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Final Project Report

CRADA with United Solar Technologies and Pacific Northwest Laboratory (PNL-021): Thin Film Materials for Low-Cost High Performance Solar Concentrators

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Prepared for U.S. Department of Energy
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Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America

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CRADA with United Solar Technologies and Pacific Northwest Laboratory (PNL 021): Thin Film Materials for Low Cost, High Performance Solar Concentrators

Purpose/Objective

The objectives of this project were as follows:

- develop and evaluate promising low-cost dielectric and polymer-protected thin-film reflective metal coatings to be applied to preformed continuously-curved solar reflector panels to enhance their solar reflectance.
- demonstrate protected solar reflective coatings on preformed solar concentrator panels

The opportunity for this project arose from a search by United Solar Technologies (UST) for organizations and facilities capable of applying reflective coatings to large preformed panels. PNL was identified as being uniquely qualified to participate in this collaborative project.

Summary of Activities Performed

Project activities were initiated in February, 1992. United Solar Technologies is developing solar concentrator modules for domestic active and passive solar energy generation. Their objective is to manufacture and market these modules. The solar concentrator consists of fourteen parabolically-shaped preformed aluminum panels. To perform to design specifications, the panels must be highly-reflective to the solar spectrum.

UST tasks for this CRADA were:

- to build the facility to manufacture the aluminum panels
- manufacture the aluminum panels
- apply a polymer smoothing layer to the panels
- characterize the reflectance and optical scatter of the panels after PNL applies the reflective coatings
- assemble the coated panels into the concentrator modules

The tasks performed by PNL were:

- design the protective solar reflective coating
- develop the process to apply reflective coatings to the solar concentrator panels
- apply the solar reflector coatings onto solar concentrator panels
- evaluate a polymer dirt sluffing layer

PNL's primary responsibilities were to design and apply the solar reflective coating to the solar concentrator sections supplied by UST using PNL's large optics coating facility. Magnetron sputtering was the deposition technique. UST's primary responsibilities were to build the facility to manufacture the solar concentrator panels, and to supply panels for PNL to coat.

The ultimate goal of this, and follow-on work, was to demonstrate low cost thin-film process for application of the reflective/protective coatings to solar concentrator panels. To accomplish this, PNL is developing the high-rate magnetron sputtering process, and a new polymer multilayer coatings technology, which UST will evaluate in follow-on work. Polymer coatings can be deposited at much lower costs and higher rates than conventional magnetron-sputtered coatings. Because of the relative low funding level ($49K) for the initial project, only a small part of PNL activities was directed at evaluating the use of polymer layers in the solar reflective coatings.

Experimental

PNL's work was divided into three tasks:

- Process conceptual testing and development
- Process pilot scale evaluation
- Process improvement

Task 1. Process Conceptual Testing and Development

The objective of the Process Conceptual Testing task was to determine on a small scale which sputtered and polymer coatings were best suited for UST's 7.5-foot aluminum solar concentrator panels. Actual panels were coated in PNL's large optics chamber. All test coatings were deposited by reactive magnetron sputtering in PNL's small coating chambers, such as that shown in Appendix 1. The following coatings were applied to small 4-in square and 2-in square aluminum test pieces:

- silver (Ag) on bare Al
- Ag on Al precoated with a polyamide polymer smoothing layer
- Al on bare Al
- Al on Al precoated with a polyamide polymer smoothing layer
- Ag on Al precoated with urethane, Krylon, enamel, lacquer, epoxy, and varnish smoothing layers

The smoothing layers were either sprayed or dipped. The dipping method was thought to be preferred because the material would uniformly harden during application.

Table 1 summarizes the reflectance measurements on the Al test pieces. The reflectance of the Ag on the dipped Al pieces was very close to that of Ag deposited on smooth glass (~96% at 550 nm), while the reflectance of the sprayed pieces varied from a few percent from specular to as much as 30% below specular. Adhesion of the Ag to the dipped piece was good, but varied from poor to good on the sprayed pieces. Adhesion was determined by the MIL-SPEC tape test. Reflectance of the bare Al test pieces was unacceptable.

Table 1. Reflectance of Ag on Al test pieces.

Material	Smoothing Process	Reflectance(550 nm)	Adhesion
Polyamide	dip	94	pass
Krylon plastic	spray	92	fail
Urethane	spray	82	fail
Lacquer	spray	70-80	pass
Enamel	spray	82	pass
Varnish	spray	80	fail
Epoxy	spray	60	pass
Bare Al		16	

The clear choice for surface precoat is the Polyamide dip. All sprayed smoothing layers were unacceptable due to either poor reflectance or poor adhesion. Note that the dip process, however, requires that the 7.5-ft panel be dipped in a reservoir of polyamide, which is more costly than spraying.

Aluminum oxide (Al_2O_3) and silicon dioxide (SiO_2), with layer thicknesses of about 1 μm were candidates for the protective overcoat layer. Appendix 2 shows that Al_2O_3 enhances the reflectance as well as protecting the Ag layer from abrasion and chemical attack. Al_2O_3 was chosen for this application because deposition of SiO_2 sometimes oxidizes the Ag layer.

Task 2. Process Pilot Scale Evaluations.

The objective of this task was to scale up the magnetron sputtering process to apply the protected reflective coatings to UST's solar concentrator panels, and to evaluate any process problems and issues. Appendix 3 shows the PNL large optics chamber, and Appendix 4 shows a UST solar concentrator panel which was coated. The panel is 7.5 ft long, 53 in wide at the base, and 17 in wide at the top. The chamber is capable of applying precision multilayer coatings onto curved, rotationally-asymmetric optics as large as 2.2 m (7.1 ft) diameter, or 2.25 m (7.5 ft) long, with thickness uniformities of ± 2% over the entire surface.

PNL has successfully scaled up the reactive magnetron sputtering process to apply multilayer laser mirror coatings to 2.1 m optics for the Strategic Defense Initiative Organization (SDIO). Activities for this project defined operating parameters for coating solar concentrator panels with temperature sensitive polyamide smoothing layers, substrate jigging procedures, hardware needed to hold the panels in the planetary substrate holder, and materials/process compatibility issues.

Aluminum and silver were chosen as base metal reflective layers for the panel. Aluminum oxide was applied as the reflectance enhancement/protective layer. Krylon plastic, lacquer, and polyurethane smoothing layers were sprayed onto sections of the chamber as shown in Appendix 4. One section was left bare.

A silver layer was applied to one half of the section and an aluminum layer was applied to the other half by magnetron sputtering. An aluminum oxide layer approximately 0.5 μm thick was then applied to the entire panel.

The panel was then evaluated for:

- coating delamination
- coating/smoothing layer compatibility and quality
- coating uniformity
- effectiveness of the smoothing layer
- reflectance

The magnetron sputtering process for all coating materials went flawlessly. No problems were encountered here. Both the Al and Ag layers were very reflective. Deposition time for the metal layers was 20 min. The Al_2O_3 was deposited with ion assist with excellent results. Deposition time for this layer was 90 min. Coating thickness uniformity was better than ±3 %, which should have no effect on solar reflectance. All substrate jigging worked as planned.

The major problem experienced with the panel was the smoothness of the sprayed base layers. Surface roughness reduces specularity, causes optical scatter, and reduces the reflectance. All base coatings showed some degree of scatter. This roughness is attributed entirely to the spray process, during which the materials harden nonuniformly. Non uniform hardening causes ripples, craters, lumps, and cracking (mud flat appearance). UST has had experience with the dip coating process, and feels that the problem will be corrected if the panels are dipped. Note that all dipped test coupons supplied by UST demonstrated specular reflectance.

The reflectances (at 550 nm wavelength) of the panel sections, measured with a fiber optic diode array spectrophotometer were ranked. The sections with the

Krylon smoothing layer had the highest reflectances; 80% for the Al-based coating, and 43% for the Ag-based coating. The sections with the urethane smoothing layer has reflectances of 54% for the Al-based coating and 69% for the Ag-based coating. The sections with the lacquer smoothing layer had the highest degree of cracking and roughness. Reflectance for the Al-based coating was 44%, and 35% for the Ag-based coating.

As expected, the reflectance of the coating on the bare panel section was very low, about 21% for the Al-based coating, and 34% for the Ag-based coating.

Although the smoothing layers cracked, the adhesion of the reflective/protective coating to the UST panel appeared to be good.

Significant Accomplishments

The significant accomplishments of this project were:

- demonstration of the magnetron sputtering process for application of high reflective/protective coatings to the UST solar concentrator panels
- when applied to a dipped polyamide smoothing layer, the PNL solar reflective coating meets UST's requirements
- dipped polyamide smoothing layers must be used as a base for the PNL solar reflective/protective coating
- UST has built the facility for manufacturing solar concentrator panels, and is currently fabricating the panels

High-quality Ag and Al-based solar/protective coatings were deposited on UST solar concentrator panels by the PNL large optics facility using magnetron sputtering. No other government facility, and possibly only one other private facility in the U.S., has this capability, The jigging and deposition process were defined and executed with no problems. This process is now ready to coat UST prototype panels, and eventually transfer to UST.

United Solar Technologies is now manufacturing Al solar concentrator panels, by a hydrostatic pressing process. As with all forming processes, the panels do not have an optical surface quality. They have small scratches, roughness, and stains that scatter light and severely reduce specularity. To achieve a specular reflective coating, a smoothing layer must be applied by dipping the panels in polyamide or some other polymer. UST is currently building the facility to dip the panels to form the smoothing layer.

The coatings deposited by PNL meet the reflectance requirements for the solar concentrator panels. The coatings consisted of an Al or Ag metal reflective layer with an aluminum oxide protective overcoat. The aluminum oxide also enhanced the reflectance. Coatings with reflectances as high as 92% at 550 nm wavelength were deposited onto smoothing layers. UST requires a reflectance of 90% or better for their panels to meet design specifications.

UST is currently fabricating solar concentrator panels in a facility they recently completed. The facility hydrostatically forms the Al panels. Present output is two panels per day. After the polyamide smoothing layer has been applied, the panels are shipped to PNL for application of the solar reflective coating.

Significant Problems

The major problem in executing this CRADA was the delays UST experienced in building the panel forming facility. The PNL coating facility was configured to coat the panels two times, and twice dissembled. Only recently has a panel been coated. UST appears to have solved this problem, but now must build the facility to apply the polyamide smoothing layers.

Industry Benefits Realized

UST now has access to a process to apply highly reflective/protective coatings to the solar panels they manufacture. Without this process, their product would not function properly or meet design specifications.

Recommended Follow-On Work

UST still needs 28 solar concentrator panels coated with reflective/protective coatings to demonstrate the operation of their solar concentrator system. They also need assistance in developing a dirt sluffing layer, and in designing a dual-function panel forming and coating chamber.

Follow on work would entail:

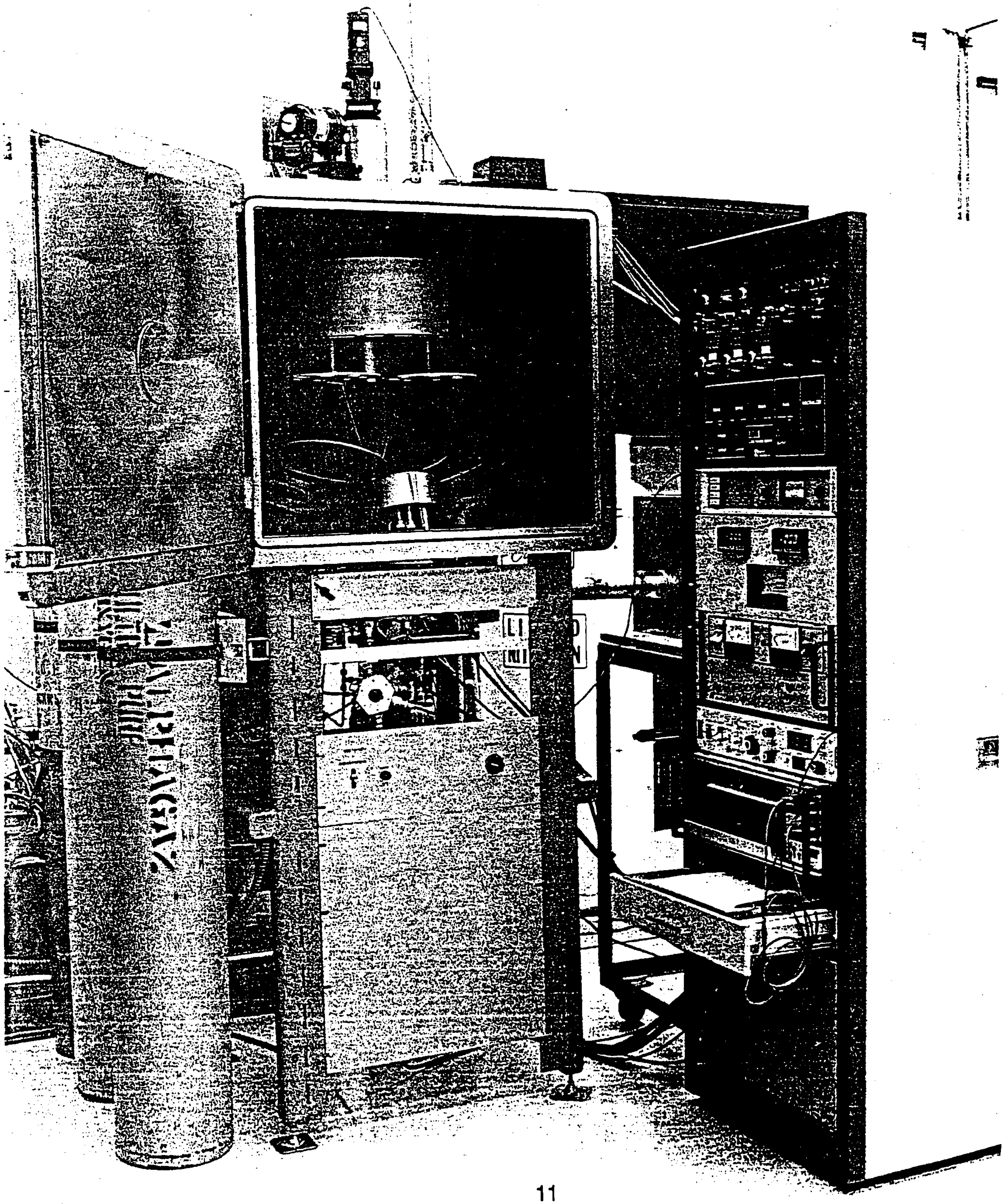
- application of the reflective/protective coatings to 28 solar panels
- development and application of the polymer dirt sluffing layer to 28 solar panels
- design and assistance to UST for the advanced coating/forming facility
- tech transfer of the coating process to UST

Potential Benefits from Pursuing Follow-On Work

If successful, the UST solar concentrator system has the potential to revolutionize domestic energy generation and management. UST has still to manufacture a complete solar concentrator system. The follow-on work with PNL would allow them to enter the market with this product, and to field test the concentrator. This work would also assist UST is manufacturing the entire concentrator system. PNL would benefit from the technology transfer, and potential follow-on work with a joint program with UST and the National Reusable Energy Laboratory (NREL).

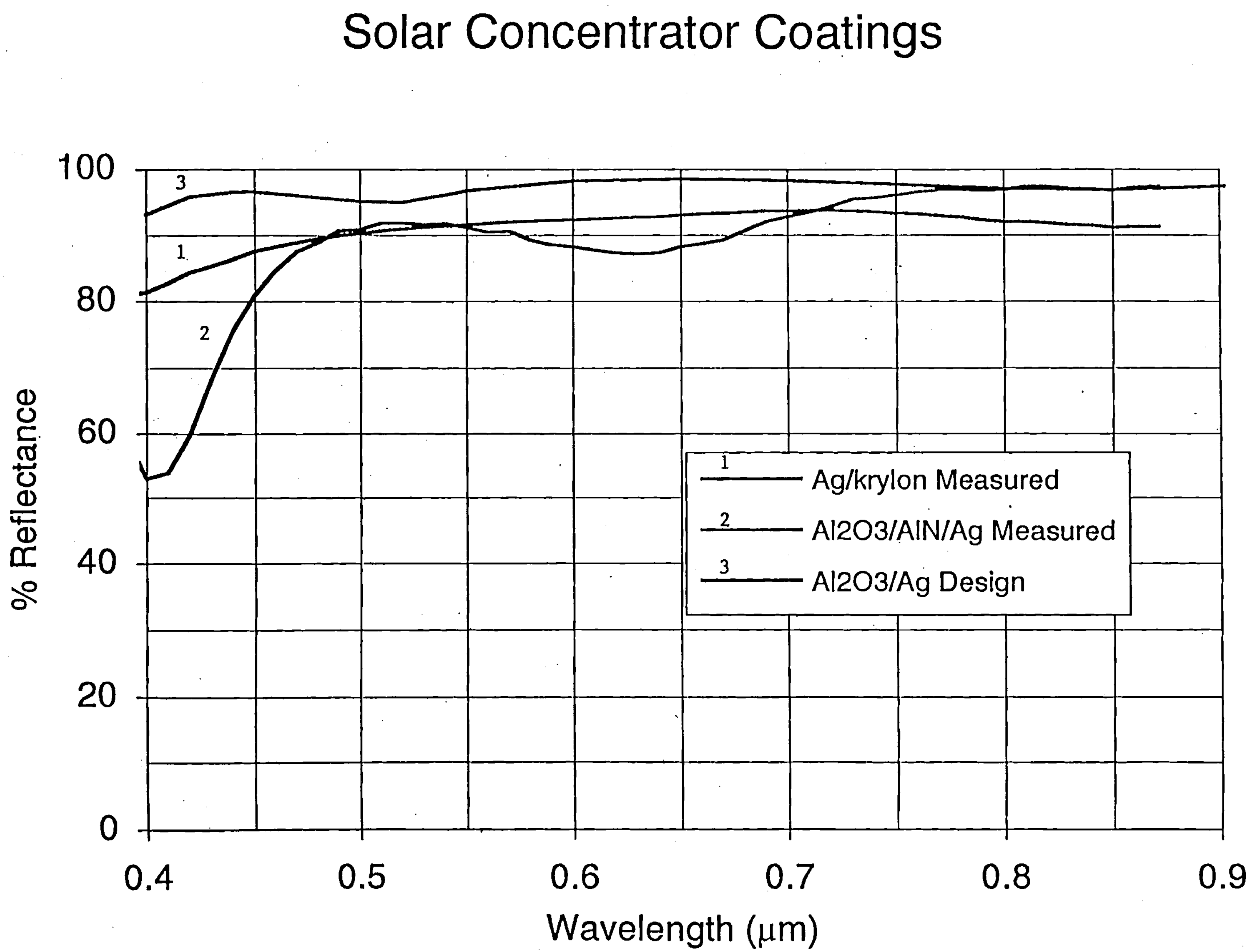
APPENDIX 1

Optical Coating Chamber Used for Small-Scale Depositions



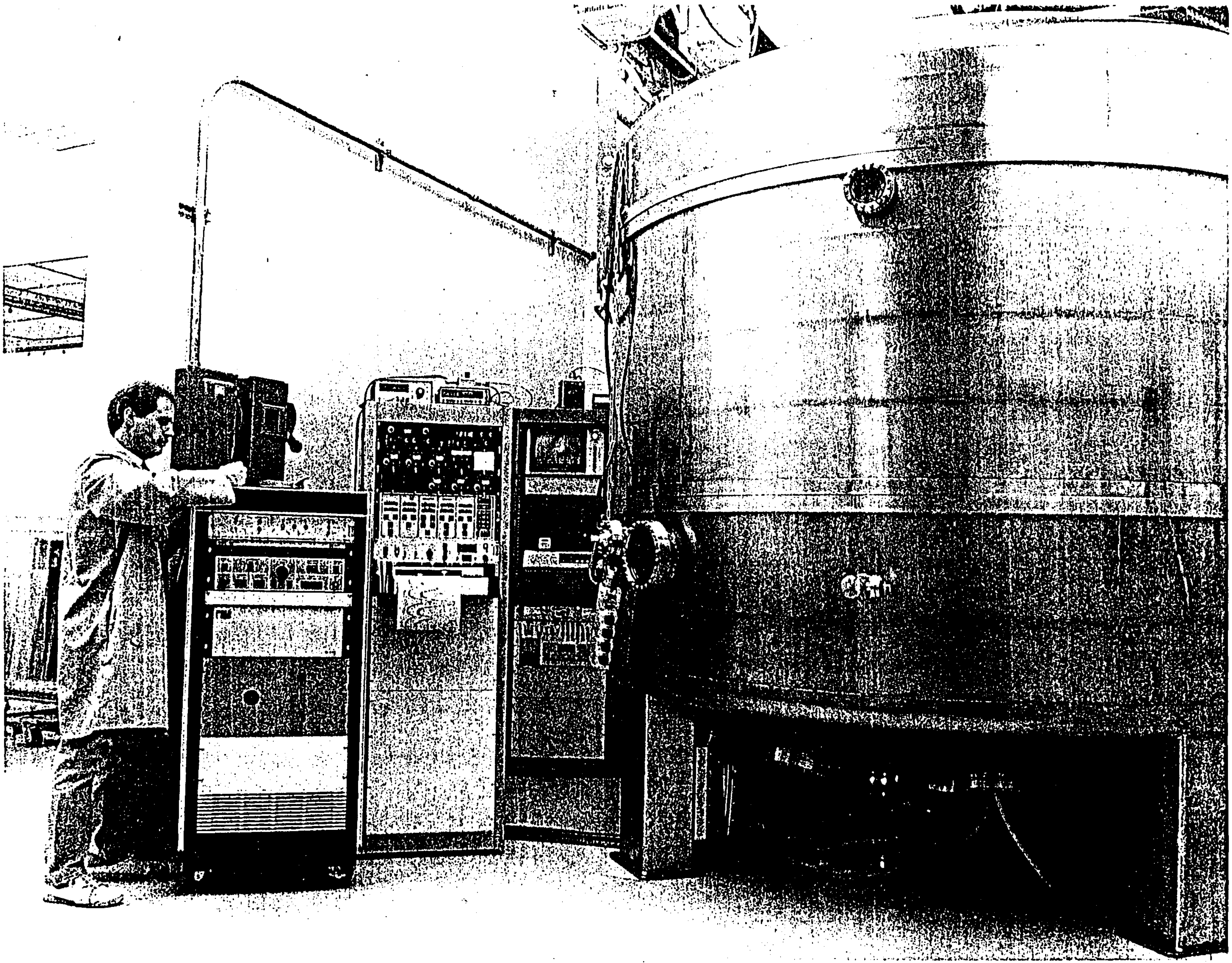
APPENDIX 2

Transmission Spectrum of Protected Solar Reflective Coating


Solar Concentrator Coatings
100
80
60
40
20
0
% Reflectance
0.4
0.5
0.6
0.7
0.8
0.9
Wavelength (μm)
1
2
3
1 Ag/krylon Measured
2 Al2O3/AlN/Ag Measured
3 Al2O3/Ag Design

APPENDIX 3

PNL Large Optics Coating Chamber

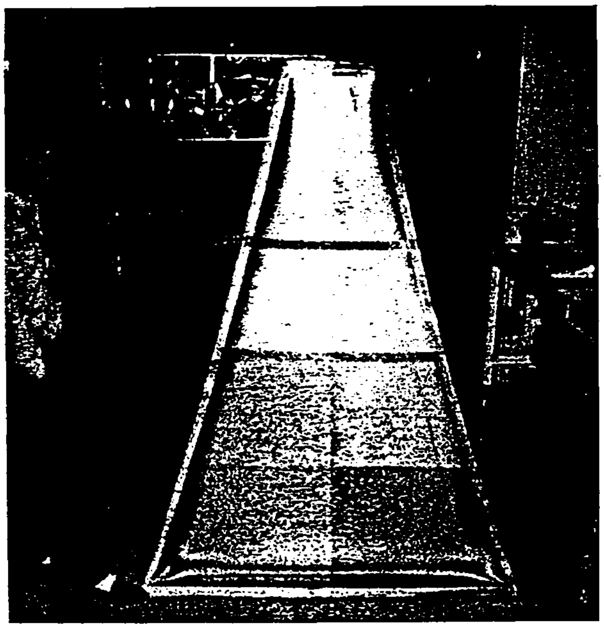


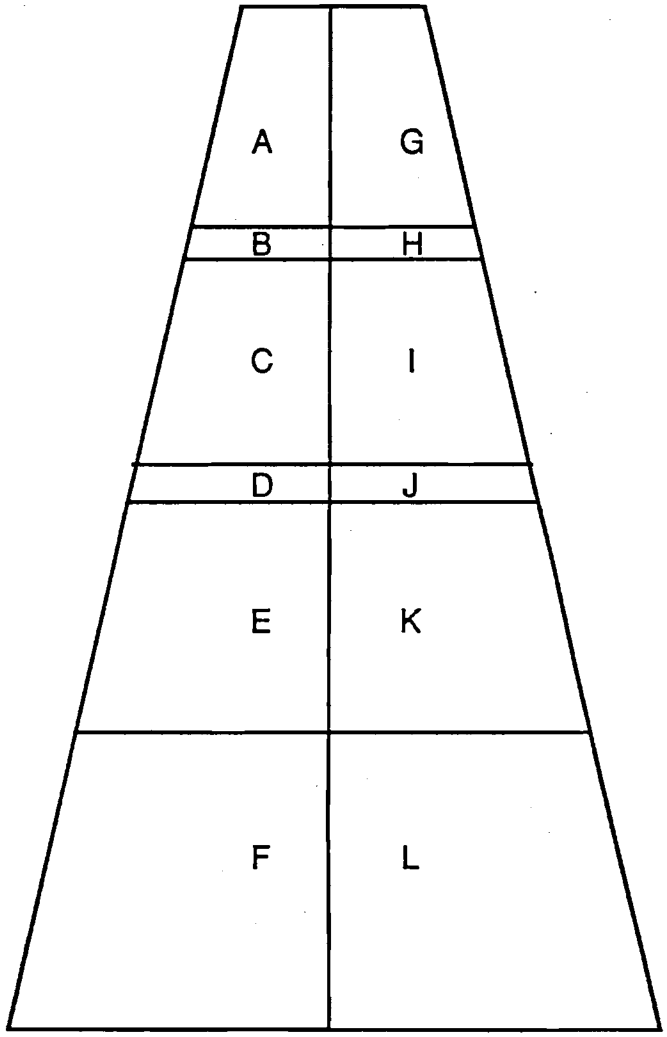
APPENDIX 4

UST Solar Concentrator Panel Section

APPENDIX 5

Diagram and Photo of the Coated UST Solar Concentrator Panel





A = Krylon / Ag / Al_2O_3
B = Ag / Al_2O_3
C = laquer / Ag / Al_2O_3
D = Ag / Al_2O_3
E = polyurethane / Ag / Al_2O_3
F = Ag / Al_2O_3

G = Krylon / Al / Al_2O_3
H = Al / Al_2O_3
I = laquer / Al / Al_2O_3
J = Al / Al_2O_3
K = polyurethane / Al / Al_2O_3
L = Al / Al_2O_3

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