U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

DOE Solar Energy Technologies Program Peer Review

Technical Track: CSP

Project Name: CSP Applied Research

Principal Investigator: Cheryl Kennedy

Denver, Colorado

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Objectives

- Reduce cost of concentrator by 50% in order to reduce the cost of solar electricity produced by CSP to be cost competitive with electricity produced by traditional means by 2015

Activities

- Mirrors
  - CSP Applied Research
    - Advanced Concepts R&D – NREL
    - Advanced Concepts FOA Support – NREL
    - CEC/CSP Collaborations
- Receivers
  - Parabolic Trough Development
    - Trough Solar Field
      - Advanced Absorber Materials R&D

Team members
Points of Contact

- Mark Mehos – Program Manager (CSP/NREL)

- Mirrors
  - Cheryl Kennedy – Advanced Concepts Task lead
  - Gary Jorgensen – SkyFuels/Reflectech CRADA lead
  - Mark Oddo – Advanced Concepts research technician
  - Chase Latta – Advanced Concepts undergraduate student intern
  - Robert Tirawat – Advanced Concepts undergraduate student intern

- Receivers
  - Dr. Chuck Kutscher – Parabolic Trough R&D team lead
  - Cheryl Kennedy – Advanced Absorber Materials R&D
  - Chase Latta
  - Robert Tirawat

Advanced Concepts R&D

Advanced Solar Mirrors and Optical Materials

Objectives: Mirrors

- Develop advanced reflectors with:
  - >90% specular reflectance into <4-mrad cone angle
  - 10-30 year lifetime
- Reduce cost of traditional parabolic trough mirror by at least half
- Test durability of optical materials to determine lifetime

Activities: Mirrors

- Advanced Concepts
  - Mirror characterization and durability testing

- Advanced Concepts Support
  - Technical support for CSP FOA Advanced Concepts contracts:
    - 3M – Hardcoats for polymeric mirrors
    - Abengoa – Advanced front surface polymeric reflector
    - Alcoa – Aluminum reflector
    - PPG – High-value mirrors

Mirror Characterization

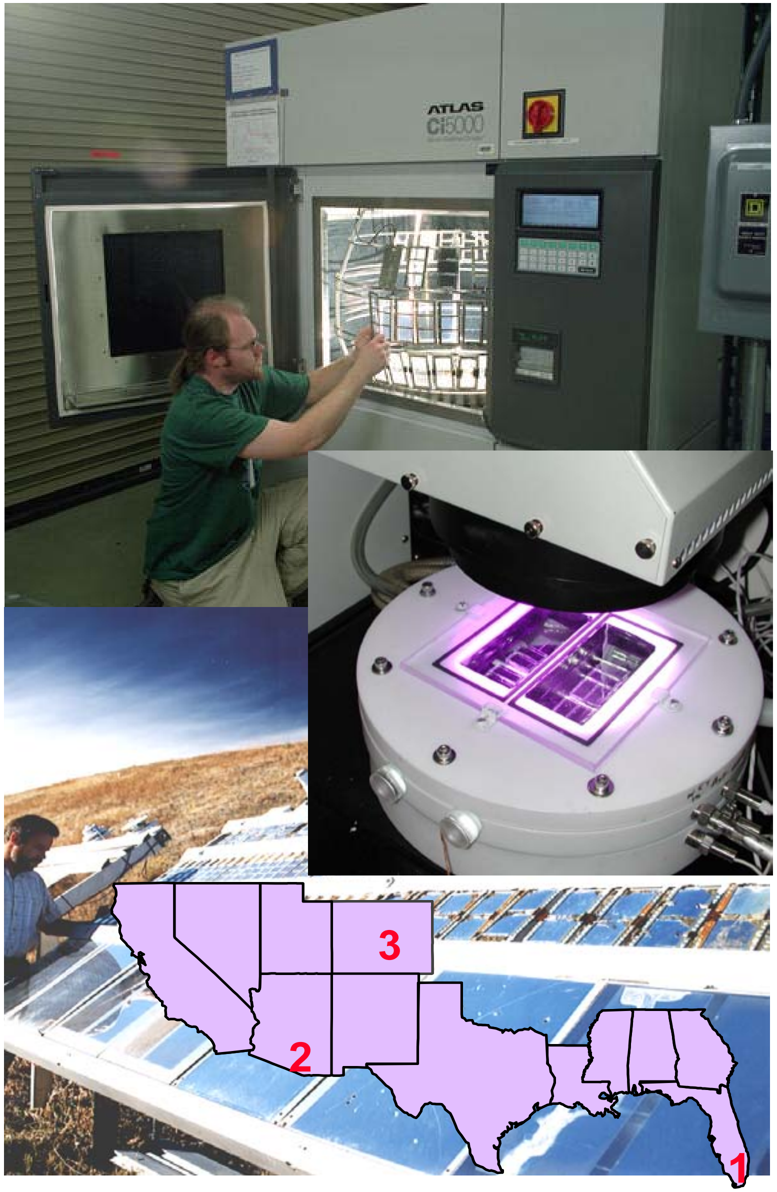
- Samples supplied by:
  - *Industry*
  - *Subcontracts*
  - *Developed in-house*

- Measure optical and mechanical properties of potential solar materials

- Characterize samples initially and as a function of outdoor and accelerated exposure time
  - *Typically characterize 800-1000 samples/mo*

Durability Testing

- Durability of solar materials tested as a function of exposure time
- Samples are exposed at three outdoor exposure test sites and in several accelerated exposure test chambers
  - *Roughly 7000 advanced reflector & solar selective samples are currently under test for CSP (& CPV) industry*
  - *Database of solar materials contains:*
    >1000 experiments
    >20,000 samples
    >300,000 measurements
    >21 yr



Broad Industry Collaboration: Glass

- Thick (>3-mm) Glass
  - Flabeg (trough mirror supplier)
  - RioSolar (new trough mirror)
  - Cristaleria Espanola S.A (i.e., Saint-Gobain)
  - Saint-Gobain
  - PPG (CSP FOA)
  - Veridian
    (formerly Pilkington Australia purchased by CSR purchased by Veridian)
  - Guardian
  - AFNA
    [formerly AFG purchased by Asahi Glass Company (AGC) renamed ASG (A) Flat Glass (F) North America (NA)]
  - NSG Pilkington
    [formerly Pilkington purchased by Nippon Sheet Glass (NSG)]
  - Arch
  - Cardinal
  - Gardner
  - Vitro America
- Thin (~1-mm) Glass
  - AFEU
    [formerly Glaverbel (Belgium) purchased by Asahi Glass Company (AGC) renamed ASG (A) Flat Glass (F) EU]
  - AF Thailand
  - AF Indonesia
  - Galvalux
  - Naugatuck Glass Company
    (recently purchased by Flabeg)
- Mirror Coating
  - Valspar
  - Fenzi
  - Spraylat
  - Peacock
- Equipment Manufacturers
  - GlassTech

Architecture of Glass Mirror

Low-iron Glass (1-mm to 4-mm thick)

Reflective Layer (wet-silver)

Back Layer (Cu)
(Cu-less)

1st coat Paint Layer (20% Pb →2.5% Pb)
(lead-free <0.15% or <5 ppm Pb)

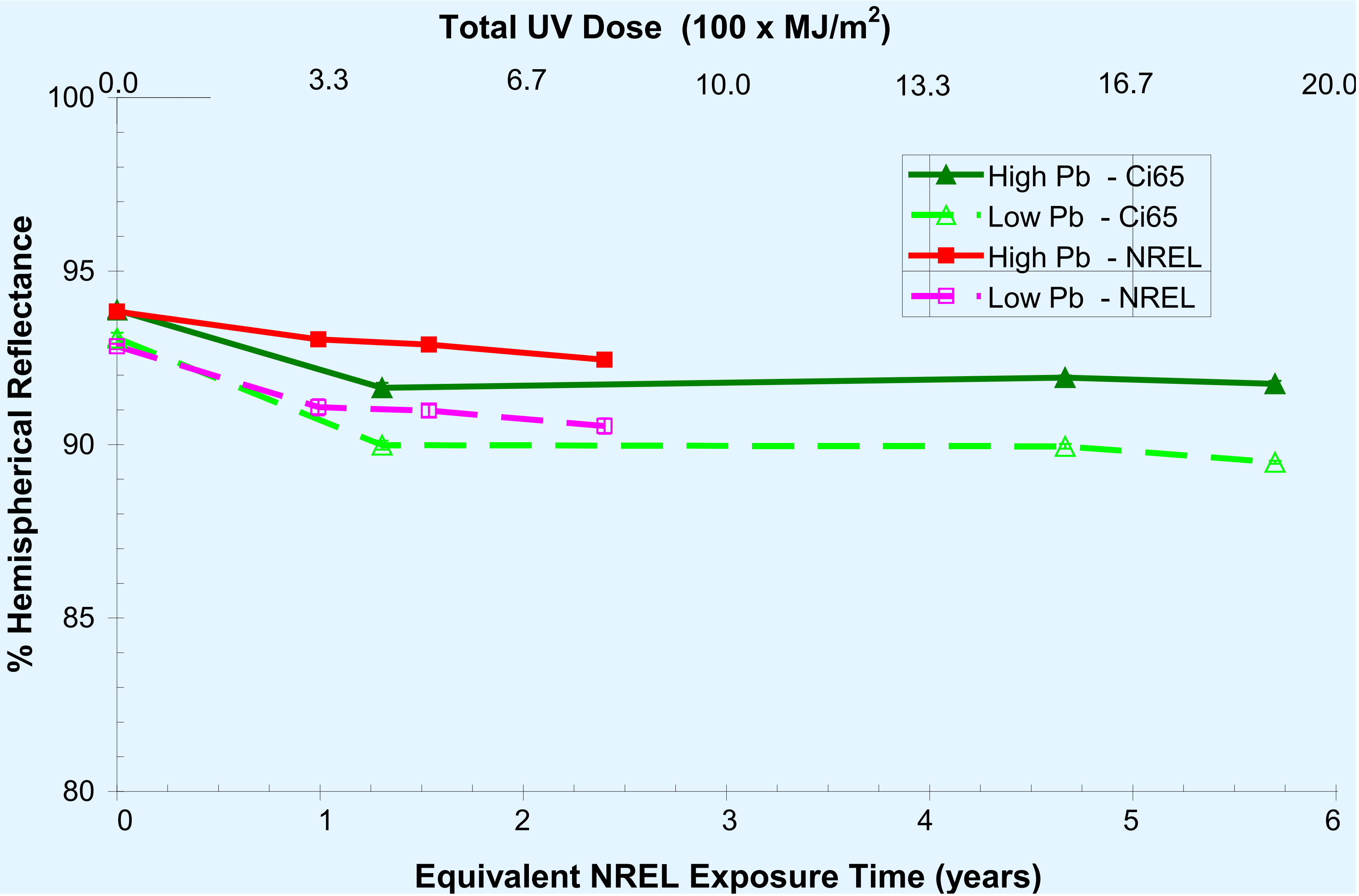
2nd coat Paint Layer (10% Pb →1% Pb)
(lead-free <0.15% Pb or < 5 ppm Pb)

UV / Moisture / Adhesive Barrier Layer

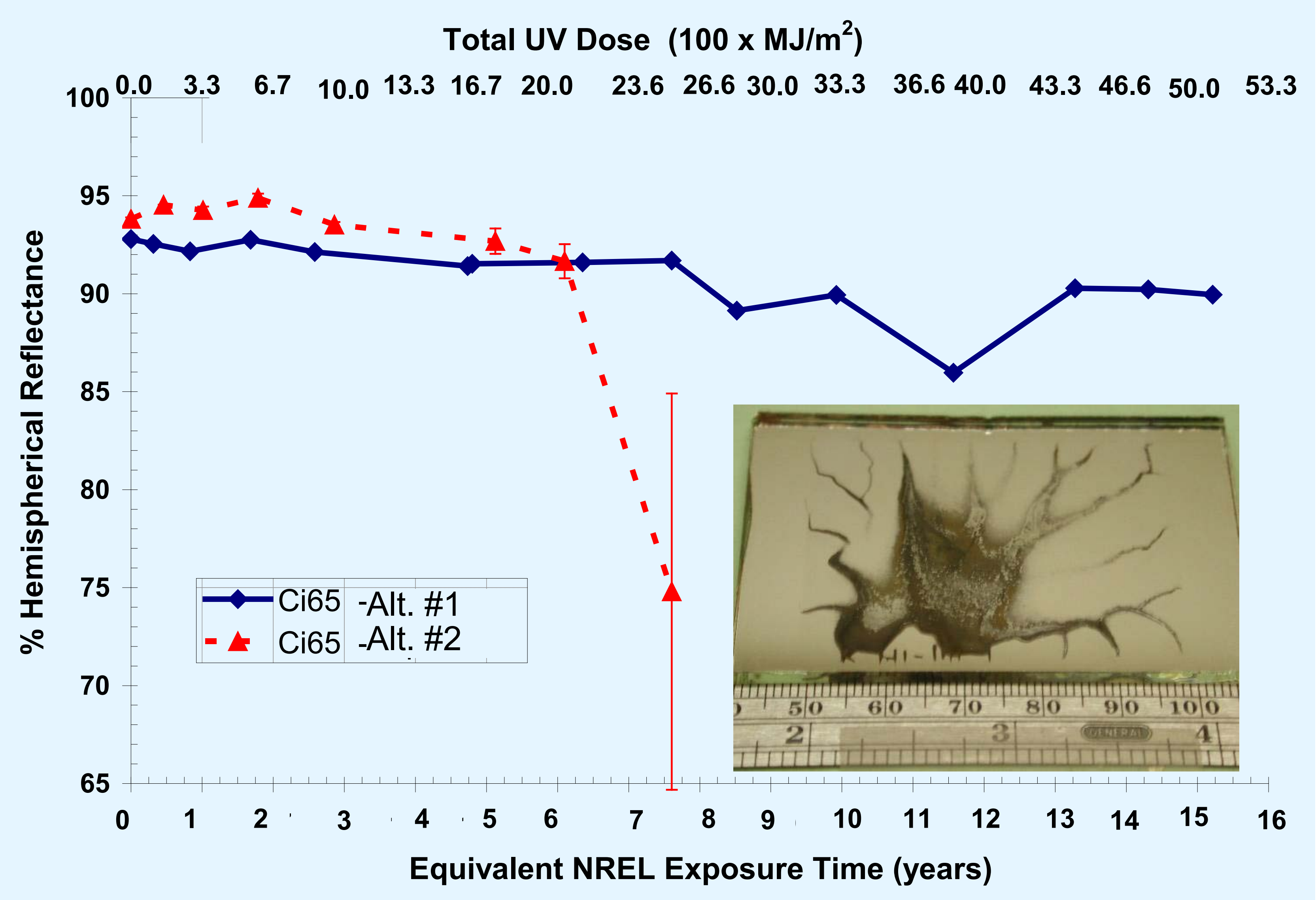
Adhesive (PS, spray)

Substrate (SS, Al)

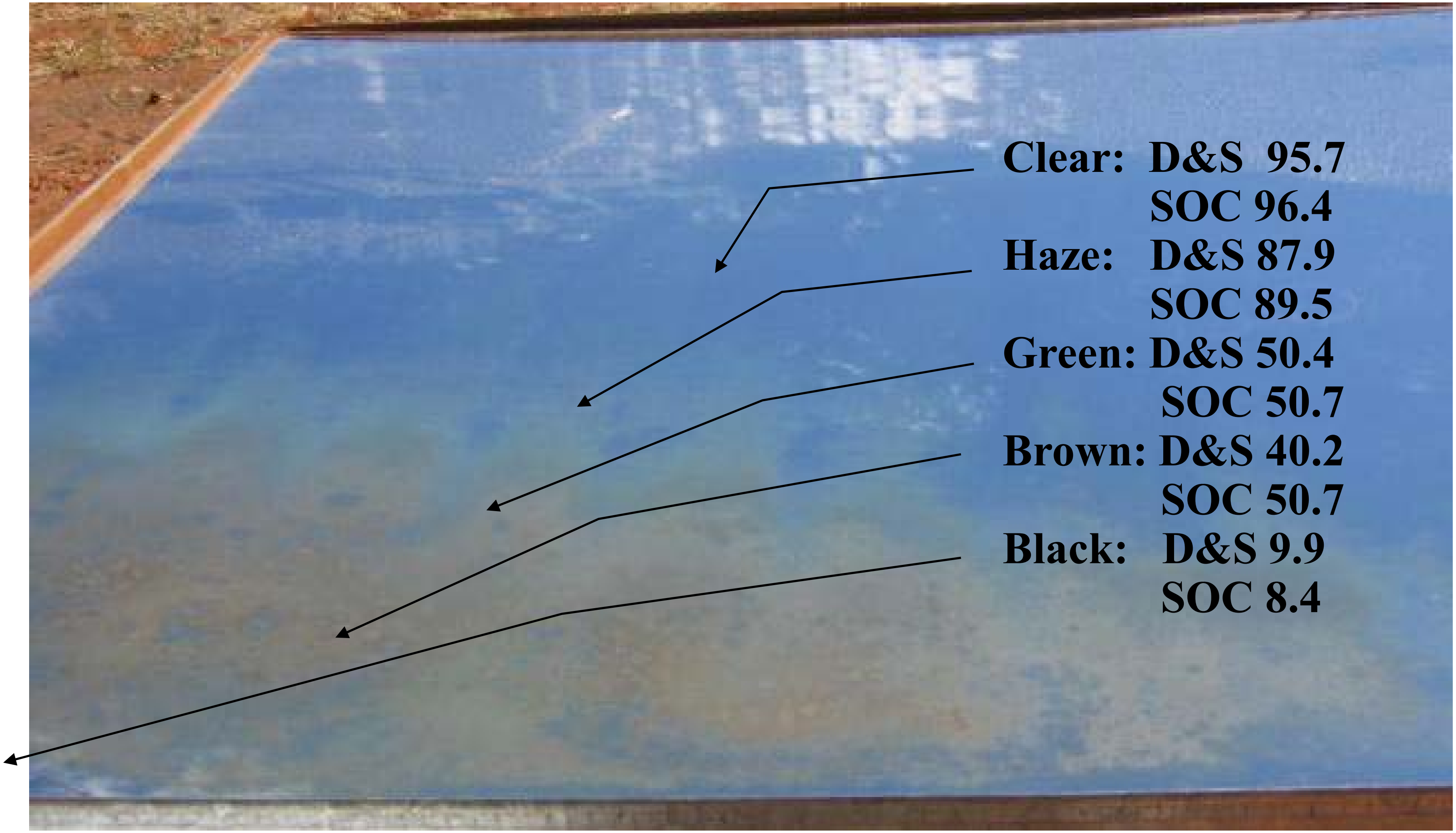
Durablity of Low-Pb 4-mm Glass Mirror



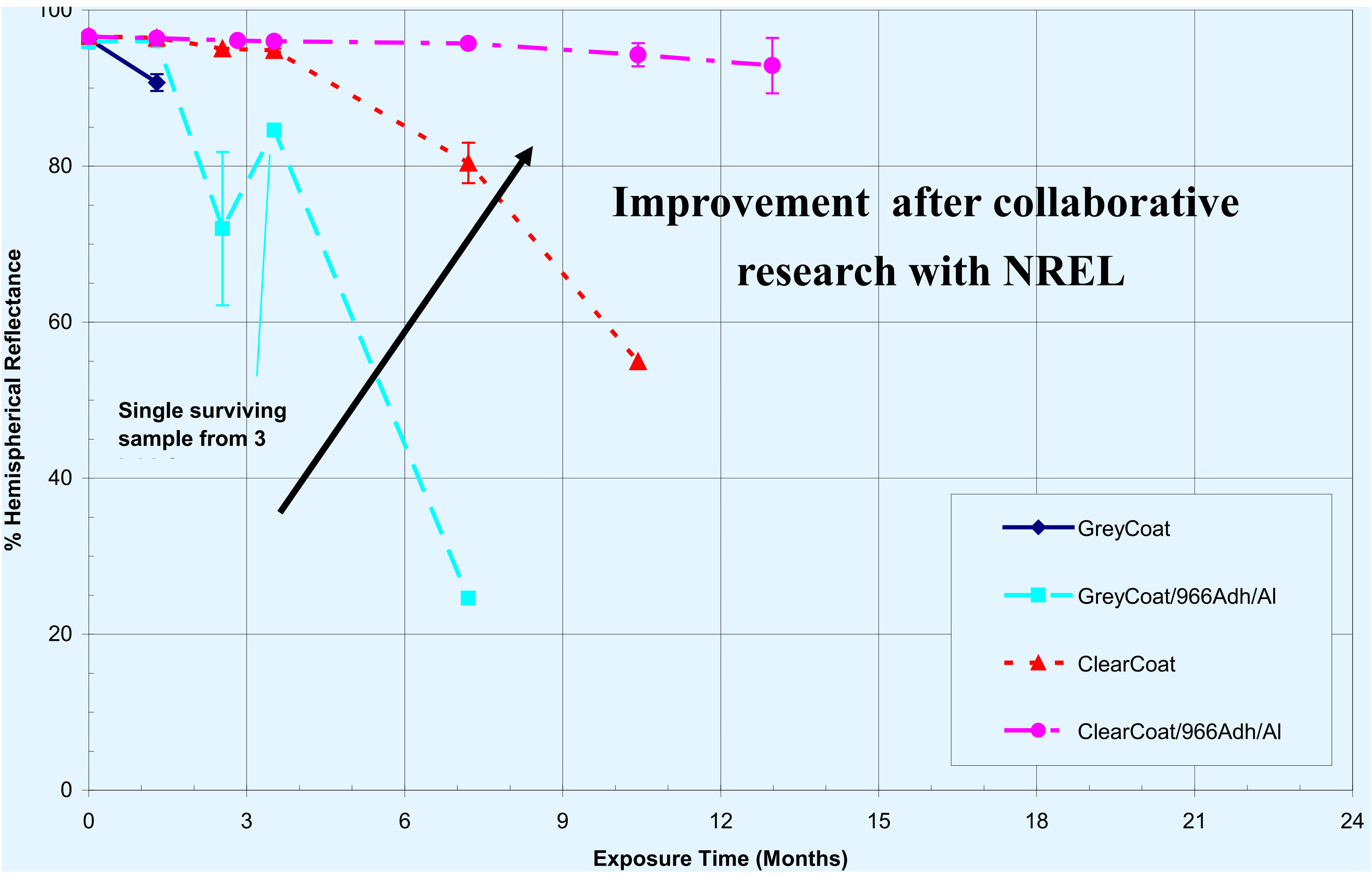
Alternate Thick Glass Mirror



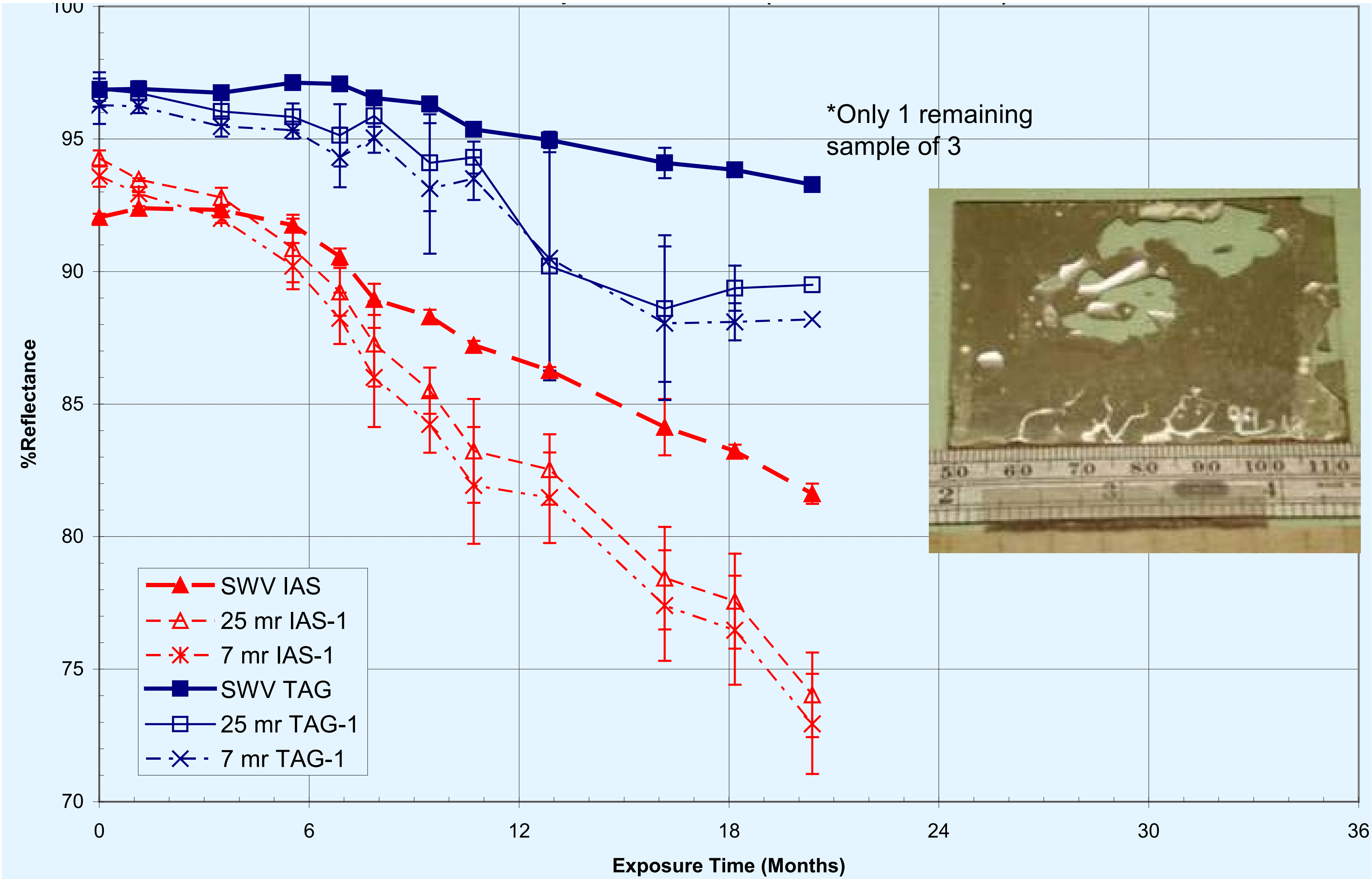
Mirror Corrosion after ~2 y in Field



Thin Glass Mirror



Durability Varies between Lines



Issues that Affect Glass Mirror Durability

- Glass
  - Ag since float (<6 mo)
  - Fe content (sand, campaign)
  - Glass thickness
- Glass Cleaning
  - Glass cleanliness
  - Glass sensitizing ($SnCl_2$ vs. $PdCl_2$)
- Silver
  - Silver air side of glass
  - Silver thickness ($0.8\ g/m^2 < t < 1.2\ g/m^2$)
- Back layer
  - Copper vs. copper-free
  - Separate lines/equipment 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
- Edge finishing/protection
- Self-cleaning advantage

- No standards for solar glass mirrors
- Using qualification tests for indoor mirrors
  - 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
- No warranties given
  - Limited 3 y warranty until mounted in use
- Aggressive warranties being requested

Broad Industry Collaboration: non-Glass

- Anodized Aluminum
  - Alanod
  - Alcoa (CSP FOA)
  - Alcan
  - Aluminum Coil Anodizing (ACA)
  - Hydro Aluminum
- Polished Metal
  - Nitinol
  - Microengineered Metals
- Equipment Manufacturers
  - Von Ardenne
  - VaporTech
- Silvered Polymer
  - 3M (CSP FOA)
  - ReflecTech (SkyFuels)
  - Southwall
  - Bennett
  - SolarTech
  - Evoniks
  - GE
  - Rohm &Haas
  - Dow
- Front Surface
  - Abengoa (CSP FOA)
  - Science Applications International Corp. (SAIC)
  - JDS Uniphase (JDSU)
  - Solel

Advanced Concepts R&D

- Major FY 2008 Accomplishments:
  - Performed and published solar material durability testing
  - Provided significant industry support to CSP (& CPV) industry
    - Purchase and installation of new optical & accelerated weathering equipment
    - Assessment of solar mirrors durability in field
    - OET results for thin-glass Cu- & Pb-free Ag mirrors
  - Consensus reached new solar mirror specular reflectance, life-time, & cost goals, standards, and qualification tests consistent with current CSP program objectives needed
    - Steering Committee for DOE "Specialty Glass Needs of the U.S. Solar Industry" workshop
- Issues:
  - Equipment installation unavoidably delayed
  - AET results delayed for thin-glass Cu- & Pb-free Ag mirrors because of installation delays

- Planned Accomplishments in FY 2009 with FY2008 carry-over:
  - Continue to perform & publish solar material durability testing
    - AET thin-glass mirrors at different RH/T conditions & report OET & AET results
  - Continue to upgrade optical characterization & durability testing
    - Upgrade database to web accessible
    - Develop capability to measure 2-mrad specular reflectance in laboratory
    - Complete installation of new accelerated weathering testing capabilities ordered in FY 2008 but delivered in FY2009

CSP FOA Support

- Major FY 2008 Accomplishments:
  - Provided technical support, critical reviews, optical characterization, and durability testing of reflectors provided under FOA subcontracts
    - 3M – Hardcoats for Polymeric Mirrors
    - Abengoa – Advanced Front Surface Polymeric Reflector
    - Alcoa – Aluminum Reflector
    - PPG – High Value Mirrors
- Issues:
  - 3M received no-cost extension pending cleanable coating data
  - Abengoa received no-cost extension because subcontract signing delayed until Sept 08
  - Alcoa transitioned to Phase II and added reflective surface down-selection pending specular & accelerated testing results to Phase II
  - PPG requested early transition to Phase II

Future Work: Mirrors & Lab

- Mirrors:
  - Continue to perform mirror characterization and durability testing
    - Develop correlation between accelerated exposure testing and outdoor exposure testing for different classes of solar mirrors
  - Continue to provide laboratory support to CSP FOA Advanced Concepts Phase II & III contracts
    - Develop correlation between barrier coating properties and durability of FOA solar mirrors
    - Apply service lifetime prediction (SLP) methodology to FOA materials
  - Develop advanced hardcoats, antisoiling coatings, and cleaning techniques (FY2009 EN >> FY 2010)
  - Develop standards and qualification tests for solar mirrors, CSP components, and systems (FY2009 EN >> FY 2010)
    - SolarPACES Standardization Workshop held at NREL March 3-4, 2009
    - Survey CSP & reflector industry, use SAM to determine specularity and cost goals

- Lab Improvements:
  - Upgrade/install new optical characterization, deposition, & accelerated exposure chambers and upgrade lab space (FY 2009 – FY 2010)
    - Complete upgrade of DC/RF deposition system to closed field unbalanced magnetron (CFUM) and upgrade process & control (FY09 - FY10)
    - Move five-chamber (2 PECVD, DC sputter, thermal evaporation) deposition system and upgrade process & control system (FY10)

Receivers:

Advanced Absorber Coatings

Objectives: Receivers

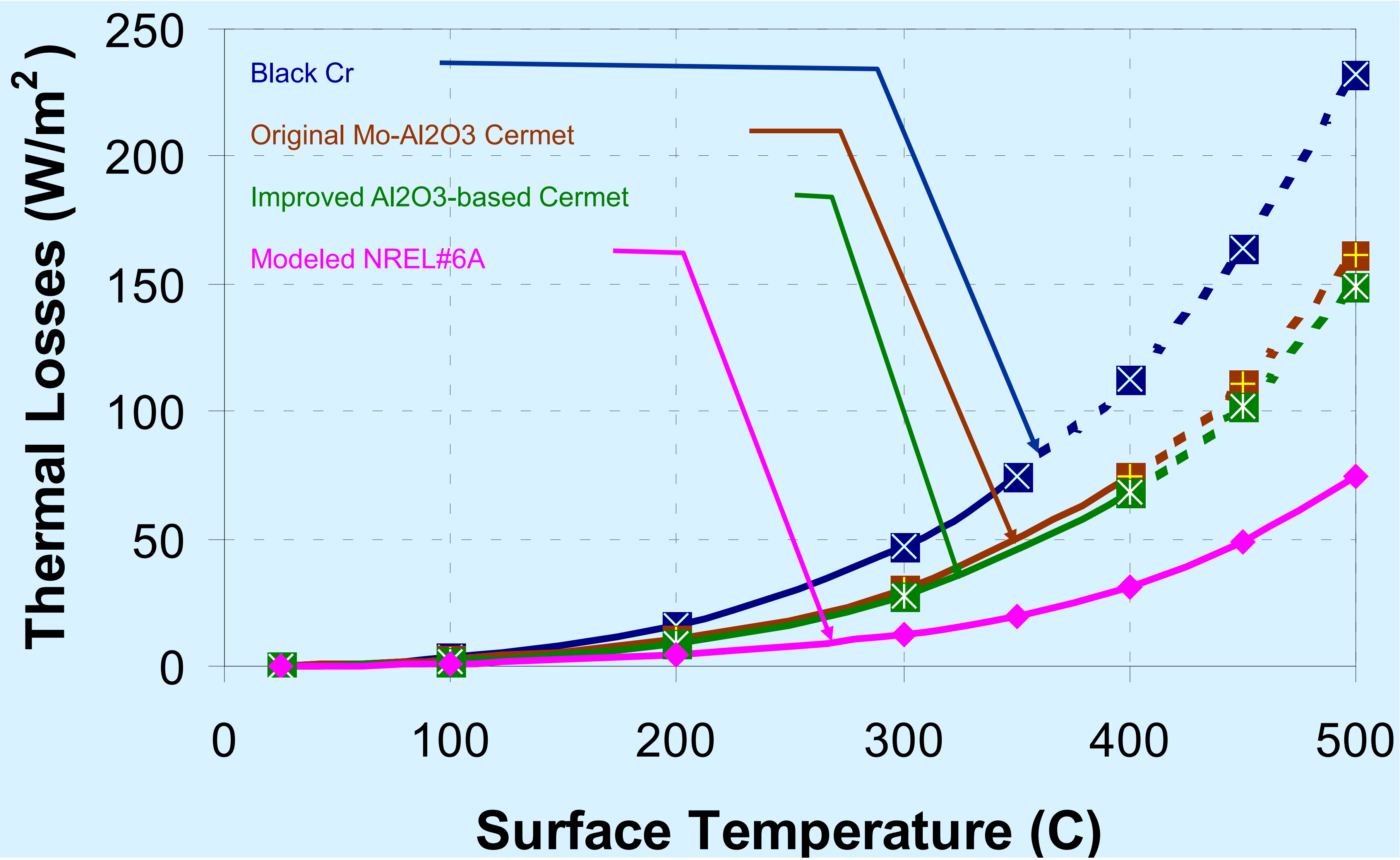
- Develop new, more-efficient advanced solar selective coatings for receivers with:
  - High solar absorptance ($\alpha > 0.96$)
  - Low thermal emittance ($\varepsilon < 0.07$ @ 450ºC)
  - Thermal stability > 450ºC, ideally in air
  - Improved durability and manufacturability
  - Reduced cost
- Encourage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

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

Thermal Losses for NREL Modeled Coating

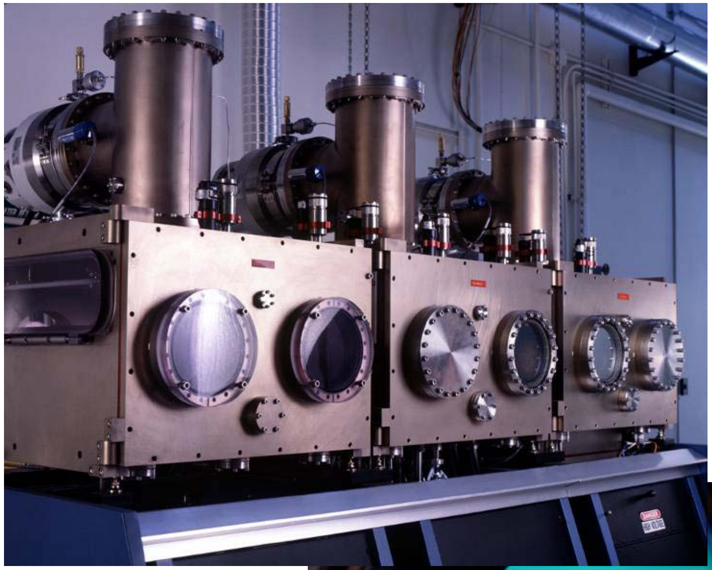


Activities: Receivers

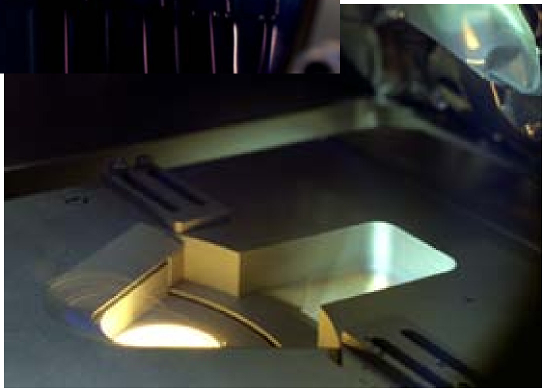
- Research and development of advanced solar selective coatings

- Work with NREL Technology Transfer Office to identify U.S. industry partners to rapidly commercialize NREL improved solar selective coating

Receiver Research: Deposition Facilities



Sputtering Chamber

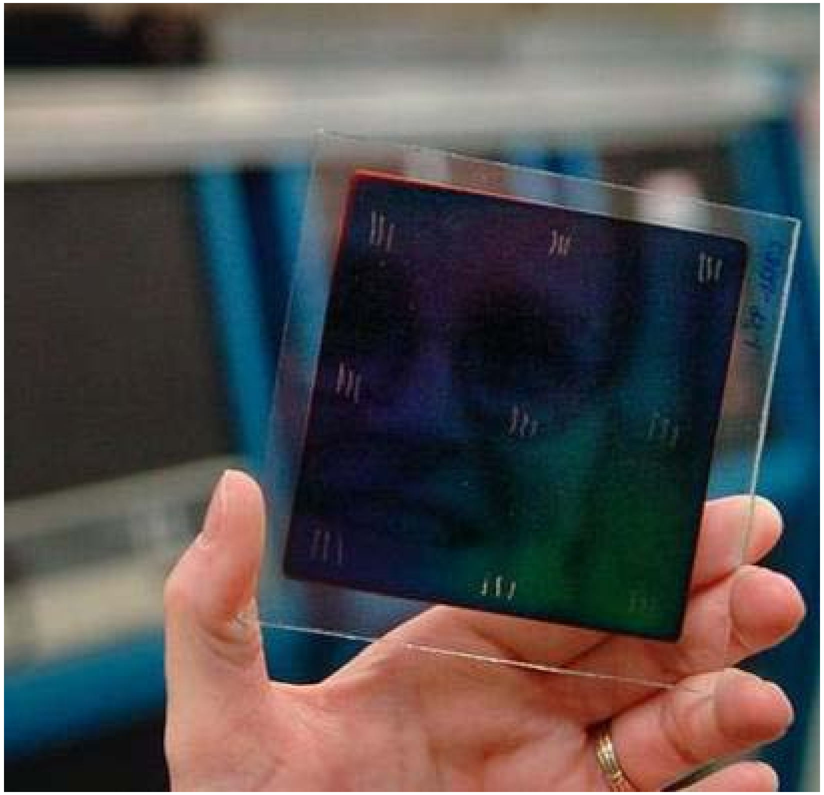


E-Beam Chamber

- 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
  - 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
      - OES
      - IRESS
      - Pressure/Gas
      - DAQ
      - Computer

β-version Prototype Absorber Development

- Codeposited individual layers and modeled coating
  - Proof-of-concept development used E-beam/IBAD chamber because of cost and flexibility
  - Deposited α–version prototype by e-beam from compounds sequentially (because of cost)
  - Deposited β-version prototype by elemental e-beam codepostion
    - Upgraded e-beam system to codeposition
    - Deposited individual layers
    - Deposited modeled structure
    - Characterized properties
  - Optical performance lower than modeled but extremely encouraging despite known errors in:
    - Thickness
    - Composition
    - Measurement



Rapid Commercialization Receiver CRADA Support

- Major FY 2008 Accomplishments:
  - –Deposited β-version of modeled solar selective coating with $\varepsilon > 0.07$, $\alpha > 95\%$, $T_{stable} > 500^{o}C$
  - –Filed for patent (11/07)
  - –Competitive bid for partner (1/08) to rapidly commercialize NREL coating
  - –Selected partner (5/08)
  - –Negotiating CRADA and negotiating license agreement (started 6/08)
  - –Specified & ordered equipment for upgrade of cosputtering and process & control

- Issues:
  - –CRADA signing waiting for CRADA partner and DOE to finalize negotiation of one term of CRADA document
  - –Equipment delivery delays

Future Work: Receiver CRADA Support

- Support CRADA to rapidly commercialize NREL advanced coating
  - Optimize sputtering parameters on stainless steel coupons at NREL (FY 2009)
    - Upgrade sputter chamber on NREL deposition system
      - Dual cathode pulsed DC reactive cosputtering
      - Automate process & control
    - Optimize coating by reactive cosputtering
      - Iteratively deposit optimized coating by sputtering
      - Iteratively characterize and evaluate optical, thermal, and material properties
        - Optimize phase formation from Pretorius effective heat of formation model using differential scanning calorimetry (DSC)/thermogravimetric analysis (TGA) data
    - Evaluate deposited coating vs. modeled and perform economic analysis
  - Scale-up to pilot production run (FY 2009 - 1st Qtr FY 2010)
    - Optimize sputtering parameters on full-size stainless steel tubes on commercial production equipment (single tube at a time)
      - Iteratively deposit coating with optimized sputtering conditions
      - Iteratively characterize & evaluate optical, thermal, material properties of tubes
    - Construct receiver tube with evacuated AR glass
      - Iteratively evaluate receiver tubes
    - Evaluate deposited coating vs. modeled and perform economic analysis
  - Limited quantity series run – exact manufacturing specifications (2nd Qtr FY10)
    - at least 100 tubes (quantity TBD depends on field test site - possibly 1 loop)
  - Field testing (FY2010 – FY2011)

Future Work: Advanced Solar Selective Coatings

- Convert multilayer structure to cermet and deposit resulting cermet architecture
- Examine improved solar selective coatings:
  - Explore potential higher-temperature thin-film material systems
    - Ashby-type diagrams of potential higher temperature material systems
  - Explore feasibility of candidate improved materials:
    - Hydrogen barrier coatings
    - Higher-temperature stainless steel substrates compatible with storage
    - AR layers for glass envelope
    - Getters
  - Explore lower-cost deposition methods that still provide high optical and thermal stability properties
  - Tune coatings for power towers and CLFR applications

- Issues:
  - Some work only partially funded while on continuing resolution
  - Need to hire additional staff