Progress toward Developing a Durable High-Temperature Solar Selective Coating

2007 Parabolic Trough Technology Workshop
March 8-9, 2007, Golden, Colorado
NREL/PO-550-41427 March 2007

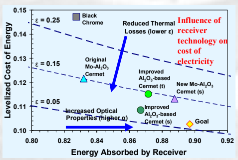
Cheryl Kennedy and Hank Price

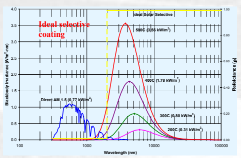
National Renewable Energy Laboratory
Golden, CO 80401

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

1. Abstract

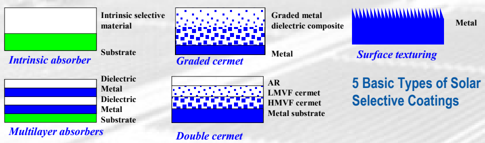
Increasing the operating temperature of parabolic trough solar fields from 400ºC to >450ºC will increase their efficiency and reduce the cost of electricity. Current coatings do not have the stability and performance necessary to move to higher operating temperatures. The objective is to develop new, more-efficient selective coatings with both high solar absorptance ($\alpha > 0.96$) and low thermal emittance ($\varepsilon < 0.07$) that are thermally stable above 450ºC, ideally in air, with improved durability and manufacturability, and reduced cost.





2. Technical Approach

- Review literature to determine potential high-temperature oxidation-resistant solar selective coatings
- Use modeling software to optically model solar-selective designs or refine existing ones and extract optical constants used in the design.
- Develop modeled high-temperature solar-selective coatings using physical vapor deposition (PVD).
- Characterize material and optical properties, perform high-temperature optical characterization and durability testing to verify functionality.



5 Basic Types of Solar Selective Coatings

3. Literature Review

Candidate High-temperature >400ºC Solar Selective Coatings

- 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
- $Ti_{1-X}AlXN$
- Quasicrystals multilayers & cermets
- Surface Texturing

4. Oxidation Resistant Properties

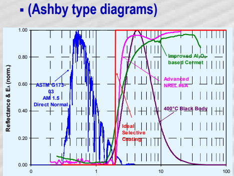
Desirable Properties for stable coating in air > 400ºC

- 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

5. Optical Modeling

- 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.
- Plan to model:
  - Error analysis
  - Measured properties
  - Cermet
  - Material selection properties
    - (Ashby type diagrams)

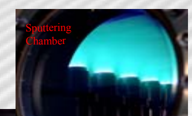
	Original Mo-Al_2O_3 Cermet	Improved Al_2O_3-based Cermet	NREL 6A
Solar α	0.938	0.954	0.959
Thermal ε @			
25°C	0.061	0.052	0.027
100°C	0.077	0.067	0.033
200°C	0.095	0.085	0.040
300°C	0.118	0.107	0.048
400°C	**0.146**	**0.134**	**0.061**
450°C	0.162	0.149	0.070
500°C	0.179	0.165	0.082

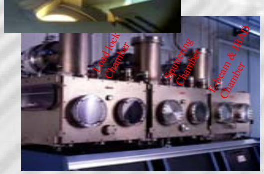


Ideal, commercial, and modeled selective coating

6. Deposition Capabilities

- Pernicka Three-Chamber Deposition System
  - Load-Lock Chamber
  - Pulsed DC Sputtering Chamber
    - 2- 3"x12" Linear Magnetron Cathode (or)
    - 3- Linear arrays of 5- 1.5" Mini-Mak Guns
    - Pulsed DC Power Supply
  - Electron-Beam Chamber
    - Multi-Pocket (6) E-Beam Source (or)
    - Codeposition plate w/ 2 single e-beam sources
    - IBAD w/ 12" Linear Ion Gun
  - System
    - Turbo molecular drag pumps
      - $2x10^{-8}$ torr
    - 12" x 12" ambient or heated substrate
    - Codeposition
  - Monitoring
    - Residual gas analysis (RGA)
    - Quartz Crystal Monitor
    - Pressure/Gas
      - 4 Reactive Gases
    - Computer





7. Prototype Development

Key issue then becomes trying to make the coating – prototype development underway

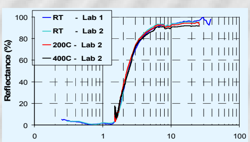
- Initial prototype by compound evaporation
  - Individual layers and characterization completed
  - Preliminary runs of compound multi-layer deposited & optical properties characterized
  - XPS showed compound evaporation produced layered stoichiometry
- Despite depositing layers with over- and under-thickness 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
  - Upgrade Gas control system
  - Plus upgrade of associated air, water, electrical, & control systems
  - Installed e-beam base plate lift (safety concerns)
- Compounds with various compositions codeposited by manually varying the power and deposition rate of the materials and/or increasing the amounts of the reactive gas.
  - Individual layers of codeposition coating deposited and characterized
  - Preliminary runs of codeposited modeled multi-layer solar selective coating deposited & optical properties characterized
- Optical properties of codeposited modeled solar selective coating lower than modeled.
  - From error analysis, errors in layer thickness lead to errors in absorption, but errors in stoichiometry lead to errors in both absorption and emittance.
    - Layer thicknesses for the codeposited solar-selective coating were badly overshot by 21.2% ±31.5% on average.
    - Reflectance of the reflective layer compound varied significantly depending on ratio of constituent materials.
    - XPS showed reflective layer not correct stoichiometry
  - Next steps:
    - Perform rigorous analysis to determine optimum composition that gives the highest reflectivity
    - Predict thin-film phase-formation sequence using the effective heat of formation model
    - Finish automation of deposition process for finer control of layer thickness & deposition properties and to eliminate thickness errors.

8. Selective Coating Performance

- 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 & 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 & hydrolysis)
    - Atmospheric corrosion (pollution)
  - Diffusion processes (inter-layer substitution)
    - Chemical reactions
    - Poor interlayer adhesion
- Therefore it is important that ρ is measured accurately & to measure ε of the selective coating at operating temperatures & conditions before using calculated ε ⇒Round robin test

9. Round Robin Testing

- 4 Commercial Coatings
  - Black Ni, Mo-cermet, UVAC A & B
- 3 Laboratories
  - 2 commercial
  - NREL
- Preliminary Results
  - Room Temperature (RT) measurements within error of 400°C measurements
  - 2 Commercial laboratories give comparable RT results
  - NREL near-IR more noisy



Comparison of UVAC reflectance measurements made at two laboratories and at low- and high-temperature.

⇒ Purchased IR spectrophotometer & NIST traceable standards

10. 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 (600ºC) Inert Gas Oven

11. Accomplishments

- Using computer-aided optical design software, a solar selective coating exceeding the goals has been modeled. A solar selective coating with α = 0.959 and ε = 0.061 at 400°C composed of materials with high-temperature stability has been modeled. This exceeds the goal specification by about 1% overall, because 1% in emittance equates to about 1.2% in absorptance.
- Initial prototype deposited by compound e-beam evaporation & characterized showed need to codeposit modeled structure.
- System upgraded significantly to perform codeposition.
- Codeposition of prototype showed stoichiometry of reflective layer important. Working to determine correct stoichiometry of reflective layer and to deposit coating without thickness errors.
- Round robin test performed, preliminary data analysis completed. Data analysis and report needs to be completed
- Upgraded testing and durability capabilities with purchase of IR spectrophotometer & standards, and high-temperature inert gas oven.
- Patent being pursued.