history of the mirrors. J.D., please review the test classification.

WALTON - I don't know if a mirror outdoors in a sealed enclosure is really a valid indication. Referring to page 38 of the discussion paper, we hope to get some kind of critique to improve upon this position. First category is the test of copper/silver films, which might be a better test as information to the manufacturer rather than the user, with regard to compromises. Second is a test of protective coatings, basically of the salt spray type, except the electrical conductivity test. The third category imposes thermal cycling adding the impact of both temperature and humidity effects. Fourth category is accelerated outdoor weathering. The fifth is materials compatibility. The comment was made that you couldn't tell the origin of a mirror using salt spray, yet one had a better reputation in the Caribbean and S. Florida. Is there a test that might show the difference?

TOUSSAINT - We want to decide what test we should use?

MADDOX - Yes, one point is: can we work backwards from the results of a test to correlate lifetime?

COOK - Are we asking the right question, since regarding the main present concern, heliostats, the environment is the U.S. Southwest, not S. Florida. Also we have seen that where you did have moisture but it was allowed to escape, you didn't have a problem. So the question is, do we really need to provide a new protective backing for high humidity?

MADDOX - But there was mixed experience; Mt. Louis was good but Odeillo was bad.

COOK - It seems important then to find out exactly what the coatings were.

WALTON - We do plan to analyze a Mt. Louis mirror, we don't have an Odeillo mirror as they were all stripped and resilvered.

MUTZBERG - We can analyze it at PPG if anybody can. Possibly could even differentiate if it was a two-coat backing.

WALTON - The mirrors at the Georgia Tech facility use a standard, single-coat backing and are free to drain. I suppose we have acid rain conditions, these are still not the best conditions and it may be an undesirable constraint on designers if we say we must use this system.

BLAKE - As a heliostat manufacturer, we are not asking for a new backing, we are standing on the cornerstone that manufacturers got us to and we are changing with the utmost caution. We have twice made 30-year mirrors (CRTF -Alberquerque and Barstow), they just haven't been tested that long as yet. Mt. Louis got 20 years exposure with just a coat of paint. If you laminate glass, then yes 30 years can be achieved. The question is, can it be done cheaper, then the question is about paints. The problem was to modify an interior mirror, so added automotive paint, then found the mirror was sitting with a sponge of water, yet it didn't degrade. The only possible problem area is the chemistry of the paint.

MADDOX - What about the question of comparitive tests, laminated vs. painted mirror?

BLAKE - In humidity tests performed by Sandia, differences as great as 20:1 were reported between mirror samples from manufacturers, using interior paint. Take a good mirror, add the backing paint, so that should do it. The worst sample lasted one year, so the best should be good for 20 years, so you're pretty well down the road.

STEINMEYER - We have been running weatherometer tests with no edge deterioration, even without edge seals, for many hours with no problem on our laminated mirrors.

MADDOX - Is there a way to transfer the experience with laminates, which appear too expensive, to painted mirrors?

STEINMEYER - It is too simple to say the laminated mirror may be too expensive because of weight. There are other features to consider, such as higher reflectivity achieved by use of thin front surface glass and increased stiffness to handle wind loads. So it is not simply to solve one problem (durability) that you go to lamination. Look at the total system if you want to trace bottom-line costs; after all glass is a fairly cheap commodity.

BALIK - Again, thin glass is available to produce an overall 1/8 inch laminate. It is not in high demand but could be produced.

MADDOX - Can anyone correlate weatherometer data with exposure?

STEINMEYER - Can be related to stress type durability overall, we do know that true failures, those that fail in exposure, will fail very rapidly in the weatherometer. But for those that don't fail quickly in the weatherometer we don't have a correlation.

COFFIN - For either salt spray or weatherometer, the manufacturer doesn't get the results until well after the product has probably been shipped. Since you can't recall the mirrors, how do you solve the problem?

MADDOX - For heliostat applications, couldn't you hold the mirrors or put a trace on them?

COFFIN - How about in the future when heliostats are common? Mirrors don't sit around our plant.

TURNER - When the subject of guarantees came up, someone once said if mirrors last one year they will last a lifetime. The question was, why not age them. Nobody had a warehouse big enough.

MADDOX - Regarding the weatherometer, is there a standard test procedure?

WALTON - Related to Florida, does anybody have weatherometer data that shows that problems might be expected in that environment?

KEITH - One mirror manufacturer had some tests run by South Florida Testing Service. Was it any of you? (No)

MADDOX - Is there another test we can use?

SCHRAUTH - European tests are two DIN standards, humidity and salt spray. Sandia, Sam Martin, has translated at least one of them.

WALTON - Mr. Toussaint, can you tell us?

TOUSSAINT - All tests are based on the Belgian norms 23001, which are about 10 years old. During production there is the adhesion test of the silver/copper bonds (peel test - Scotch tape). After production, we scratch the backing (crosshatch test). This classifies the mirror into five categories, and gives data on the adhesion of the paint on copper. We have two tests on products coming off the line - damp test and salt spray. The damp test is run at 100% relative humidity, results in 3 types of quality (A,B,C). It reveals mainly defects in the silver layer, 759 hours-A, 500 hours-B, and 250 hours-C, at 50°C, no alteration of the surface may occur. The salt spray test is mainly used to examine edge corrosion, not surface. Again rated in 3 qualities. 5% NaCl in de-ionized water at 35°C. For automotive applications, the thioacetimide test is used, but it is not a Belgian norm. Used mainly for German cars. Solution of water with 5% thioacetimide, a very short test, 24 hours, followed by 1 hour wash, then dry 23 hours at 70°C. Test is for 3 cycles. No corrosion may be observed. This is one of the most severe tests for us. Also we are doing, especially for solar, cycling chamber tests, quite similar to Sandia Alberquerque, -20°C to +50°C, 2 hours at -20, 2 hours rise up to +50, 2 hours at 50, 2 hours down to -20 again.

WALTON - Is there a correlation between tests and experience?

TOUSSAINT - No, but I feel that the automotive-type tests are the best for outdoor exposure of 10 years. We have made laminated mirrors for the last 10 years and we give a 5 year warrantee for indoor applications, like bathrooms. I don't think a mirror manufacturer could now give a guarantee for a simple, unlaminated, glass mirror.

SCHRAUTH - No manufacturer can give a guarantee to a mirror, even for automotive use where it could be subjected to any type of handling. There is no control over what will be done to it. The manufacturer needs to be informed of the heliostat design and build for it.

MADDOX (to Toussaint) - Are tests run on each batch?

TOUSSAINT - The Belgian norm calls for at least 20 samples, 10 x 10 cm. The tests must be run on finished samples. If the mirror is to be ground, for example, then that must be done first.

MUTZBERG - We have a customer in Italy, he got samples from two different American mirror manufacturers and they passed these tests with flying colors. Also there was a CASS test in the series. They are using PPG paint but they are not getting the same performance. The point is A. Good US mirrors will pass European tests; B. Having the right supplies is not necessarily all that is required to produce good mirrors. QA includes keeping logs and trying to minimize and trace errors. Glass is important, including cleaning glass and the type of glass.

WALD - Francois, what is your experience with Glaverbel mirrors, what % ABC?

TOUSSAINT - B is a mean value. We produce only A and B.

MUTZBERG - Do you know why you are getting A and B?

TOUSSAINT - No tests have determined that. We have observed that the difference seems to come from the glass state, especially from the product used to package the glass.

MADDOX - Have the same tests been used here? Are there correlations?

MUTZBERG - My operation has; I can't see the correlation. A lot of the tests don't give any indication of the service life. I'd like a better test but I don't want to overtest. All tests seem to indicate quality of workmanship, largely paint, somewhat metal solutions, also glass cleaning.

MADDOX - Then the tests are primarily QC tests, checking for consistency.

MUTZBERG - You have to know when to stop testing.

TOUSSAINT - I think the tests are valid because they are also used for automotive mirrors.

WALTON - Have you seen mirrors pass the tests and subsequently fail outdoors?

SCHRAUTH - I've seen clouding and delaminating, as Red says it depends on the manufacturer. Is there a test that will show that any manufacturer using the same materials will produce the same mirror - no.

WALTON - I guess that mirror mounting for automotive use is pretty standard.

SCHRAUTH - The mirror companies and automotive designers work together, rather than being fragmented. Probably a greater interchange results in better consistency of the end product. With regard to adhesives and enclosures, they found some condensation in the housing so now they use a double-stick tape and the mirror is stuck on the housing.

WALTON - There seems to be some problem with the tests available. They all test the same thing, and this redundancy leads to a lack of correlation. What I am hearing is that we don't really have a valid test.

MUTZBERG - What we do have is empirical data on interior-use mirrors, and an interior mirror will last 30-40 years. What then are the differences for exterior use on which to base exterior tests? The reason for the new Barstow paint was to improve water resistance, so now the current criteria and tests should measure improvements in water resistance. But, as Ross (Cook) pointed out, the mirrors will actually be placed in the Southwest, a low humidity enviornment.

SCHRAUTH - The humidity is low, but you do get condensation.

MADDOX - The national labs and industry brought up that water was a central problem, if not causitive at least catalytic. Should our focus be on water resistance?

TOUSSAINT - The humidity test is mainly used to reveal surface defects. With laminated mirrors, you mainly have edge problems. For edges, salt spray is the best test.

MUTZBERG - Then the question is, of the failures, why have they failed? What is the purpose of each step - paint protects copper from what? First you'd like to eliminate permeability, then for a laminated mirror you need edge protection. Remember that a cut mirror has no protection on the edge, and most survive.

STEINMEYER - We do believe failures (edge deterioration) of laminated mirrors we have seen was a combination of the paint and the laminating process.

MUTZBERG - So a paint should be designed to meet the needs of laminated mirrors.

ROYALL (to Steinmeyer) - How deep was the edge penetration you saw?

STEINMEYER - An inch at the most, 1/4 inch on average. And most of the mirrors have been out there since 1977.

WALTON - The CRTF mirrors were laminated four years ago. In June we inspected them and could find no visible edge penetration. If lamination is the way to go, I think it's appropriate to try to get the same lifetime without lamiantion if only to provide designers with another option. If you use really low-iron glass, you don't need thinness, Schott says they can give 94% reflectivity on a 6 mm glass mirror.

MADDOX - To summarize where we are, we have two candidate tests: 1. weatherometer - seems to indicate both success and failure in the field; 2. A connection between the tests done in Europe and outdoor exposure. The question is, are these two sufficient?

ROYALL - It's tough to wait 30 years for the results to see if the test was any good. The majority of the failures seem to be related to the installations, and how the mirrors were used rather than the quality of the mirror itself. For example, those boxed-up mirrors appeared to lead to more failures than those open to the air.

MADDOX - Although, again, remember the Odeillo mirrors failed quickly.

MUTZBERG - There have been many papers now published on degraded mirrors. If we can identify the degradation product, then we can address the protection (and test) needed to meet that need.

ANDERSON - I don't think you'll find an accelerated test to answer all the questions. The tests are relative screening tests. There is no substitute for real-time testing at many different locations. Local micro-environments strongly affect materials. At DSET, we don't have much experience in second-surface mirrors. We only can rank one material against another by our tests, we don't have a test that can give a guarantee of 1-5 or 30 years life expectancy. The French mirrors may have held up well for a variety of reasons, especially local climate and pollution levels.

MADDOX - It sounds like we need a compromise.

MUTZBERG - All of the data we have now is very arbitrary. We need to try to identify every variable involved, we need a good handle on all factors of the mirror that was produced and how it was used and installed. Some researchers I know of got some mirrors from a job shop and did $500,000 worth of research on them - the mirrors were just some culls or cut-offs.

COFFIN - What can we do - we could analyze it by stripping it and seeing how much and what kind of paint, silver, and copper was there.

MUTZBERG - Whoever does the research needs to know what the variable are.

COFFIN - Has anybody proved that more silver makes a better mirror?

ROYALL - We saw it the other way. We found that when your copper gun stops up you'll get the mirrors back after a while.

MADDOX - We don't know much about the oldest mirrors; the question about the thicknesses of the metal layers has been answered both yes and no. Ultimately, the only way to find out is to build a mirror, know what it's made of, and test it in the field for a period of time. But we now must make a compromise. As Jim (Rannels) said, he can't afford a bad technical failure early on.

SCHRAUTH - As far as film thicknesses go, I want to throw out the results reported by Dr. Gupta of JPL. They have determined that there are small voids in standard silver and copper layers, and that UV radiation is going through and degrading the paint. The thickness is an important variable, and atmospheric variations at the specific site can lead to significant variation. Perhaps then thicker layers and/or UV inhibitors in the paint could help. This could be tested by EMMA or EMMAQUA.

BAHLS - The most logical approach may be nothing more than humidity testing since the Battelle reports indicate water most likely must be present for degradation to occur. But a data base must be developed because there is very little in the mirror industry. Perhaps the humidity test could be coupled with sunlight if that is a factor.

THURSDAY, JULY 30, 1981

IV. First Morning Session

MADDOX - Let's spend a few minutes summarizing our discussion of testing from yesterday. There appear to be four areas needed in any test series - 1. liquid water, 2. thermal cycling, 3. radiation, and 4. materials compatibility. Are we agreed upon this? (Apparently so.) Let's now turn to the question of mirror durability. A typical mirror crossection has been drawn on the board. Starting with glass, we add silver, copper, backing coat, possible adhesives, backing sheets or laminates. We would like to use this figure together with the list of questions in the discussion paper to decide where one would look to build a better mirror for outdoor applications.

DIETER-POHL - You are making the premise that mirrors are not presently being produced right. All major manufacturers have controls and log every production run every day, several times a day. Ours are computerized back to 1961. We don't need the security blanket of one test or another test, it is a confirmation of our confidence in our production run. We can trace what happened on any given day. I think all good mirror companies have that sort of control. You should have some confidence in your supplier. We as an industry have already made great strides for solar. We don't need a battery of tests for security. All mirror companies have made experiments of various methods of manufacturing. Mirrors made today are under far better control than was possible in the past. We know exactly the weight of silver and copper, within $\pm$ 2.5%. You should start with the premise that the manufacturer knows how to make his product.

MADDOX - I agree that the product today is very good; the question is whether a new set of engineering compromises needs to be made for solar heliostats.

SCHRAUTH - As Jim Rannels said, the technical spec of a 25-30 year mirror is required. That mirror is available. The problem is the way they are used. The Mt. Louis mirrors were OK. The Georgia Tech mirrors were OK except where damaged by cleaning solutions. It is the engineering design of the application - there needs to be a better interchange made with the mirror manufacturers by the heliostat manufacturers.

MADDOX - Is there a general concensus that indoor mirrors can last 30 years outdoors?

LAMENSDORF, COOK, TURNER, HEARD - Yes, perhaps with another paint.

DIETER-POHL - You need to know what the environment is.

MADDOX - What about Florida?

DIETER-POHL - I have no problem with Florida.

LAMENSDORF - You adjust to the case, by providing edge sealing or whatever.

COFFIN - I have seen a lot of mirrors with edge corrosion just as they come out of the crate.

LAMENSDORF - I would hate for the DOE and this group to leave with the impression that the National Mirror Manufacturers Association and the individual manufacturers are not trying to improve the product. My company has 30 people in the R&D section in New York as well as a private firm.

COOK - Ask the paint manufacturers if they think they're satisfied with the product.

MUTZBERG - What we're all saying is that we all believe the present quality mirrors will survive providing field conditions are not unusual. Also we'd like to hear what conditions the design is going to expose the mirrors to. Many of us could make an evaluation before the fact whether the mirror would meet the design conditions or whether a modified mirror would be required. For example that's what developed in the Barstow case. The entire mirror, after surviving the adhesive, was encapsulated, which seemed to be even better than indoors. Then the assembly was tested in a humid environment and there was water trapped. So then we had to add water resistance, which was the second coat of paint. In actual usage, the Barstow mirrors shouldn't be in contact with any water, unless perhaps from condensation.

MADDOX - From the heliostat manufacturers, is there any indication of what will be required?

OLDHAM - There are basically two things that drive the mounting design. The first is cost, a leading and overriding theme, in spite of what Mr. Rannels said yesterday. The mirror is one component of the cost, maybe you could save some on the mirror but the overall cost is paramount. Second is wind loading, the fact that this thing acts like a very large sail. Also you can get hailstone damage. The problem with a mount like your bathroom mirror has upstairs is that it can't hold up in the wind. We have had to do a lot of work and make many compromises, like Red (Mutzberg) says, for Barstow.

MADDOX - The greatest degree of confidence I have heard was in laminates, except for their cost. Can we draw some conclusion from this?

STEINMEYER - Yes, but once again you have slipped up by saying the laminated mirror has a higher cost. It is the system cost that is important. You must compare the total cost of holding that mirror. It is not clear that that is or is not a lower cost method. Regarding the comment about foam backing -the data was not presented but we have been able to make a sealed foam-backed mirror last for at least a couple of years. We abandoned that design on the basis of cost, laminated mirrors having a lower total system cost.

MADDOX - There have been two alternaties presented, laminated and those with a second coat of paint. Are there other compromises?

BROWN - For government procurement, we are required to produce a heliostat that is all-purpose, to survive all over the world. If we could compromise, we might change some of our designs or tailor our designs.

TOUSSAINT - When you speak of special coating formulas, I don't think you will get 20 or 30 year lifetimes because it will depend on the local environmental conditions, for example mountains or seashore. For me, the best coating is to laminate, then you have only one coating, glass or steel. Then the mirror back is protected and all you need to worry about is the edge. I don't think they will be very severely corroded if the back is protected.

MADDOX - I heard at least one vote for lamination, but I also heard we can tailor the design to suit requirements.

OLDHAM - I heard, from I guess London Labs, about increased copper thickness. Will that increase durability?

HEARD - Yes, in general it should improve quality of the mirror, but not if it's put in a box of water.

LAMENSDORF - What exactly did you say about copper?

HEARD - We have a copper process by which you can add copper in much greater thicknesses without destroying the adhesion of silver to the glass as happens with galvanic copper. We have applied up to 700 mg per sq. ft., but we can't guarantee this as a panacea, especially in the presence of much water.

MUTZBERG - We are back to the testing question.

HEARD - If you know what the type of heliostat application will be, you can decide on the thickness of copper you might use.

TURNER - We've had quite a lot of experience with copper films. Back in

1932 we copper plated all of our production. I think electroplated copper films are highly superior to the galvanic. But if you're going to put copper on thick, you need a thick coat of silver. Back then we silvered the bottom of some light bulbs, then we dipped it into copper and plated it, with a thick layer of silver. The silver was applied without even sensitizing because you didn't need to. You couldn't even remove the copper with pumice. I had those bulbs around my desk for 10-12 years with no coating on the copper. I have a very strong feeling about the copper coating and the protection it gives. Looking at a galvanic chart, silver is +.8 v, copper is +.35, just about any other metal is negative and will corrode faster, for example chromium is -.71 and cobalt is -.3. If you put that couple in a humid atmosphere it will spoil, so it also depends on the environment. The coating we had was not specular or reflective copper, it was granular, perhaps even somewhat porous. It was very thick but probably less than 200 mg. per sq. ft.

SCHRAUTH - One thing that may be a problem is DOE saying you must meet conditions anywhere in the world, so the cost goes up. Yet according to Rannels and Reagan, they are stepping out of the picture but want to see commercialization. I think we need to look closer at what is really required for the actual commercial application, rather than what DOE requires.

COFFIN - As far as the laminated mirror goes, when it leaves the manufacturer's building, I know of no further problems. I think it can last 30 years. The coated mirror I don't feel confident about for 5 years, I don't have any idea how long it will last. For example, in the Florida market there have been problems. I believe the laminated mirror is a sure thing, the other is an unknown.

MADDOX - Do we have any experience with laminated mirrors in Florida?

TURNER - I don't think many have been sold because of the cost. I have a house in Florida, one year I left my Olds sitting out all summer. When I came back it was so bad I had to have it repainted. The dew on the car tastes salty, when it dries the salt is still there. I saw one Belgian mirror in Hialeah, with a sign saying it could withstand boiling water, but it was very expensive.

COFFIN - Another product is the monolithic mirror. It is vinyl-backed and used in showers. It has been very successful.

DIETER-POHL - That was tried in 1971, but was not successful outdoors.

MADDOX - What about the question now of tailoring, there was opinion expressed that a manufacturer doesn't want to use his line to produce special products, and today we have heard something a little different.

SCHRAUTH - You would consider cost as a factor. You might have a few different designs to suit the local climate-mountains, seashore, or industrial pollutants.

MADDOX - Then there are two cost factors - one for all environments, one for tailormade.

LAMENSDORF - We all do that already. We make a tub enclosure mirror, we do special things for Florida, we will do specials for solar. But first you determine how big is the market, what needs to be done to the product, and can I make a profit.

MADDOX - Laminates, new backing coat, are there any other alternatives?

BOMAR - What about more silver again. The national labs say it's the thing to do, the manufacturers seem to dislike it.

SCHRAUTH - Dr. Gupta has indicated that there are pinholes in standard mirrors.

LAMENSDORF - I am not sure that 70 mg. per sq. ft. is the right amount, but I don't think putting on 3 times the silver will help.

COOK - In fact I think JPL has said that at over 100 mg you begin to lose reflectivity.

HEARD - No, but I think you may begin to lose adhesion. We tested 30 mg (which looked black) to 150 mg silver-layered-mirrors in salt spray tests and we saw no differences. Reflectivity is the only reason for the thickness being what it is. Optical reflectivity begins to drop at around 56 mg. (providing the silver is copper-backed). Anything heavier than that is a waste. The reason for 70 mg., is to provide a safety margin for thin spots.

DIETER-POHL - Don't you have a very flat curve above 55 mg.? The reflectivity leveled off at weights heavier than 55 mg. per sq. ft.

HEARD - Yes, above that point it is practically the same as bulk silver.

TURNER - I agree, and if you put on a thick coating of silver and then thick copper you can practically peel it off.

SCHRAUTH - At what level do you begin to lose adhesion?

HEARD - I don't know, but I guess around 100 mg.

BAHLS - With regard to the fact that there are pinholes, we think our Dispro Copper can help solve this problem.

HEARD - We supplied Sandia with mirrors having 600 mg copper. They found that the total reflectivity of the mirror was higher, mainly due to increased UV reflection. Copper reflects UV whereas the silver is a sponge for UV.

MUTZBERG - We don't know why mirrors are failing, that's what we've got to define. Is it silver thickness, UV degradation, paint, glass, or what? What must the total system withstand? We have seen examples where the standard mirror is holding up quite well.

MADDOX - The one general conclusion in the literature is that water must be present. It appears to be acting from the rear and from the edges. The national labs are looking for other factors at the atomic level, but at the macro level it appears that water is the main culprit. Another question is other metal coatings, such as chrome or others, instead of or in addition to copper.

TURNER - You might protect it if the metal was not too far from copper on the galvanic chart, but nothing really comes close. Tin is - 1v, cadmium -4, nickel -2.5, Under humid conditions you would have a battery.

MUTZBERG - Assuming water is getting through the backing, then you must have something else since water alone doesn't attack copper. Something dissolving out of the paint, perhaps. If we know, then we can exclude these contaminants from the paint.

SOLTYS - Mr. Turner's reference to the galvanic chart shows why copper is such a good sacrificial metal. It is the same principle as putting a protective anode on the hull of a ship. If you put a coating on silver without copper, it will spoil in 30 days on its own, or overnight in a humidity bath. Industry likes to put on 30 mg. of copper. When copper oxidizes, it picks up two electrons wheras silver gains only one. So copper at 30 mg. is better than silver at 60 mg. Also the difference in molecular weights gives copper another 2:1 advantage. So the 30 mg. copper layer is equivalent to an extra thickness of silver, except that the copper must go first and in so doing it does not lead to any loss of reflectivity. There is no question that the composition of the paint could contribute to spoilage. I don't want anybody to leave thinking there is no room for improvement. Starting with what the gentlemen from Belgium said, you are at the mercy of the glass company. The glass ages very quickly. Glass cleaning is most important. We really should be working from the bottom up. There is room for improvement.

TURNER - I don't think the cleaning methods we all use today are so effective. In the old days, we blocked (repolished). Back in the '20's, all glass was put on the blocking machine with red rouge, which took out the sleeks and rubs which we had in glass but you don't have today. So I agree, there is room for improvement, but this adds more cost. We're not having too much trouble with glass today. Because of the new float glass, I think all the old blocking machines have been junked. At Odeillo, where they used plate glass, and resilvered it, they must have blocked it to polish it.

SCHRAUTH - On the Barstow float glass, did they determine which side of the glass was the virgin side, not the tin side, for silvering?

SEVERAL MFR'S - We always check.

COFFIN - But at 2:00 a.m., there are times on occasion when the wrong side gets silvered.

MUTZBERG - It usually makes no difference, but sometimes it does.

SMITH - How long does an unpainted mirror stand up?

HEARD - Christmas ornaments are made this way, and they last for years, but indoors.

COFFIN - Another market is the decorative mirror, these are silvered and then etched away.

V. Second Morning Session

MADDOX - Let's try now to work toward a concensus. Let me recapitulate on testing. There was no agreement on specific tests that ought to be performed. There were desirable characteristics, such as: 1. liquid water, 2. thermal cycling, 3. radiation, 4. materials compatibility.

SOLTYS - Musn't exclude salt spray because it does serve a function. You can distinguish between two batches of paint by the degree of undercutting. So it's one of the best tests we have.

WALTON - Perhaps we should say these characteristics in addition to salt spray.

HEARD - Is it possible to analyze some of the French mirrors, to compare them with today's mirrors?

WALTON - Yes, we intend to try this.

MADDOX - Would it be wise to also try to get others as standards?

ROYALL - Here's an old mirror (holds one up). We can try to make history repeat itself but I don't think you could stand it. In 1957, everybody was using cold silver.

DIETER-POHL - And there was a different paint formulation.

MUTZBERG - Yes, it was different.

WALTON - We must be able to characterize the old mirror, how it was made.

ROYALL - This mirror has about 80 mg of silver, 25 mg of copper, and one coat of the earlier Mirror-con paint (PPG). We can't use that paint now in North Carolina for environmental reasons.

MUTZBERG - The new paint is better.

LAMENSDORF - Are you saying the old mirror is better than those made today?

ROYALL - No, today's are better.

MUTZBERG - We have some mirrors now on our exposure farm in Florida to test the effects of UV on paint, but we don't have any conclusions yet.

MADDOX - A third area brought up was keeping records of the mirrors supplied for heliostats. Is that being done?

DIETER-POHL - It is requested as part of the spec, but it is done routinely anyway.

MADDOX - Is there access to this information for review?

DIETER-POHL, LAMENSDORF - Sure.

MUTZBERG - At a previous meeting, it was said that they were going to try alternative methods, make one heliostat of each and try them.

STEINMEYER - That is in the program now. There is an attempt being made to place the mirrors used in the Second Generation Heliostats in a number of locations.

OLDHAM - But they are simply placed on racks.

BROWN - Glaverbel is putting mirrors on one of our heliostats in Almeria, Spain.

MADDOX - Regarding the suggestions on alternatives or mirrors themselves, can we make a summary? First, laminates. (no response).

WALTON - Can we agree that commercial technology produces a mirror with a 30 year lifetime if it is protected from the atmosphere? It is the protection that is the problem.

COFFIN - What is the mirror protected from?

WALTON - Water, chemicals, etc.

DIETER-POHL - The techniques are there, the QC is there. The additional protection is added depending on whatever the hostile environment demands.

WALTON - Is it paint, more copper, more silver, or just what?

MUTZBERG - It is a total system.

WALTON - Isn't keeping the environmental elements out the first priority?

ALL - Yes (general agreement).

OLDHAM - I have some reservation; an existing mirror lives 30 years indoors, where there is no thermal cycling below freezing, no UV, and little or no condensation. There are some unknowns because nobody has been able to demonstrate a 30 year mirror outdoors. The French have some early experience, but since that time they've made installations in which they've had problems.

WALTON - Mt. Louis does not get too cold, maybe +10°F.

OLDHAM - On the second try they didn't do as well.

WALTON - They used a much less expensive mirror the second time.

MADDOX - Protection can then be accomplished in several ways. Laminination appears to have advantages.

LAMENSDORF - About three years ago, we supplied laminated mirrors to the Navy for use in Florida. I have heard of no problems.

COFFIN - I have heard of no problems with laminated mirrors anywhere.

MUTZBERG - You just need to make a good mirror inside.

HEARD - It may not give the heliostat manufacturers quite as much flexibility, but you are sure that under any circumstances the mirrors will be OK.

SCHRAUTH - I believe it is also possible to have an unlaminated mirror, just painted, that can survive. Automotive manufacturers have done it, I know of a 1953 Ford truck, the mirrors are in great shape.

COFFIN - But automotive mirrors are small.

SCHRAUTH - But it is being done. All I hear is tht laminating is the way, you do have the higher mirror cost though.

WALTON - We're talking degrees here, maybe that's why we have been stressing lamination. The point is that you can just about guarantee the reliability of a laminated mirror; paint can be made to work but can also be subjected to conditions in which it will fail. Does anybody disagree that laminated mirrors provide the highest degree of confidence?

DIETER-POHL - There is one reservation I have about lamination, that is the type of glass. For instance very thin glass is different to prepare for silvering.

WALTON - Do you mean 1/8 inch thickness, or is it less?

STEINMEYER - We have about 0.080 inch glass in our present laminated mirror design. There are a number of other considerations in making heliostats with laminated mirrors, but in terms of durability it is the solution. Our cost numbers are quite different from those shown in the discussion paper. We have also successfully tested 0.060 inch glass.

MUTZBERG - With regards to paint, if laminated mirrors are to be used, we can make an appropriate paint for the lamination process. We have a paint made in another division of PPG that we guarantee for 20 years; it's used for prefab aluminum buildings. They are sellling a lot of it. It is teflon-based, a flourinated hydrocarbon, and is cured at a low temperature, maybe 350°F for 10 minutes. There are a lot of things that are feasible, again the economics are a factor, including the facility to apply and cure such a coating. Again, nothing specific in this area has been developed for the mirror industry.

WALTON - For reliability it is still the laminated mirror.

MADDOX - Yes, I am hearing that there is high confidence in the laminated mirror to last outdoors.

SOLTYS - I don't think there has been enough development done, specifically as applied at Barstow. It should have had a special base coat as well. I think a non-laminated mirror can be just as reliable with a non-corrosive paint coat and the requirement for post-fabrication removed. Also if the Barstow top coat was an off-the-shelf paint, problems may later occur because you need buffers. I don't think the industry has addressed itself to the problem. It's not a matter of dollars either because the paint chemist can put together something quickly.

MADDOX - Let's address paint further.

HOCHHEISER - There's another step. If laminated mirrors will last, why not stop there? We need to address the engineering compromises that resulted and find out why heliostat manufacturers chose not to use laminated mirrors.

WALTON - It's flexibility in design. Does anyone have experience with aluminum paint?

SOLTYS - No, not specifically, but Mr. Turner reminded me that old paints were ordinary shellacs with a lot of copper powder. Definitely copper or aluminum powder should help, as buffers, in protecting from corrosive chemicals.

TURNER - You must keep them out of contact with silver. Over copper the paint might be quite effective.

SCHRAUTH - Yesterday, I mentioned the railroad crossing reflectors, one I saw had an aluminum-colored backing to it. It is outdoors, boxed and contained, I don't know if it has any breathing.

OLDHAM - I think laminated mirrors are great too, but we have only about 5 years experience with laminated mirrors. I have seen laminated mirrors that have corrosion. PVB is a hygroscopic material. If you ingest moisture into the PVB and it interacts with the paint, you might see a catastrophic failure.

ROYALL - Has anybody asked the French manufacturer how those mirrors were made?

COFFIN - Remember PVB was used in laminated sheet glass because of its transparency. Perhaps for mirrors there are other materials that would be better.

WALTON - The years of experience with laminated glass in the auto industry have been very good, but there are edge seals.

BROWN - Our exposure tests show that you do get corrosion around the edges.

WALTON - Remember we saw no corrosion at the CRTF.

BROWN - I should point out that Martin-Marietta supplied those mirrors. We have kept some at our facility, that have had corrosion, though the environment is different.

MUTZBERG - There you are.

SCHRAUTH - If you use glass that is too thin, you laminate it.

TOUSSAINT - We are mirroring glass that is 6/10 mm without much difficulty.

SCHRAUTH - With the absorptive-type glass you must reduce the thickness to get high reflectivity. There are glasses that can get you up to 90% reflectivity at 17 mm thickness.

COFFIN - Can you make it in 4x8 ft. sheets?

SCHRAUTH - It's possible. The glass substrate needs to be addressed.

MADDOX - Let's go back to laminates and report the reservations. There was high confidence expressed in laminates. Does everyone still say yes?

LAMENSDORF - How about qualifying by saying "based on the information available..."

BOMAR - You must also mention the reservations regarding thermal cycling and hygroscopic PVB.

DIETER-POHL - Physical or mechanical stress also.

LAMENSDORF - I know the way to go is the regular painted-back mirror. We only got into laminated mirrors about five years ago. You asked if there was a market for the laminated mirror in Florida and I said no. The product we made for you Lloyd (Oldham) is different than we make today.

OLDHAM - Is it better?

LAMENSDORF - Yes...based on the data available.

MADDOX - So are painted-back mirrors the way to go?

LAMENSDORF - Yes, based on cost.

STEINMEYER - No, it's not.

LAMENSDORF - Based on the cost per square foot of mirror.

MADDOX - Let's see if we can deal with durability, recognizing that there are cost considerations either way. The question then is the durability of a painted-back mirror. Can one produce a paint that is not a contaminant in itself and protects the films?

MUTZBERG - Yes. I think we have agreed on the need for postfabrication being removed. As a result, you can vastly improve the permeability of the back. I'd now like to hear what else we need to protect the mirror from. But how can I prove this to anybody over 30 years or so?

MADDOX - You say you make a paint guaranteed for 20 years. How big a step is it to put this paint on copper?

MUTZBERG - Aluminum has a shingling effect of overlapping layers. Most paint films in the final analysis are degraded by UV. There is very little vehicle to be degraded by UV in these paints because you have the aluminum flake in the paint, which gives the shingle and protects the underlayers. You must only be concerned with galvanic cells and so forth.

MADDOX - But the aluminum flakes are oxidized at the surface so there is no possible galvanic action.

MUTZBERG - Yes, but you still may have vehicle to be protected in the layers. In summary, I have no doubt that we can develop a superior paint but it will take development. We don't have 20 years experience with this paint, although we guarantee it that long, only about 3 years. Repainting these monumental buildings might be worse than heliostats.

SCHRAUTH - What is PPG doing for sandstorm resistance?

MUTZBERG - I made paint for artillery shells, for abrasion resistance we added PVB, to give resilience to the paint, rather than being harder. That shouldn't be a problem.

ANDERSON - I'd worry more about the glass in a sandstorm area.

WALTON - Remember, most sand damage occurs low, close to the ground, whereas heliostats are about 10 ft. up, where there is just a little dust.

MUTZBERG - Yes, they did some tests and showed very little damage above 2 feet.

SOLTYS - Would new paints go toward the single or double coat route? Also, what about the aluminum mirrors, what is the paint they use? I think it's a double coat.

MUTZBERG - The system for aluminum is equivalent but different technology, since there are different needs. We would like a single coat and that's feasible. Back to square one, I don't know how to test it. I can improve it substantially but I don't know if the tests to show this are valid to real life. I can run water tests and show better resistance, but remember it's the total system. Another reason for the copper is that all paint films shrink, you can't avoid it, which produces stresses and subsequent lack of adhesion of the silver to the glass, which can be interpreted as corrosion. Copper relieves the stress. More or less copper might help, depending on the total system, if we have a more shrinking type of paint. Must look at the total mirror system if you want to make an improvement on any one component.

MADDOX - So there is some confidence then in the ability to make a durable paint within existing technology. What other evidence is there that paint is a durable coating?

COOK - The fact that we have concluded that water is the worst enemy and paint does not adequately keep that out is important.

MADDOX - What level of confidence is there then?

BROWN - We've hung our coat on it. We will soon have a year's experience with the Barstow backing paint.

HEARD - With regard to the St. Gaubain aluminum paint, 20 years ago I tried aluminum flake paint unsuccessfully. But it was painted directly on silver. You may need something in between.

DIETER-POHL - They used orange shellac.

LAMENSDORF - What tests led Martin-Marietta to go to paint?

BROWN - Extensive humidity and thermal cycling tests with mirrors as well as components and subassemblies.

SOLTYS - Aluminum power is usually coated with stearic acid. The interaction of this with silver is unknown, so the proper application of wetting agents must be considered. The paint is great to coat steel, but for coating thin films, stearic acid is deadly.

MUTZBERG - That's why we test paints with mirrors we make in the lab. For example when we developed the paint for sputtered mirrors, we wanted to get it to the point where the paint for silver mirrors was.

OLDHAM - You must look at the total heliostat system, not just the mirror coating. We looked at some other coatings but they couldn't take the mechanical stresses.

ROYALL - What about open-backed mirrors?

OLDHAM, BROWN - The requirements placed on us by DOE, as far as captivating the mirror and wind loads, showed that this would be a more expensive way to go.

MADDOX - It sounds like a new compromise in paints will be required for outdoor applications.

VI. Final Afternoon Session

MADDOX - Let me restate what we've heard. There is very high confidence in the reliability of laminated mirrors and high confidence in the ability to develop a backing paint that will survive. Now what about sealing behind the backing coat - pitch, grease, slip plane - is there any confidence in this approach?

BOMAR - What kind of pitch was used?

DIETER-POHL - In Germany in the 1920's, mirrors that were exported had asphalt.

TOUSSAINT - The Germans are still doing mirrors with a bituminous backing. It does not make any improvement in lifetime; they have the same reliability as a standard mirror. Not a great improvement in quality, for indoors applications. I think the German company is Flabek.

MADDOX - What about silicone grease?

MUTZBERG - The shatter-sensitive filling is another possibility, you could select the right plastic for water resistance.

DIETER-POHL - This is also another possible source of contamination, too.

BROWN - The report should state that laminate can be something other than PVB. The system could be glass to glass, glass to metal, or anything that can protect the back surface.

MADDOX - Yes, the idea of lamination also applies to other materials.

TOUSSAINT - Sandia tested Glaverbel mirrors for one year in a cycling chamber with good results, but this was just one year. Sandia says one month in the chamber corresponds to four months in normal use, but they don't know if it is true.

SCHRAUTH - What is the laminate used?

TOUSSAINT - It is an acrylic.

MADDOX - What about edge sealing?

OLDHAM - There are two examples, Northrop's and our (Martin-Marietta) second generation.

MADDOX - I got the feeling that there is low confidence in the encapsulation design.

BROWN - Box construction is a good structural design, but a watertight box is difficult to achieve economically. Sandia tests have shown that, since adding the second coat of paint and a vent hole to the box, there have been no problems. We have also sent some fully sealed boxes through and they have no failures.

MUTZBERG - What were the differences?

OLDHAM - Several, one was the presence of sulfur in one of the materials, also the double coat backing paint.

MADDOX - Is sealing the box required?

BROWN - No, it's not required, but you do need to limit the amount of liquid phase water admitted to the box.

MADDOX - Then a breathing box is a more reasonable approach?

BROWN - Yes.

MADDOX - What about the use of thicker metal layers or additional metal layers?

TOUSSAINT (to London Labs) - Is there a critical ratio of silver to copper?

SOLTYS - Yes, you need a minimum copper thickness of 15 mg per sq. ft. The silver thickness doesn't matter, but you need 15 mg of copper to get galvanic protection.

BAHLS - 20-25 mg. is used by most manufacturers.

SOLTYS - We recommend 200-250 mg. per sq. meter. I'd like to see 30 mg. per sq. ft. (1 sq. meter about equals 10 sq. ft.)

TOUSSAINT - We use 300-350 mg per sq. meter for solar mirrors at Glaverbel.

SOLTYS - More copper gives greater protection, this makes sense if it is acting as a buffer. The thickness of copper should project the longevity, because it takes a longer time for the impurities to penetrate through the copper.

MUTZBERG - If the mechanism is through corroding the copper, then more copper makes sense.

SOLTYS - Using salt spray as a criterion, I don't think thicker copper will show greater longevity. You need a field test. Heavier copper is in the right direction, and it doesn't cost much. Other metals must be electrolytically compatible with the mirror line. Nickel might be a possibility, but applying it uses a process which generates a lot of hydrogen gas which is deadly since it lifts the silver right off the glass and you no longer have sensitized bonding to hold it, just some kind of physical bonding. Also the limiting parameter is speed. The galvanic process is over in 3-10 seconds. Machines for silver like to have 60 seconds, copper about half that.

MADDOX - What other practical limitations are there? You mentioned line speed, what about copper recovery?

SOLTYS - The galvanic copper method is about 20 percent efficient. Our process is about 15%, so either way you have to recover 80-85% of your copper but with ion exchange methods this is not a problem.

BAHLS - The copper can also be precipitated out, using lime, down to EPA levels. The problem is sludge handling and disposal.

SOLTYS - European processes use zinc, but they have a problem with too much zinc being present. American lines use iron as the reaction catalyst and have the opposite problem, not enough iron.

MADDOX - What thicknesses are possible?

SOLTYS - Up to 100 mg per sq. ft. or more can be compatible with present line speeds. Concentration is the variable you manipulate, not thickness per se. You just increase the concentration to increase the thickness of deposition.

MADDOX - Can we make a summary statement about glass and glass cleaning? Anything beyond proper cleaning and handling?

BOMAR - Can the quality of glass be compromised, with respect to defects, for solar? Bubbles or defects don't affect performance very much.

DIETER-POHL - At the sizes of glass now being specified and used, the quality is not perfect anyway.

BAHLS - A defect may later serve as a site for breakage.

COFFIN - That's not a consideration, these are primarily cosmetic defects.

MADDOX - What about the structural question?

COFFIN - I seriously doubt that it is a consideration.

DIETER-POHL - I do think gas bubbles will have an effect on stresses.

OLDHAM - Usually bending of the glass is not enough to break it, but thermal stresses introduced by the sun might.

BROWN - We did some testing at Pueblo with Ford glass, unfortunately it was not the best quality. We ran a series of tests on completed mirrors, heating them to 120°F then moving them into a refrigerated trailer. We did many cycles and didn't break any.

COFFIN - I remember some experiments we made on glass where we found severe gas inclusions. We cycled them through a heat lamp and ice but couldn't break them. I am concerned about nickel - sulfide stones in glass.

MADDOX - How big a problem is this?

BROWN, MUTZBERG - Not a problem.

OLDHAM - One crack we've seen is due to people hanging on the mirror assembly, so it was caused by the way it's put together.

KEITH - What about the dimensions of the mirrors? I've heard complaints that maybe the specs aren't reasonable.

COFFIN - Heliostat manufacturers want large, thin glass - which is like pulling in two different directions at once. There is an initial learning curve to figure out how to handle the glass.

DIETER-POHL - I agree with that.

BROWN - We need to divorce today's world from the anticipated later world of mass production. That problem can be overcome.

SCHRAUTH - It can be overcome through techniques in materials handling, or the learning curve as you said. Also the thickness of glass which is a factor in cost, handling, strength, and transmission factor. Thin glass was specified to increase mirror reflectivity. But there is glass that can match or exceed the thin glass in transmissivity.

COFFIN - Another factor is that the cost for glass, on a square foot basis, is a bell-shaped curve, with the lowest cost at 3/32 inch.

SCHRAUTH - I would say the bottom is fairly flat from 3/32 to 1/4 inch. Laminating then adds cost.

STEINMEYER - Our approach is as a user of glass and mirrors we are constantly talking to our suppliers. There are things which are or are not now available that were or weren't two years ago. We are building a system and we put it together at that time. At any given time, costs are changing.

MADDOX - Is there a summary on development? Paint is one area, are there other areas that could use more work?

DIETER-POHl - I think the mirror companies are all constantly working on improvement. We devote a great deal of time every day to improving what we do now.

MADDOX - Specifically for solar, are there areas?

DIETER-POHL - This is a competitive business and it behooves us to come out with a better mousetrap. We have things on the drawing board that might make what we do now obsolete; I'm sure all manufacturers do.

MADDOX - Can anything be done now, in advance of the market?

DIETER-POHL - Every facet, if done to improve the quality of the mirror, will improve the product's suitability for other uses as well. Improvements in indoor mirrors will benefit solar. We have been fortunate to build a goodly quantity of solar mirrors and I believe the last mirrors were better than the first ones.

MADDOX - I hope so.

DIETER-POHL - I know so.

SCHRAUTH - Especially for the automotive market, we are doing constant development. But we need to look at the total system vs. what is the real market. That is the biggest gap. Jim Rannels said we have one order of around 1 million sq. ft. Somebody else said we need 100 million sq. ft., every year, for a valid market. Float glass is what is being used and it is very high volume production item. Why change formulations for a 4-hour production run? Maybe there is a need for developing a sheet glass that is acceptable to the industry. Low or no-iron glass is needed, but removing iron destroys refractory and introduces contaminants. Perhaps a borosilicate glass is required, but maybe the cost will be too high and thermal expansion characteristics will be unsuitable.

OLDHAM - We would like to see more development in: (1) glasses -borosilicates, soda-lime, and aluminasilicates, (2) new copper processes, (3) new save-all coating from PPG, (4) cost: low-cost laminating with capabilities at least as good as PVB but at a lower cost. From then on it is our charge.

BROWN - And, if there was an immediate market, we might assume some of those.

TOUSSAINT - There exist sheet glasses which are low in iron, such as made by the Swiss (Romont).

SCHRAUTH - Sheet glass was previously tested and rejected, but was a suitable sample checked? Window glass, which is a relatively low anneal, was tested but there are other sheet glasses available.

BROWN - Is the cost comparable to float glass?

SCHRUATH - There's very little difference, especially when you take the reflectivity into account.

TOUSSAINT - There are applications where the quality of sheet glass must be higher than for solar, for example for display cases and photography the flatness quality must be higher.

MADDOX - Can we summarize then?

COFFIN - I wish there was a short duration test for mirrors that could be run before they are released to the environment. All of the tests we have now are after the fact.

ROYALL - That's 100% true. We can't test mirrors for everything you're going to expose them to. We can make a mirror to withstand any environment. We just need to know where the mirror is going to be put and how it is going to be used, the design, adhesives, and so on.

STEINMEYER - The problem is you're trying to learn the results before production. It sounds like Tom (Coffin) wants a QC test after you know what you're designing to meet.

ROYALL - That's why you have incoming QC tests.

COFFIN - Yes, but there are instantaneous QC tests in other glass industries.

ROYALL - The mirror industry has been a very small part of the GNP, just now were getting some attention. If we were here discussing paint for the auto industry, you'd need a ballroom. Our industry is small, we don't get any help.

MUTZBERG - To any future participation, my appeal is to have reliable data so that future researchers can back-track and know what the variables were. Also, when and if you get a failure with those installations in operation now, analyze that failure and find out how it occured and how to improve upon it. We still really don't know what the heliostat needs are.

SCHRAUTH - And also to disseminate those results, especially for failures. I have had a great deal of trouble getting data. I have written letter after letter to Sandia trying to get results. For example, on the faceted dish project, there was never a published paper on it, and the stacks of data just mushroomed.

MADDOX - Does anyone have any other closing remarks? We would like to thank each of you for participating in the workshop. Jim would you like to say a few words?

RANNELS - Yes, I would also like to thank everyone for taking time out from their busy schedules in order to attend the workshop. I know some of you had other important commitments and I appreciate your coming here instead. I was very pleased with the attendance and your openness and willingness to discuss these subjects. For me the workshop was quite successful. At home last night in the mail I received the latest copy of IEEE Spectrum (holds it up). As you can see, we made the cover with our Barstow heliostats. I think this is an indication of the kind of interest that exists in this technology, and I hope you can leave here with some confidence that the market for your products will indeed develop. Again, thank you for coming.

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Addendum to the
Final Report of the Workshop
July 29-30, 1981

Durability of Reflecting Surfaces Used in Solar Heliostats

Technology Applications Laboratory
Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia
January 1982

Subsequent to the workshop, project efforts were concentrated on three major activities:

- o Preparation, production, and review of the workshop proceedings, which form the bulk of written material and the final report.
- o Attempts to locate and characterize samples of old heliostat mirrors from Mont Louis and Odeillo, two heliostat installations in France with the longest records of exposure.
- o Discussions with testing laboratories, mirror manufacturers, and suppliers concerning their participation in further testing of mirrors, development of new testing procedures, and development of new mirror backings.

The first of these activities is represented by the final report of the workshop, which is also the major project report . The latter two activities are briefly described as follows:

Summary of Activities to Study the Mont Louis and Odeillo Mirrors

As a result of the workshop, efforts were initiated to obtain samples of the heliostat mirrors used at the CNRS Solar Furnace at Odeillo to compare with that obtained at Mont Louis. As pointed out in the workshop, these mirrors represent extremes in heliostat mirror durability.

The Mont Louis mirror, obtained in 1973, was the subject of preliminary efforts to determine the thickness of the silver, copper and paint layers. These efforts were directed toward using optical and scanning electron microscope techniques to study the components of this mirror. They include various combinations of breaking, cutting, polishing, mounting, and cleanning samples and microscopic examination to determine coating thicknesses. Unfortunately, the extreme differences in the hardness and integrity of these four materials (glass, silver, copper and paint) prevented conventional specimen surface polishing and preparation techniques from providing samples with sufficient smoothness to allow the interfaces of these materials to be resolved.

Since the workshop, meetings were held with the technical staff of Saint Gobain, manufacturer of the glass for the heliostats at Mont Louis and Odeillo, and Mr. Claude Royere, engineer in charge of the solar furnace at Odeillo. It was learned that the Mont Louis mirrors were silvered and coated with electrolytically deposited copper and that a specially formulated aluminum paint was used as the backing paint. The Odeillo mirrors were silvered by a commercial mirror company and coated with a standard backing paint.

Although the composition of the backing paint used on the Mont Louis mirror was not recorded and the man who formulated it is deceased, Saint Gobain and Mr. Royere have indicated interest in assistsing in any efforts to reconstruct this paint, and Saint Gobain would be interested in being a subcontractor in any study to reproduce the Mont Louis mirror.

Summary of Activities to Develop Further Testing and New Barking Coatings for Heliostat Mirrors

Following recommendations of the workshop, efforts were undertaken to determine methods to develop test procedures that featured radiation, temperature, and moisture as important contributors to mirror degradation. Development of new backing coats was also discussed with several interested parties.

The president of London Laboratories was contacted to determine if his facilities and trained staff could be made available for reproducing the mirror types used at Mont Louis and Odeillo and for developing new mirror assemblies. Since London Laboratories has the equipment to duplicate near any galvanic silver and copper coatings, only the addition of a paint coater would be necessary to provide a complete prototype operation. London Laboratories indicated willingness to provide whatever services were required.

Gardner Mirror representatives were contacted, and they agreed to provide samples of regular production and Barstow mirrors for testing. These mirror samples would supply current average and state-of-the-art examples for testing.

Most of the necessary environmental testing apparatus is available at Georgia Tech, and such equipment was identified. Its availability was confirmed. An outdoor testing organization, Desert Sunshine, was contacted and agreed to participate if such special facilities and accelerated testing as Desert Sunshine provides was found to be useful.

Finally, a work scope to conduct characterization, development, and testing of mirror coatings was constructed. This effort brought together and summarized the findings of major activities conducted after and apart from the workshop. The work scope is presented as Exhibit 1. It reflects the line of inquiry recommended by the mirroring industry.

Exhibit 1

SCOPE OF WORK OUTLINE: DURABILITY OF REFLECTING SURFACES USED IN SOLAR HELIOSTATS

Objectives

1. To develop second-surface glass mirrors which are capable of retaining good reflecting qualities during exposure to outdoor environments for periods of up to 30 years.

2. To develop mirror lifetime test methods which give a high degree of correlation between the test performance of mirrors and their longevity in outdoor use.

3. To emphasize the development of protective coating systems for mirror backs in preference to lamination with a second sheet of glass; examples of such coating systems include metallic layers and paints which can be applied during the mirror manufacturing process at relatively small incremental cost.

Program Tasks

1. Characterization of Old Mirrors

   Characterize the Mont Louis mirror currently in possession of Georgia Tech and get either the data from an old Odeillo mirror or a mirror which can be inspected. The properties of interest include thicknesses of metallic films, pigments and vehicles used in paints, thicknesses of paint layers, and any data on methods of application of metals and paints.

2. Define Environmental Conditions Leading to Past Failures

   Based on the data acquired during the previous study on heliostat mirror experience, assemble a list of mirror failures including failure times and probable contributing factors. Currently recognized contributing factors include exposure to water, exposure to sunlight, temperature cycling, and exposure to chemical agents such as sulfur and chlorine in bonding adhesives. Supplement published data where possible by interviews with persons having direct knowledge.

3. Reproduce Selected Mirrors for Use as Standards

   Prepare approximately 100 square feet each of "standard" mirrors such as Mont Louis, old Odeillo, and the Carolina 1957 mirror which are known to have been exposed to weather for lengthy periods. Purchase about 100 square feet each of other "standards" such as Gardner regular production (used at ACTF), Barstow mirrors, and Odeillo "copper pigment" mirrors. It is desired that these "standards" correspond to mirror types which have been used in solar facilities and whose outdoor lifetime is approximately known. The standard mirrors which cannot be purchased (Mont Louis and old Odeillo) will be made up by a subcontractor having mirror fabrication capability, using the best available data on the mirror constructions, developed in Task 1.

4. Prepare Advanced Mirror Assemblies

Prepare approximately 100 square feet each of six to eight advanced mirrors, based on current knowledge of the factors which govern mirror lifetimes in outdoor applications. Directions which might be pursued in defining advanced mirror concepts include deposition of thicker copper layers by the disproportionation reaction, the addition of a nickel layer over the copper, the use of paints with metallic pigments (particularly aluminum), the use of advanced paint systems such as heat-cured acrylics and fluoroelastomers.

The advanced mirrors will be made by one or more subcontractors having mirror fabrication capability, with collaboration by Georgia Tech personnel.

5. Define Test Program

Define an accelerated test program and organizations which will conduct specific test activities. The test program will adopt test procedures which appear to adequately cover exposure to water, exposure to sunlight or simulated sunlight, temperature cycling, and exposure to common chemicals known to be detrimental to mirrors, such as sulfur and chlorine or ions containing these elements.

Georgia Tech has the facilities to perform the bulk of the test program, using standard procedures common in the mirror manufacturing industry. It is possible that an accelerated solar test would be specified, which would be performed by DSET. The test program should be designed for completion within one year.

6. Performance Testing

Conduct test programs in accordance with the plan developed in Task 5. Approximately 10 to 12 types of mirrors will be tested, including the standards prepared or purchased in Task 3 and the advanced mirror assemblies prepared in Task 4. Test emphasis will be concentrated on ranking the specimens in each separate test, so that correlations relative to the historical performance of the standards can be acquired.

A major portion of the testing will be performed at Georgia Tech in order to maintain good control of the test procedures and to identify mid-course corrections promptly. Any subcontracted testing will be under the direction and periodic supervision of Georgia Tech personnel.

7. Evaluation and Reporting

Assemble test data at the end of one year of testing and develop statistical correlations which define "probable lifetimes" of several types of mirror assemblies, based on relationships among the advanced mirrors, the standard mirrors, and the historical performance of the standards.

Identify mirror types which are particularly vulnerable to specific environmental stresses, such as chemical agents, and define use limitations where appropriate. Evaluate test procedures used and define modifications as necessary. Identify the mirror construction concepts which are most successful in extending mirror lifetimes and assemble corresponding cost estimate data. Define recommendations for future mirror construction and employment and define additional research if required.

Subcontracts and Major Procurements

1. Mont Louis and old Odeillo mirrors for Task 3

   London Laboratories or PPG Industries

2. Carolina 1957 mirror for Task 3

   Carolina Mirror Corporation (if they can find production records to exactly identify the paint used) or PPG Industries

3. Odeillo "copper pigment" mirrors for Task 3

   London Laboratories or PPG Industries

4. Gardner regular production and Barstow mirrors for Task 3

   Gardner Mirror Corporation and possibly Martin Marietta Corporation (for Barstow mirrors)

5. Disproportionate Copper for Task 4

   London Laboratories

6. Nickel Plating for Task 4

   London Laboratories

7. Paints with metallic pigments and advanced paints for Task 4

   PPG Industries

8. Testing Services for Task 6

   DSET, perhaps Sandia Laboratories for thermal cycling tests

Test Equipment at Georgia Tech

1. Salt Fog Cabinet, ASTM B117 (5% NaCl fog, 95^{o}F)

2. Cleveland Condensing Humidity Cabinet, ASTM (operates at 100^{o} F, continuous condensing humidity condition or programmed for wet and dry cycles.)

3. Atlas Weather-O-Meter, (Controls light and moisture exposure; provides cycling of both; logs ultraviolet exposure from 6500 W xenon lamp; relative humidity controlled.)

4. Atlas UV-CON Weather-O-Meter, (Similar to Weather-O-Meter but has different ultraviolet spectral distribution and provides for condensing humidity.)

5. Infrared Spectroscopy, (Gives rough indication of class of organic materials and polymers, such as paint vehicles.)

6. Gas Chromatography/Mass Spectrometry, (Can be used to identify organic chemical bonds in great detail; stable materials like paint vehicles would have to be pyrolyzed or chemically broken down with a substantial effort required to perform analysis.)

7. Scanning Electron Microscopy, (Layer structures and thicknesses, elemental analysis of pigments.)

8. Electron Microprobe Analysis, (Elemental analysis of layers and pigments.)