High-Temperature Solar Selective Coating Development for Power Tower Receivers

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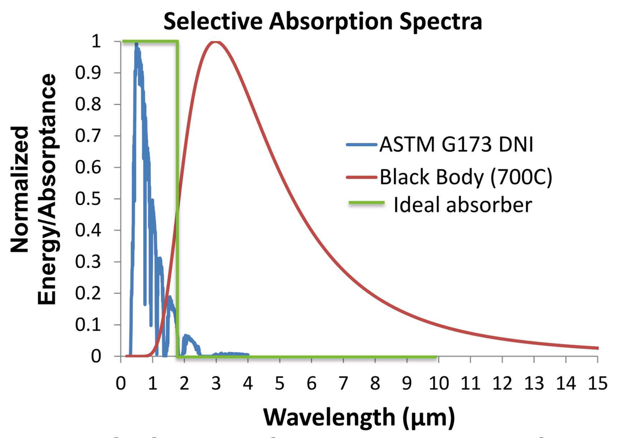
CSP SunShot SUMMIT 2016: RECEIVERS

PROBLEM STATEMENT

To meet the SunShot goal of Levelized cost of energy (LCOE) ≤ 6¢/kW$_h$ by 2020, next generation power towers will operate at temperatures > 600 °C in order to take advantage of increased efficiencies of high-temperature operation. Current receiver coatings such as Pyromark 2500, while highly absorptant, suffer from high emittance and have been reported to degrade during operation at T > 600 °C. Advanced solar selective absorber (SSA) coatings are required *that have a solar efficiency, η, surpassing that of Pyromark® 2500, are stable at ≥ 600 ºC in air, have high thermal conductivity, and are nonvolatile.*



VALUE PROPOSITION

Formulations of mixed-metal oxides, such as spinels (AB_2O_4) and perovskites (ABO_3), are promising candidates for next-gen receiver coatings. They are stable at high-temperatures, oxidation resistant, can be easily deposited via techniques such as thermal spray, and are amenable to cation doping and substitution to chemically tailor their properties. Refractory metal silicides are another class of materials that display inherently high absorptance and low emittance in multilayer SSA coatings. Both families are reported herein.

An increase in the thermal efficiency of SSA coatings by 4% at 650 ℃, and 7% at 800 ℃, can potentially reduce the LCOE by an estimated 0.25 ¢/kWh.

OBJECTIVES

Optimize, evaluate, and characterize coatings → **Initial on-sun and durability testing** → **Refine coatings and final on-sun testing**

- Optimize spinel and thermal spray formulations
- Evaluate refractory metal compounds
- Develop surface modification techniques to enhance solar selectivity
- Incorporate cost and durability into LCOE-like metric that can compare coatings across-the-board

- Performance optimization of coatings supported by isothermal testing at temperature
- Perform tests of candidate selective absorbers applied to tubes and/or plates on sun (furnace and/or tower)
- Evaluate durability of candidates as a function of temperature and heating cycles

- Refine coatings based on optical performance and durability
- Final on-sun tests of most promising selective coatings

TEAM

SNL				
Clifford Ho	Lam Banh	Marlene Knight	Paul Ndione	Brian Gorman
Aaron Hall	James Pacheco	Bonnie McKenzie	Cheryl Kennedy	Michele Olsen
Timothy Lambert	Cheryl Ghanbari	Landon Davis	Kaan Korkmaz	Marlene Bencomo
Antoine Boubault	David Adams	Pylin Sarobol	Ross Larsen	Judy Netter
John Lewis	David Saiz	NREL	Vincent Wheeler	Greg Glatzmaier
	Danae Davis	Robert Tirawat	Tim Wendelin	Brian Li
	Andrew Hunt		Katelyn Kessinger	

DOE Funding: $2,517,000/ 3 years (ending Dec. 2015)

RESULTS

Levelized Cost of Coating (LCOC)

Solar Selectivity, η_{sel}

$$\eta_{sel} = \frac{\alpha_s Q - \varepsilon \sigma T^4}{Q}$$

α_s = solar absorptance
Q = irradiance on the receiver
ε = thermal emittance
σ = Stefan-Boltzmann constant
T = surface temperature (K)

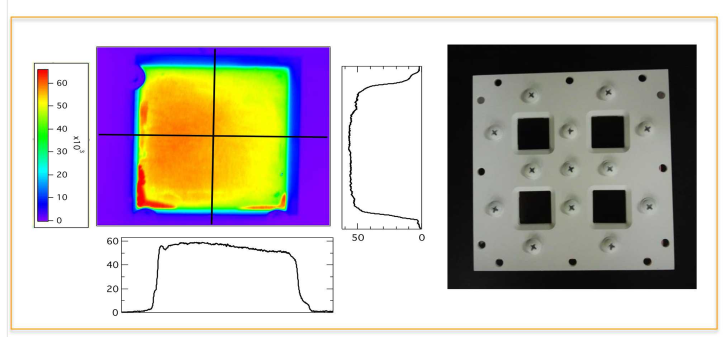
LCOC = $C_{annual}/E_{thermal}$

C_{annual} = Total annualized coating costs
= Initial coating cost/life of plant + Recoating costs/ recoating interval + Cost of additional (or fewer) heliostats to yield baseline power

$E_{thermal}$ = Annual thermal energy absorbed (new) – Lost energy absorbed due to degradation – Lost energy absorbed due to recoating down time (annualized)

Solar selectivity, η_{sel}, evaluates the optical properties of a material, which impacts the thermal energy absorbed. LCOC also incorporates degradation rate, material costs, and reapplication costs resulting in a more comprehensive cost estimate.

Solar Testing Facilities



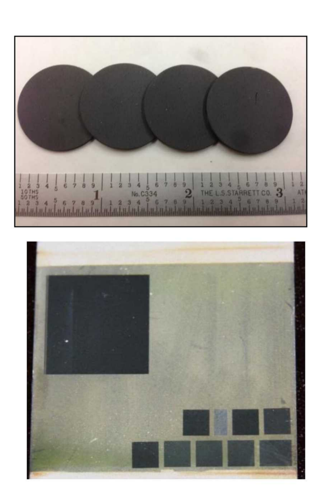
NREL: Solar furnace test stand
- Simultaneous measurement of multiple samples (direct comparison)
- Uniform illumination of samples
- Minimal "cross-talk" between samples
- T ~700 ºC at 500 kW/m²
- Delivers 650 kW/m² over 4"x4" area

SNL: Solar furnace test stand
- Spot size: 6 inches
- Peak irradiance: 6 MW m^{-2}
- Average irradiance: 5 MW m^{-2}
- Operational hours/day: 6
- Power consumption: < 1 kW
- Air cooled

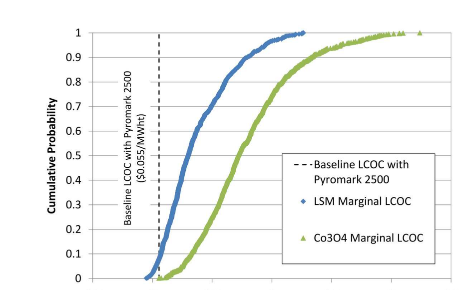
SNL: Solar simulator
- Spot size: 1 inch
- Peak Irradiance:1.3 MW/m²
- Average Irradiance: 0.9 MW/m²
- Operational: 24/7
- Power consumption: < 1 kW
- Automatic, robotic sample holder for multiple sample testing

Thermal Spray LSM (SNL)

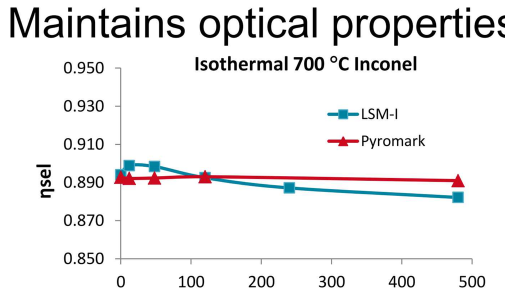
- High-surface area coating technique
- Ability to coat in the field
- *Novel laser treatment of surface improves optical properties without changing composition or phase of coating (Patent pending)*
- α and η competitive with Pyromark, but ε is still high (> 0.85)
- Crystallographic phase and microstructure remain stable after isothermal aging 240 h at 800 °C in air
- Maintains optical properties after 150 cycles on-sun

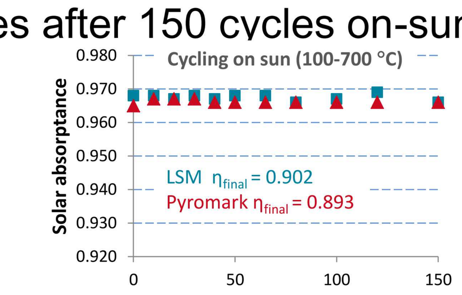


(Top) Thermal sprayed LSM coupons (Bottom) Cr_2O_3 sample after laser-treatment (top left and bottom right corners)

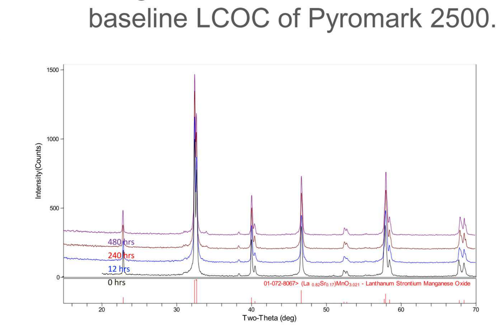


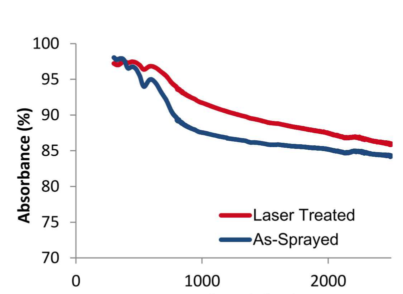
With the current cost assumptions and performance data, there is a ~10% chance that LSM will yield a marginal LCOC less than the baseline LCOC of Pyromark 2500.



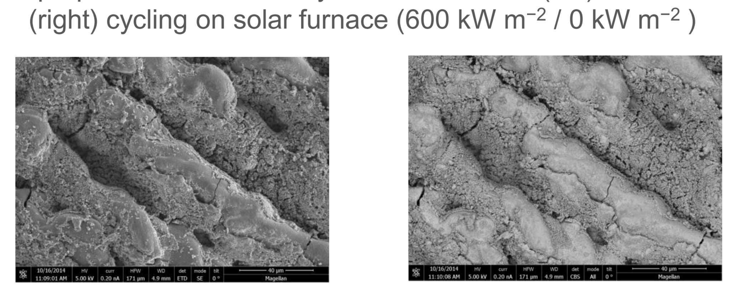


Optical properties of LSM vs. Pyromark at 700 °C (left) isothermal and (right) cycling on solar furnace (600 kW m^{-2} / 0 kW m^{-2})

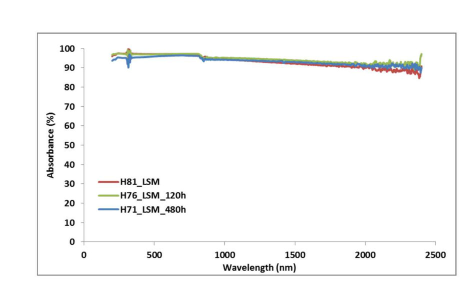




Diffuse reflectance of TS coating before and after laser treatment



SEM of surface-modified LSM before (top) and after (bottom) isothermal aging, 700 °C/ 480 h



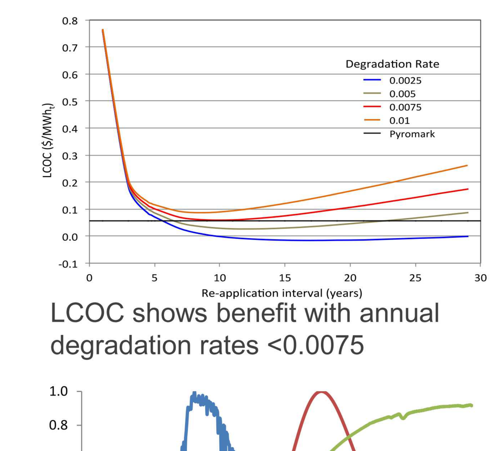
Little change in XRD (top) or diffuse reflectance (bottom) upon aging (700 °C)

Physical Vapor Deposition (NREL)

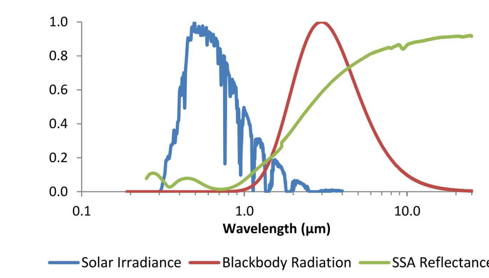
- $TaSi_2$-based multilayer stack shows promise as SSA coating
- Stack efficiency as designed exceeds that of Pyromark
- Stack Design is air stable at T<500 °C
- 1 μm Al_2O_3 barrier mitigates substrate interference of $TaSi_2$ crystallization
- Parameterized stack design components and characterized contribution to final efficiency

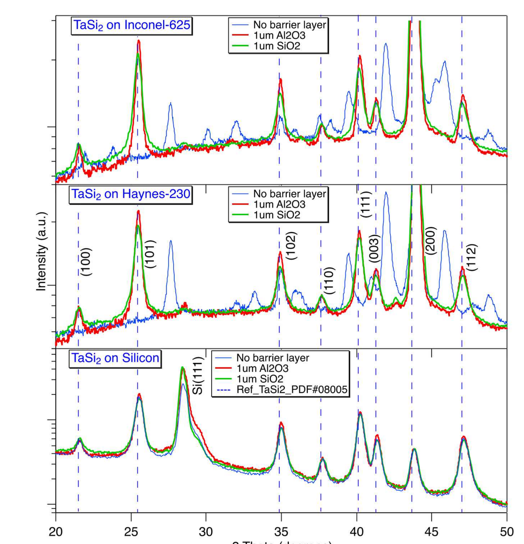
Design/Material	"9"	Pyromark
Solar Absorptance (%)	0.945	0.962
ε_{700}	0.373	0.847
Irradiance (W/cm²)	η_{abs} (700 °C)	
10	0.755	0.532
20	0.850	0.747
30	0.882	0.819
40	0.897	0.854
50	0.907	0.876
60	0.913	0.890
70	0.918	0.901
80	0.921	0.908
90	0.924	0.914
100	0.926	0.919

New $TaSi_2$ design showed better performance than Pyromark across full irradiance spectrum at 700 ºC (above and right)



LCOC shows benefit with annual degradation rates <0.0075

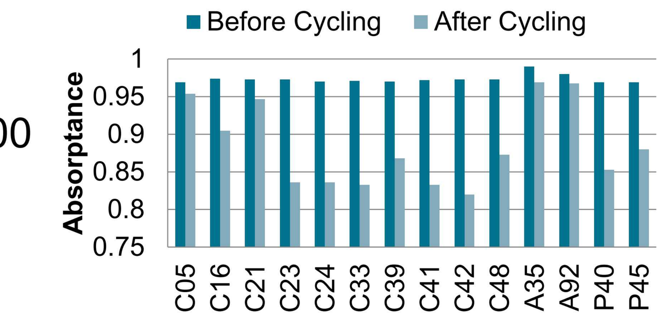




Cation diffusion between Ni-alloy substrate and coating requires deposition of a barrier layer.

Pyromark

- Deposition parameters of Pyromark 2500 were investigated in order to identify factors that contribute most to coating performance
- Design of Experiment executed; many of the coatings delaminated during curing (top right)
- Coatings that survive the curing process generally survive isothermal aging at 700 °C / 96 h with no change in optical properties
- Analyses point toward the following optimized deposition parameters to maximize likelihood of intact coatings with most favorable η:
  - Grit blasted (rough) substrate surface
  - Small paint thickness (25 – 30 μm)
  - Slow curing rate (5 °C/min)
  - Curing temperature near 650 °C
- However, when exposed to rapid cycling at 600 kW/m² / 700 °C on solar simulator, coating properties degrade quickly; results are preliminary and the mechanism of degradation has not yet been determined (bottom right)



PATH TO MARKET

- File IP to protect our technology and make licensing available to interested industrial partners
  - Aaron C. Hall and David P. Adams, "High Durability Solar Absorptive Coating and Methods for Making Same." Filed 26-Feb-15, Appl. #14/632,838 (SNL)
  - C. E. Kennedy "High Temperature Solar Selective Coatings," Patent # 8893711, Awarded 11/25/2014. (NREL)
- Partner with key players through CRADA and FOAs (e.g. SBV, TCF) to maximize deployment opportunity
- Develop techno-economic analysis to accurately determine the effect of integrating new SSA coatings into a CSP plant
- Encourage stakeholders to utilize LCOC tool to evaluate costs of various SSA coatings throughout industry using a common metric

PUBLICATIONS

Pacheco, J. E. *Final Test and Evaluation Results from the Solar Two Project*; SAND2002-0120, Sandia National Laboratories 2002. § Ho, C.K.; Mahoney, A.R.; Ambrosini, A.: Bencomo, M.; Hall, A.; Lambert, T.N., 2013, "Characterization of Pyromark 2500 Paint for High-Temperature Solar Receivers," **136**(1), pp. 014502-014502. § Ambrosini, A.; Lambert, T. N.; Bencomo, M.; Hall, A.; vanEvery, K.; Siegel, N. P.; Ho, C. "Improved High Temperature Solar Absorbers For Use In Concentrating Solar Power Central Receiver Applications." 5th International Conference on Energy Sustainability, ASME: Washington, DC, 2011. § Hall, A.; Ambrosini, A.; Ho, C., "Solar selective coatings for concentrating solar power central receivers." *Adv. Mater. Process.* **2012,** *170* (1), 28. § Kennedy, C. E.; Price, H. "Progress in development of high-temperature solar-selective coating." International Solar Energy Conference, Orlando, FL , ASME: Orlando, FL, 2005; pp 749. § M.L. Olsen, E.L. Warren, P.F. Ndione, A. Zakutayev, J. Netter, A. Gray, M.H. Gray, R. Tirawat, P.A. Parilla, E.S. Toberer, D. S. Ginley (2016) "A Versatile System for the Study of High-Concentration Solar Thermoelectric Generators," Review of Scientific Instruments (submitted). § A. Boubault, C.K. Ho, A. Hall, T.N. Lambert, A. Ambrosini ,"Levelized cost of energy (LCOE) metric to characterize solar absorber coatings for the CSP industry, "*Renewable Energy,* 85, p472-483, 2015. 10.1016/j.renene.2015.06.059. § Ho, C.K. and J.E. Pacheco, "Levelized Cost of Coating (LCOC) for selective absorber materials", *Solar Energy,* 108, p 315 – 321, 2014. § Ambrosini, A.; Lambert, T. N.; Boubault, A.; Hunt, A.; Davis, D. J.; Adams, D.; Hall, A. C. "Thermal Stability of Oxide-Based Solar Selective Coatings for CSP Central Receivers." ASME 2015 9th International Conference on Energy Sustainability, San Diego, CA, Amer Soc Mechanical Engineers: San Diego, CA, 2015; p V001T05A022.