A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

NREL National Renewable Energy Laboratory

Innovation for Our Energy Future

Advances in Concentrating Solar Power Collectors: Mirrors and Solar Selective Coatings

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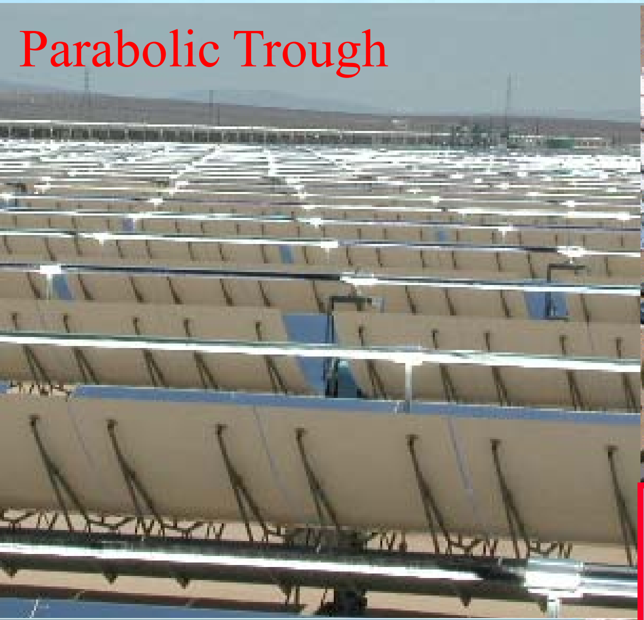
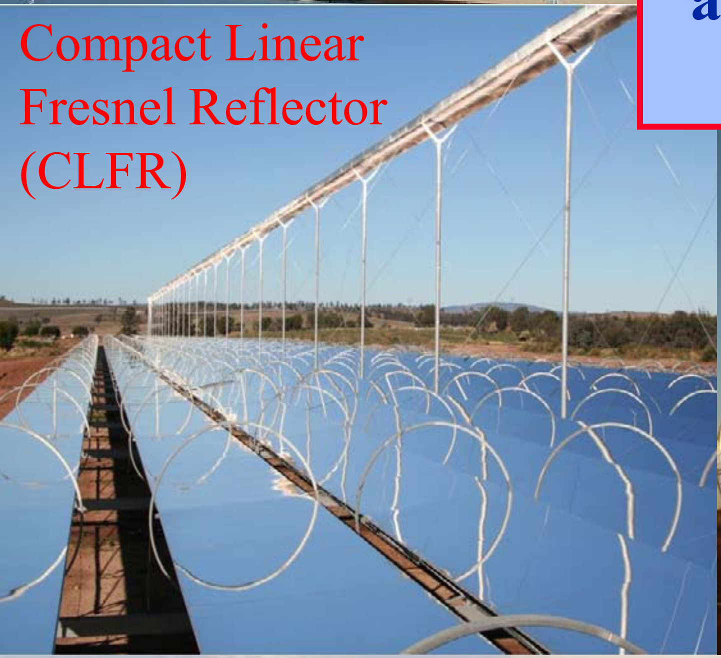
Outline

- Solar Market Potential
- Solar Reflectors
- Solar Selective Coating
- Conclusion

Concentrating Solar Power Technologies

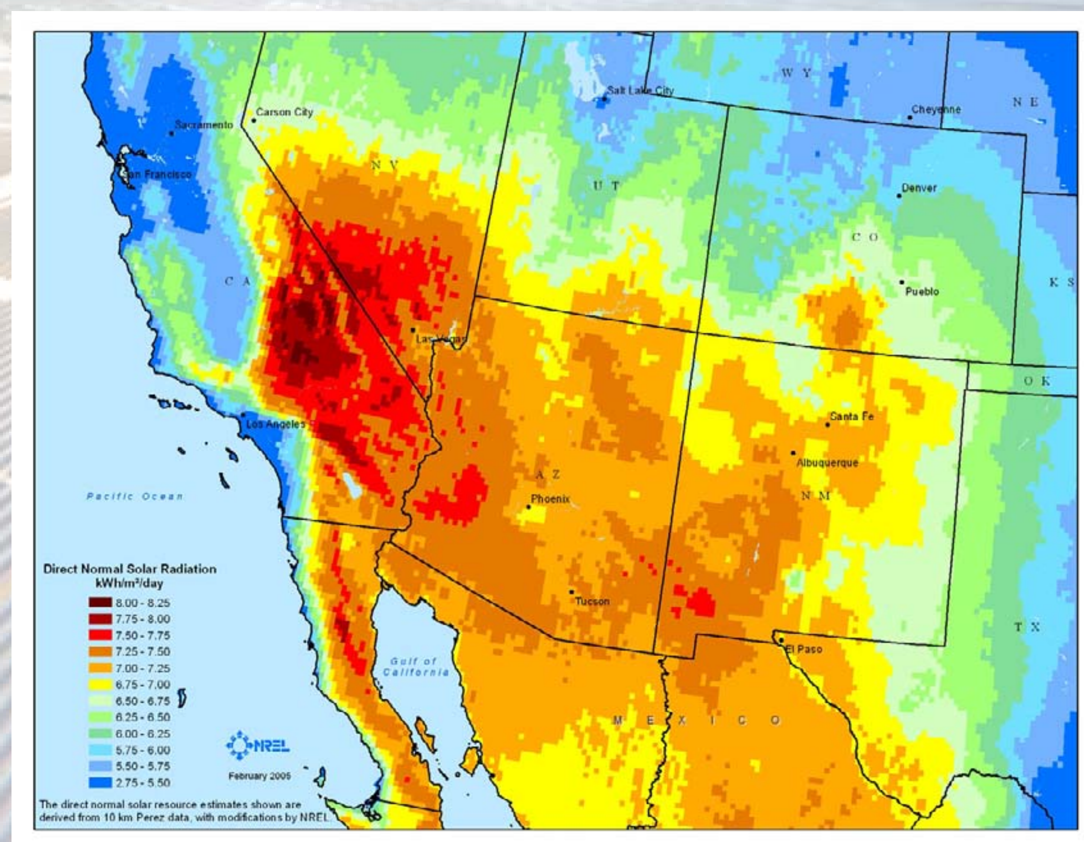


Solar concentration allows tailored design approaches



DOE & WGA determined feasibility of 1000MW in SW

Southwest Solar Resources



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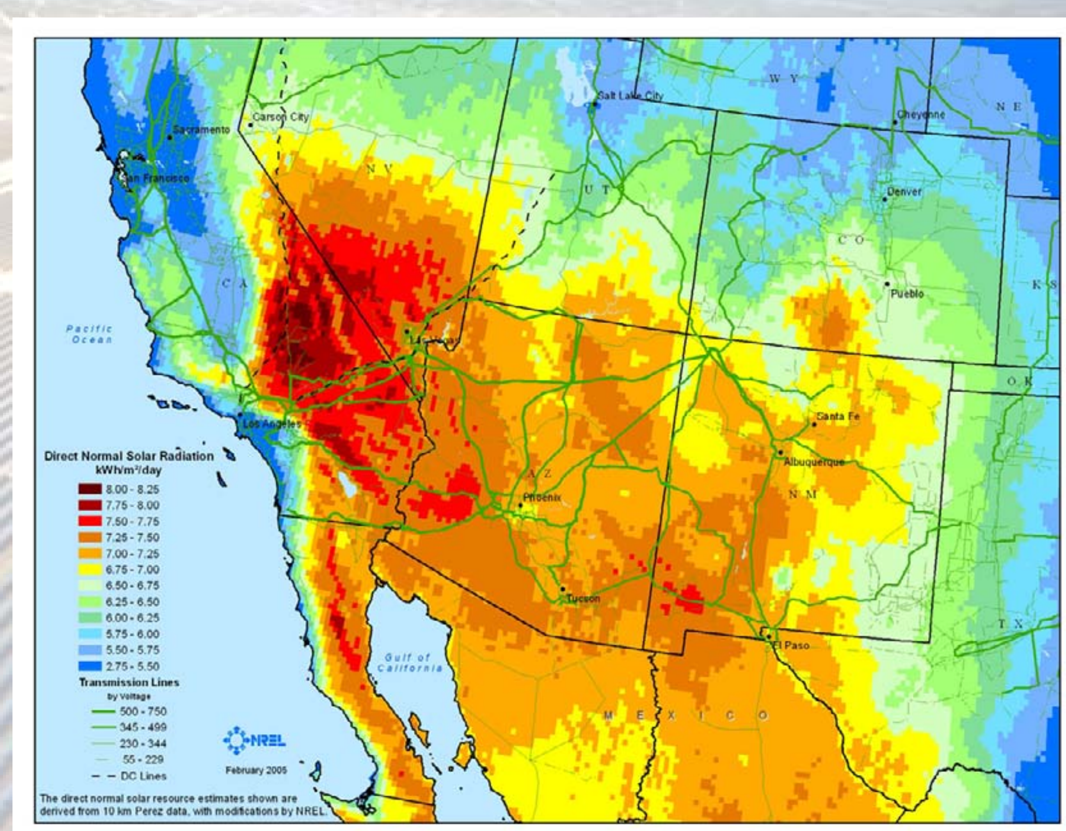
Transmission Overlay



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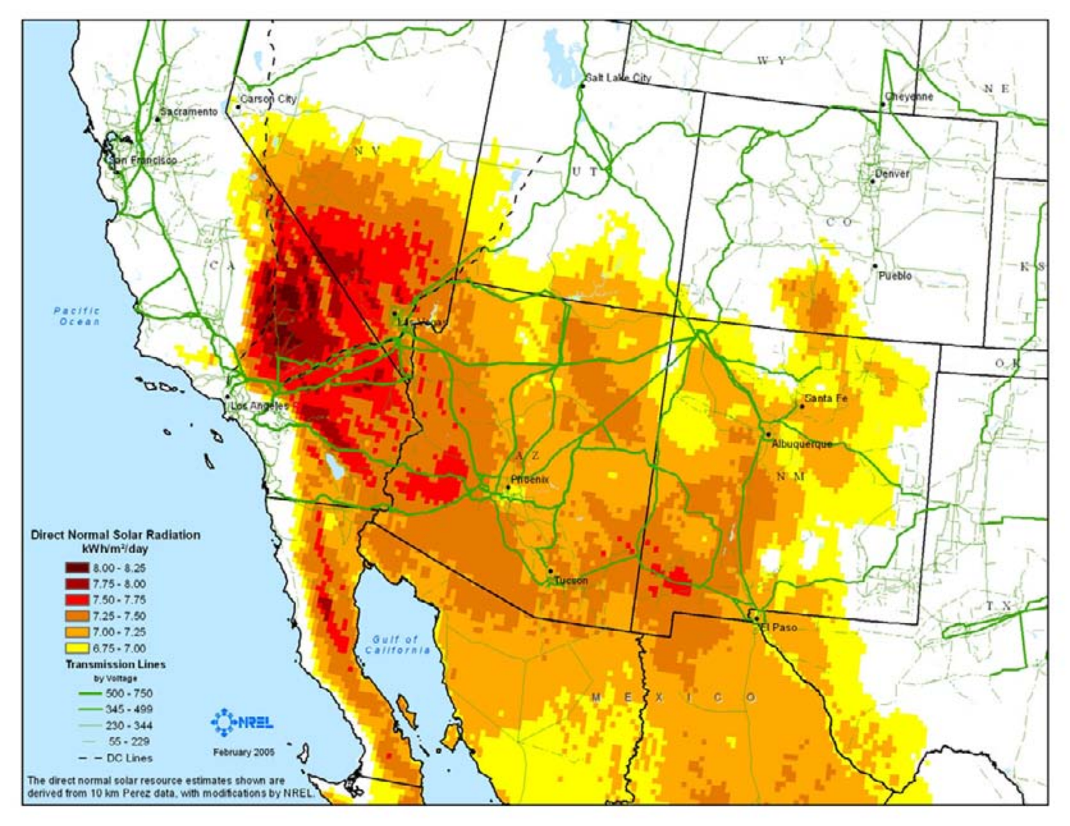
Transmission Overlay

Eliminate locations
< 6.75 kwh/m^2/day



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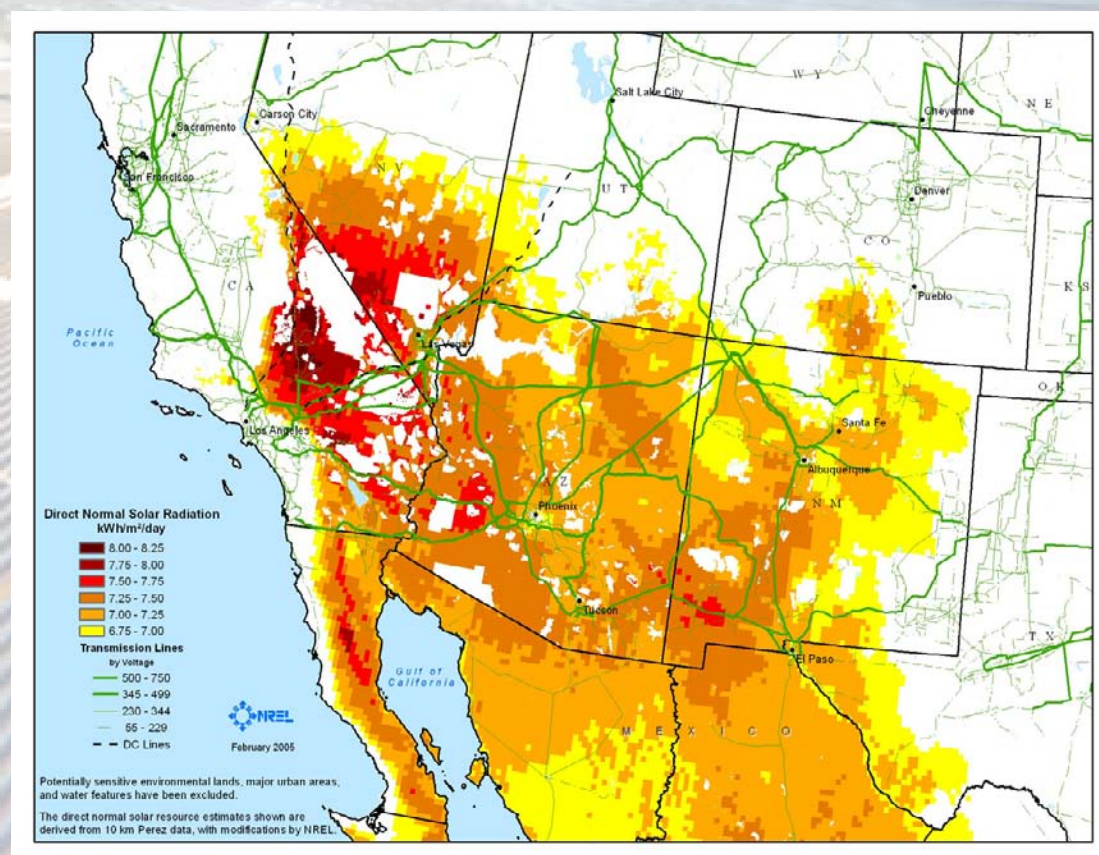
Transmission Overlay

Eliminate locations < 6.75 kwh/m^2/day

Exclude environmentally sensitive lands, major urban areas, and water features



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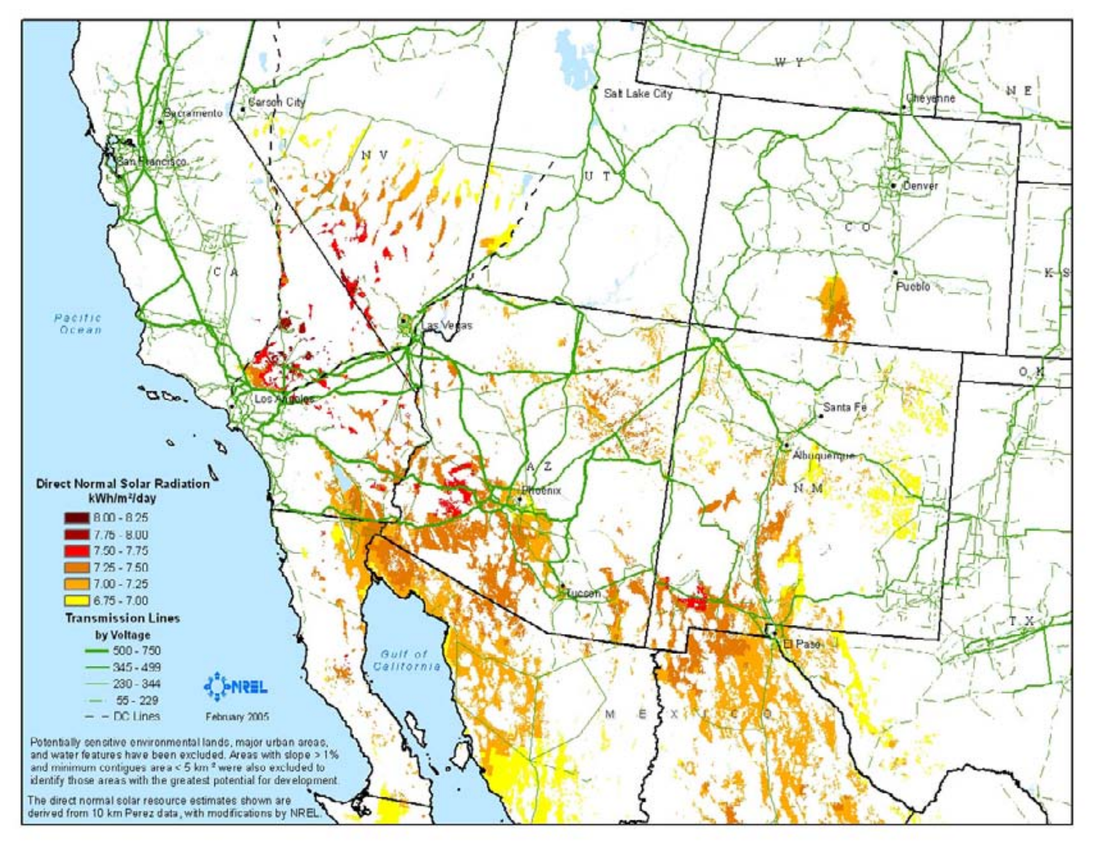
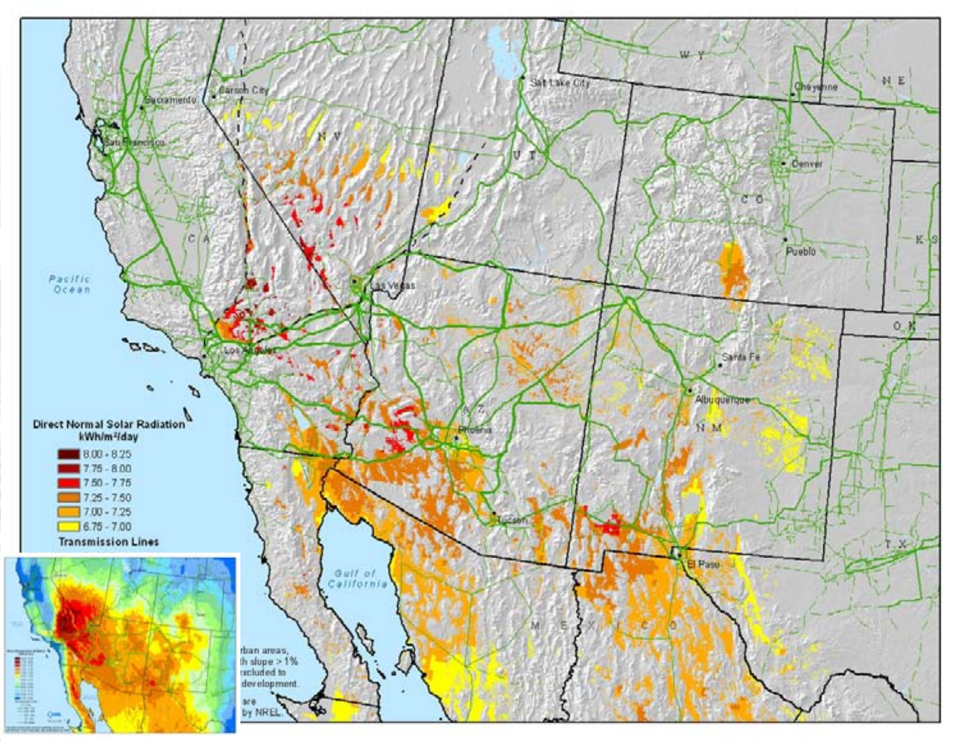


Remove land areas > (3%) & 1% average land slope

Remove land <5 contiguous km^2

SW Solar Energy Potential

State	Land Area (mi²)	Solar Capacity (MW)	Solar Generation Capacity GWh
AZ	19,279	2,467,663	5,836,517
CA	6,853	877,204	2,074,763
CO	2,124	271,903	643,105
NV	5,589	715,438	1,692,154
NM	15,156	1,939,970	4,588,417
TX	1,162	148,729	351,774
UT	3,564	456,147	1,078,879
Total	53,727	6,877,055	16,265,611

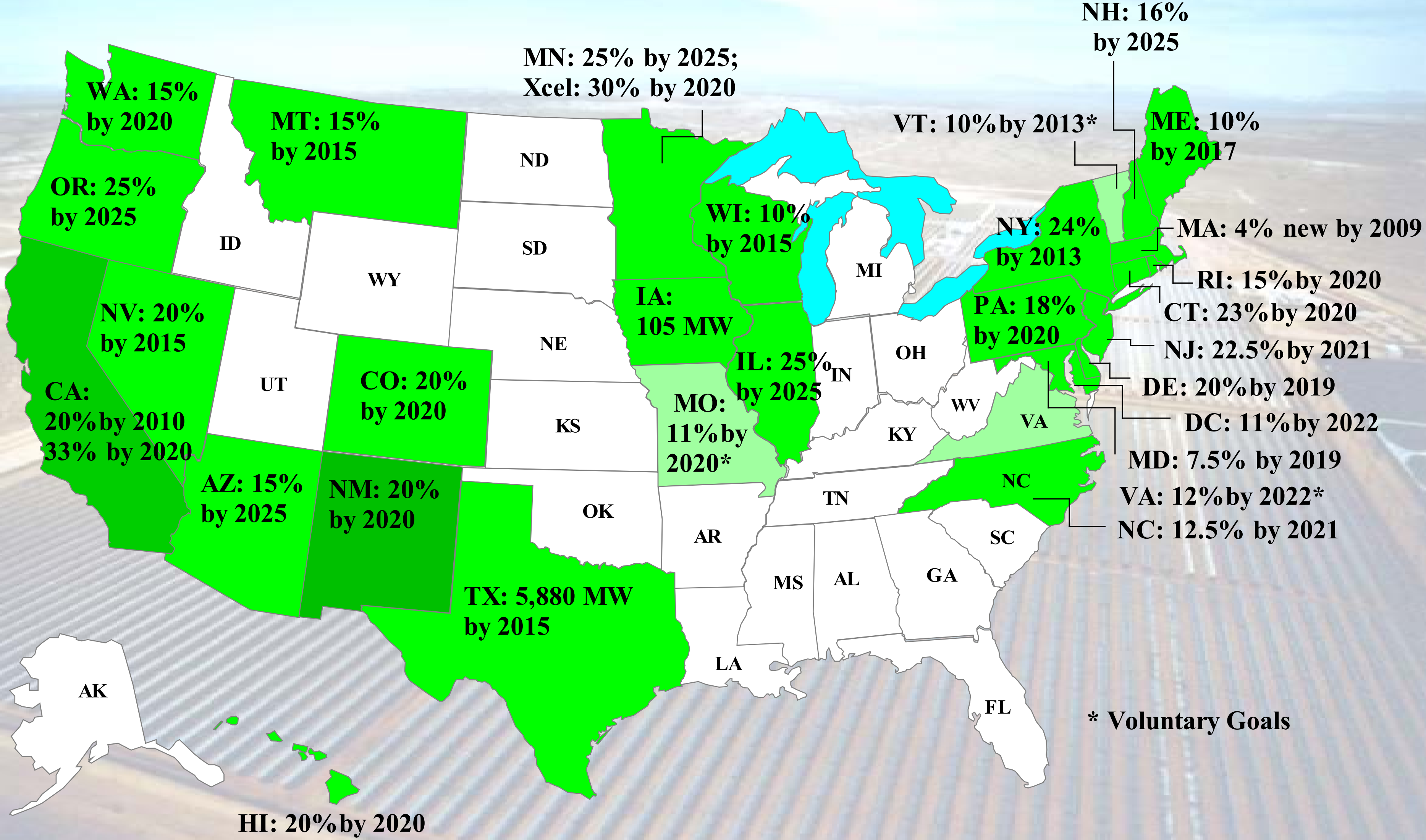


The table and map represent land that has no primary use today, exclude land with slope > 1%, <5 contiguous km², & sensitive lands.

Solar Energy Resource ≥ 6.75 kwh/m²/day
Capacity assumes 5 acres/MW
Generation assumes 27% annual capacity factor

- Current total generation in the U.S. is 1,000GW w/ generation approximately 3,800 TWh

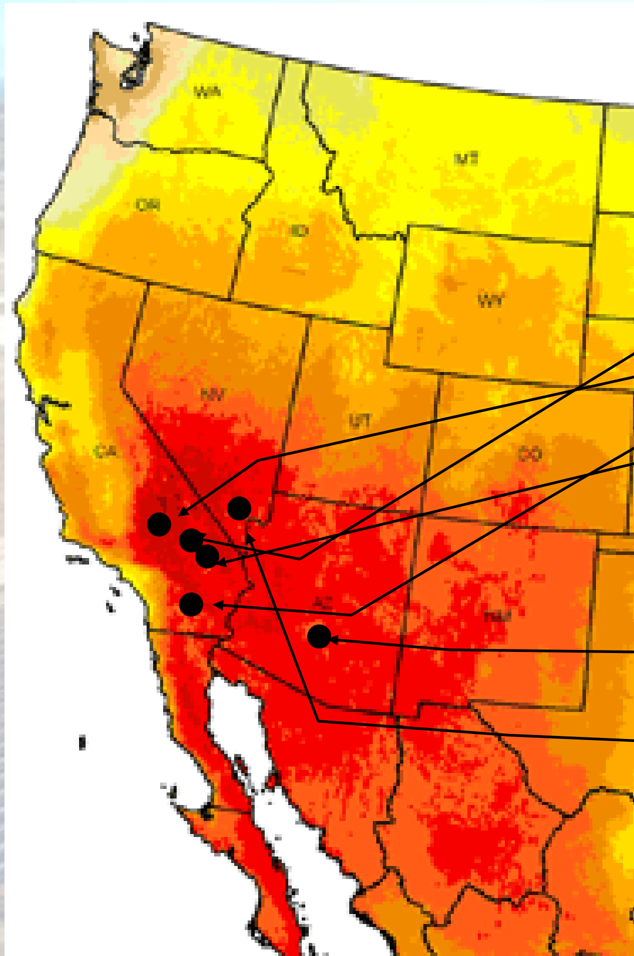
Renewable Portfolio Standards



State RPS mandates successfully jump-starting desirable growth

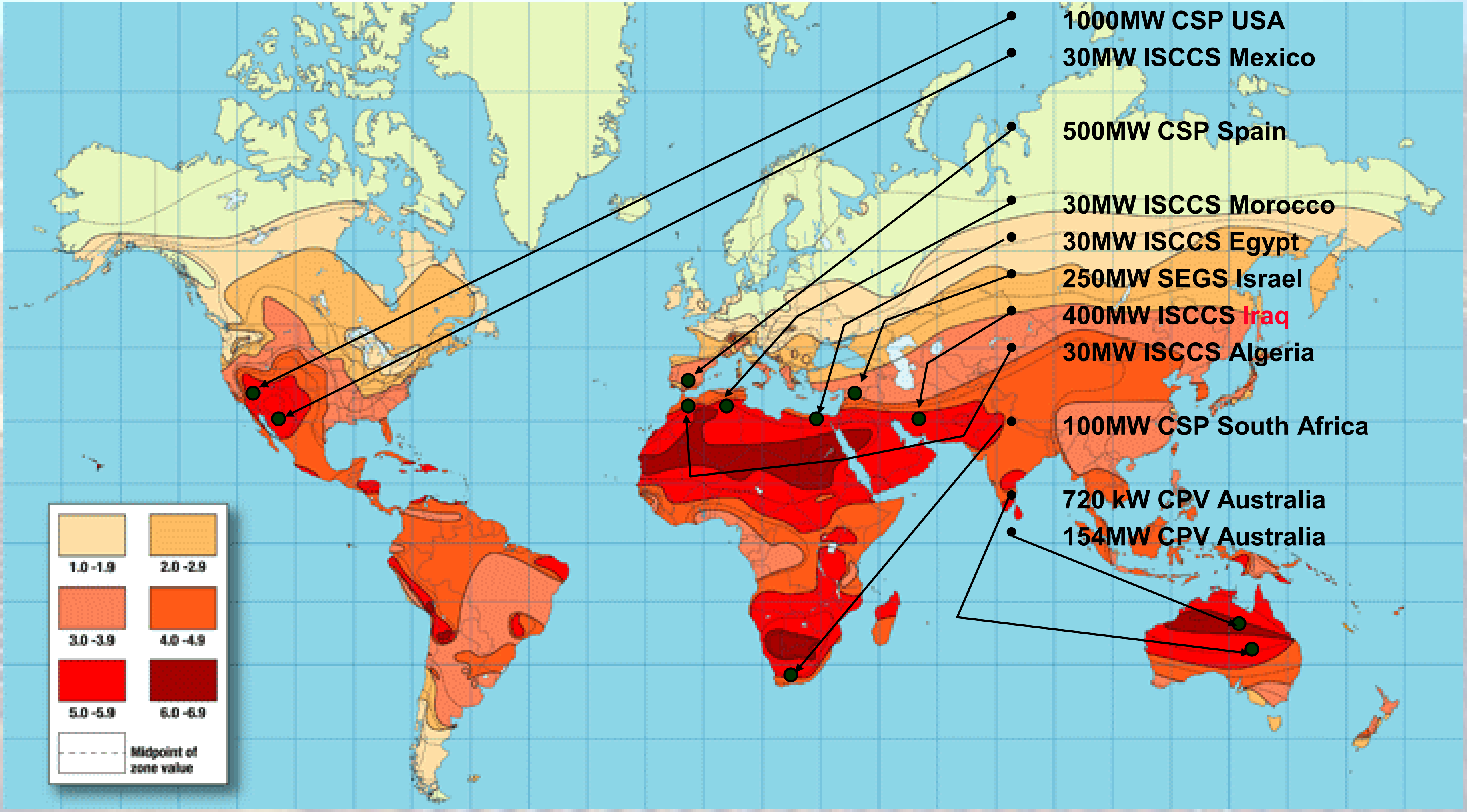
Market for Solar in US SW

10,000 MW of CSP by 2020



- California:
  - 500 MW by 2010
  - 8,000 MW by 2020 –peaking demand
    - **354 MW SEGS trough plants in CA**
    - **2 PPAs for 1.75 GW Dish Stirling plants in Southern CA**
      - 500 MW (option to expand to 850 MW) – Mojave Desert
      - 300 MW (two options to expand to 900 MW) – Imperial Valley
    - **553 MW PPA signed PGE, CA**
    - **300 MW PGE, CA Pending contractual announcement**
    - **175 MW PGE/FPL CLFR (commitment)**
    - **200 MW FPL CLFR (commitment)**
    - **1000 MW PGE (commitment) probably in CA**
- Arizona: 2,000 MW
    - **1 MW trough plant in AZ**
- Nevada: 1,500 MW
    - **64 MW trough project in NV**
- New Mexico: TBD
- West Texas: 1,000 + MW
- Colorado:500 MW after 2010
    - **Numerous RFP's in CO, TX, AZ,**
- Florida: 300 MW CLFR (FPL Commitment)
    - **10 MW initial (w/ option to expand to 300 MW)**
    - **500 MW FPL (commitment) in CA, FL, & other states**

International CSP Project Developments

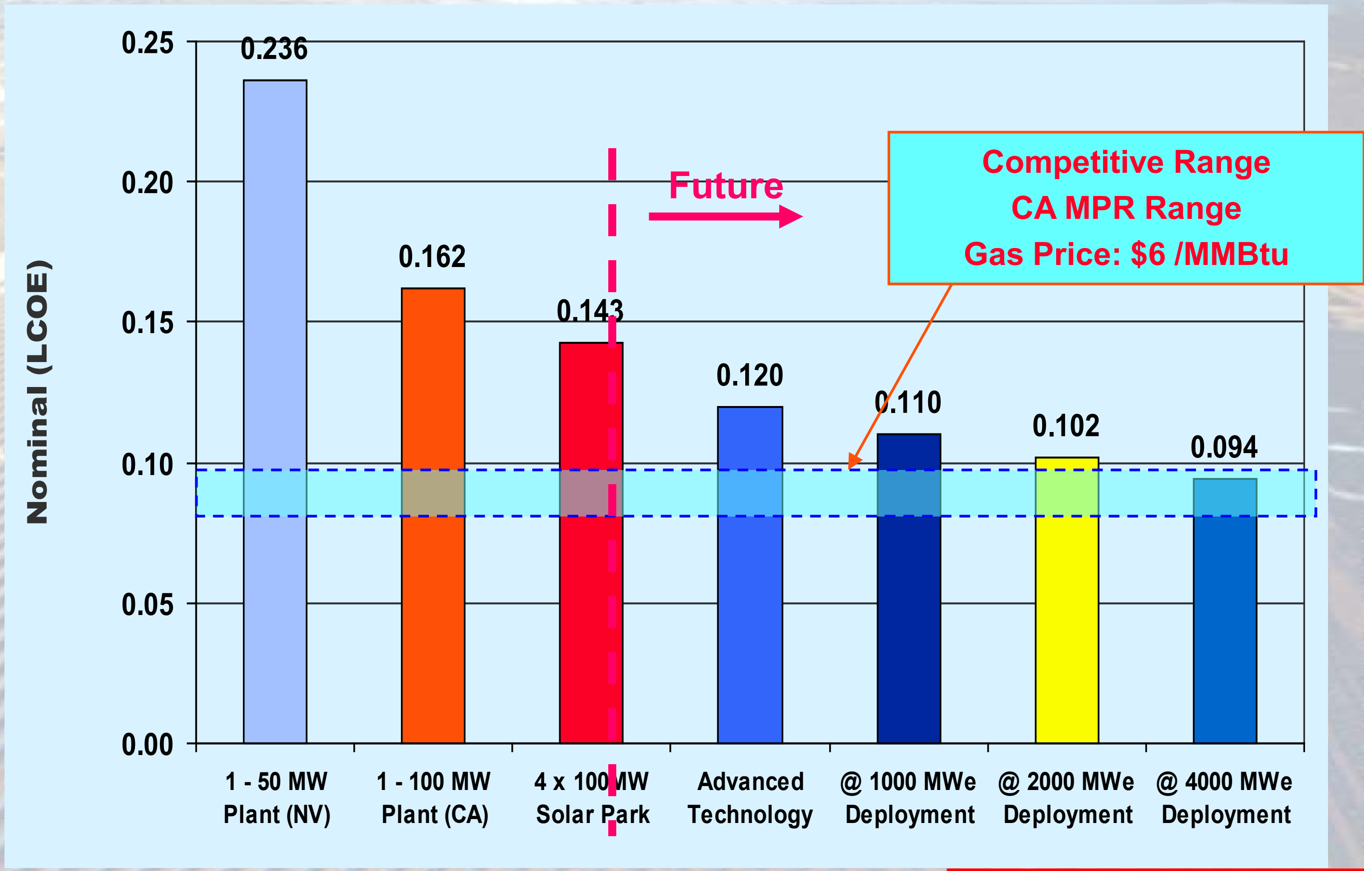


Parabolic Trough Plants


Source: KJC Operating Company

Parabolic Trough Cost Reduction Scenario

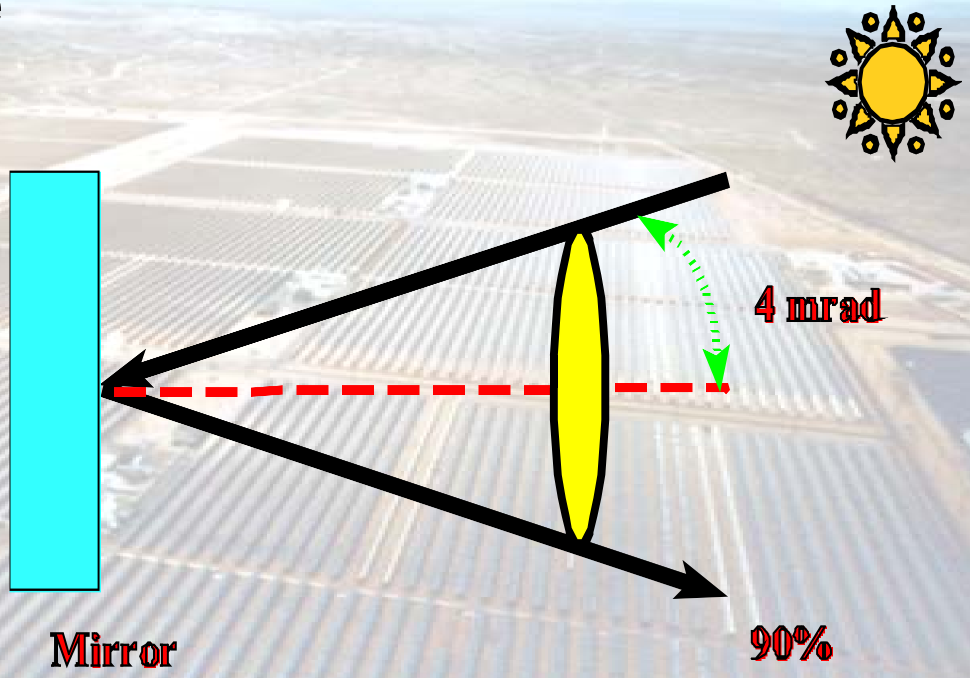
- Good Solar Resource Site
- Advanced Technology
- Learning & Competition
- Increasing Plant Size
- Alternative Financing
- Tax Neutrality for Solar Fuels
- Tax Incentives



Location: Barstow, CA
Incentives: Current California
Deployment Assumes:
- 90% PR in Solar Field
- 95% PR in Power Plant

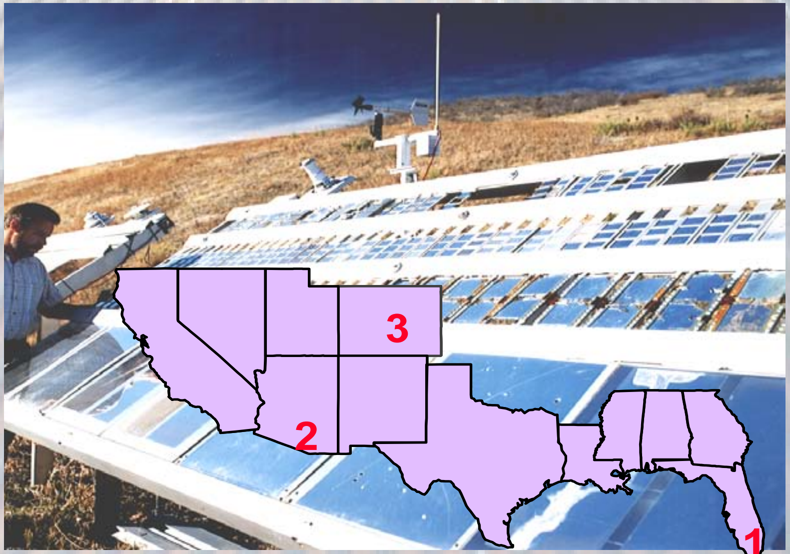
Goals for Improved Optical Materials

- >90% Specular reflectance into a 4-mrad cone angle
  - Unofficially 95%
- 10 - 30 year lifetime
  - Unofficially 30 y
- Manufacturing cost $10.76/m^2 ($1/ft^2)
  - 1992 Cost Goal
  - Adjusted for inflation to $15.46/m^2 ($1.44/ft^2)
  - Structural (self-supporting) mirror to $27/m^2 ($2.50/ft^2)

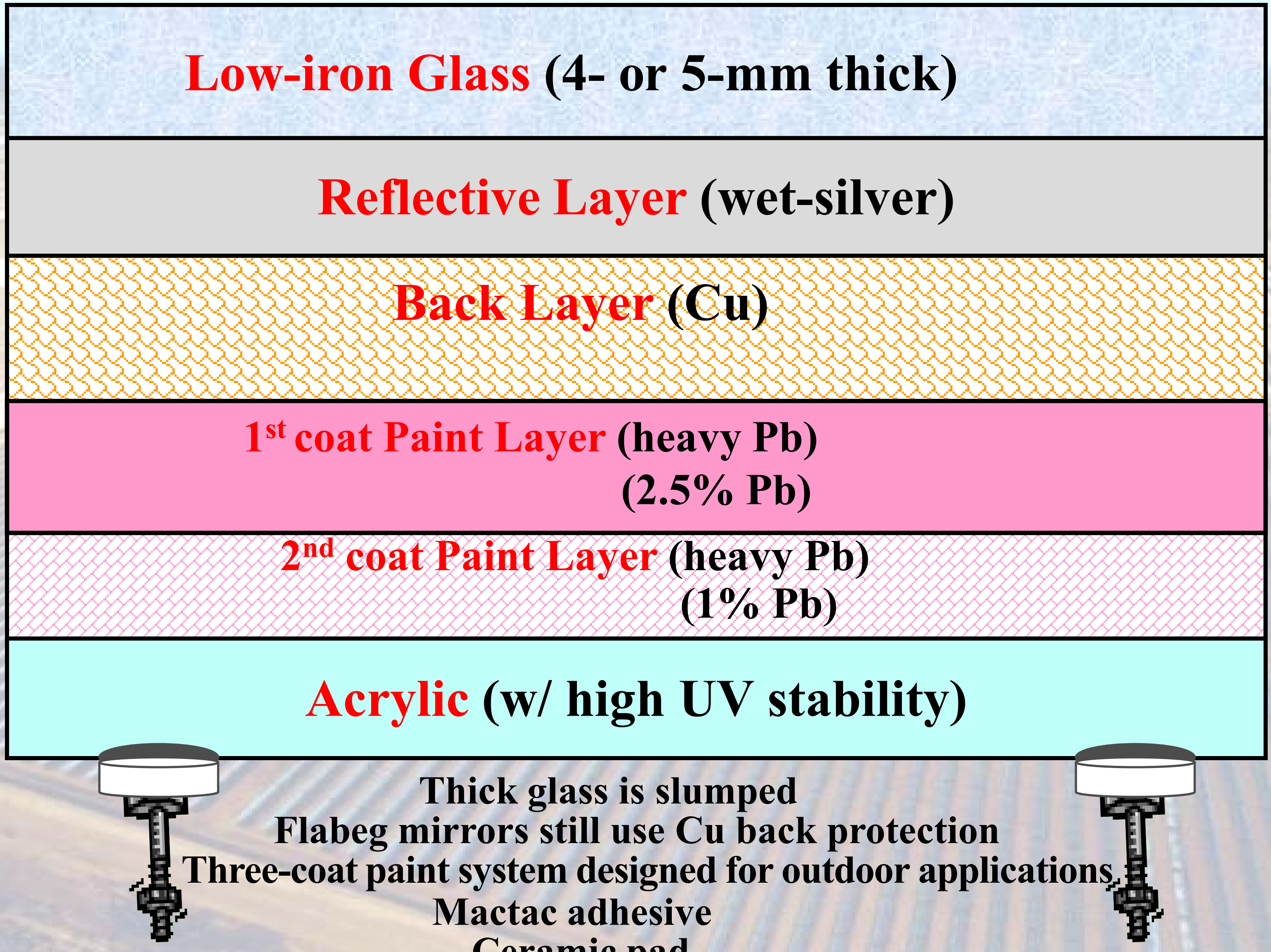


Technical Approach

- *Samples supplied by:*
  - *Industry*
  - *Subcontracts*
  - *Developed in-house*
- *Optical Characterization:*
  - Perkin-Elmer (PE) Lambda 9 & 900 UV-VIS-NIR spectrophotometers (250-2500 nm) w/ integrating spheres
  - PE IR 883 IR spectrophotometer (2.5-50 μm)
  - Devices & Services (D&S) Field Portable Specular Reflectometer (7, 15, & 25-mrad cone angle at 660 nm)
- Outdoor (OET) & *Accelerated Exposure Testing (AET):*
  - Atlas Ci65 & Ci5000 WeatherOmeters (WOM) (1X & 2X Xenon Arc/60ºC/60%RH)
  - QPanel QUV (UVA 340@ 290- 340 nm/ 4 h UV at 40º / 4 h dark at 100%RH)
  - 1.0 & 1.4 kW Solar Simulators (SS) (≈5X Xenon 300-500 nm. 1.0-kW SS 80°C/ 80% RH,1.4 kW-SS-4 quadrants 2 RH &T, light /dark)
  - BlueM damp heat (85ºC/85%RH/dark)
  - 3 meterologically monitored sites at Golden, Colorado (NREL), Miami, Florida (FLA), and Phoenix, Arizona (APS)



Parabolic Trough Glass Mirror Architecture



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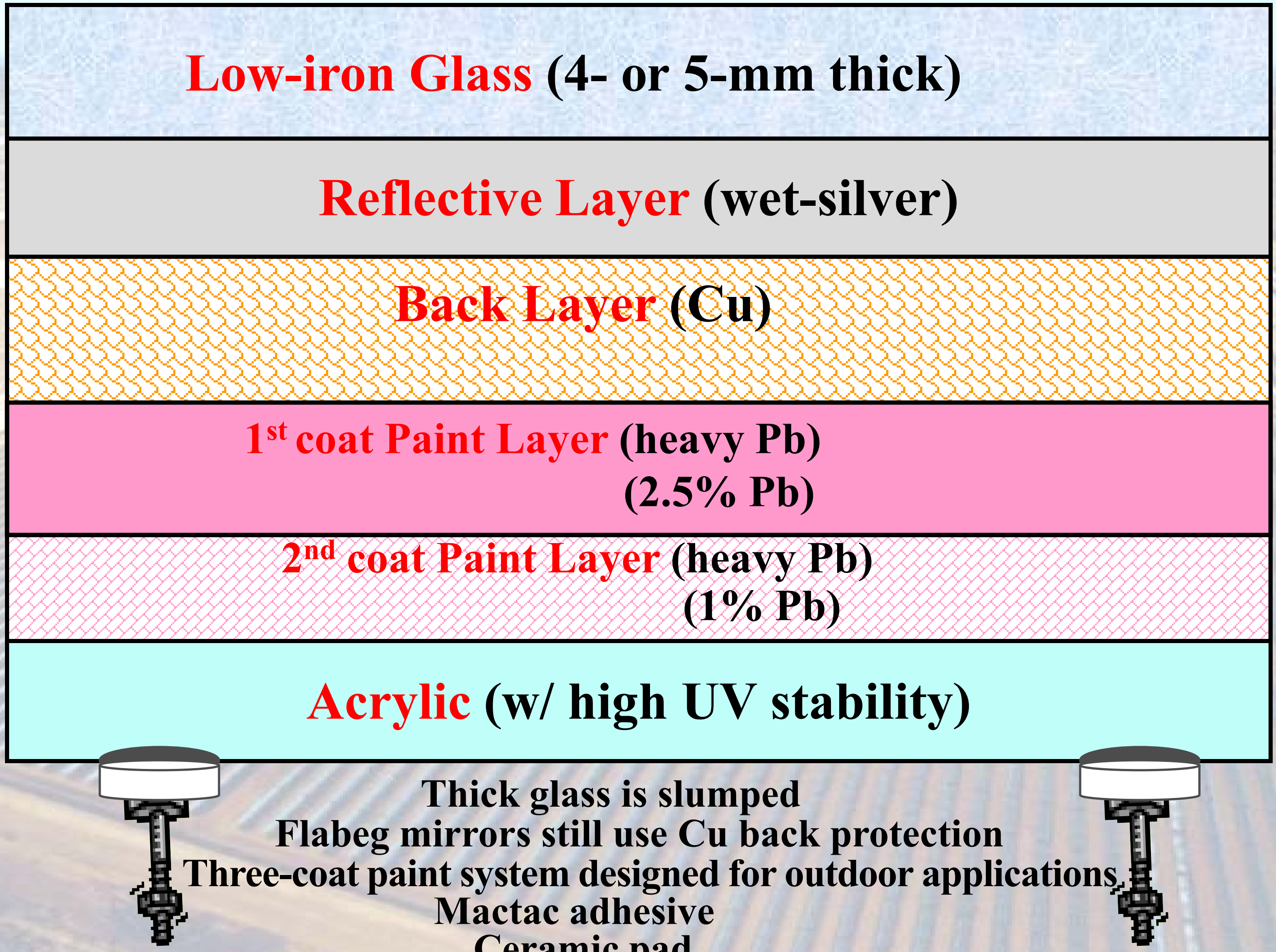
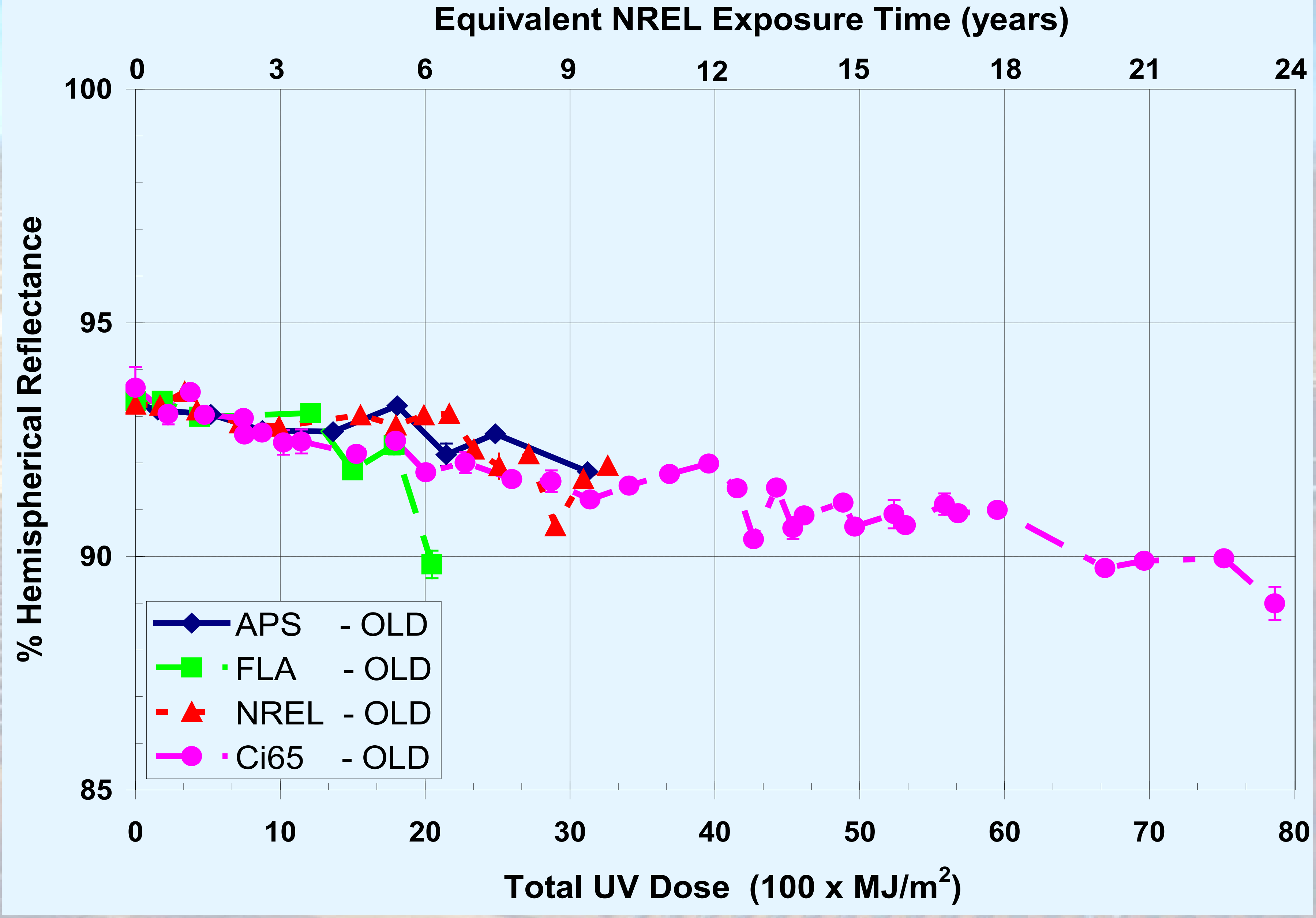
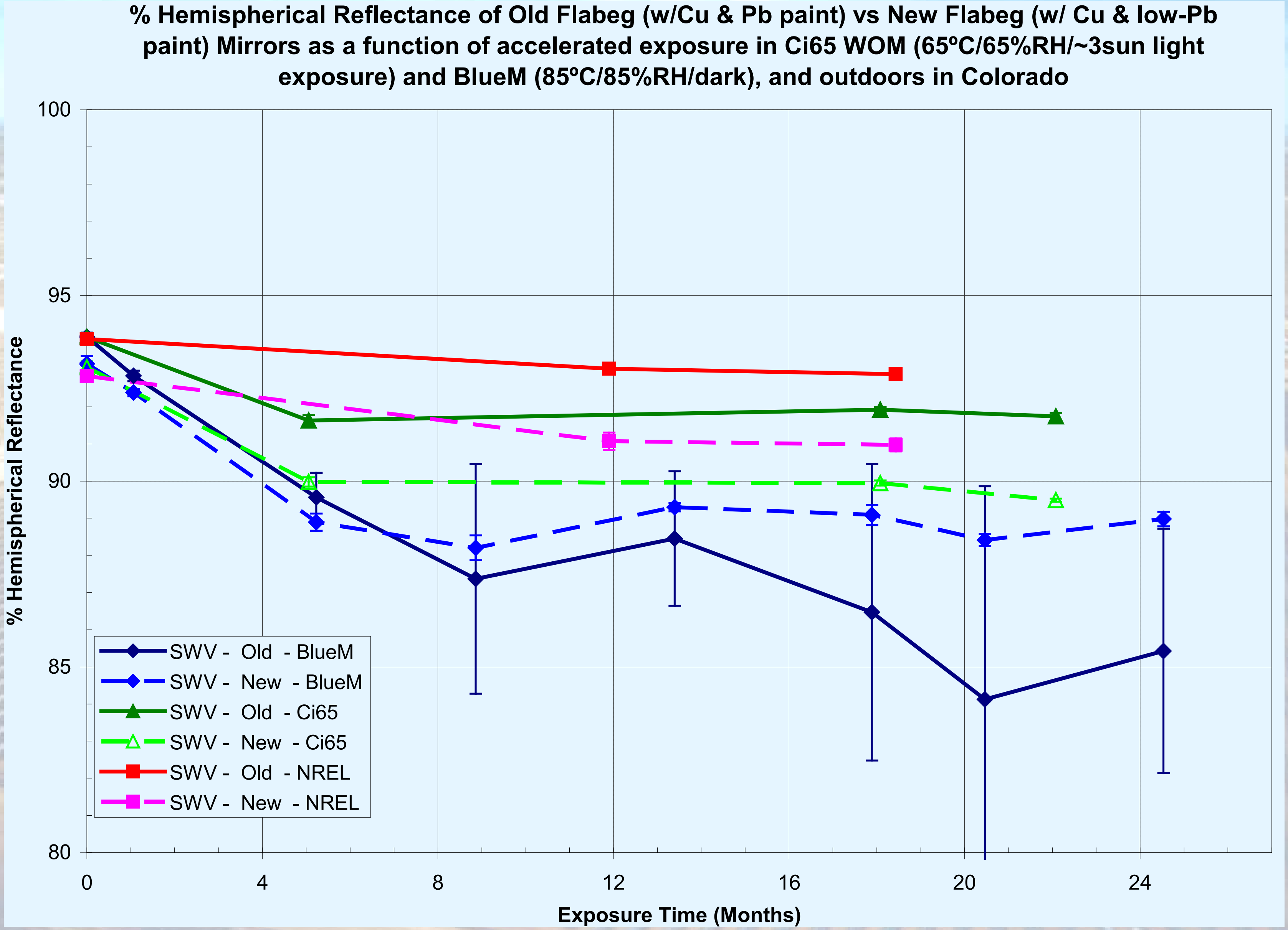


Original Flabeg Mirror



Original vs. New Flabeg Mirror



Alternate Thick Glass Mirror Architecture

Low-iron Glass (3- or 4-mm thick flat)

Reflective Layer (wet-silver)

Back Layer (Cu-less)

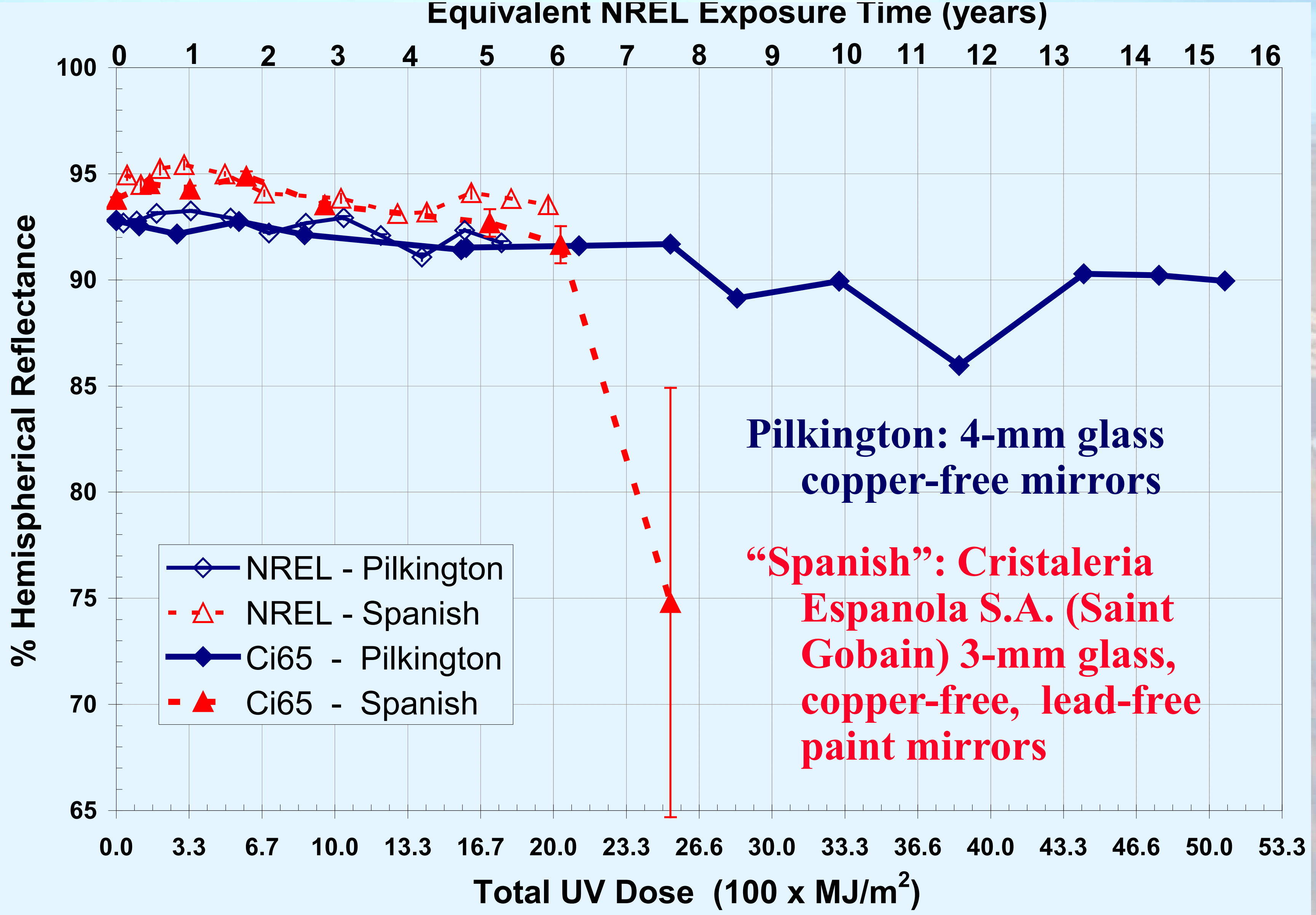
1st coat Paint Layer (lead-free <0.15% Pb)

2nd coat Paint Layer (lead-free <0.15% Pb

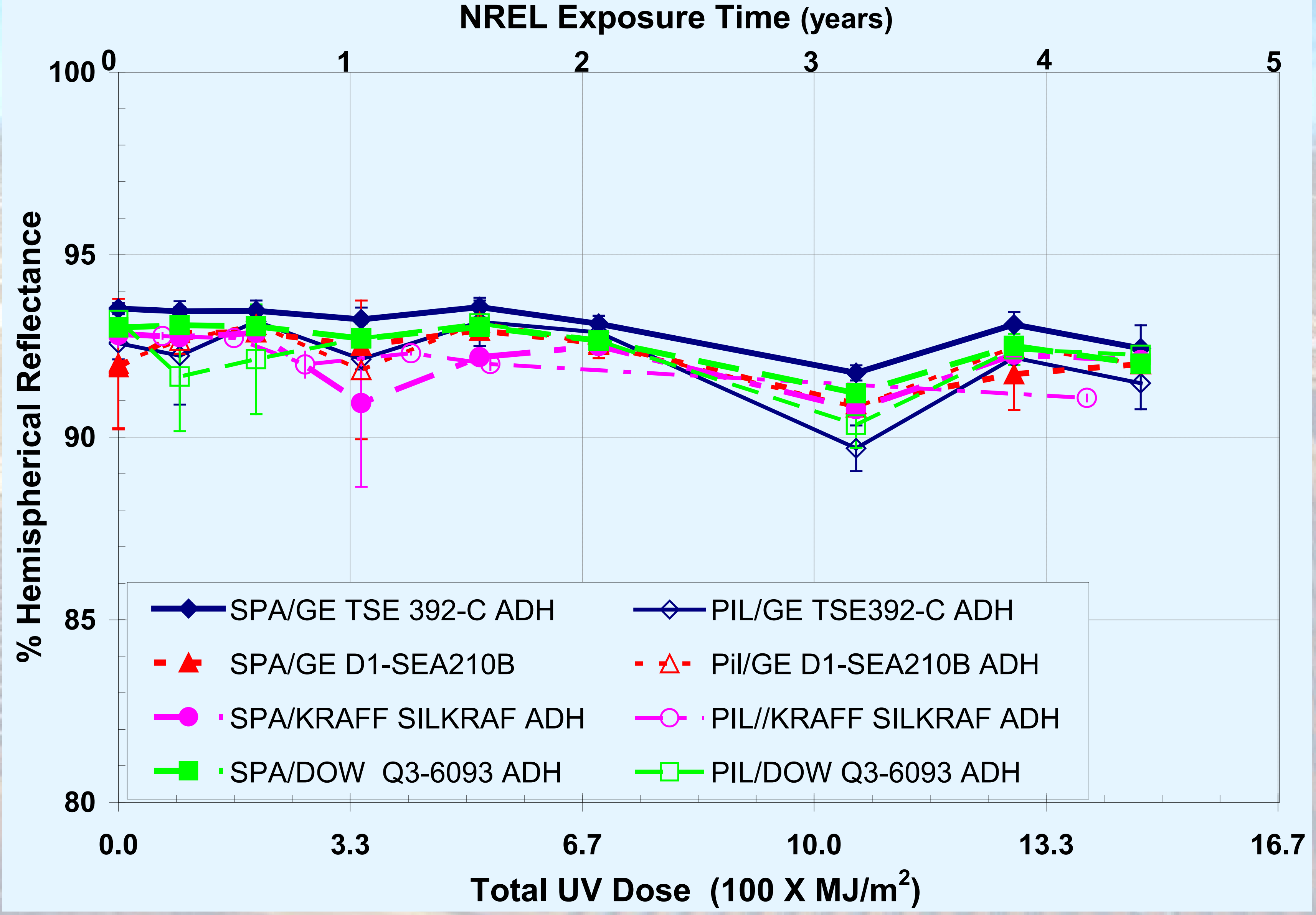
Adhesive (PS, spray)

Substrate (SS, Al)

Alternate Thick Glass Mirror



Effect of Adhesive on Thick Glass Mirror



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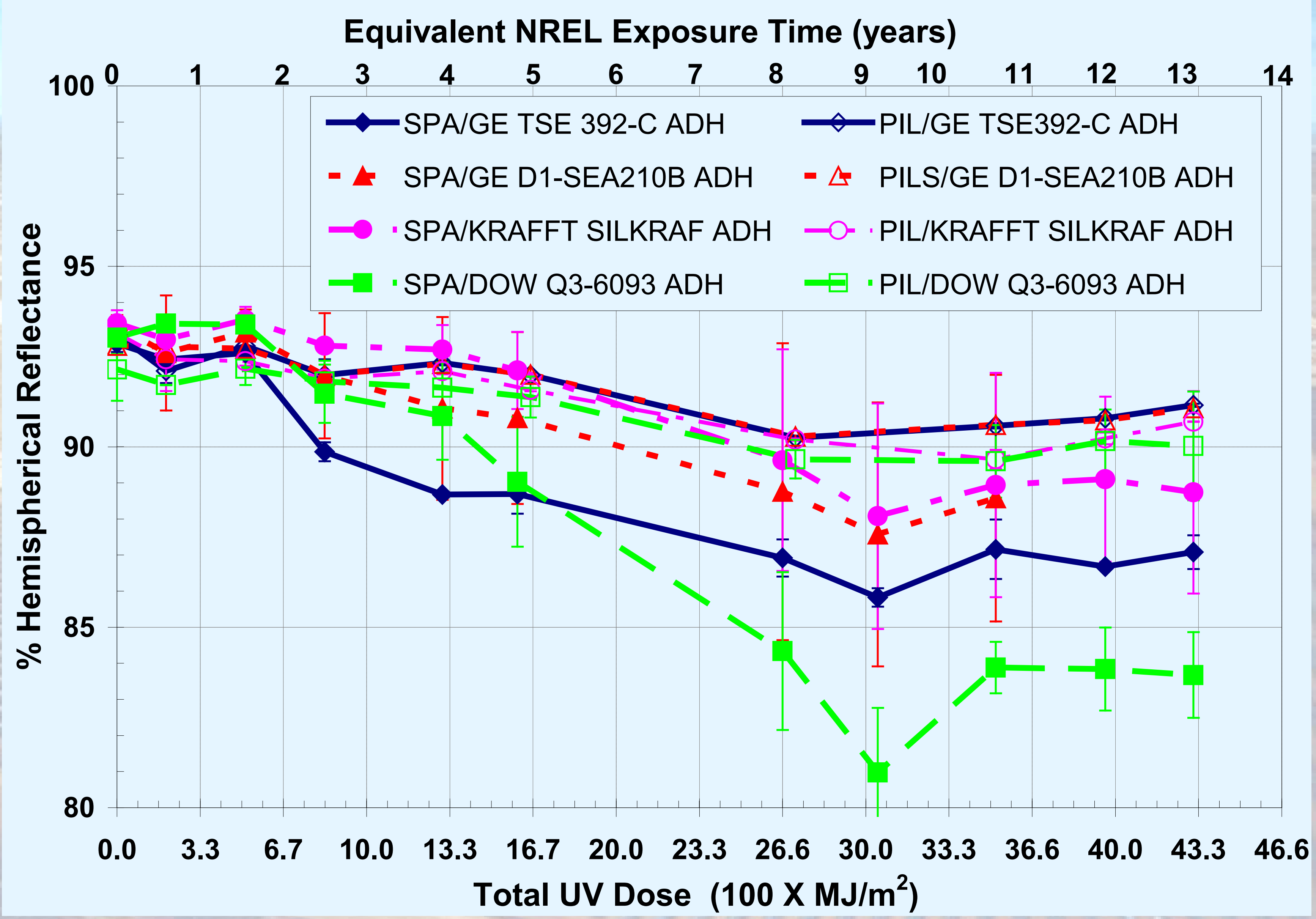
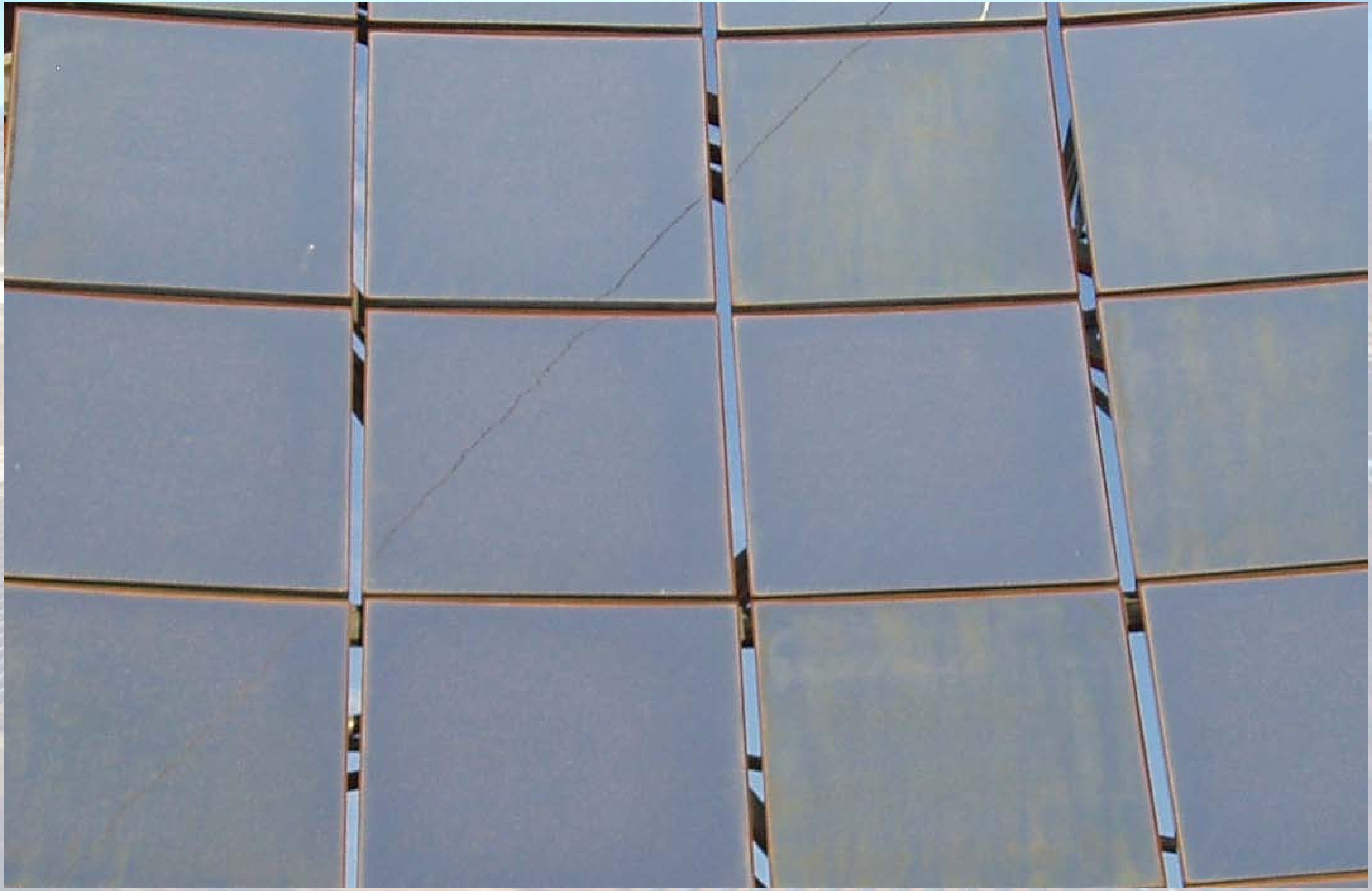


Thin Glass Mirror Architecture

Low-iron Glass (~1 mm- thick)
Reflective Layer (wet-silver)
Back Layer (Cu) (Cu-less)
Paint Layer (Pb) (Pb-free)
Adhesive (PS, spray)
Substrate (SS, Al)

Thin glass mirrors are designed for indoor applications.

Thin Glass Corrosion



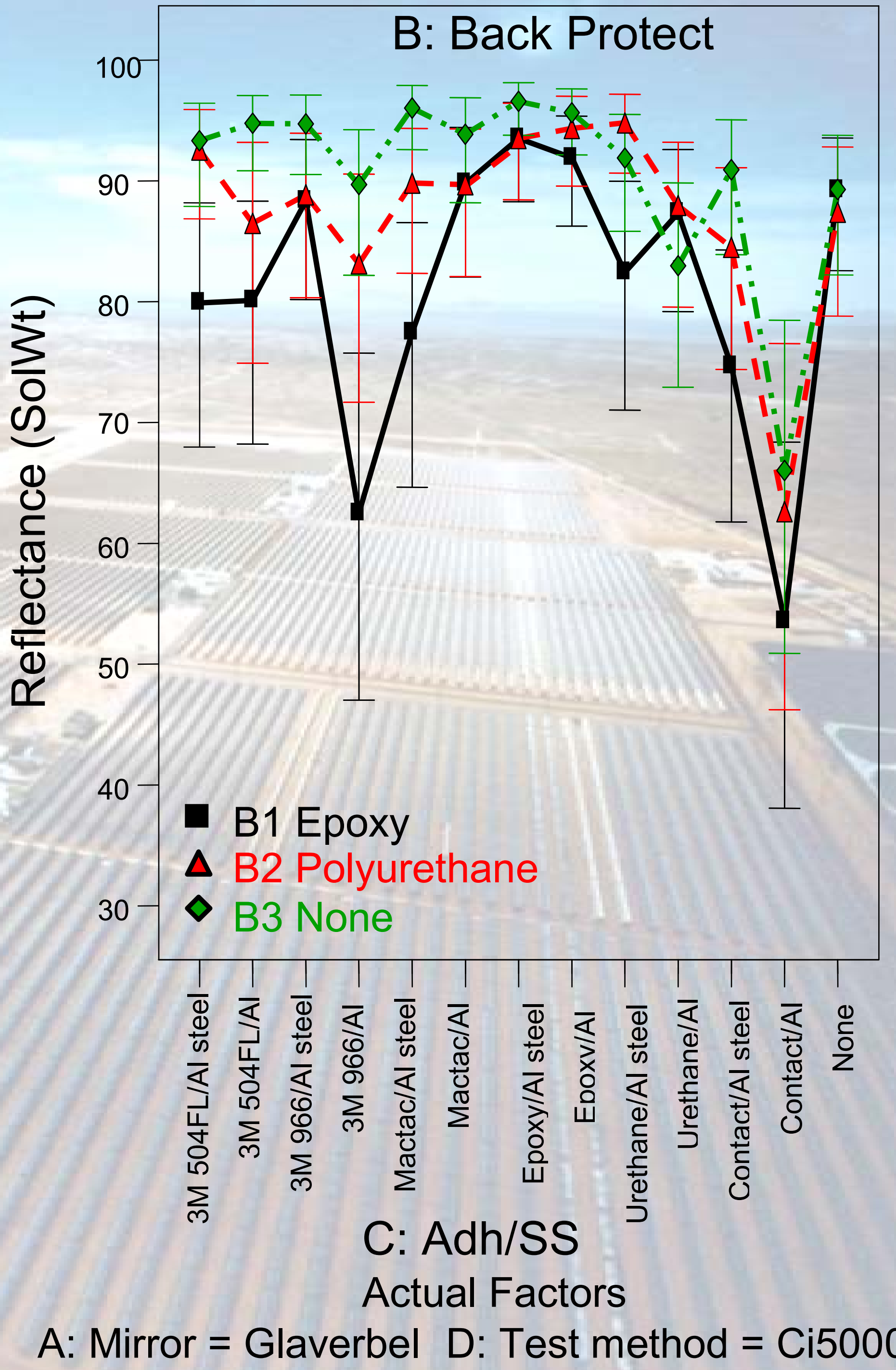
Thin Glass Mirror Matrix

D-optimal fractional factorial algorithm using Design-Expert® software

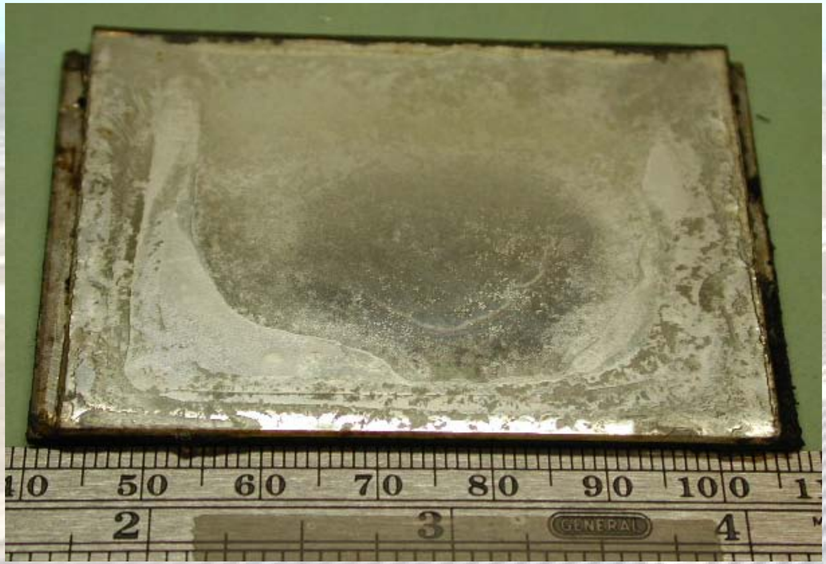
Levels	Factors					
	Mirror Type	Back Protection	Adhesive / Substrate	Edge Protection	Substrate Cleaning	Back Priming
1	Naugatuck/Cu	Epoxy	3M504FL/AL steel	None	SAIC	3M
2	Naugatuck/ No Cu	Polyurethane	3M504FL/AL	Exuded Adh.	SES	None
3	Glaverbel	None	3M966/AL steel	CPFilm		
4			3M966/AL			
5			Mactac/AL steel			
6			Mactac/AL			
7			Epoxy/AL steel			
8			Epoxy/AL			
9			Urethane /AL steel			
10			Urethane /AL			
11			Contact /AL steel			
12			Contact /AL			
13			None			

ANOVA Analysis

- Glaverbel - best overall mirror in Mirror matrix test
  - Commercial vs. prototype
  - 1- vs. 2-coat paint system
  - Difference in EU and US lead-free regulations
- Epoxy-based adhesive – probably good choice
- No additional back protection - survive the longest
- Polyurethane – poor choice
- BlueM - more accelerated exposure chamber

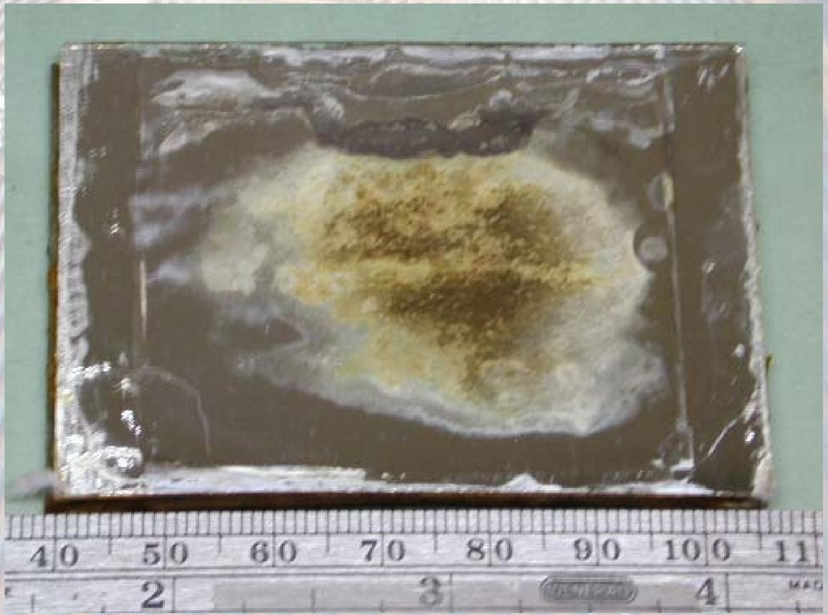


Damp-Heat results similar but ~6X faster than Ci5000

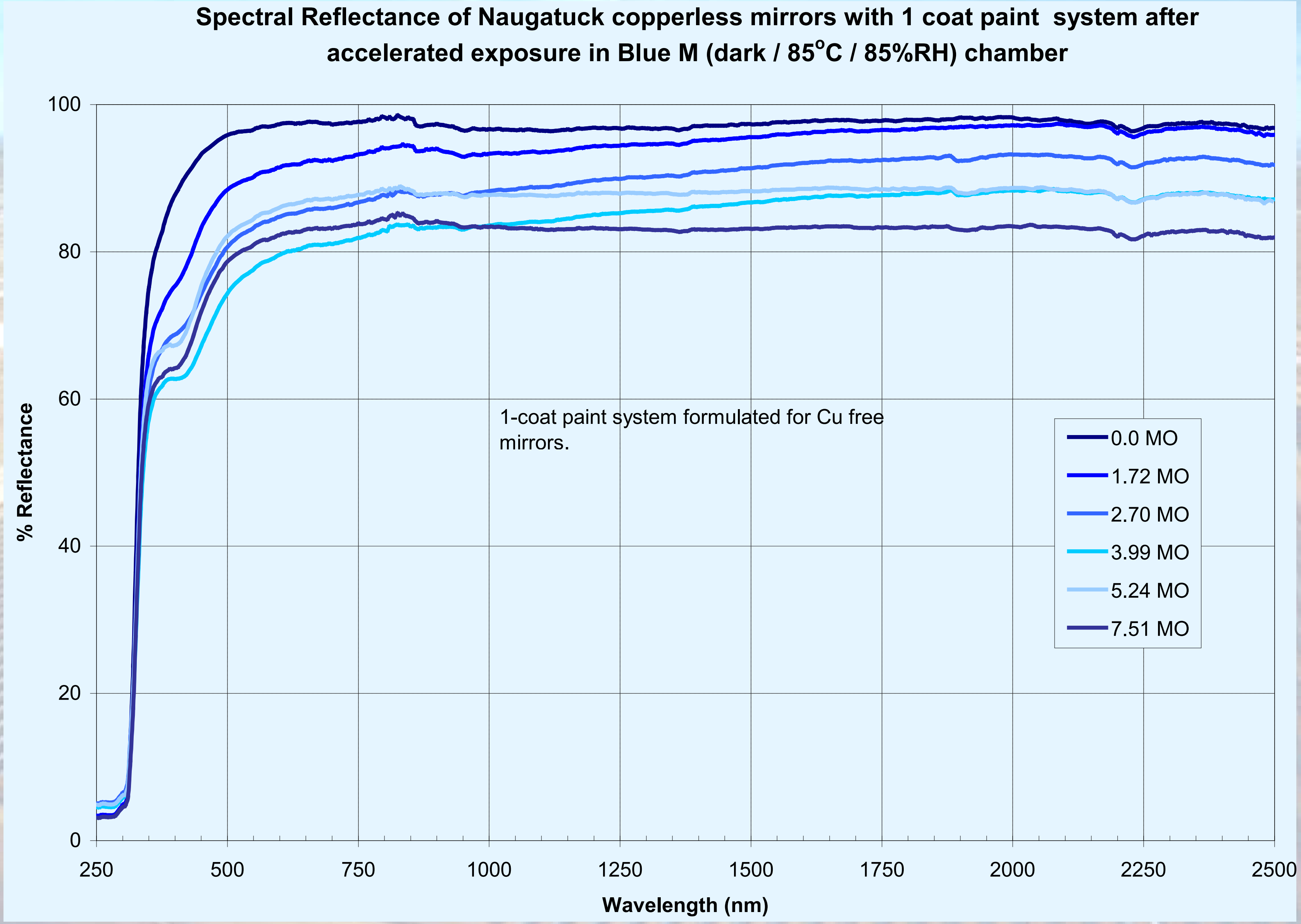


Discontinued in
Damp-Heat 5.9 MO

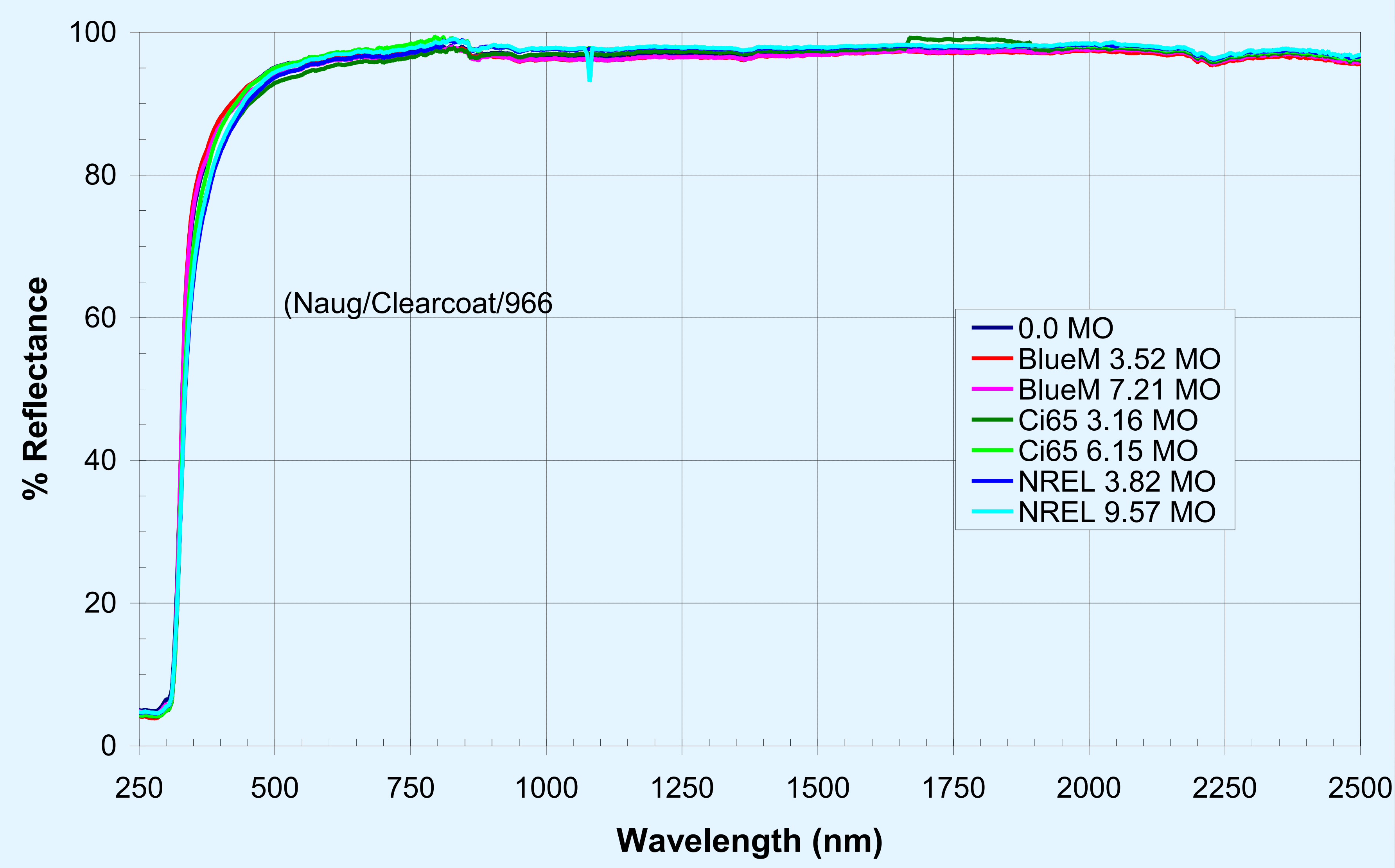
Discontinued in
Ci5000 18.9 MO



Thin Glass Mirror



Thin Glass Mirror



Aluminized Reflector Architecture

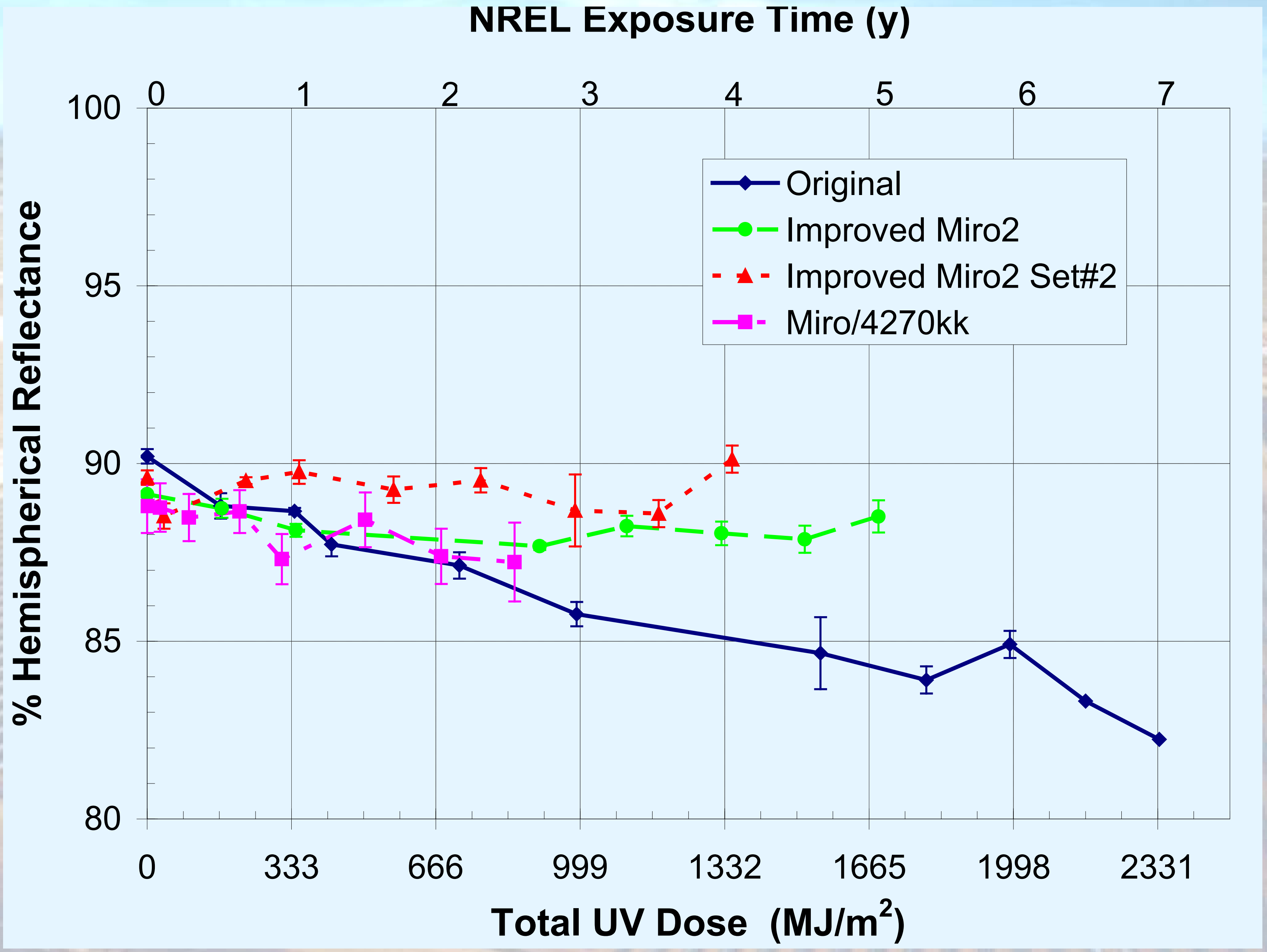
Protective Overcoat

Protective Oxide Topcoat

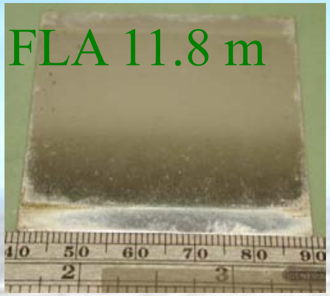
Enhanced Al Reflective Layer

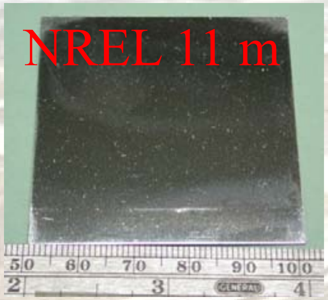
Polished Aluminum Substrate

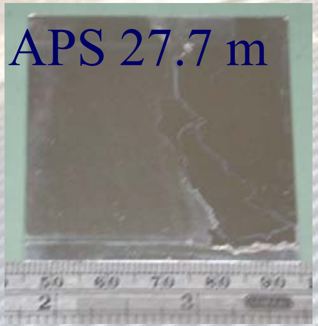
Aluminized Reflectors

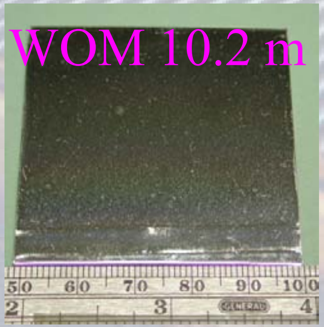


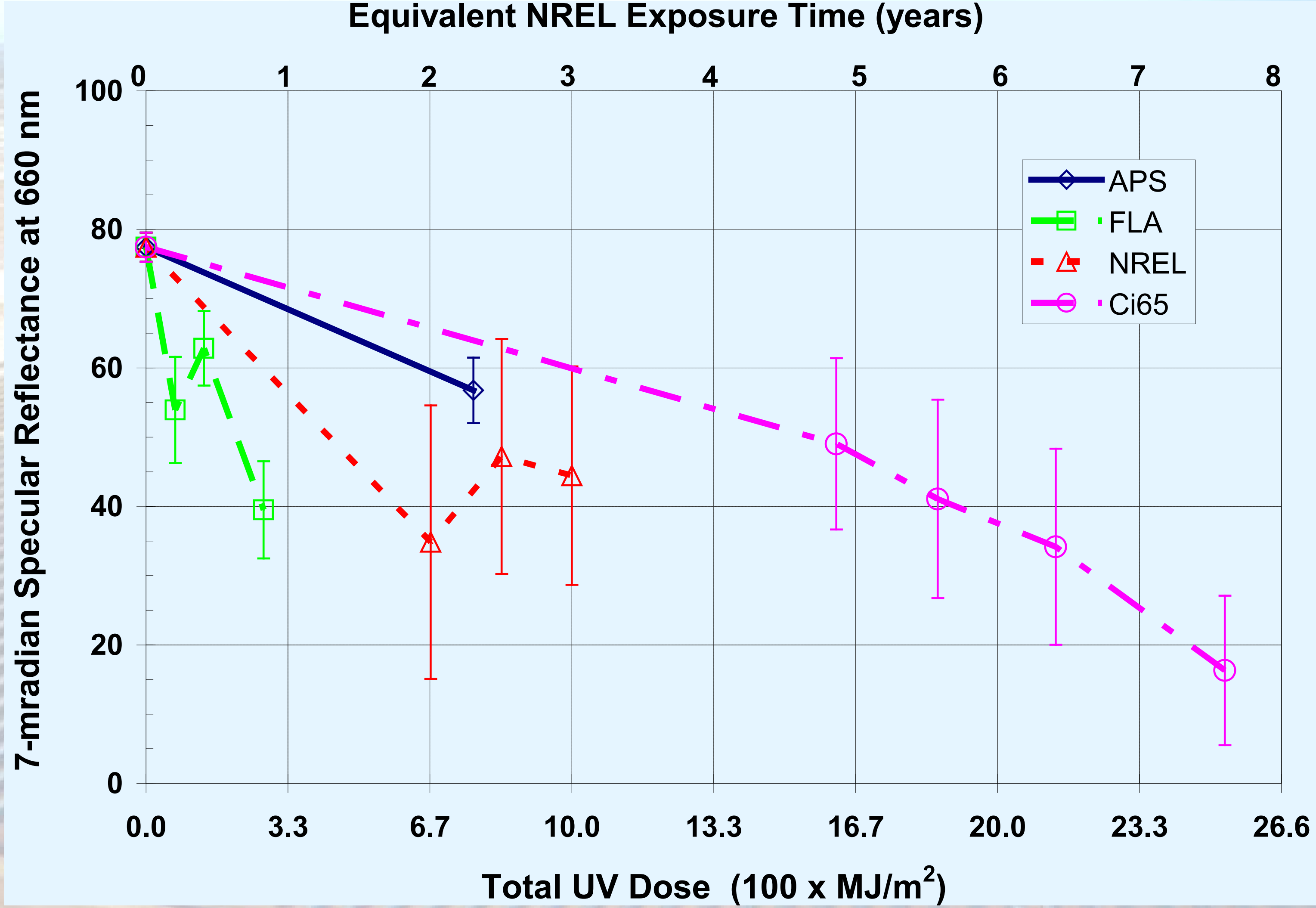
Aluminized Reflector Specularity



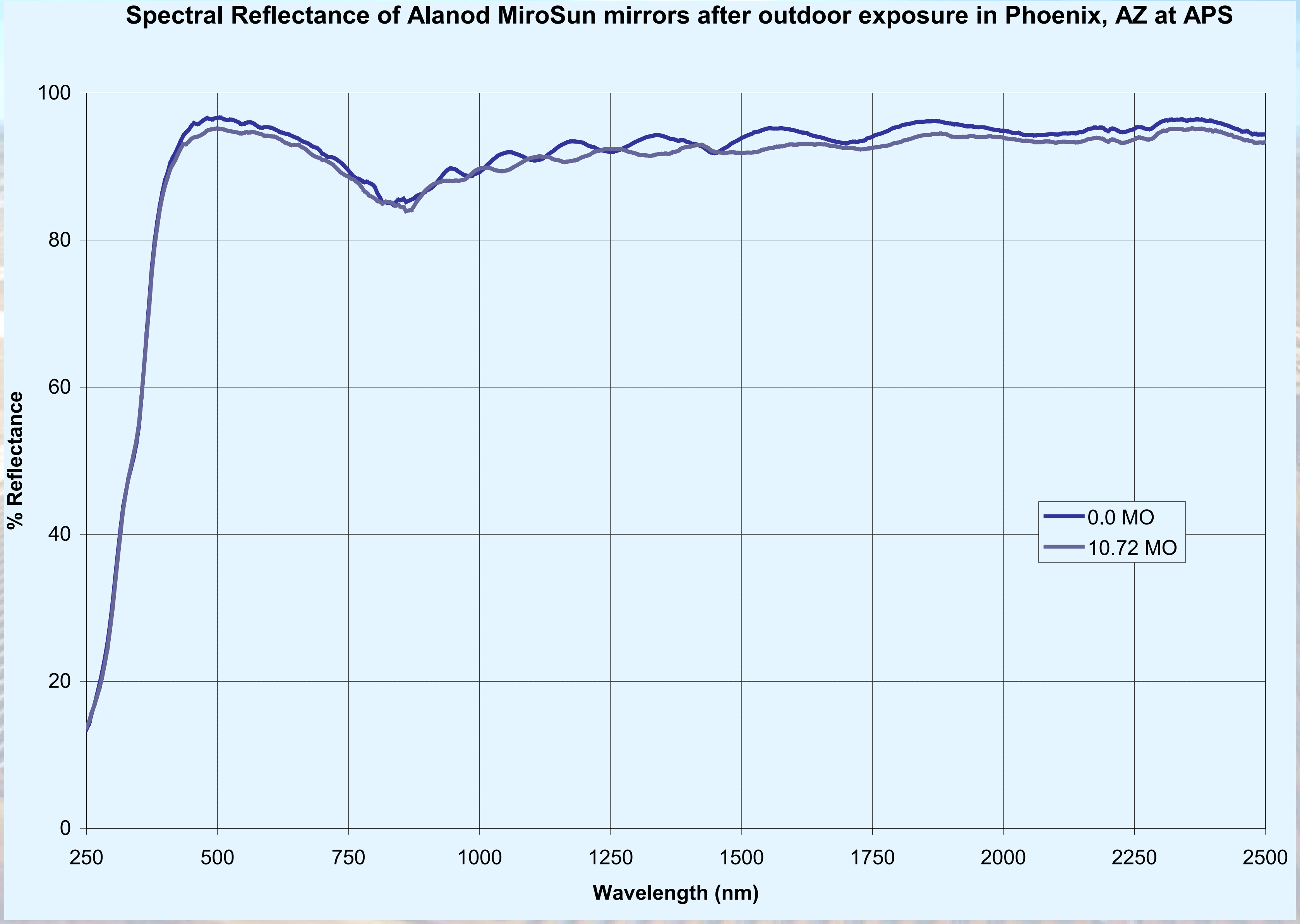








Aluminized Reflector



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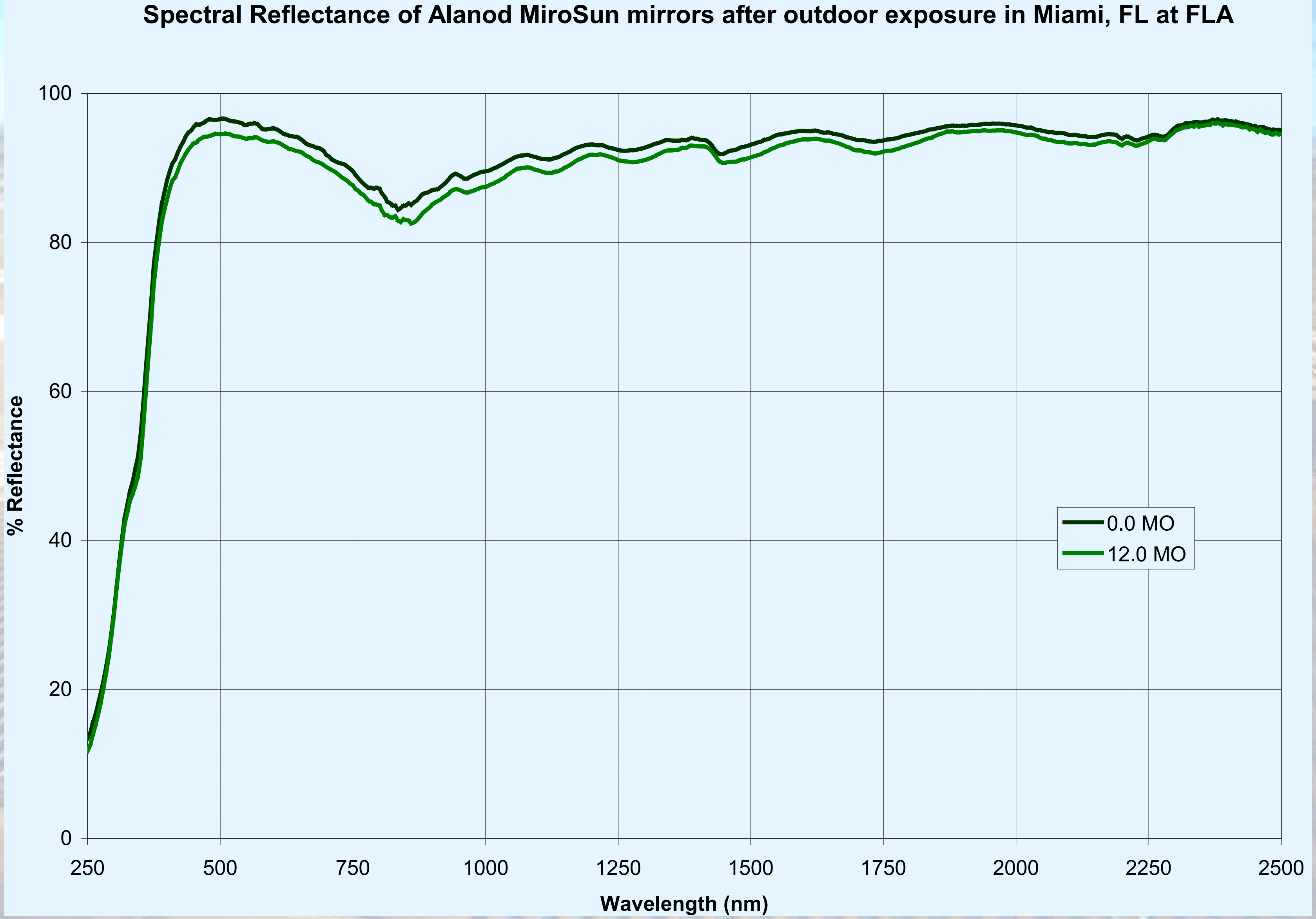
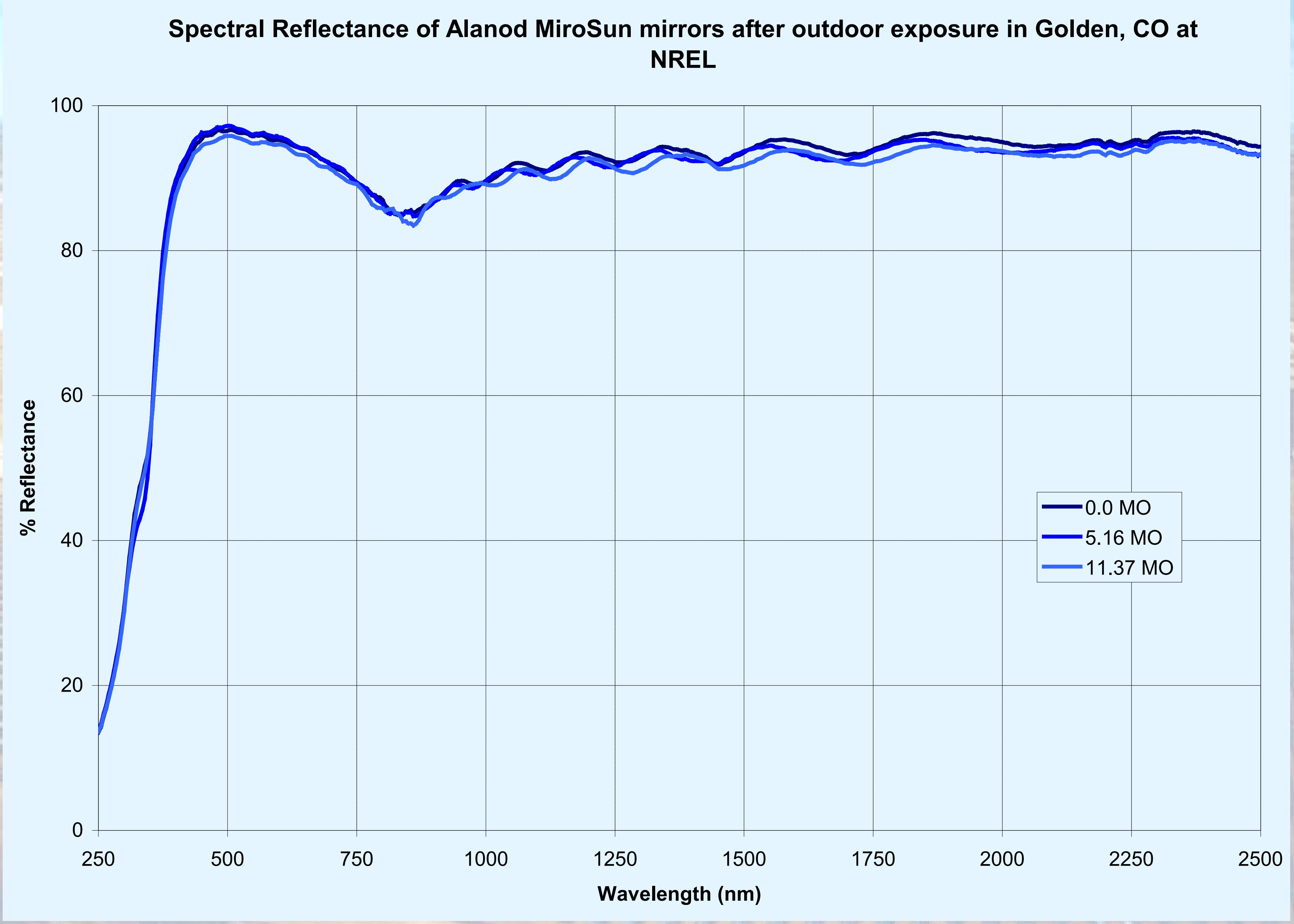
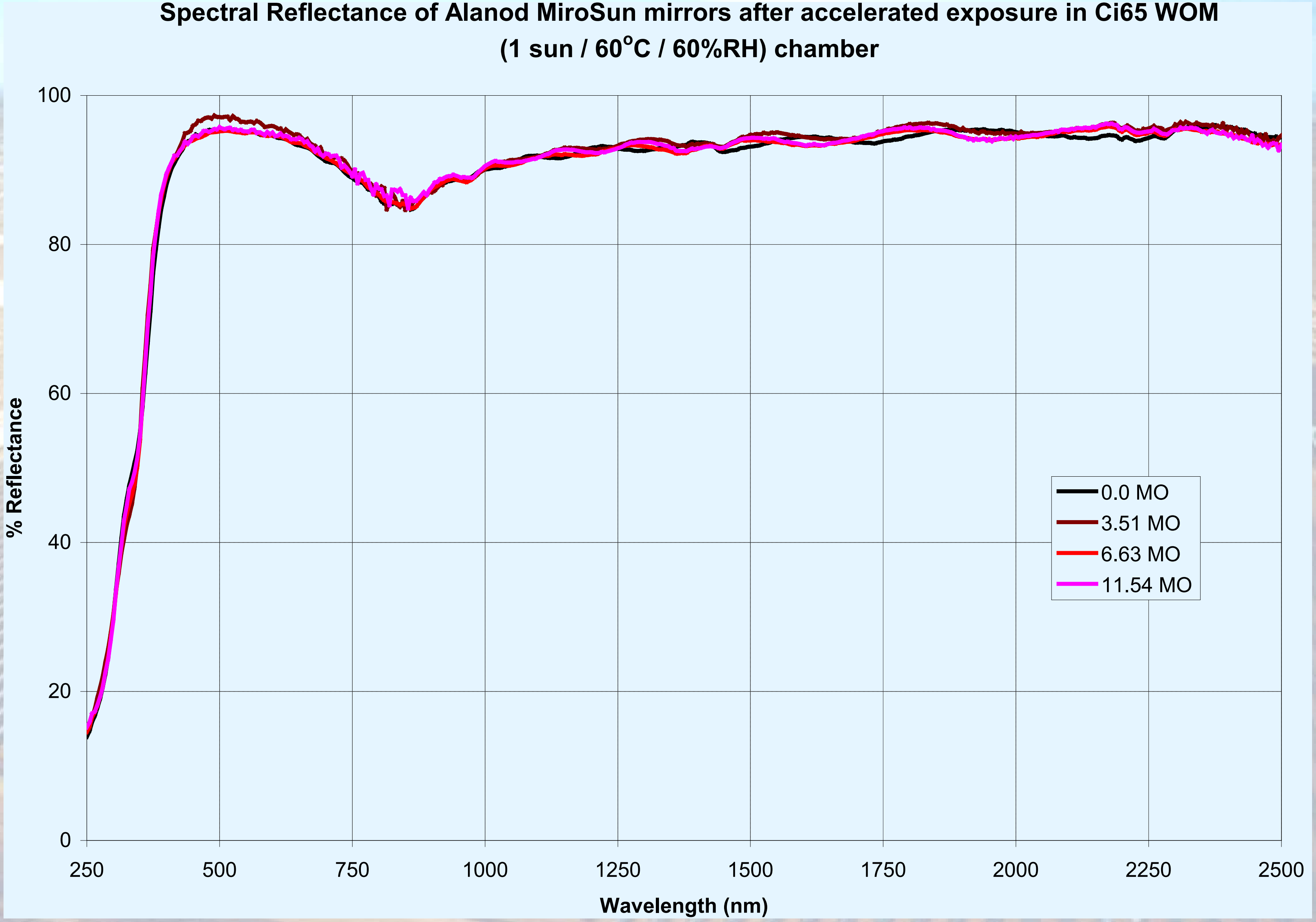


Aluminized Reflector



Aluminized Reflector



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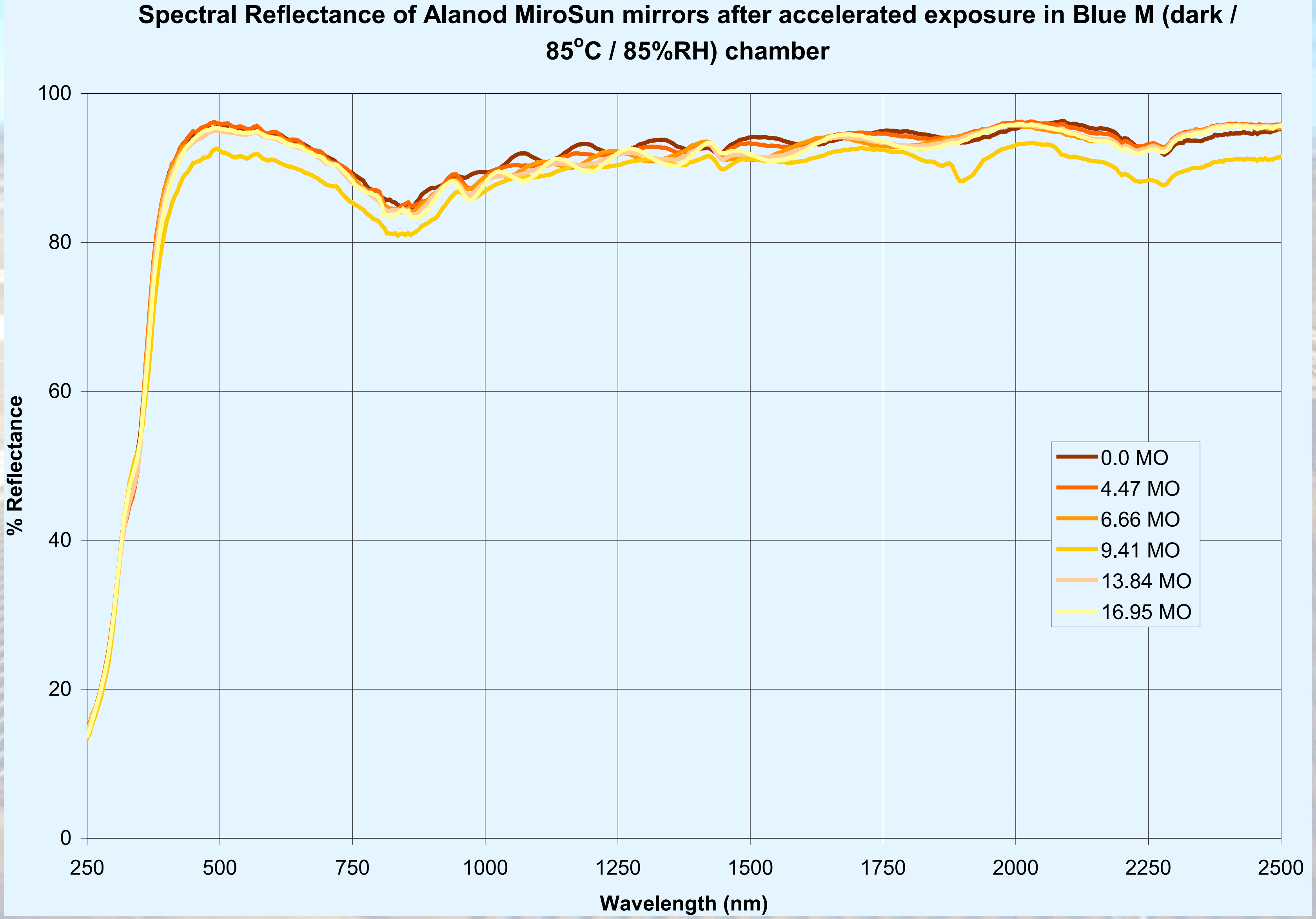

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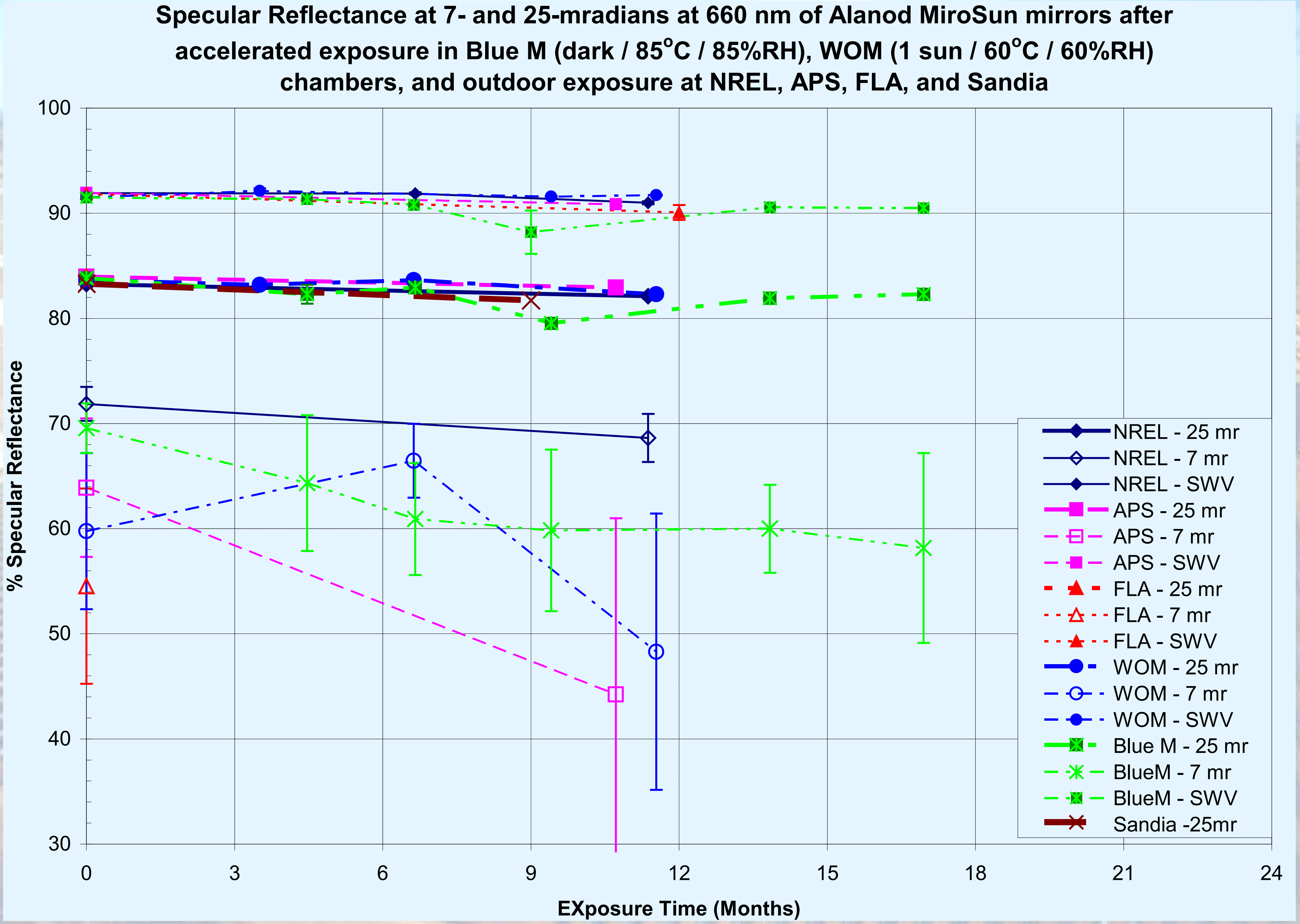
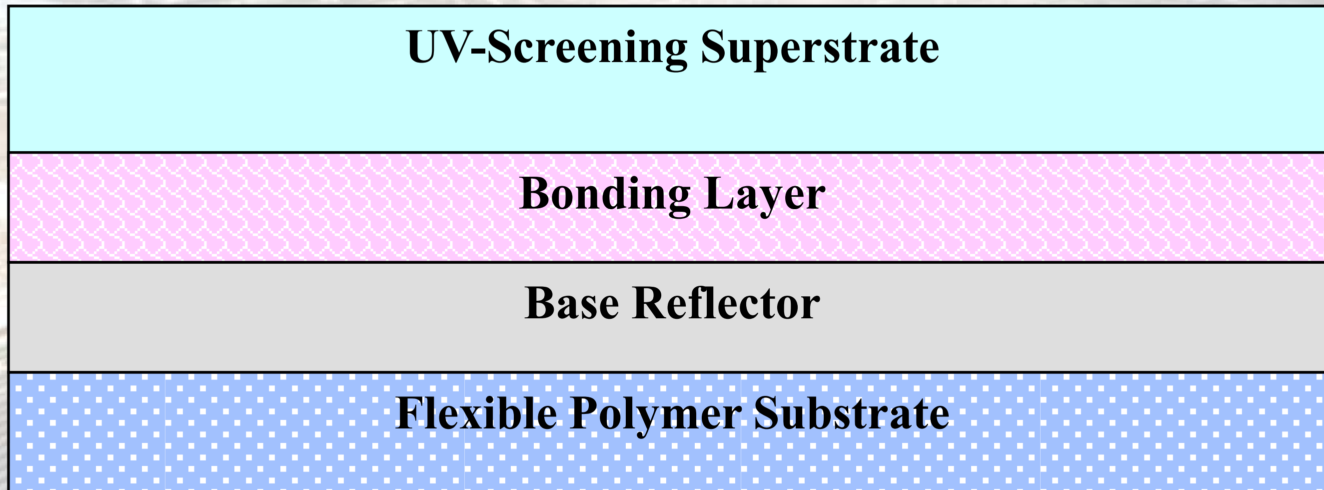
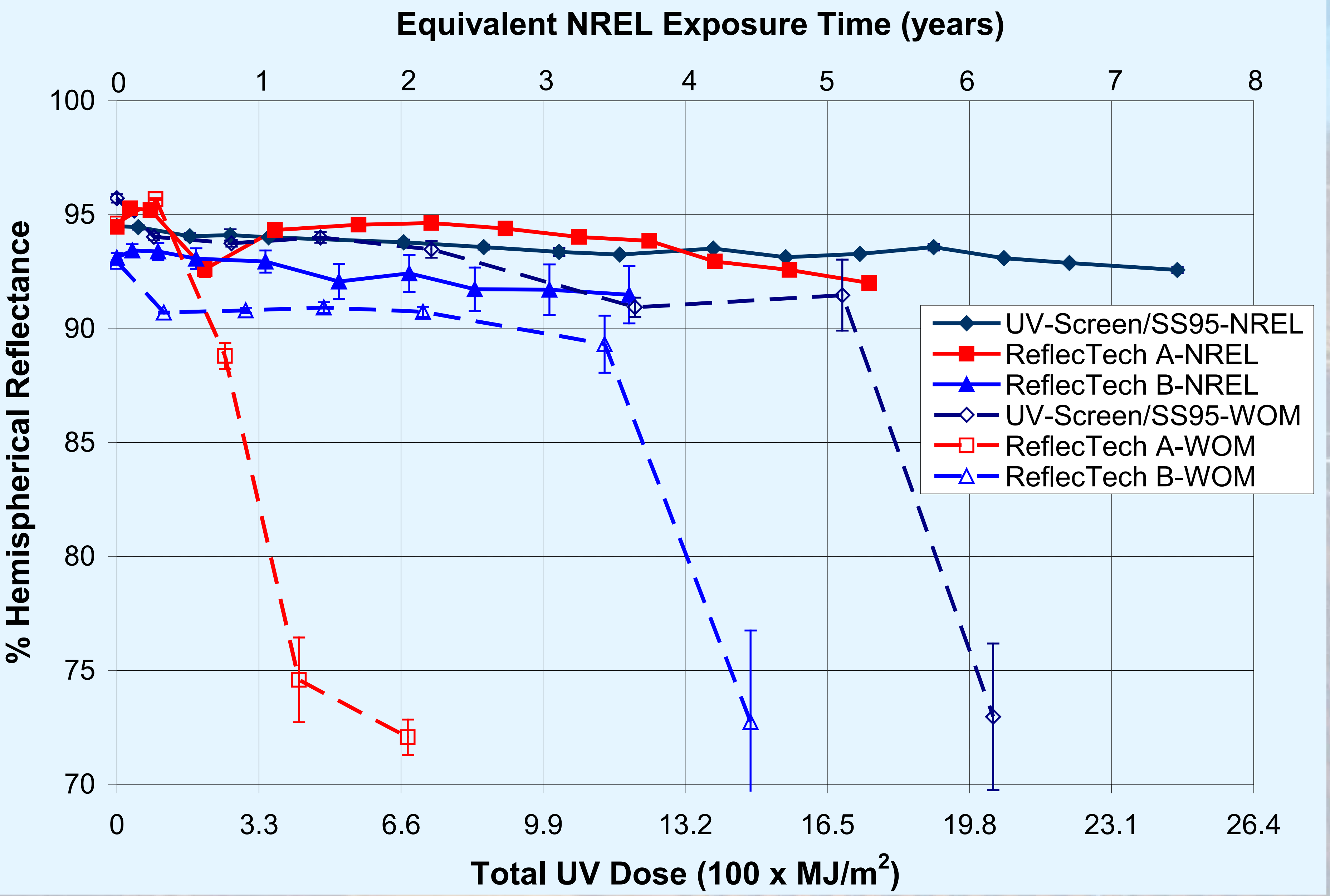


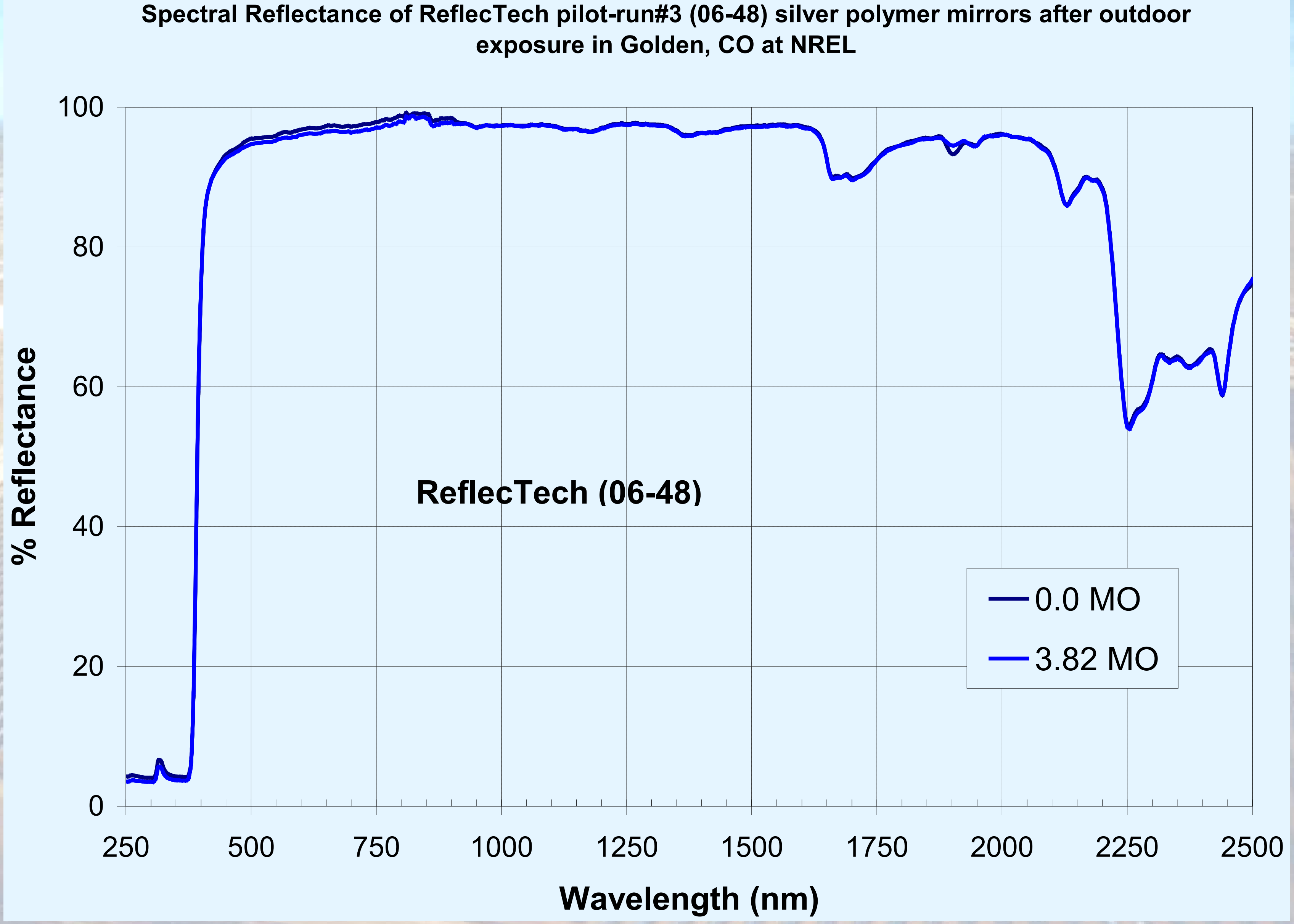
ReflecTech - Silvered Polymer Reflector Architecture



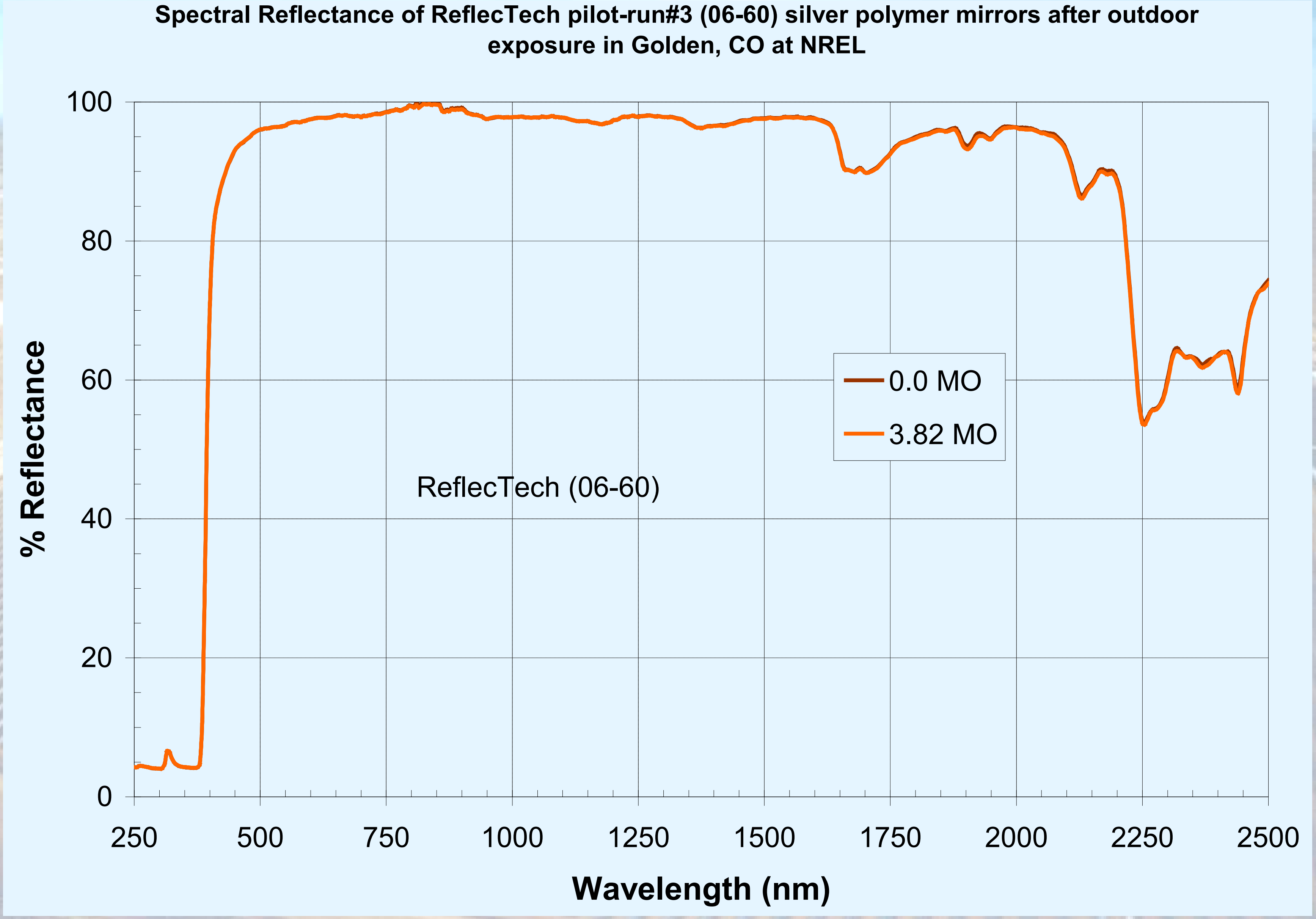
ReflecTech Prototypes



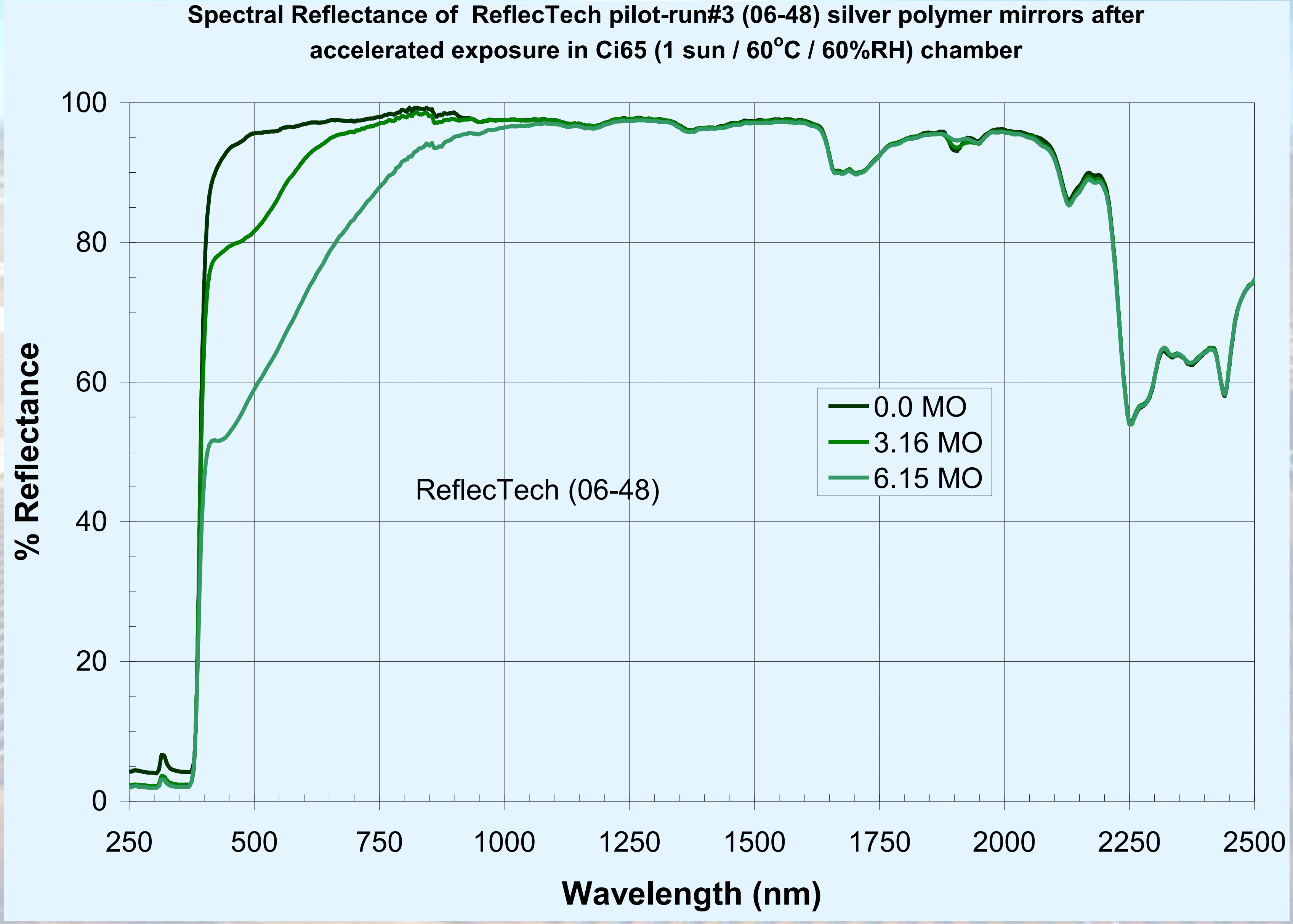
ReflecTech III -NREL



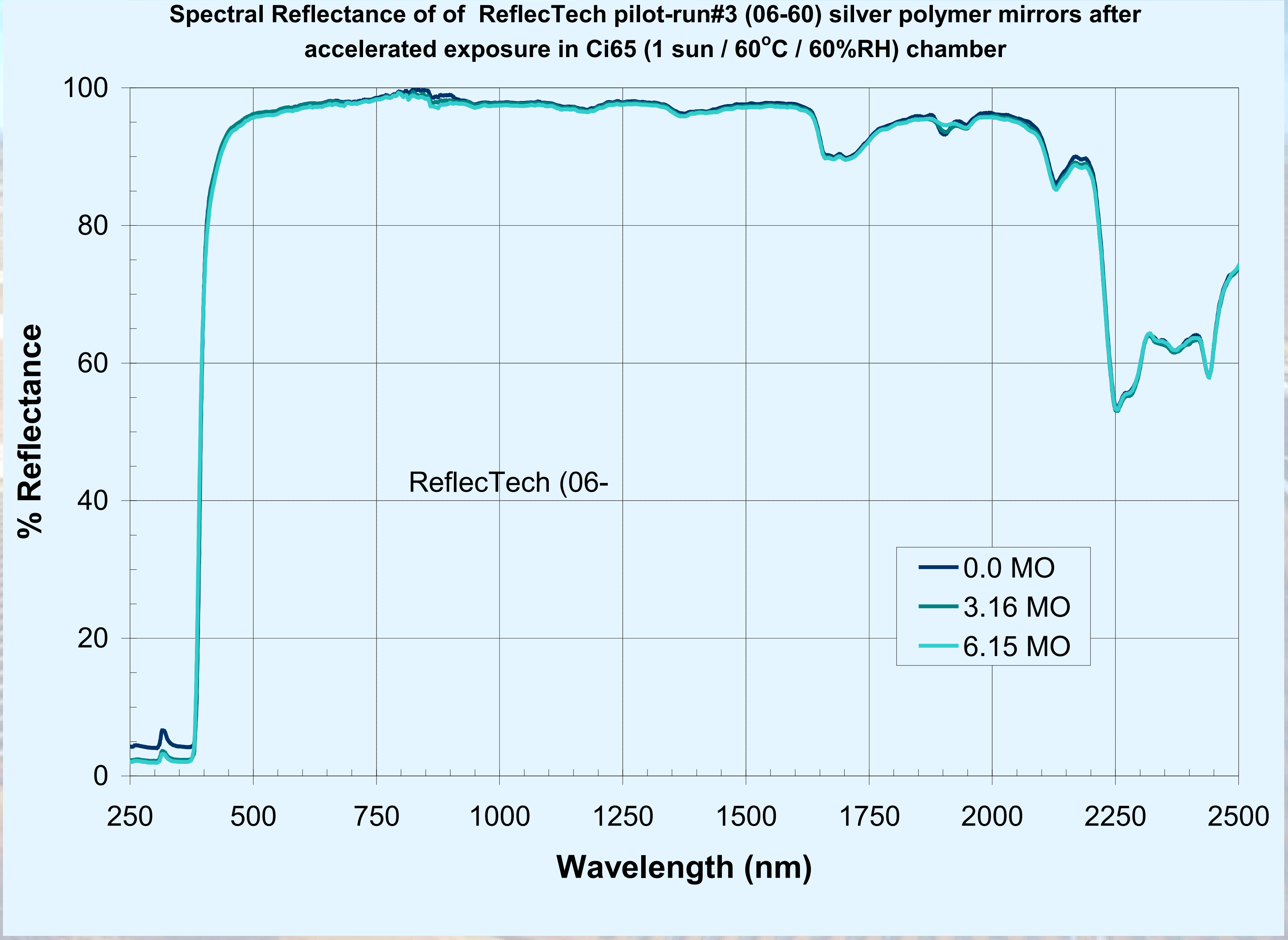
ReflecTech III -NREL



ReflecTech III –Ci65 WOM

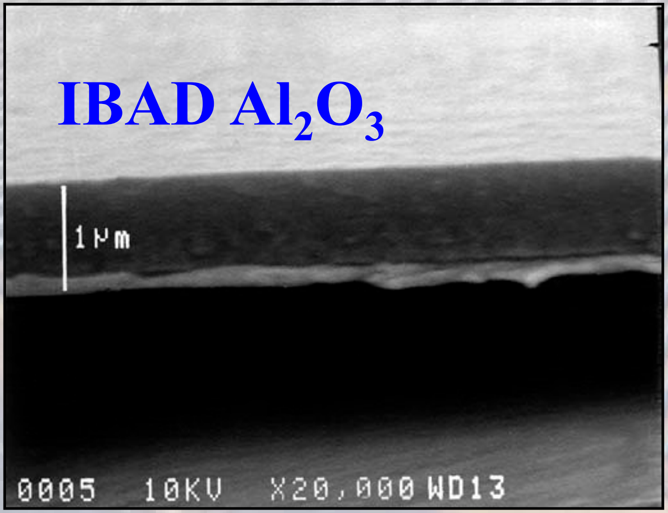


ReflecTech III –Ci65 WOM

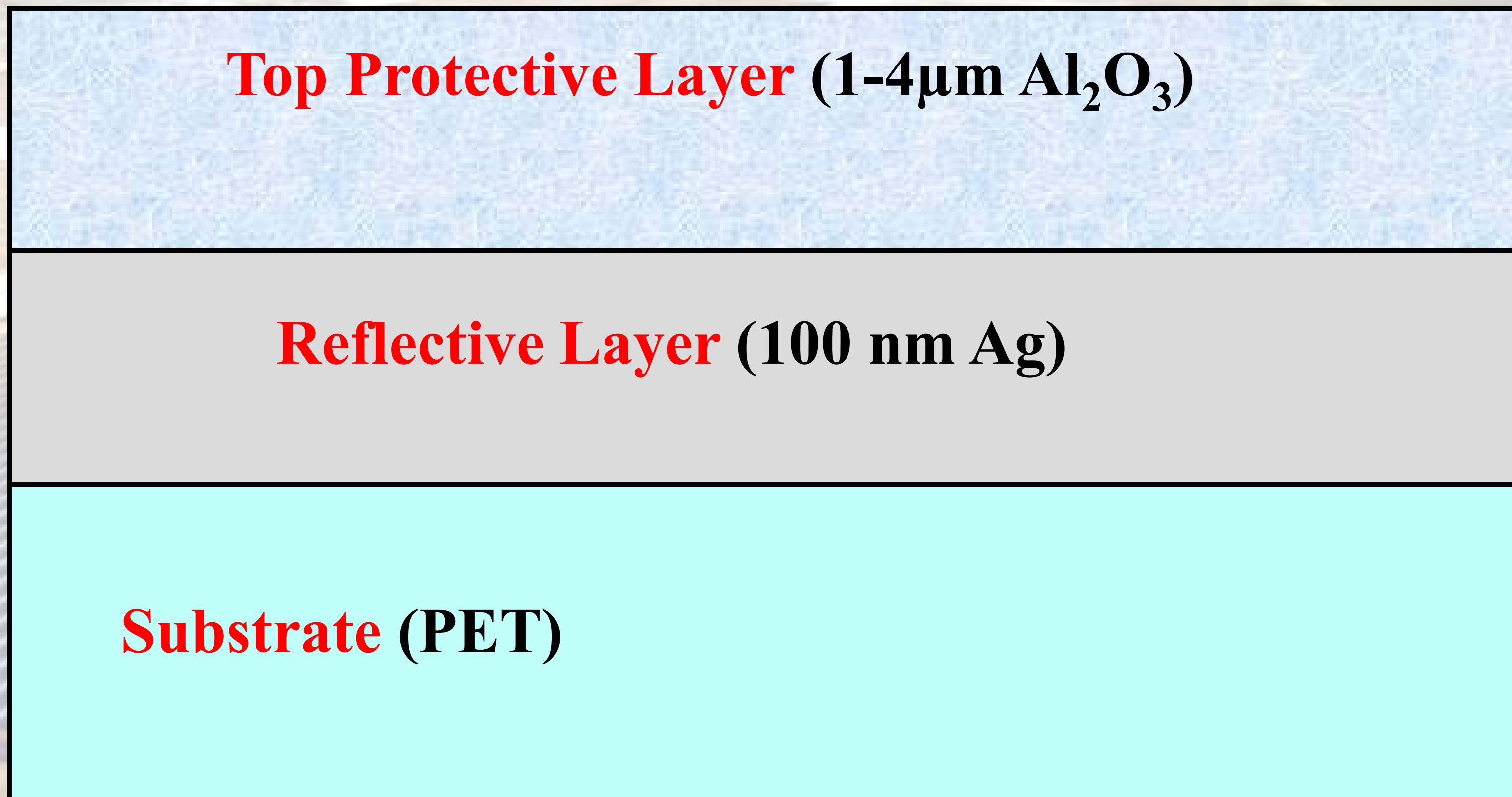


Front Surface Solar Reflector Architecture

Top Protective Layer **(1-4μm Al_2O_3)**



Front Surface Solar Reflector Architecture



Front Surface Solar Reflector Architecture

Anti-soiling Layer (100 nm TiO_2)

Top Protective Layer (1-4µm Al_2O_3)

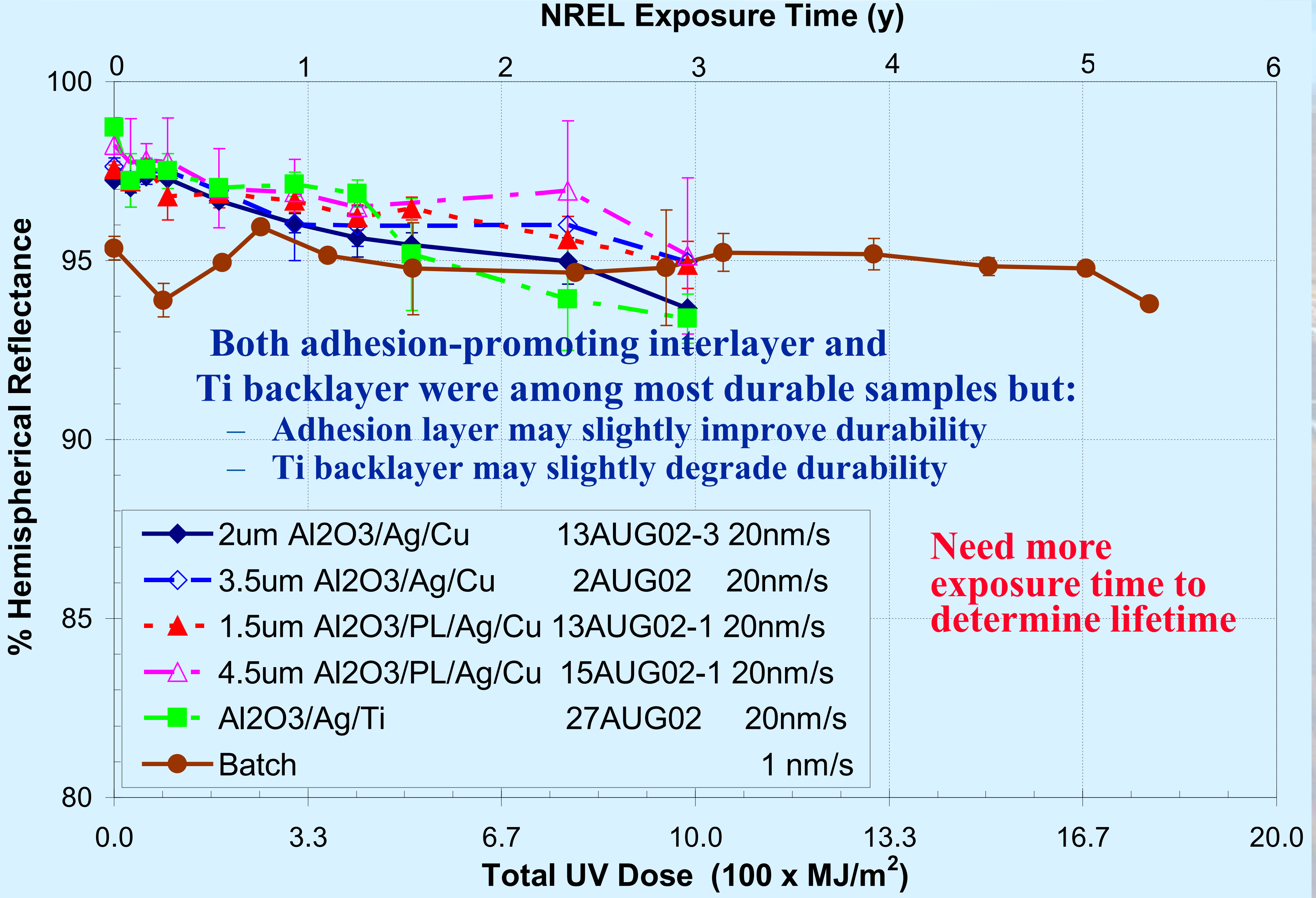
Adhesion Promoting Layer (APL) (1-10 nm)

Reflective Layer (100 nm Ag)

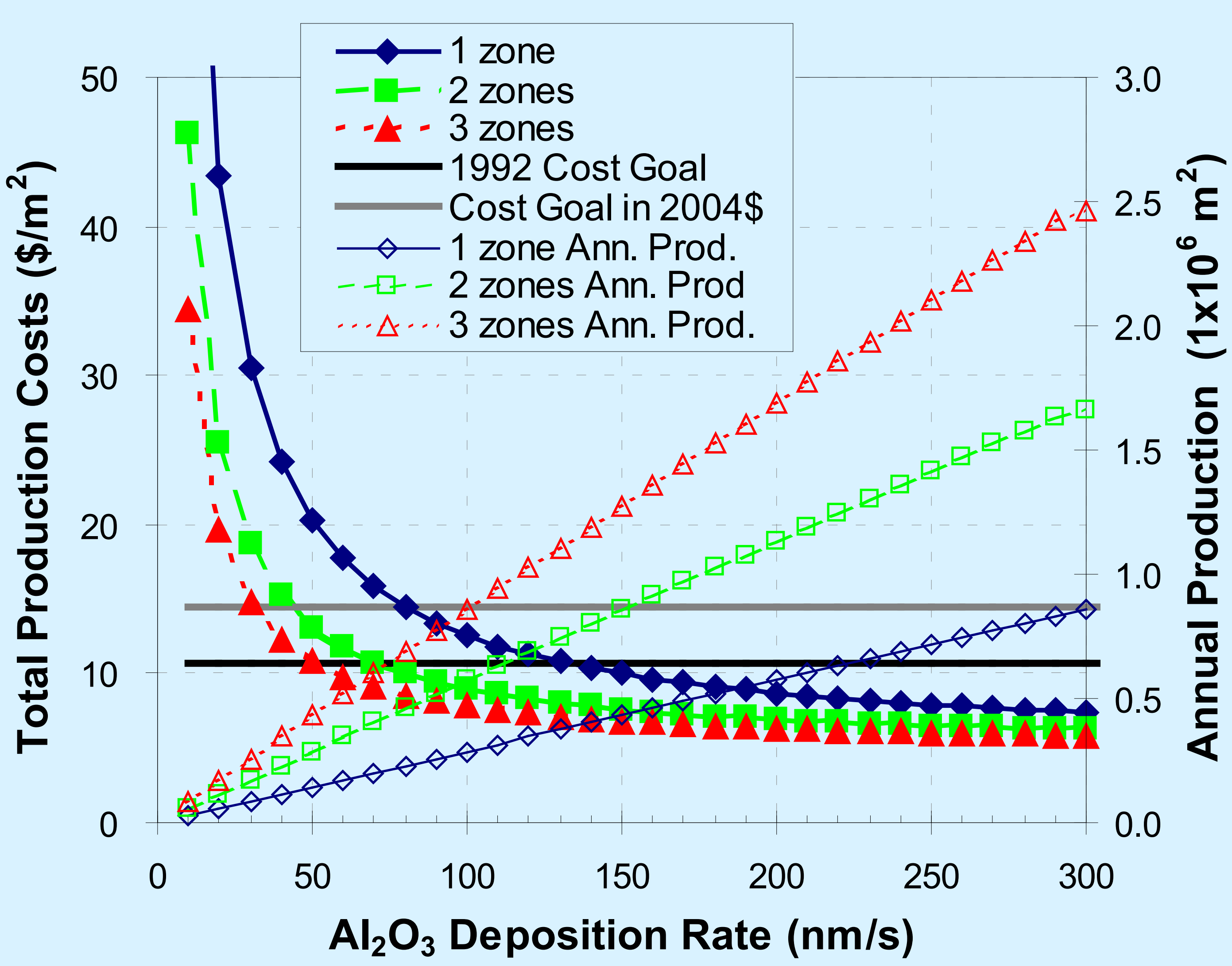
Metal Back Layer (30 nm Cu —optional)

Substrate (PET)	(Chrome Plated Steel, Leveled Stainless Steel, or Aluminum)

Outdoor exposure at NREL of Roll-Coated IBAD Al_2O_3 Samples



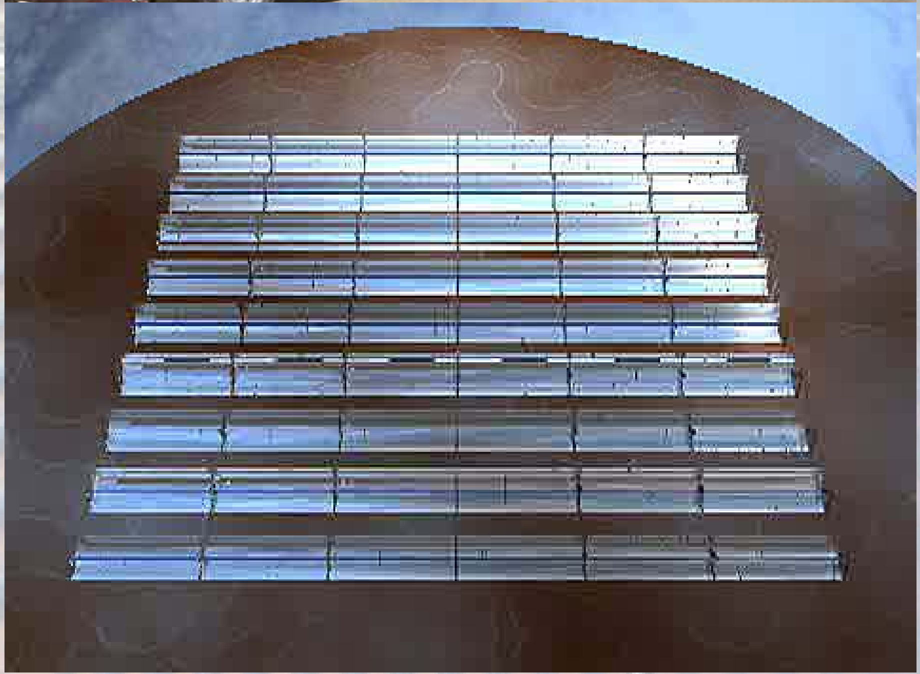
Cost Analysis



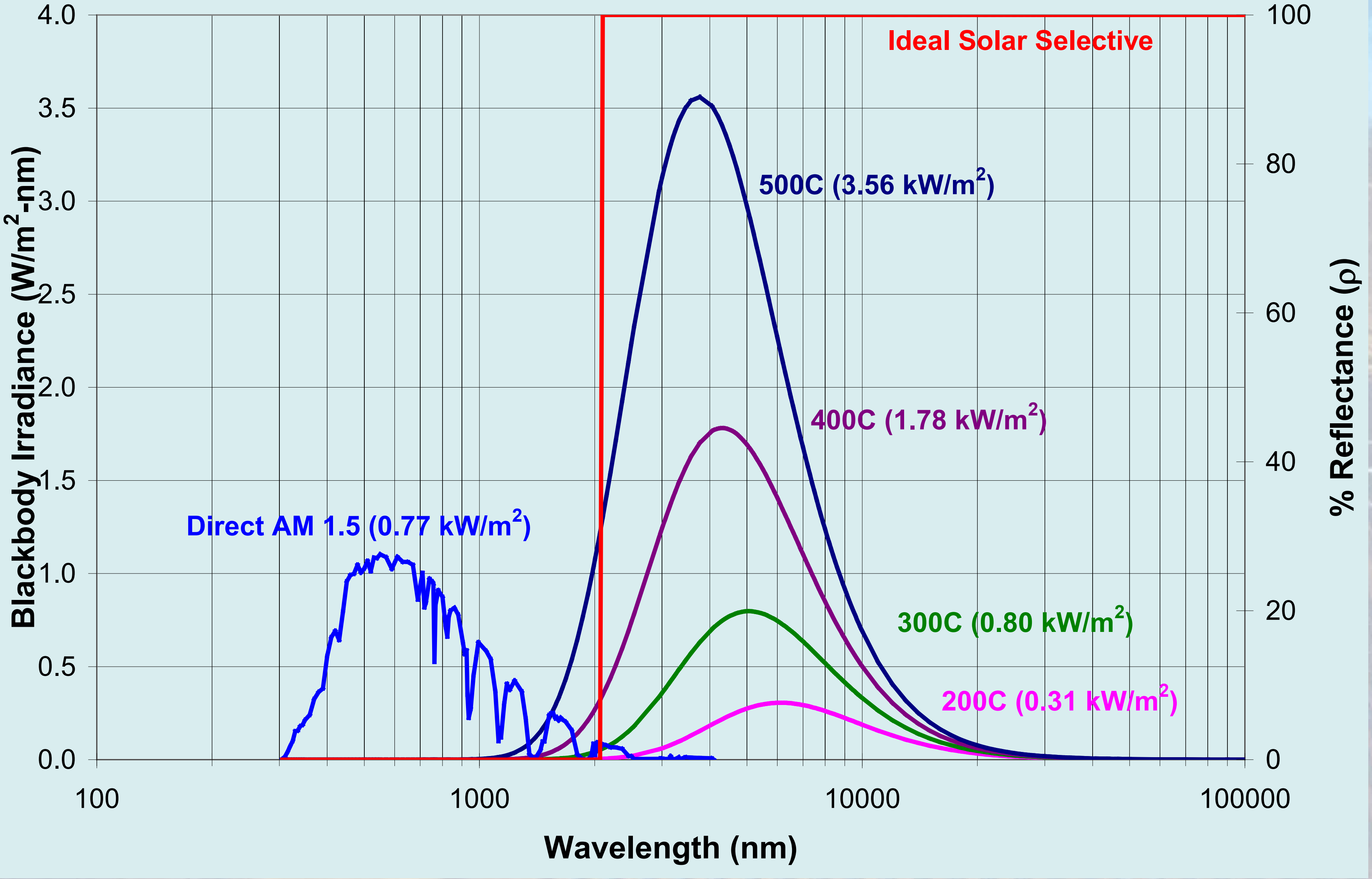
- 30% yield
- Coating 79% time
- 10 to 200 nm/s rate
- Machine cost: $2M-$4.1M
- Loan%/length: 12% for 5 yrs
- PET substrate
- 1-µm Al_2O_3
- Modified ASRM
- $200/h machine burden
- 1200-mm web
- High-purity High-volume (i.e.,$200/kg) Al_2O_3
- ✓ 1 vs. 2 vs. 3 zones in 1 machine

Field Requirements for Advanced Receivers

- Receivers:
  - 4 m (13.1 ft) long
  - 70 mm (2.25 in) diameter
  - New 64 MWe Nevada plant
    - 820 collectors and each collector has 24 (96 m) receivers
    - 19,680 receivers
    - 82 km of receivers (50 mi)
  - Existing SEGS plants have 5x this many receivers
  - New 553 MW plant will need 8.5x this many receivers
  - 3-4%/yr Failure Rate
  - ~$1000/tube

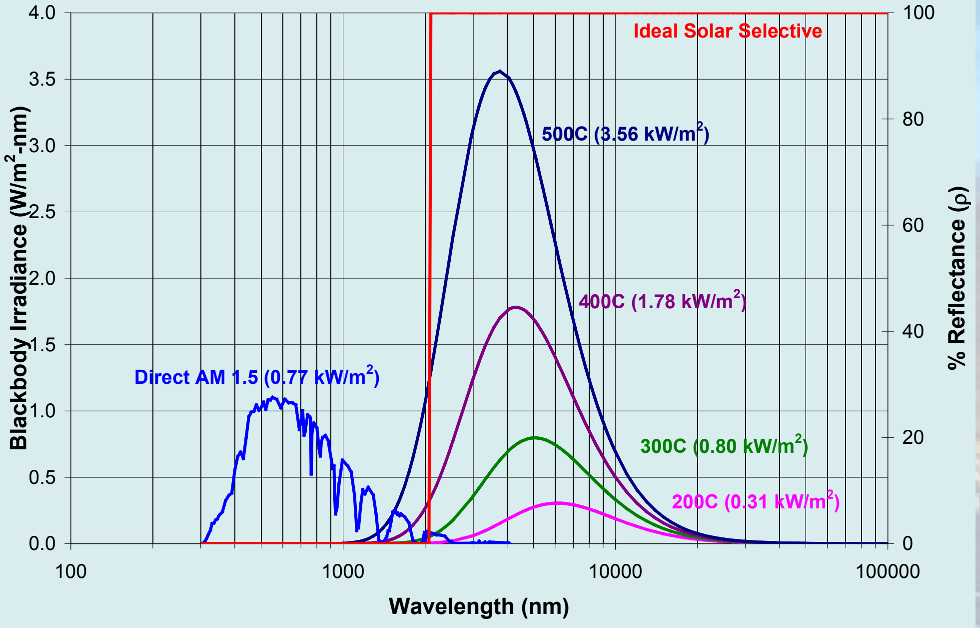


Advanced Selective Coating Goals



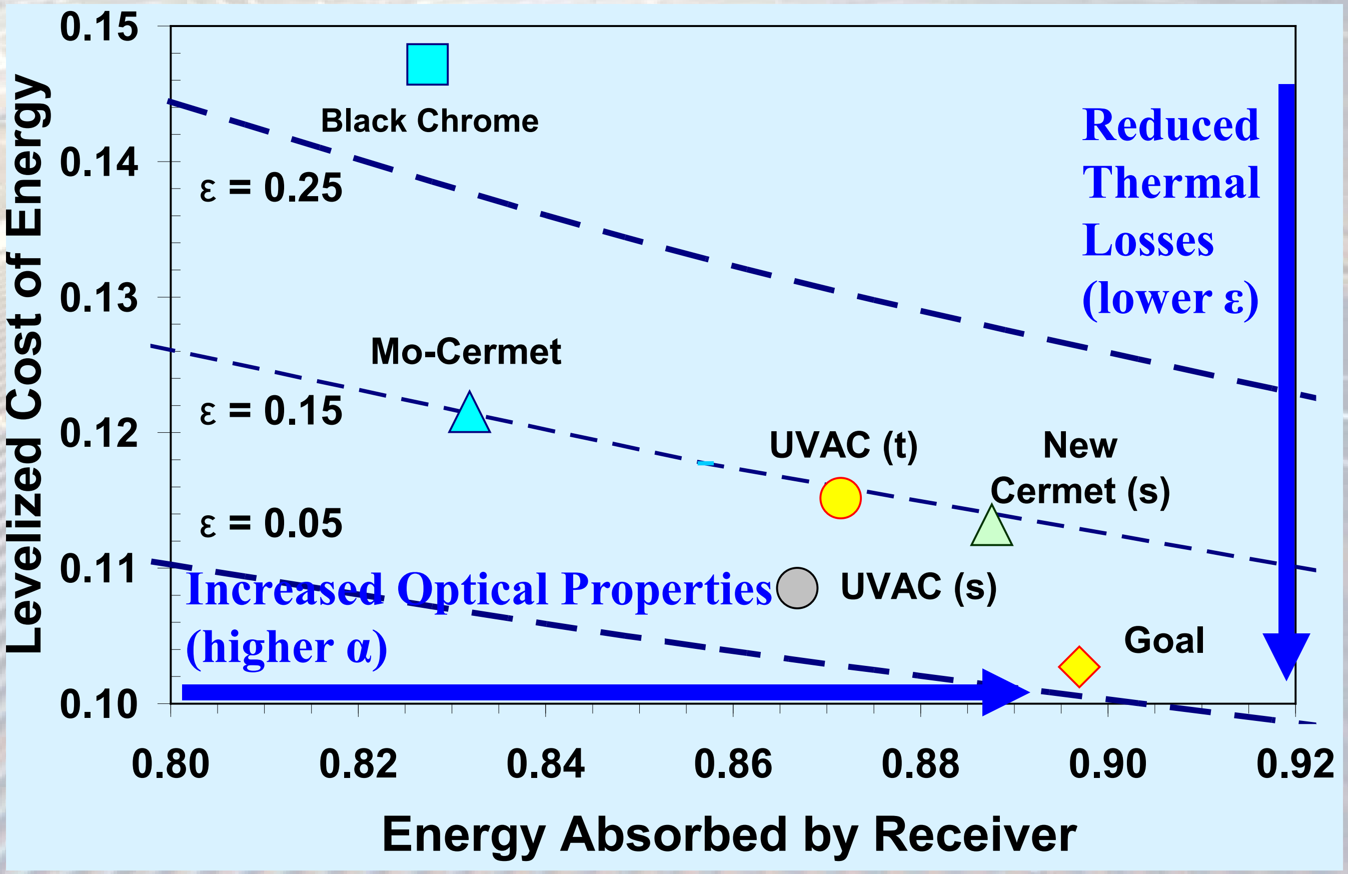
Advanced Selective Coating Goals

- To develop receiver coatings that have:
  - Good optical and thermal performance: absorptance (α) ≥ 96%, & emittance (ε) ≤ 7% >400ºC
  - High temperature stability in air at temperatures ≥ 550ºC
  - Manufacturing processes with improved quality control
  - Lower cost

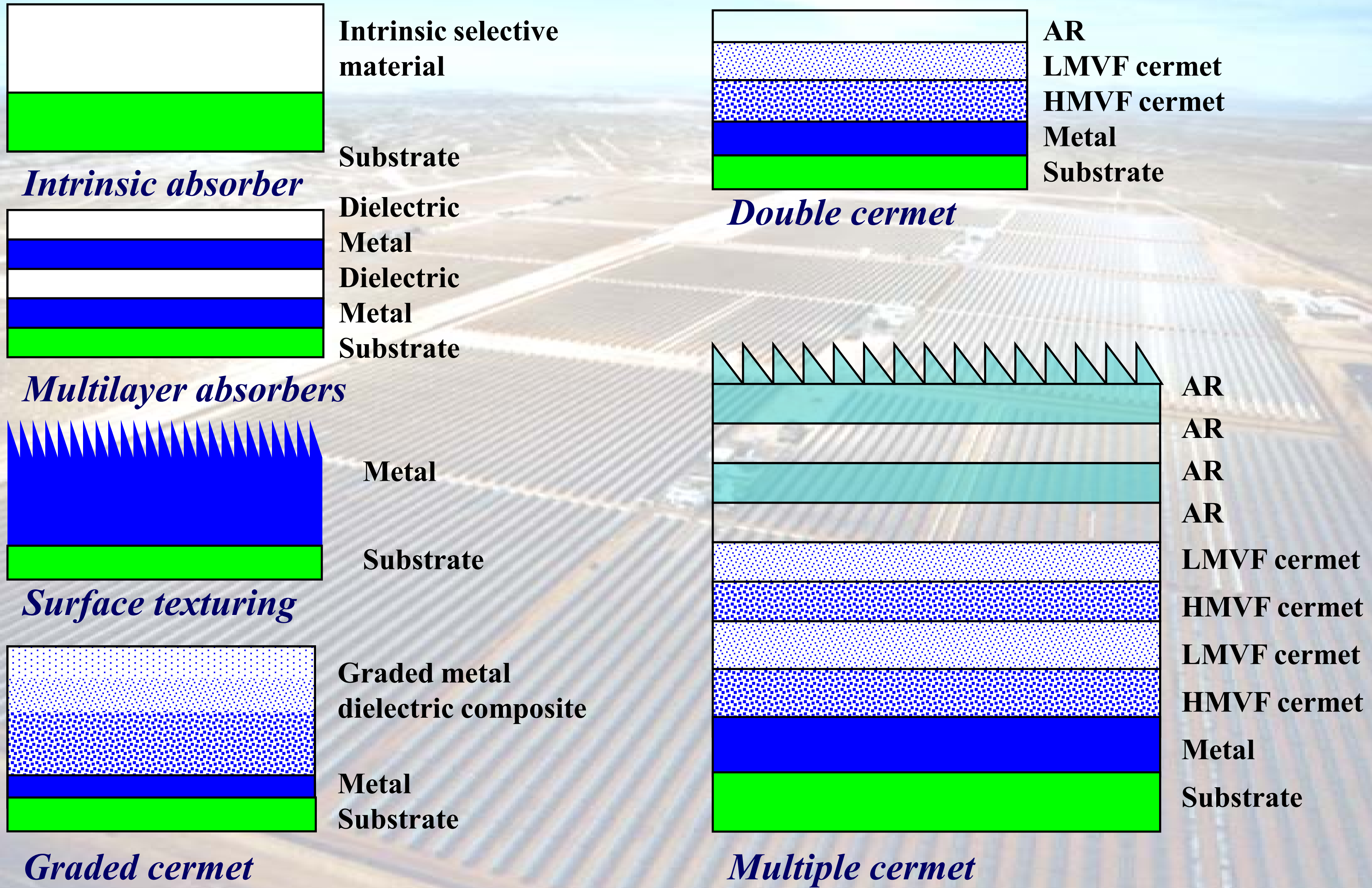


High Temperature Solar Selective Coating Development

- Selective coating properties impact collector optical performance and thermal losses.
- Improvements in the receiver can enhance collector efficiency & lower cost.
- The international community currently leads this area and there exists minimal US research & no US manufacturer of high-temperature selective coatings.



Types of Selective Coatings



Literature Review of Candidate High-temperature (> 400°C) Solar Selective Materials

- Graded Mo,W, ZrB, Pt- Al_2O_3 cermets
- Si tandem absorber
- Black Co, Mo,W
- Double cermets- SS-AlN, AlN/Mo, or AlN/W
- 4-layer V-Al_2O_3, W-Al_2O_3, Cr-Al_2O_3, Co-SiO_2, Cr-SiO_2, Ni-SiO_2
- Double AR
- Multilayers; Al-AlN_x-AlN
- Au/TiO_2 cermet
- ZrC_xN_y/Ag
- $Ti_{1-x}Al_xN$
- *Quasicrystals* multilayers & cermets
- Surface Texturing

Desirable Properties for Stable Coating in Air > 400°C

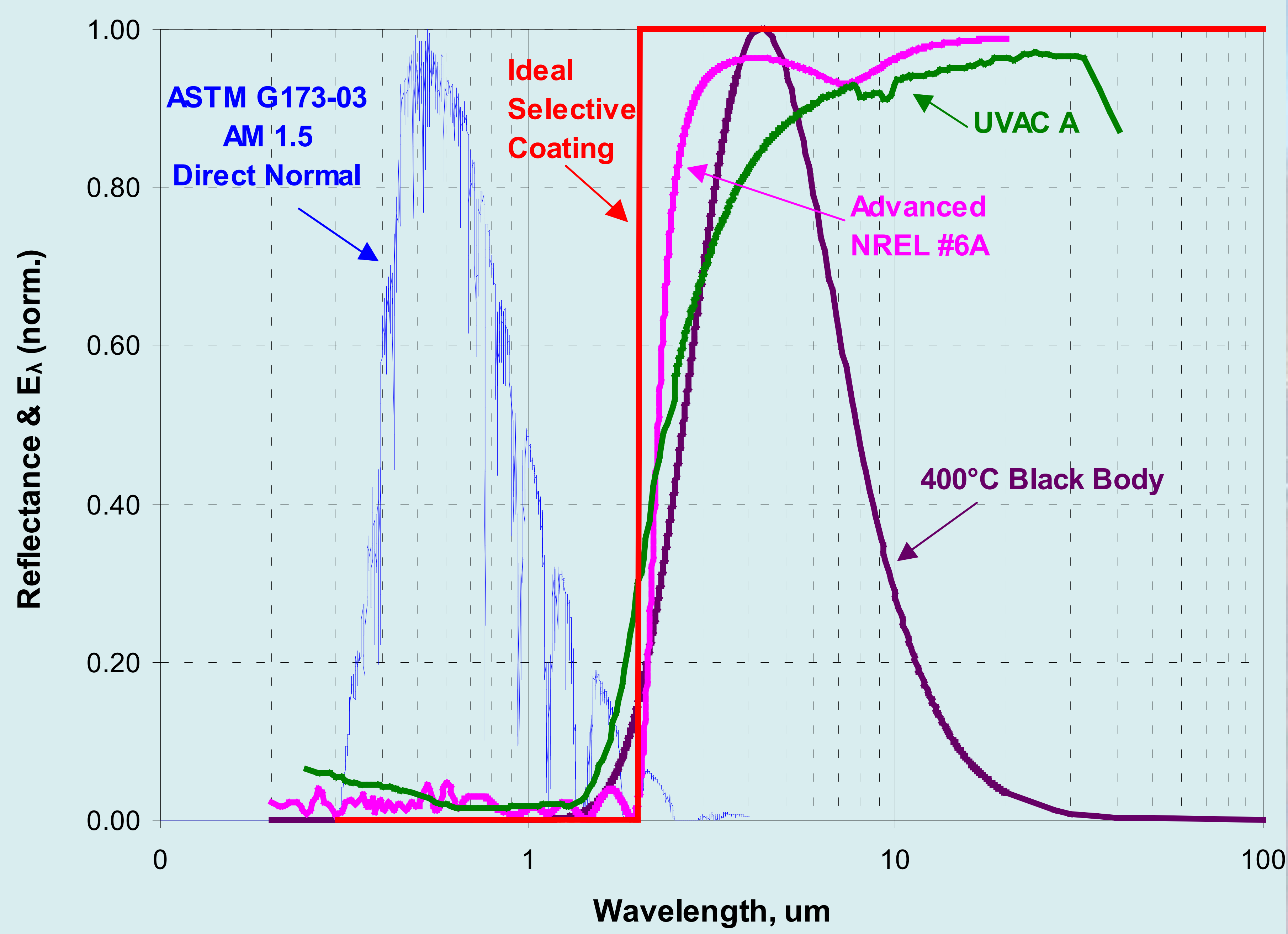
- High thermal & structural stabilities for combined & individual layers
  - Elevated melting points
  - Large negative free energies of formation
  - Materials that form a multicomponent oxide scale
  - Single-compound formation
  - Lack of phase transformations at elevated temperature
- Suitable texture to drive nucleation, subsequent growth of layers with suitable morphology
  - Stable nanocrystalline or amorphous materials
- Excellent adhesion between the substrate and the adjacent layers
- Enhanced resistance to thermal and mechanical stresses
  - Acceptable thermal and electrical conductivities
  - Higher-conductivity materials have improved thermal shock resistance
  - Some ductility at room temperature reduces thermal-stress failures
- Good continuity and conformability over the tube
- Compatibility with fabrication techniques

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	
	Black Cr	Mo-Cermet	UVAC	# 6A	# 6B
Solar Absorptance	0.916	0.938	0.954	0.959	0.950
Thermal Emittance@					
25°C	0.047	0.061	0.052	0.013	0.027
100°C	0.079	0.077	0.067	0.017	0.033
200°C	0.117	0.095	0.085	0.028	0.040
300°C	0.156	0.118	0.107	0.047	0.048
400°C	*0.216*	0.146	0.134	0.074	0.061
500°C	*0.239*	*0.179*	*0.165*	0.110	0.073

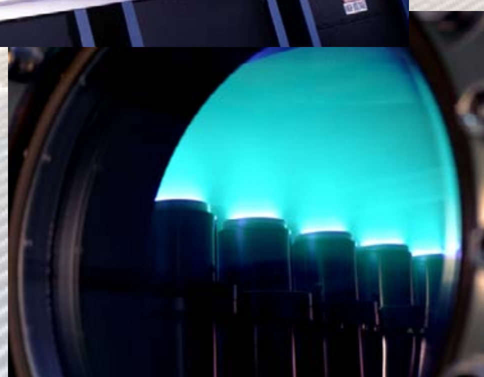
Modeled NREL Selective Coating



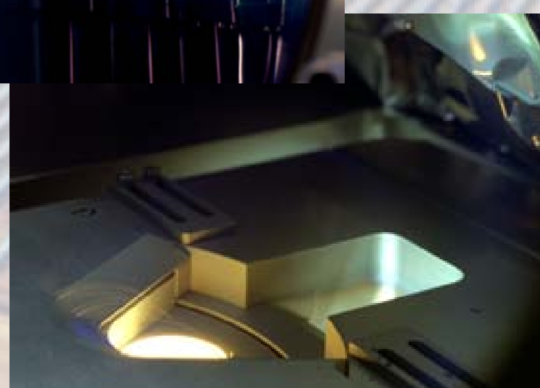
Modeling Key Results

- Solar Selective Coating Development
  - Modeled solar-selective coatings with α=0.959 and ε=0.061 that meet CSP goals
  - Emittance excellent & absorptance of modeled coatings is very good but further improvements are expected. However, trade-off exists between emittance and absorptance.

Deposition Capabilities



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
  - Electron-Beam/IBAD Chamber
    - 6 multi-pocket e-beam source
    - Co-deposition bottom plate
    - IBAD w/ 12” Linear Ion Gun
  - System
    - 12”x12” ambient or heated substrate
    - 4 Reactive Gases
    - Turbo molecular drag pumps
      - $2x10^{-8}$ torr
    - Monitoring
      - RGA
      - Quartz Crystal Monitor
      - Pressure/Gas
      - Computer

Prototyping Key Results

- Key issue is making deposited coating
- XPS showed evaporation from compounds produced layered stoichiometry
  - Despite depositing layers with over- and under-thickness and compound layered structure, the optical performance of the prototype NREL#6A was quite encouraging.
- Need to codeposit materials
  - Required significant upgrade to equipment
    - Installed codeposition guns & sweeps
    - Pneumatic shutters
    - Second quartz crystal sensor
    - Upgrade computer & RGA software
    - + associated air, water, & electrical
    - Automating control

Prototyping Key Results

- Codeposit individual layers and modeled coating
  - Codeposition development
    - Deposited individual layers
    - Deposited modeled structure
    - Characterize properties
  - Optical performance lower than modeled
    - Typically optical coating need error <1%
  - Thickness error was >5% because of manual control
    - Install optical monitor
    - Provide positive feedback between quartz crystal and optical monitor
    - Automate control –remove human error and provide steering and cutting at sensitive turning points allowing mid-course corrections to be made
  - Compositional errors because stoichiometry not optimized
    - Composition with highest reflectance
    - Phase formation from Pretorius effective heat of formation model & TGA
  - Optimize morphology with ion assist

Selective Coating Performance

- ε can be measured at higher temperatures but is typically reported based on calculations from reflectance measurements fitted to the black body curve
- Actual performance of the absorber at high temperatures commonly does not correspond to the calculated ε
  - Small errors in ρ lead to large errors in ε
  - ε is a surface property & depends on surface condition of material and substrate
    - Surface roughness
    - Surface film
    - Oxide layers
  - Selective coatings can degrade at high T due to
    - Thermal load (oxidation)
    - High humidity or water condensation on the absorber surface (hydratization and hydrolysis)
    - Atmospheric corrosion (pollution)
    - Diffusion processes (inter-layer substitution)
    - Chemical reactions
    - Poor interlayer adhesion
- Therefore it is important that ρ is measured accurately and to measure ε of the selective coating at operating temperatures & conditions before using calculated ε

→Round Robin &

Purchase Perkin Elmer 883 IR spectrophotometer

Thermal Stability

- Thermal stability is sometimes given based on the thermal properties of the individual materials or the processing temperature parameters
- Actual durability data is uncommon for high temperature absorber coatings
- Durability or thermal stability is typically tested by heating the selective coating, typically in a vacuum oven but sometimes in air, for a relatively short duration (100’s of hours) compared with the desired lifetime (5-30 years)
  - IEA Task X performance criterion (PC) developed for flat plate collector absorber testing (i.e., non-concentrating, 1-2X sunlight intensity)
  - No analogous criterion known for testing high-temperature selective coatings for CSP applications
- Building capability for long term testing of thermal stability

→ Purchased & installed high-temperature (600°C) inert gas oven

Conclusion

- DOE, the WGA, state RPS mandates, and feed-in tariffs have successfully jump-started growth in CSP technologies that would require 7 to 10 million square meters of reflector and more than 600,000 HCEs over the next 5 years.
- Commercial glass mirrors, Alanod, and ReflecTech may meet the 10-yr lifetime goals based on accelerated exposure testing. Predicting an outdoor lifetime based on accelerated exposure testing is risky because AET failure mechanisms must replicate those observed by OET.
- Experimental IBAD Al_2O_3 front surface mirror has high potential to meet need; but needs development by roll-coating company
- None of the solar reflectors available have been in test long enough to demonstrate the 10-year or more aggressive 30-year lifetime goal, outdoors in real-time

Conclusion

- Modeled solar-selective coatings with α=0.959 and ε=0.061 that meet CSP goals
- Emittance excellent & absorptance of modeled coatings is very good but further improvements are expected. However, trade-off exists between emittance and absorptance.
- Key issue then becomes trying to make the coating
- Prototype development underway. Individual and modeled structure deposited by e-beam compound and elemental codepostion & characterized. Need to eliminate thickness errors by upgrading monitor and control and determine optimum stoichiometry.
- Purchased & installed PE 883 IR Spectrophotometer (2.5- 50μ) and high-temperature inert gas oven. Round-robin data being analyzed and commercial & prototyped coating samples being put into test
- Patent being pursued

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