National Renewable Energy Laboratory
Innovation for Our Energy Future

NREL CSP Optical Materials Characterization Facilities and Capabilities in Support of DOE FOA Awards

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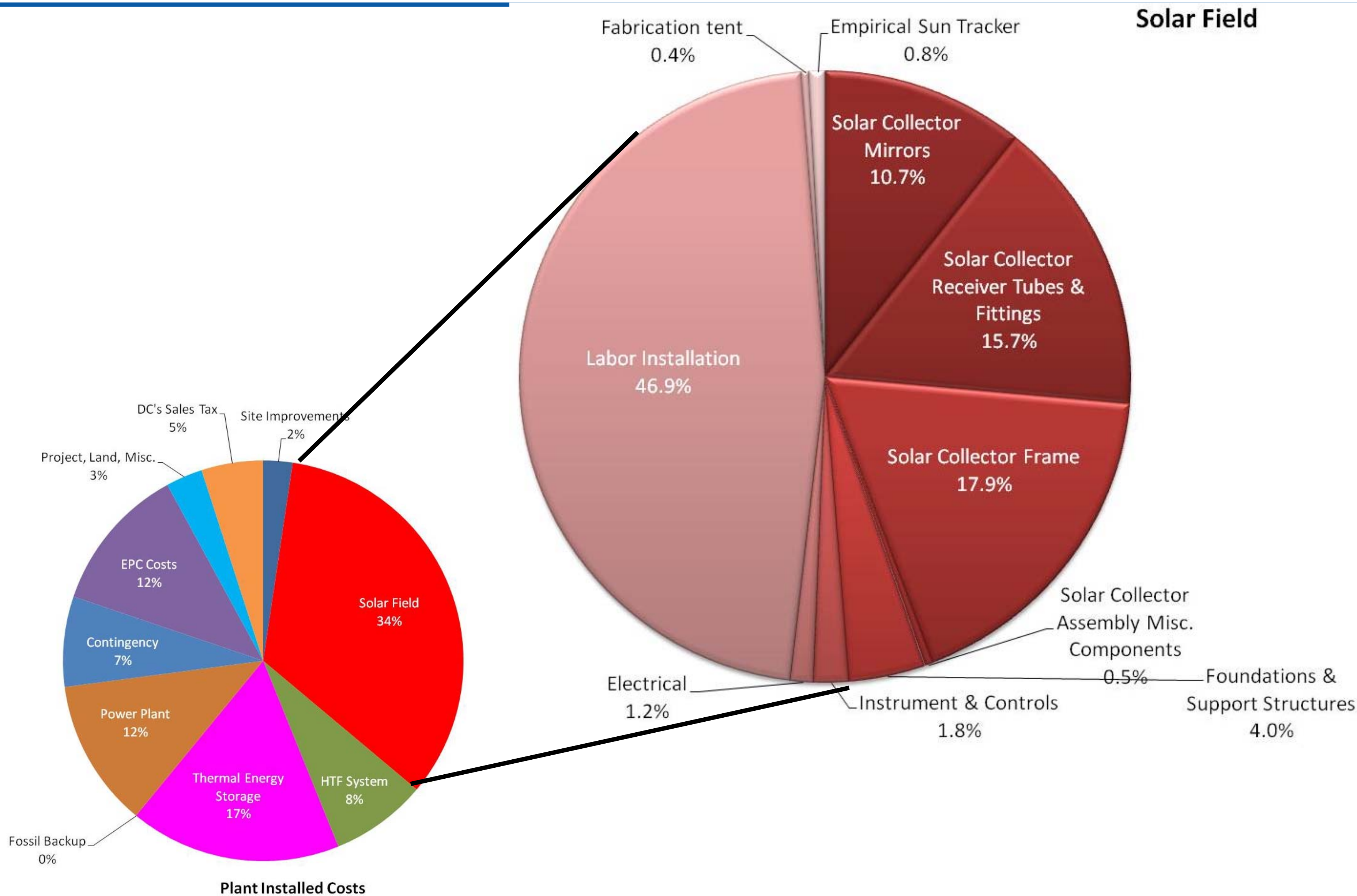
Golden, CO

CSP Cost Goal: Addressing Cost Barrier

- CSP technologies competitive in intermediate load power markets (natural gas) with 6 hours of thermal storage by 2015

- CSP technologies competitive in carbon constrained base load power markets with 12-17 hours of thermal storage by 2020.

CSP Cost Goal: Addressing Cost Barrier



To meet 2015 cost goals

- Parabolic Troughs and Power Towers cannot hit these targets without aggressive cost reductions and performance improvements
  - Need to reduce solar field costs from $334/m^2 to <$200/m^2
  - Need to lower O&M by nearly half
  - Need to reduce labor to install collectors
- Technology improvements will have a stronger effect than cost reductions alone
  - 10% cost improvement lowers LCOE by $0.08/m^2
  - 10% performance improvement lowers LCOE by $0.12/m^2
- Need revolutionary technology improvements

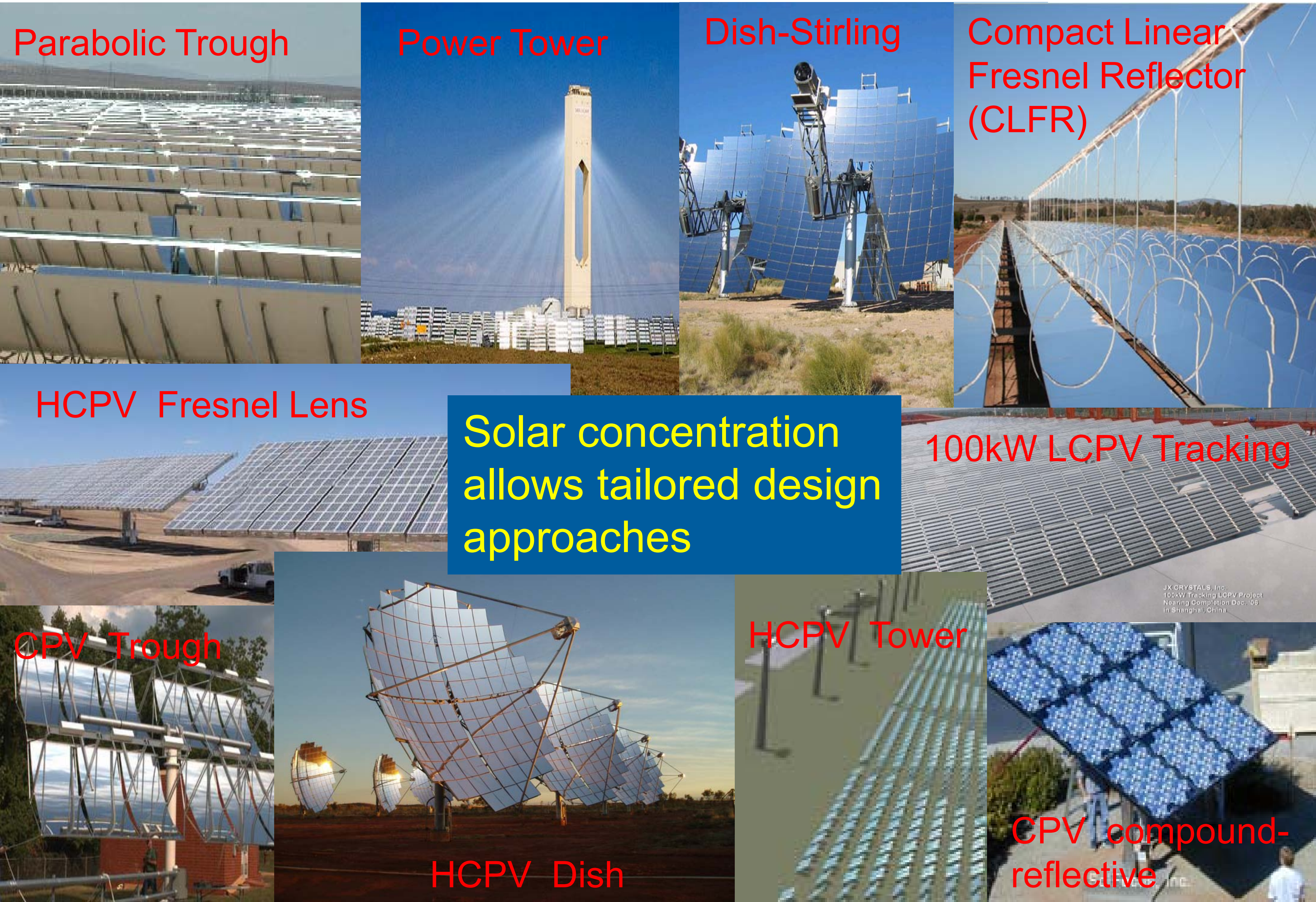
Advanced CSP R&D (i.e., Advanced Materials)

Advanced Reflectors

Advanced Reflector FOA Support

Advanced Absorbers

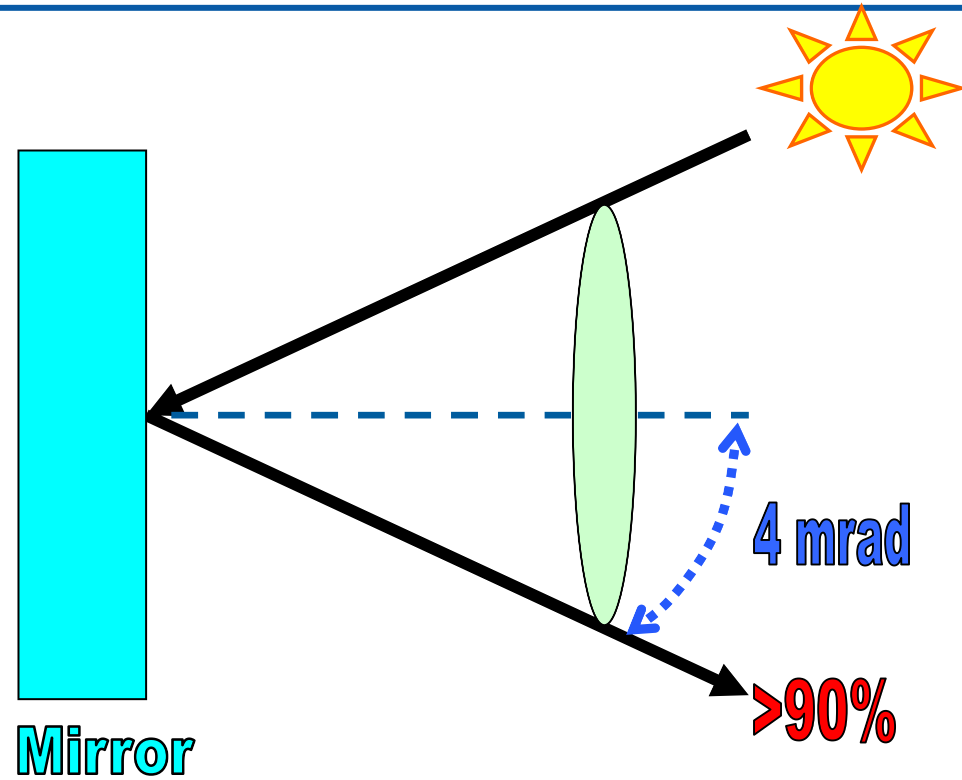
Concentrating Solar Technologies



Solar concentration allows tailored design approaches

Goals for Improved Optical Mirrors

- >95% Specular reflectance into < 4-mrad cone angle
  - Dish-Stirling need <2-mrad
  - Power tower 1 – 2-mrad



- 20 - 30 year lifetime

- Low Manufacturing Cost

  < ½ traditional parabolic trough

  (i.e., self-supporting mirror)

  < $27/m^2$ ($2.50/ft^2$)

Increased annual revenue for 1% in ρ:

100 mW CSP plant w/ 6 h storage w/ 40% annual capacity factor:

100 MWe x 8760 hr/y x 0.4 = 350,400 MWh/y

1% in ρ ≈ 1% in output:

3504 MWh/y x $140/MWh ($0.14/kwh PPA) = $490,560/y for a 100 MW plant

Download Solar Advisor Model (SAM) at www.nrel.gov/analysis/sam

Optical Durability Facilities

Samples supplied by:

- *Industry*
- *Subcontracts*
- *Developed in-house*

Measure optical and mechanical properties of potential solar materials.

- *Characterize >1000 samples/mo*

Characterize samples initially and as a function of outdoor and accelerated exposure time.

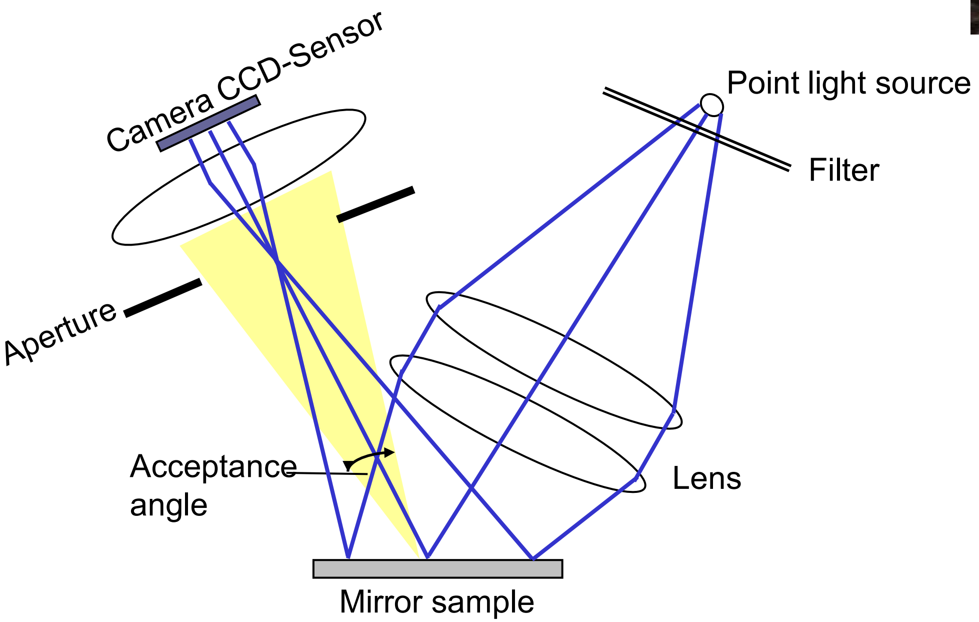
- *>7000 advanced reflector & solar selective samples currently in test for CSP (& CPV) industry*

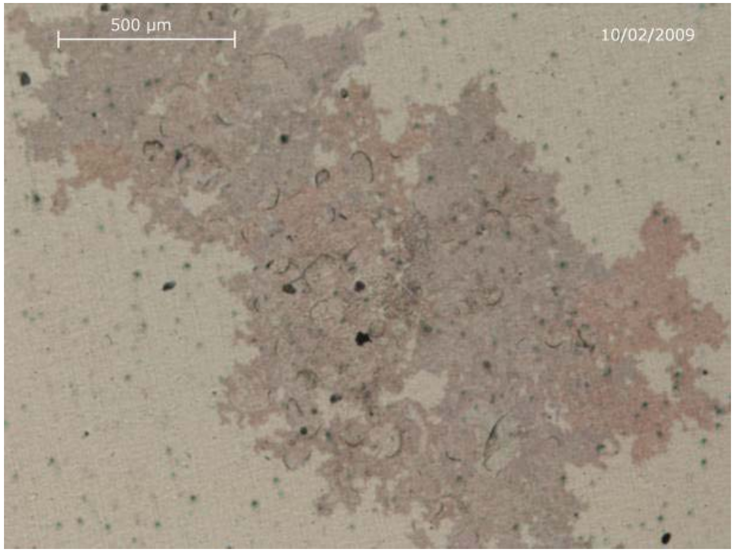
Optical Characterization: Mirrors

- **Perkin-Elmer (PE) UV-VIS-NIR spectrophotometers (250-2500 nm)**
  - **λ-9**
    - w/ 60-mm Integrating Sphere
    - Variable Reflectance Attachment
  - **λ-900**
    - w/ 60-mm Integrating Sphere
  - **λ-1050**
    - w/ 150-mm Integrating Sphere
    - Universal Reflectance Accessory
- **Devices & Services (D&S) 15R Field Portable Specular Reflectometer**
  - 7, 15, & 25-mrad cone angle at 660 nm
- **Surface Optics Corporation (SOC) 410-VIS Hand-held Reflectometer**
  - Reflectance: Total, Diffuse, Specular
  - 4 sub-bands: 400-540,480-600, 590-720, 900-1100 nm
  - 20°Incidence angle
  - 70-mrad half-cone angle

New Specular Reflectance Measurement Tools

- **Space resolved spectral reflectometer $(SR)^2$**
  - DLR PhD candidate – Florian Sutter
  - Characterize expansion of corrosion spots observed outdoors
  - Perform accelerated exposure testing
  - Determine acceleration factor with SLP





Spectral specular reflectometer

- Measure spectral hemispherical reflectance: $\rho_{2\pi}(\lambda)$
- Compute solar-weighted hemispherical reflectance:

$$\rho_{2\pi} = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} \rho_{2\pi}(\lambda)\, I(\lambda)\, d\lambda}{\int_{\lambda_{\min}}^{\lambda_{\max}} I(\lambda)\, d\lambda}$$

- Then measure specular reflectance, $\rho_s(\theta,\lambda)$, as function of acceptance angle at a particular wavelength (e.g., $\lambda \approx 660$ nm)
- Solar-weighted specular reflectance is often approximated[1] as:

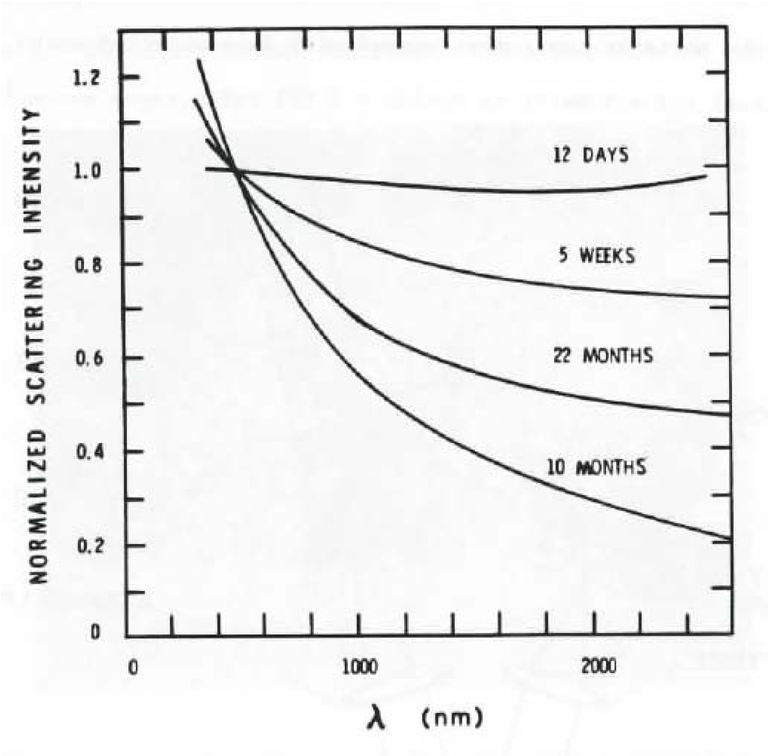
$$\rho_s(\theta) = \rho_{2\pi} * \frac{\rho_s(\theta,\lambda)}{\rho_{2\pi}(\lambda)}$$

[1]Pettit, R.B., "Characterizing Solar Mirror Materials Using Portable Reflectometers", SAND82-1714, September 1982.

Spectral Specular Reflectometer

- But specularity (σ) is wavelength dependent:

$$\rho_s(\theta,\lambda) = \rho_{2\pi}(\lambda)\left\{1 - \exp\left[\frac{-\theta^2}{2\sigma^2(\lambda)}\right]\right\}$$



Wavelength dependence of specular reflectance loss caused by dust accumulation during outdoor exposure[1]

Spectral Specular Reflectometer

- Therefore, need to measure $\rho_s(\theta,\lambda)$ and compute solar-weighted specular reflectance:

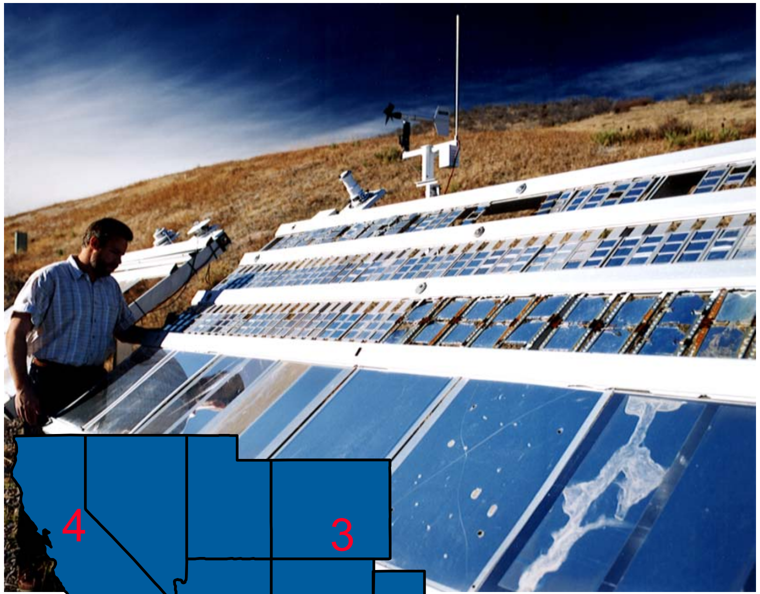
$$\rho_s(\theta) = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} \rho_s(\theta,\lambda) I(\lambda) d\lambda}{\int_{\lambda_{\min}}^{\lambda_{\max}} I(\lambda) d\lambda}$$

- New instrument being developed
  - High-speed measurements
  - Easy to use
  - Measure $\rho_s(\theta,\lambda)$ as a function of angle of incidence
  - < 2-mradian

Outdoor Exposure Testing (OET)

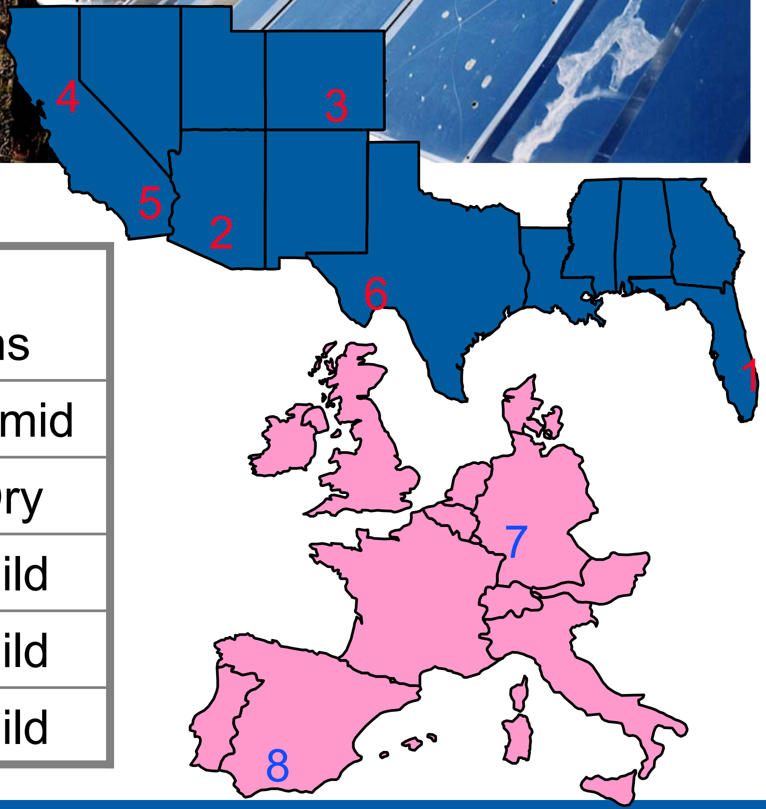
- 3 active meteorologically monitored outdoor sites

		City	State	Stress Conditions	
1	FLA	Miami	FL	Hot	Humid
2	APS	Phoenix	AZ	Hot	Dry
3	NREL	Golden	CO	Cool	Mild



- 5 inactive outdoor sites

		City	State/ Country	Stress Conditions	
4	SMUD	Sacramento	CA	Warm	Humid
5	DAG	Dagget	CA	Hot	Dry
6	TX	Ft. Davis	TX	Warm	Mild
7	GER	Cologne	Germany	Cool	Mild
8	SPA	Almeria	Spain	Hot	Mild



Accelerated Exposure Testing (AET)

Atlas Ci5000 WeatherOmeter (WOM):

- 2 Sun Xenon Arc
- 24/7
- ~ 6x NREL in terms of light exposure
- Sample capacity 336 samples/WOM

– 60ºC/ 60% RH
  - Solar Heat Program
  - 13 yr old

– 2 - 60ºC/ 60% RH
  - CSP
  - Operational 8/08
  - Operational 1/10

– Extended temperature cyclic WOM
  - TBD:
    – -10 to 120ºC w/light
    – 10-75%RH w/ light
    – dark cycle RH dependent on T
  - CSP
  - Operational 1/10

– Rain Spray WOM:
  - 40-110ºC
  - 10-75%RH w/ light
  - dark cycle RH dependent on T
  - Rain Spray Nozzles
  - CSP
  - Operational 1/10

Accelerated Exposure Testing (AET)

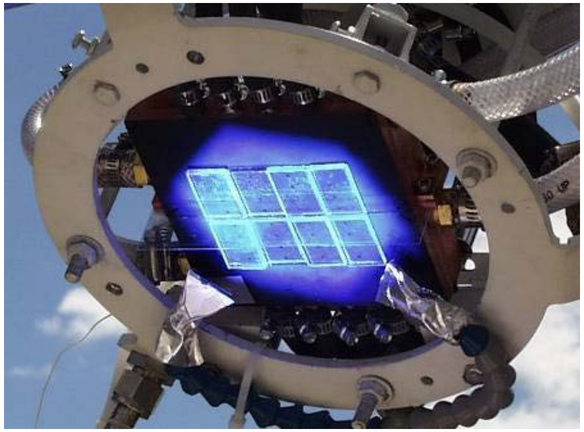
- Atlas BCX 2000 Basic Cyclic Corrosion
  - Neutral Density Salt Spray at saturated RH
  - Copper Acetic Acid Salt Spray (CASS)
  - Water Fog at saturated RH
  - SO_2 Injection
  - High Temperature, up to 71º C / 160º F
  - Operational 1/10
- Tenney T20 Cyclic Environmental
  - Temperature Range: -73°C to 200°C
  - Dark
  - Operational 11/09
- QPanel QUV
  - UVA 340@ 290 - 340 nm
  - 4 h UV at 40ºC
  - 4 h dark at 100%RH
  - ~1.4 x outdoors

- BlueM damp heat
  - 85ºC
  - 85%RH
  - Dark
  - At least 25x outdoors
  - Sample capacity 800
  - Operational 8/08
- BlueM Variable damp heat
  - 20-85ºC
  - 5-85%RH
  - Dark
- BlueM low %RH damp heat **(need to order)**

Ultra-Accelerated UV Outdoor Testing

Original dish 100X < 500 nm;
10 years of operation

New UV dish includes environmental chamber; same 100X < 500 nm, but 4x size

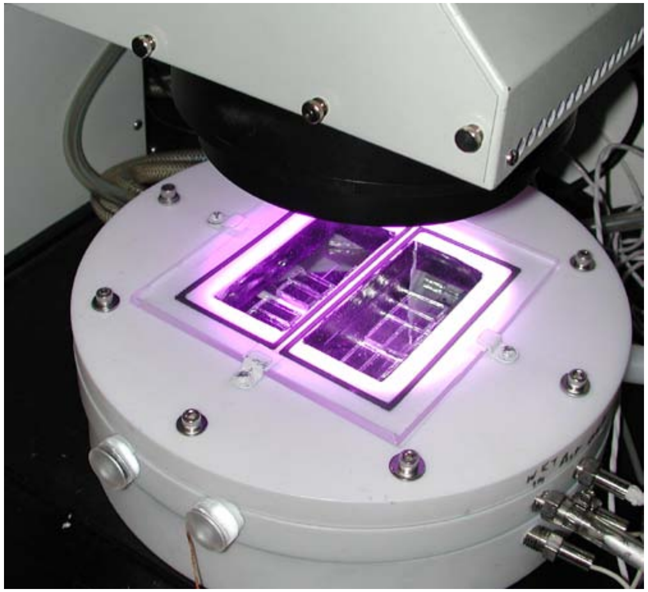


Accelerated aging of materials

EMMAQUA: Phoenix, AZ X7 to 8 cooled—near ambient sprayed w/ DI H_2O 8 min /nat. sun hr

Accelerated Exposure Testing (AET)

- 1.4 kW Solar Simulators (SS)
  - ≈5 Sun Xenon 300-500 nm
  - 4-quadrants
    - low/high RH
    - Low/high T
    - light /dark
  - 2 new SS & chambers under Stimulus FOA



- Haag Engineering Co. Ice Ball Launcher (IBL-7)
  - Stalker Pro radar gun Chrony chronograph
  - 50-60 mph (max 100 mph)
    - 25.5 – 27.4 m/s
  - 0.5 – 1.5” hail ball
    - 1.3 – 3.8 cm

- Drop Impact test
- Dart Impact test
- Building Pendulum Test
- Scrub Abrasion tester

Upgrade database

- *Database of solar materials contains:*
  - >1000 experiments
  - >20,000 samples
  - >300,000 measurements
  - >21 yr
  - Dirty/Clean
  - Older DOS menu driven RS/1
  - Newer Access/Excel
- Upgrade database
  - Subcontract w/ EMAGENIT
  - 6 mo
  - Data web accessible
  - Non-PI available
  - PI secure log-in/file transfer

Solar Mirrors

Thick Glass
- Flabeg
- AFEU
- PPG (FOA)
- Rio Solar
- Saint Gobain

Thin Glass
- AFEU (Glaverbel)
- Flabeg (Naugatuck)

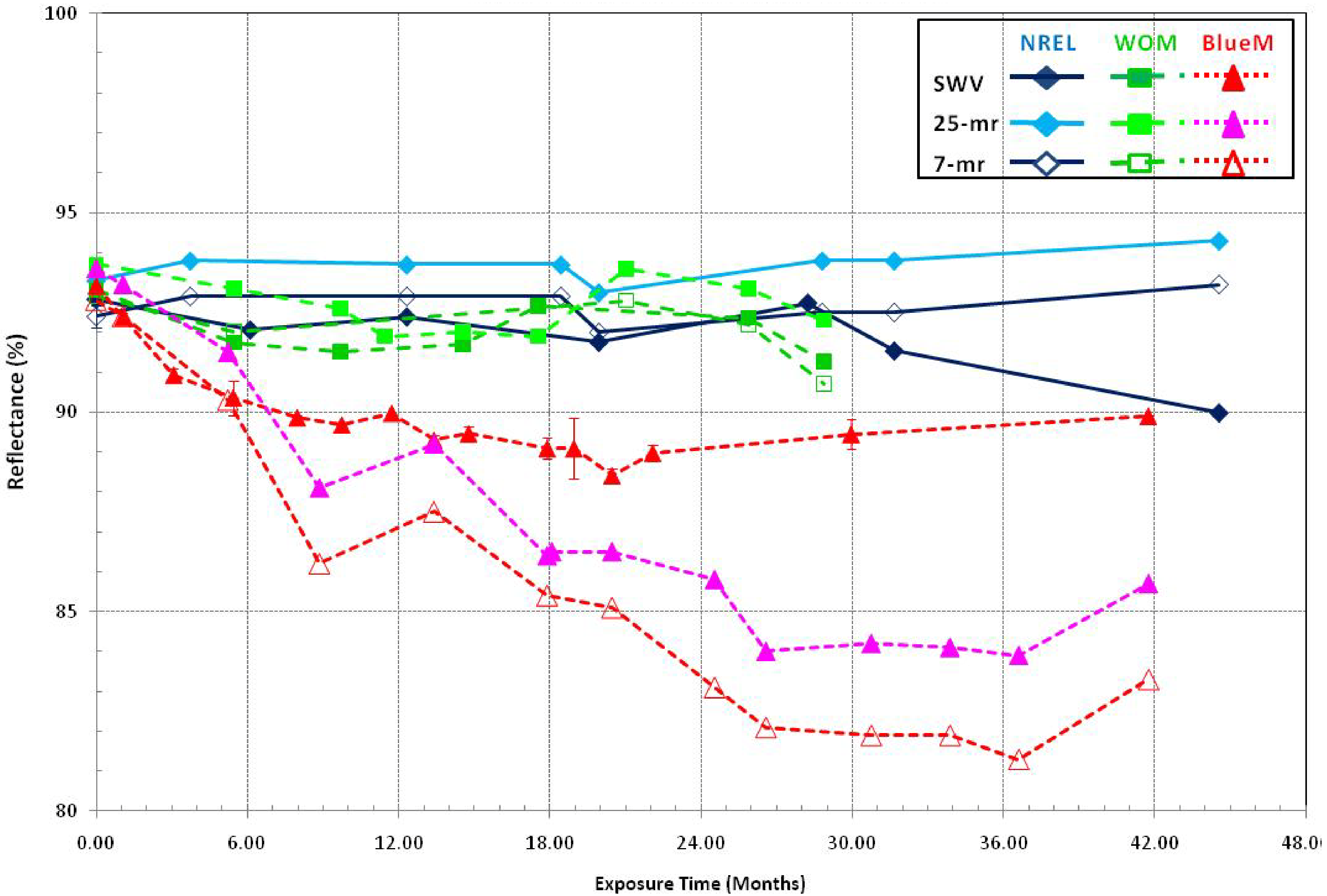
Laminated Glass
- Guardian
- Veridian

Silvered Polymer
- ReflecTech
- 3M Solar Reflector 1100 (improved ECP-305+)

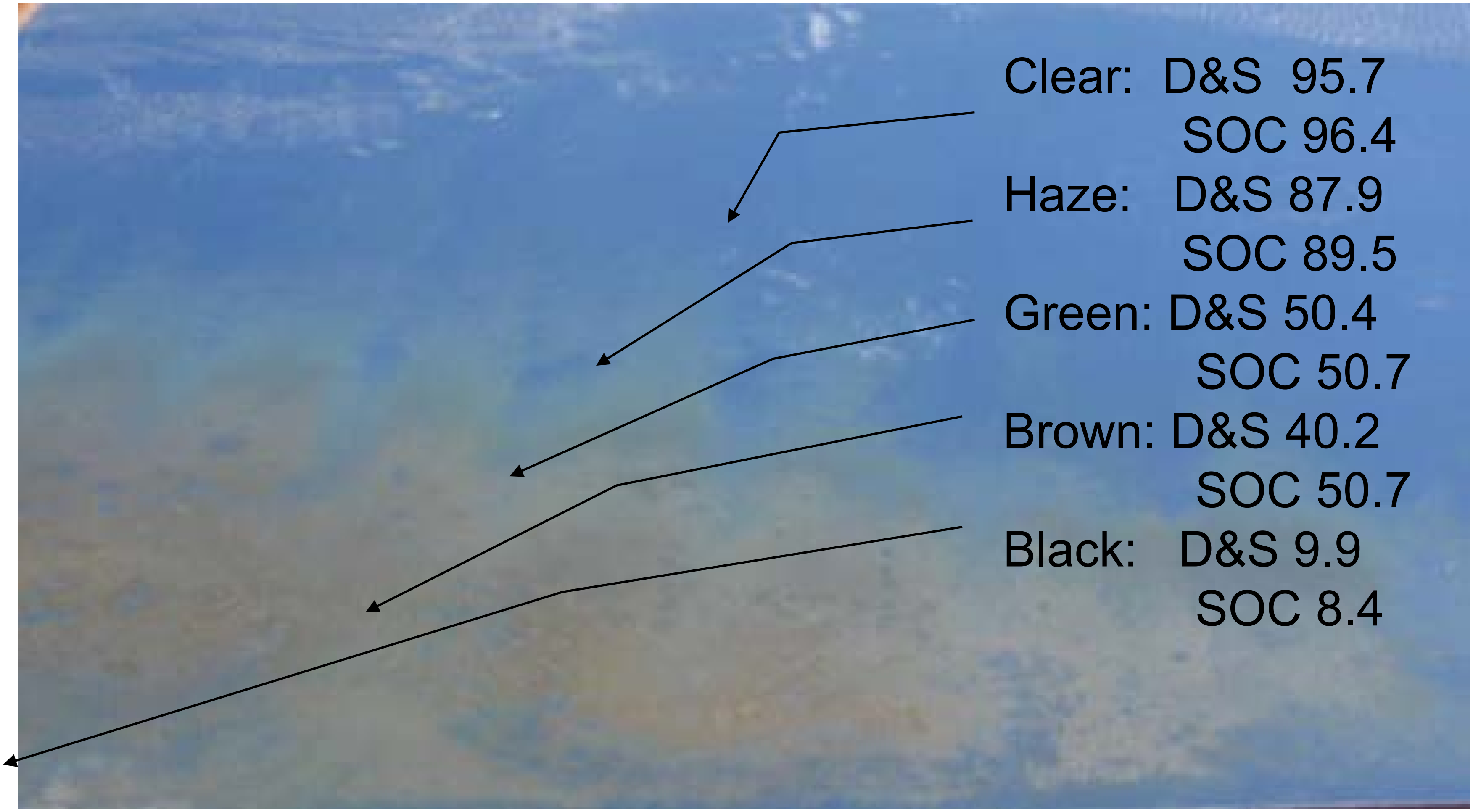
Anodized Aluminum
- Alanod
- Alcoa (FOA)
- Alubond
- Alucbond
- Aluminum Coil Anodizing (ACA)

Front Surface
- Abengoa (FOA)
- JDSU

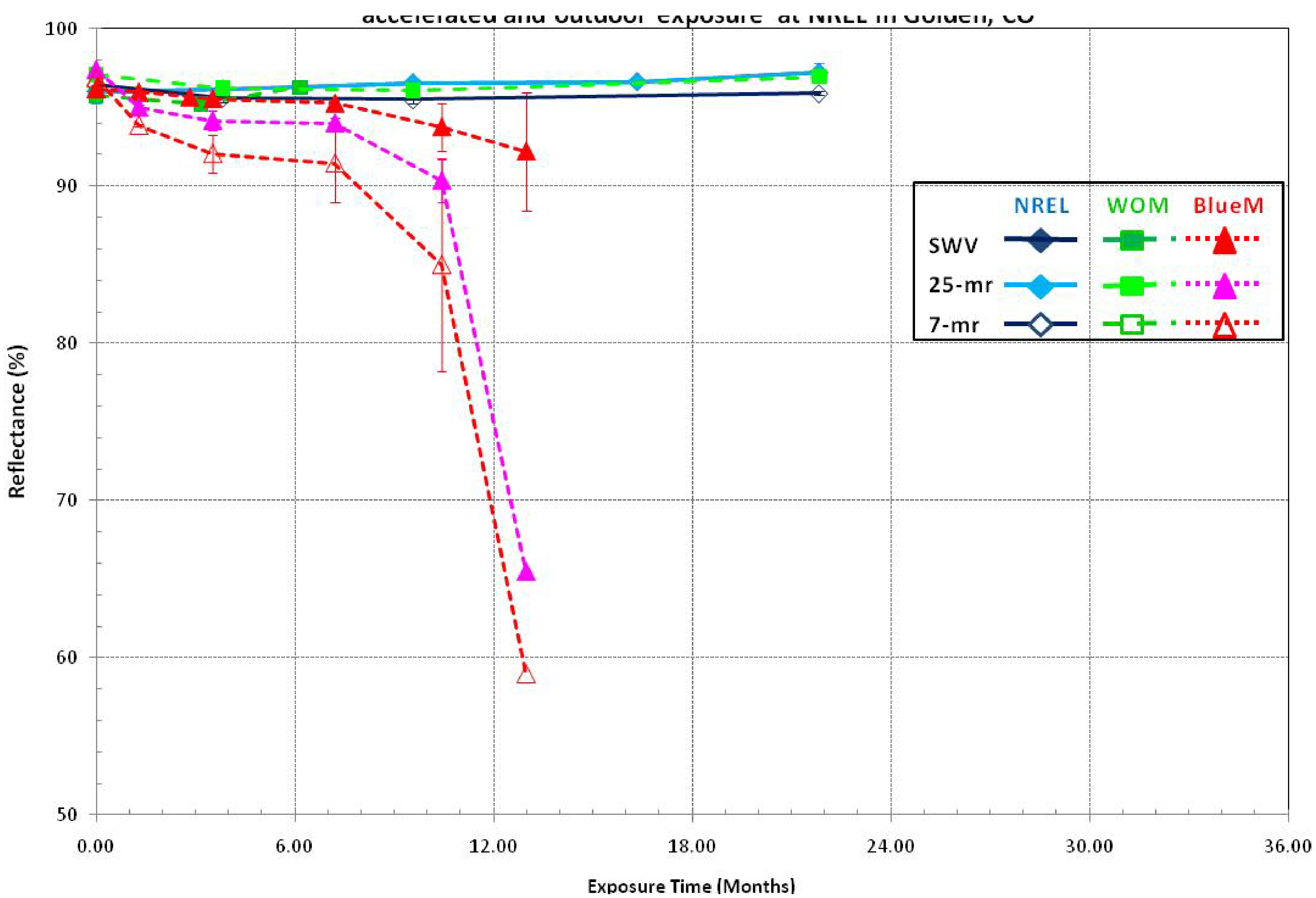
Thick Glass Solar Mirror



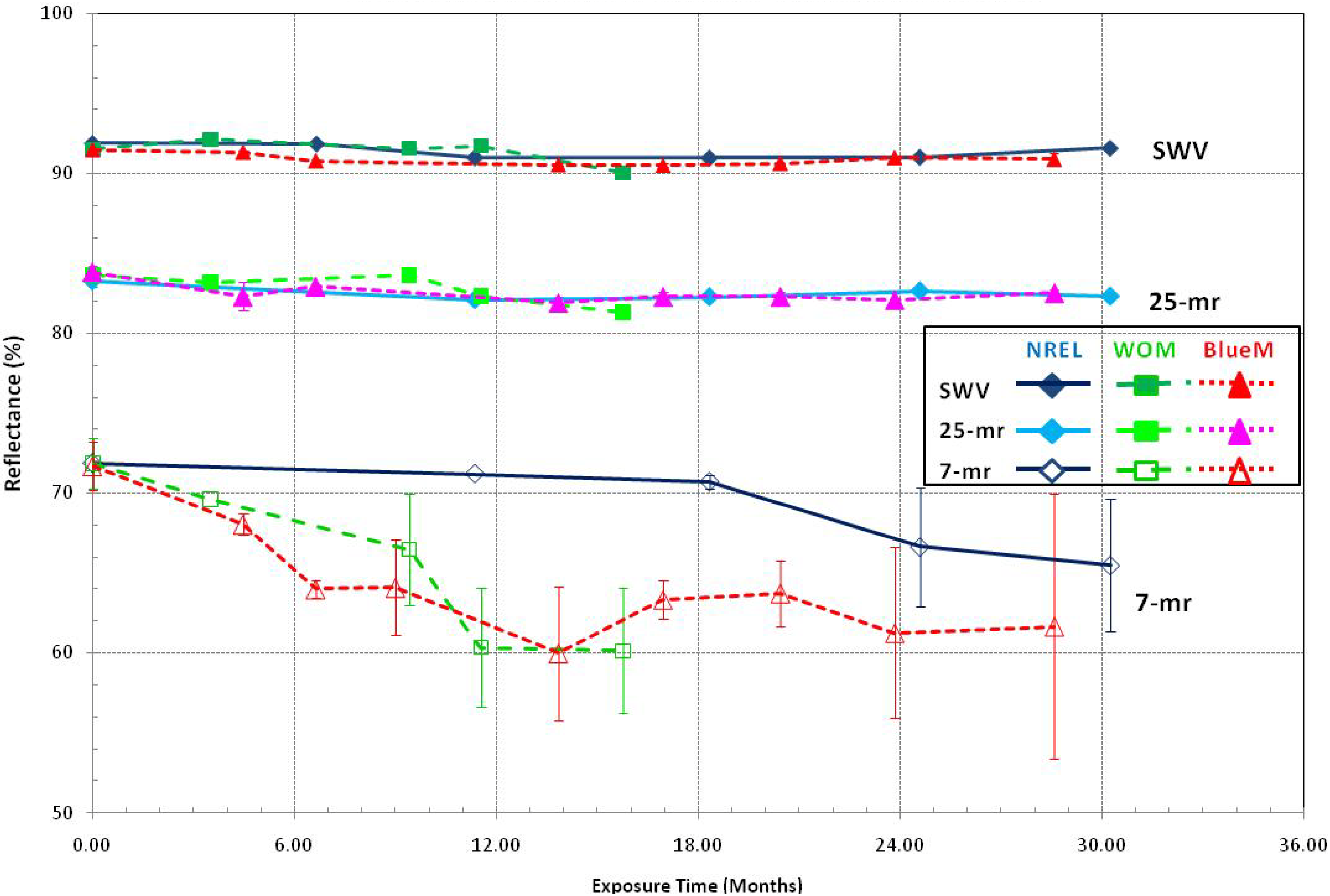
Corrosion observed in field in <2 yr



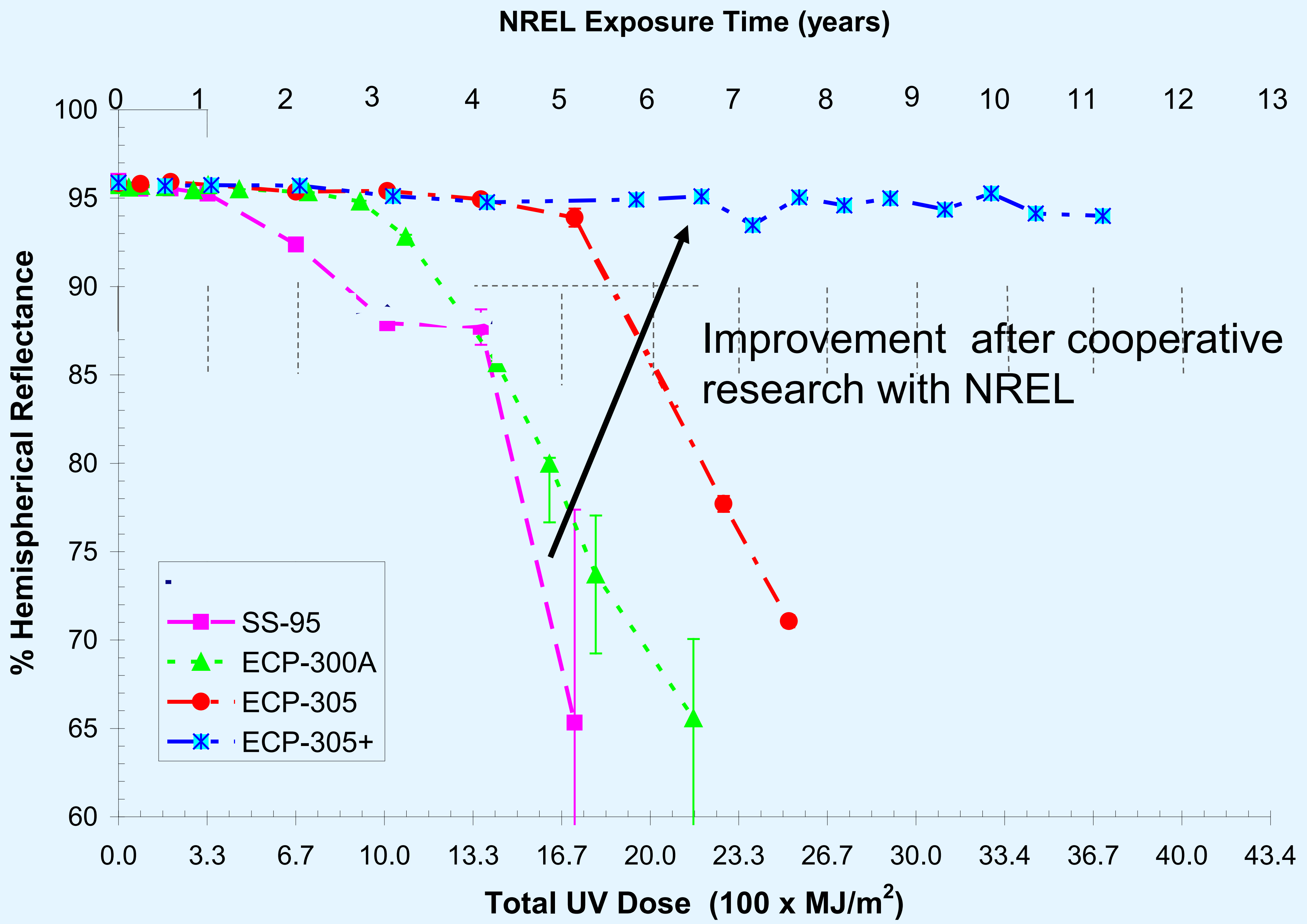
Thin Glass Mirror



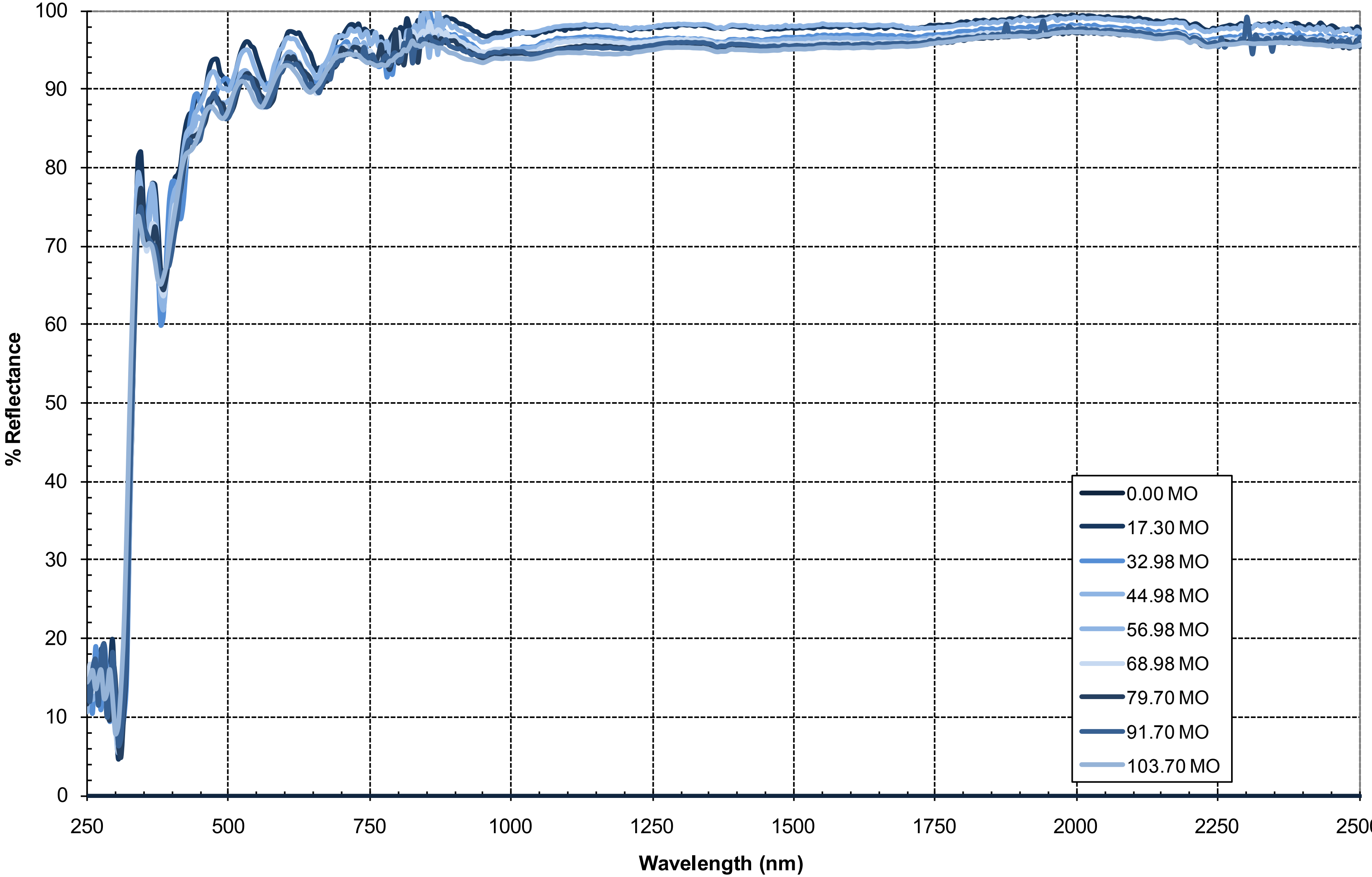
Alanod Aluminized Reflector
with Nanocomposite oxide layer



3M Metallized Polymer Films



Spectral Reflectance after 104 months of outdoor exposure in Phoenix, AZ

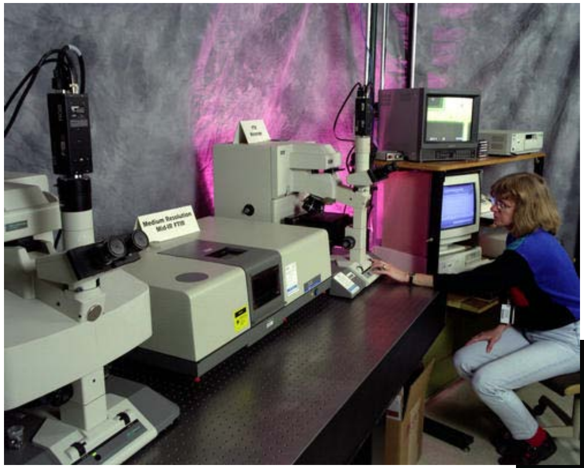


Analytical Characterization

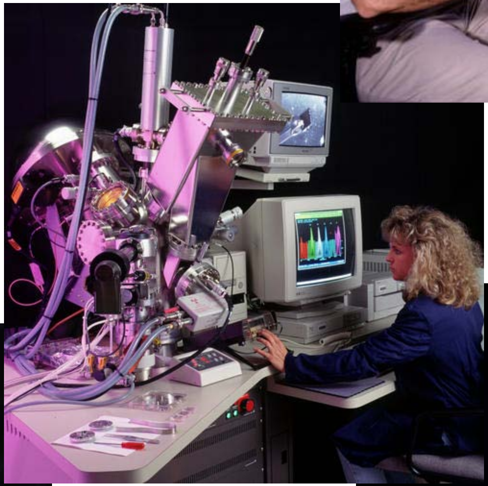
Help optimize sample preparation

Failure analysis of exposed samples

Strong industry support capabilities



Auger
XPS
XRD
Rheometer

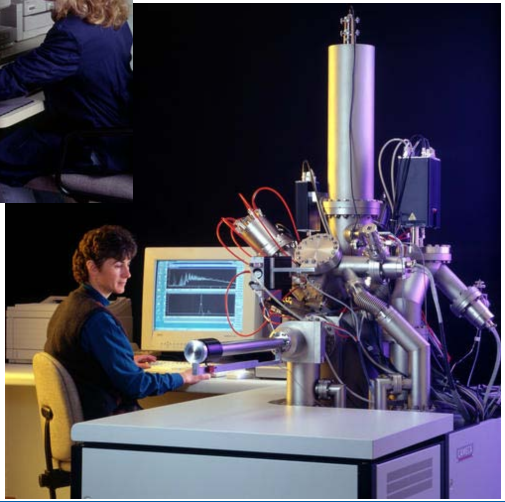


SEM
TEM

AFM
SIMS

FTIR
H_2O permeation
O_2 permeation

TGA
DSC
Instron



Advanced Reflectors

- Mirror Characterization & Durability Testing
- Service Lifetime Prediction (SLP)
  - Funds-in 3M/NREL SLP CRADA
  - Glass Mirror SLP
- Advanced Reflector Coatings Development
- Antisoiling Coatings and low-to-no H_2O Cleaning
- Reflector and Durability Standards Development

Advanced Reflectors

Advanced Reflector Coatings Development activities:

- Develop advanced mirrors that integrate antisoiling top coatings incorporating:
  - Lessons learned from NREL previous Front Surface Mirror (FSM) research
  - Advances in:
    - Adhesion promoting interlayers
    - Hardcoats
    - Barrier coatings
    - Levelized stainless steel and polymer substrates

Antisoiling Coatings and low-to-no H_2O Cleaning activities:

- Develop soiling tests and determine soil properties and soiling rates at outdoor sites
- Develop antisoiling coatings including TiO_2 and alternative antisoiling layers
- Explore replaceable vs. permanent and low vs. high surface energy coatings
- Sponsor up to three university Senior design engineering projects or teams to examine alternative low-to-no H_2O mirror cleaning concepts

Solar Glass Mirrors –
Standards & Quality Control Issues

Glass
- Fe content (sand, campaign)
- Glass thickness

Silver
- Ag <6 mo since float
- Silver air side of glass
- Glass cleanliness
- Glass sensitization ($SnCl_2$ vs $PdCl_2$)
- Silver thickness (0.8 g/m^2 < t < 1.2 g/m^2)

Back layer
- Copper vs. copper-free
- Separate lines needed
- Glaverbel vs. Valspar copper-free process

Lead-free paint system
- EU (<0.15% Pb) vs. US (1-5 PPM Pb)
- Valspar vs. Fenzi paint system
- 1, 2, 3 coat paint system
- Wax content in outer layer of paint

Adhesive
- Chlorine-scrubbed
- Low-bleed paths

Soiling Properties
- Self-cleaning advantage

- No standards for solar glass mirrors
- Qualification tests for indoor mirrors being used
  - Resistance to damp heat constant atmosphere:
    - 480 hours @ 60°C without defects per ISO 6270-1 or ASTM D1735
  - Resistance to salt spray test
    - 480 hours without defects per ISO 9227 NSS or ASTM B117
  - Resistance to cooper-chloride-acetic acid-salt spray fog tests (CASS)
    - 120 hours without defects per ISO 9227 CASS or ASTM B368
  - Aging/weather exposure test:
    - 5 weeks weather exposure test per ISO 21207, test type “B” or 480 h G1173-03 with no softening of the mounting element adhesive, separation of protective coatings, or defects
- Few warranties given
  - e.g., Limited 3 y warranty until mounted in use
- Aggressive warranties being requested
  - e.g., <1% after 30 y

Advanced Reflectors FOA Support

3M FOA

Abengoa FOA

Alcoa FOA

PPG FOA

Solar Selective Coating Objectives

- Develop new, more-efficient advanced solar selective coatings for receivers with:
  - High solar absorptance ($\alpha > 0.96$)
  - Low thermal emittance ($\varepsilon < 0.07$ @ 450ºC)
  - Thermally stable > 450ºC, ideally in air
  - Improved durability and manufacturability
  - Reduced cost
  - Encourage development of US &/or 3rd receiver manufacturer

Desirable Properties for Stable Coating in Air > 450°C

Literature review performed and different constructions modeled

Based on T_{MP}: W, Mo, Ir, Os, and Ta are prime candidates

But W, Mo, Os, and Ta have very poor oxidation resistance, and MoO_2 very volatile

Fluorides have very low index of refraction but difficult to deposit with poor oxidation resistance

Excellent properties with large number of multilayers, numerous different materials, and very thick or thin layers but hard to deposit

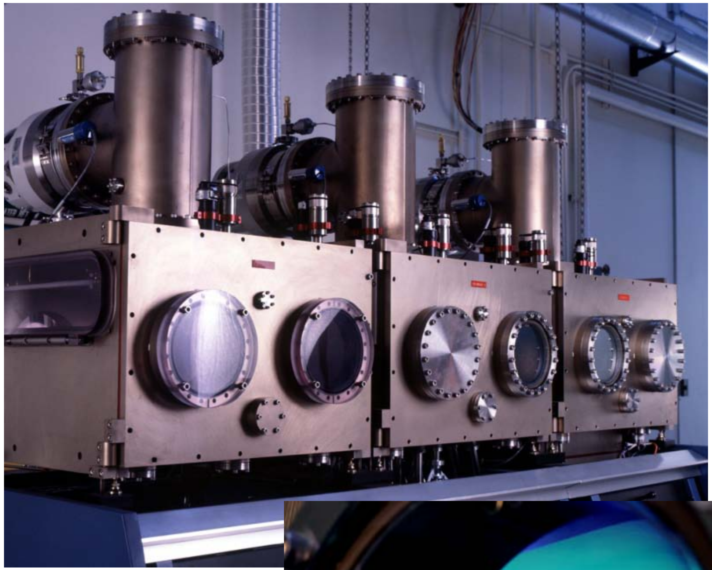
∴ Eliminated from consideration

NREL Modeled Selective Coating

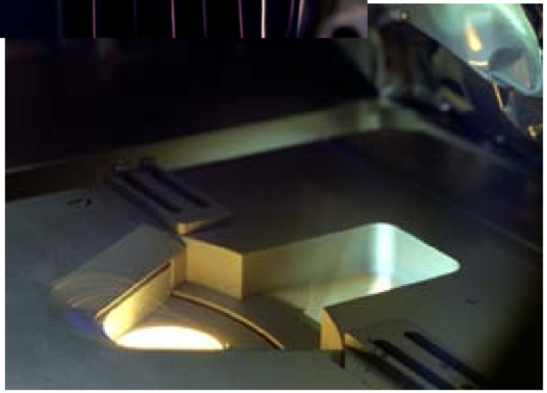
Comparison of theoretical optical properties for NREL's modeled prototype solar selective coating with actual optical properties of existing materials.

	Commercial (as tested)			Modeled NREL
	Black Cr	Mo-Al_2O_3 Cermet	Al_2O_3-based Cermet	# 6A
Solar Absorptance	0.916	0.938	0.954	0.959
Thermal Emittance@				
25°C	0.047	0.061	0.052	0.027
100°C	0.079	0.077	0.067	0.033
200°C	0.117	0.095	0.085	0.040
300°C	0.156	0.118	0.107	0.048
400°C	0.197	0.146	0.134	0.061
450°C	*0.218*	*0.162*	*0.149*	*0.070*
500°C	0.239	0.179	0.165	0.082

Deposition Facilities



Sputtering Chamber



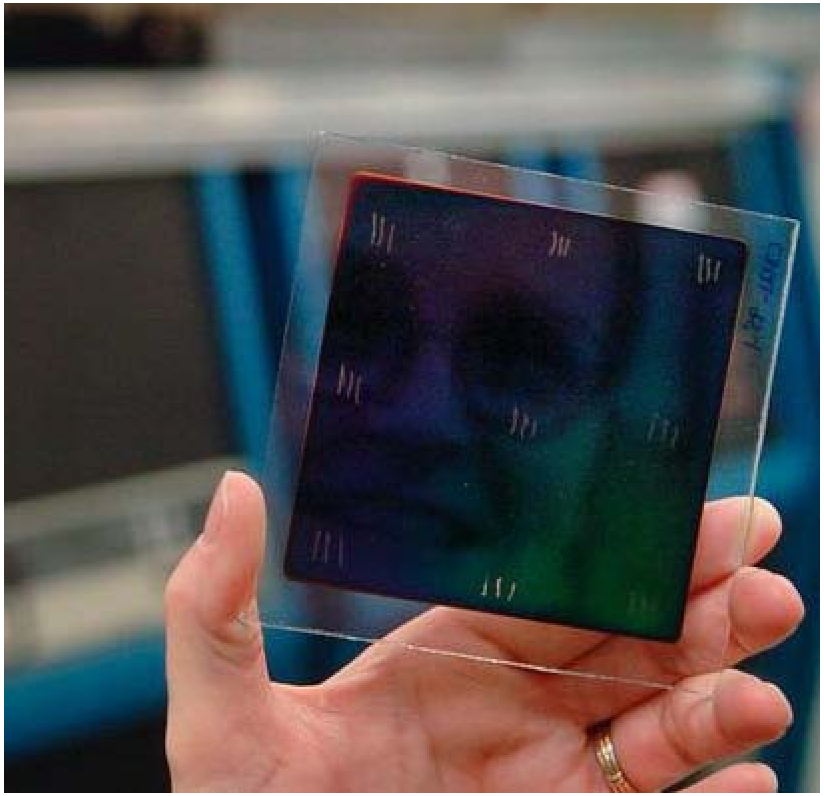
E-Beam Chamber

- Three-Chamber In-line System
  - Load-Lock Chamber
  - Pulsed DC Sputtering Chamber
    - 3 - linear arrays of 5 - 1.5” Mini-mak guns
    - 2 - 12” planar cathodes
    - Codeposition
    - Process & Control
      - RGA
      - Quartz Crystal Monitor
      - OES
      - IRESS
      - Pressure/Gas
  - Electron-Beam/IBAD Chamber
    - 6 multi-pocket e-beam source
    - Co-deposition bottom plate
    - IBAD w/ 12” Linear Ion Gun
    - Process & Control
      - RGA
      - Quartz Crystal Monitor
      - OES
      - Pressure/Gas
  - System
    - 12”x12” ambient or heated substrate
    - 4 Reactive Gases
    - Turbo molecular drag pumps
      - 2×10^{-8} torr
    - Monitoring
      - DAQ
      - Computer

β – version Proof-of-Concept Prototyping Key Results

Codeposit individual layers and modeled coating

- Proof-of-concept development used E-beam/IBAD chamber because of cost and flexibility
- Codeposition development
  - Deposited individual layers
  - Deposited modeled structure
  - Characterize properties
- Optical performance lower than modeled but extremely encouraging despite known errors in:
  - Thickness
  - Composition
  - Measurement



Optical Characterization: Absorbers

- **Perkin-Elmer (PE) 883 IR spectrophotometer (2500 nm-50 µm)**
  - 3X Beam Condenser Specular Attachment
    - NIST traceable Au Standards
  - Fixed angle (V) reflectance attachment
    - 5,10,15, 20 mm aperture
    - 71006 Al reflectance standard

- **Gier-Dunkle DB 100 Infrared Reflectometer**
  - Total emissivity
  - Room temperature
  - Weights measurement by 100°C blackbody

- **Surface Optics Corporation (SOC) ET-100 hand-held reflectometer**
  - Directional thermal emittance in IR
  - Incidence angles: 20°, 60°
  - Predicts Hemispherical Total Emittance

Inert Gas High Temperature Oven

General Specifications

Temperature range:
50°C above ambient to 593°C (1100°F)

Control Accuracy:
±0.5°C

Uniformity:
+2% of setpoint

Resolution:
+0.1°C

Performance Data (typical):

Run time: 60 minutes. (6680, 7780, 8880); 90 min. (9980)

Cool down time: 90 min. (6680, 7780); 120 min. (8880, 9980)

- Empty chamber performance at rated voltage

New Capabilities

- Optical Characterization
  - High-temperature IR spectrophotometer or FTIR

- Stability Testing
  - 3 High-temperature (450, 550, 650ºC) Vacuum oven (need to order)

Rapid Commercialization under CRADA w/Schott Solar

NREL filed a patent and solicited/selected a business partner to rapidly commercialize the coating under a CRADA

- Optimize coating by sputtering at NREL
- Scale-up to pilot production
  - Single full-size tube
- Pilot production run in limited quantity series run
  - Field test
- Key issue will be sputtering and optimizing the coating in a very short time.

Advanced Absorbers

- Schott (TCD fund-in) CRADA Support
- Advanced Solar Selective Coating Development
- Receiver Optical performance & Durability Standards Development

Upgrading Deposition Capabilities

Vac-Tec Magnetron Deposition System

Pernicka Five-Chamber Deposition System

Vac-Tec Magnetron System
- 3-5”x8” planar magnetron cathodes
  - DC & RF @ 13.56MHz
- 3 Reactive gases
- 5”x8” or 5”x20” water-cooled substrate
- Upgrading to CFUBMS

Five-Chamber System
- Load-Lock Chamber
- wo PECVD Chambers
- Pulsed DC Sputtering Chamber
  - 1- 3”x12” Linear Magnetron Cathode
  - Codeposition & Composite
  - Pulsed DC Power Supply
  - 4 Reactive gases
  - Upgrading to HPPMS
- Thermal Evaporation Chamber
  - Two-Pocket (ThermalSource
  - 4 reactive gases
  - Co-Deposition
- 12x12” ambient or heated substrate

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