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High temperature performance of high-efficiency, multi-layer solar selective coatings for tower applications

M. H. Gray[a]*, R. Tirawat[a], K. A. Kessinger[a], P. F. Ndione[a]

[a] *National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO, 80401, USA*

Abstract

The roadmap to next-generation concentrating solar power plants anticipates a progression to central towers with operating temperatures in excess of 650°C. These higher temperatures are required to drive higher power-cycle efficiencies, resulting in lower cost energy. However, these conditions also place a greater burden on the materials making up the receiver. Any novel absorber material developed for next-generation receivers must be stable in air, cost effective, and survive thousands of heating and cooling cycles. The collection efficiency of a power tower plant can be increased if the energy absorbed by the receiver is maximized while the heat loss from the receiver to the environment is minimized. Thermal radiation losses can be significant (>7% annual energy loss) with receivers at temperatures above 650°C. We present progress toward highly efficient and durable solar selective absorbers (SSAs) intended for operating temperatures from 650°C to 1000°C. Selective efficiency (η_{sel}) is defined as the energy retained by the absorber, accounting for both absorptance and emittance, relative to the energy incident on the surface. The low emittance layers of multilayer SSAs are binary compounds of refractory metals whose material properties indicate that coatings formed of these materials should be oxidation resistant in air to 800-1200°C. On this basis, we initially developed a solar selective coating for parabolic troughs. This development has been successfully extended to meet the absorptance and emittance objectives for the more demanding, high temperature regime. We show advancement in coating materials, processing and designs resulting in the initial attainment of target efficiencies $\eta_{sel} > 0.91$ for proposed tower conditions. Additionally, spectral measurements show that these coatings continue to perform at targeted levels after cycling to temperatures of 1000°C in environments of nitrogen and forming gas.

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* Corresponding author. Tel.: +1-303-275-3917; fax: +1-303-384-6103.
E-mail address: matthew.gray@nrel.gov

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1. Introduction

For next-generation power towers to operate at higher efficiency, producing lower-cost energy, they are expected to operate at temperatures exceeding 650°C. [1] The collection efficiency of a power tower plant can be increased if the energy absorbed by the receiver is maximized while the heat loss from the receiver to the environment is minimized. Thermal radiation losses can be significant (>7% annual energy loss) with receivers at temperatures above 650°C. Black paints such as high-temperature Pyromark® 2500 have a very high solar absorptance ($\alpha > 0.95$), but also have high emittance (ε ~0.87) at the temperatures of interest. [2] Selective coatings for receivers can reduce losses and increase overall efficiency by maintaining high absorptance in the solar spectrum but lowering emittance in the infrared spectrum. Such solar selective absorbers (SSAs) have been developed and deployed for more than three decades for lower temperature parabolic trough applications. [3] However, these coatings are not well-suited for power tower applications; they are sensitive to oxidation and they can typically only operate at temperatures up to ~500°C before performance degrades. Any novel selective absorber material developed for next-generation receivers must be stable in air, cost effective, and survive thousands of heating and cooling cycles.

Ongoing efforts at the National Renewable Energy Laboratory (NREL) have sought to address the issue of highly efficient and durable SSAs for operating temperatures from 650°C to 1000°C. [4-6] The low emittance layers of our multilayer coatings are binary compounds of refractory metals whose material properties [7] indicate that coatings formed of these materials should be oxidation resistant in air to 800-1200°C. On this basis, we initially developed a solar selective coating for the tube receivers used in parabolic troughs. [8] In our current work, that initial effort has been successfully extended to meet the absorptance and emittance objectives for the more demanding, higher temperature tower regime. Our development has assumed application on heat transfer fluid tubes for direct incidence tower designs. However, the final air-stable coating would be of use in any application where spectral selectivity provides a significant benefit and adhesion between the coating and the receiver surface can be demonstrated.

Nomenclature

η_{sel}	selective absorber efficiency
α_s	solar weighted absorptance
ε_T	emittance at temperature T
Q	incident solar irradiance
σ	Stefan-Boltzmann constant
T	surface temperature of receiver
SSA	solar selective absorber
LCOE	levelized cost of energy
LCOC	levelized cost of coating

2. Methods

2.1. Sample Production

We focus on the production of high performance SSAs using physical vapor deposition (PVD) methods because PVD allows extremely fine control of the morphology, stoichiometry, and crystal structure, thereby controlling the resulting optical and thermal properties. Deposition cost is considered a second-order selection criterion because lower-cost methods can be developed and utilized after a high-temperature solar selective coating with improved optical properties is developed. In addition, because the receiver surface area for power towers is relatively small, a coating that is more expensive to produce (PVD) may well be worthwhile if its performance improvement is significant and it is durable enough to last years in the field without need for reapplication. Ultimately, assessment of