SAND2012-6147P

High-Temperature Solar Selective Coating Development for Power Tower Receivers

James E. Pacheco, Andrea Ambrosini, Aaron Hall, Timothy N. Lambert, Cliff Ho
Sandia National Laboratories

Cheryl Kennedy, Matthew Gray
National Renewable Energy Laboratory

July 26, 2012

Yearly budget by institution and Project total

Lab	FY13	FY14	FY15	Total
Sandia	$350K	$350K	$250K	$950K
NREL	$568K	$531K	$468K	$1567K
Total	$918K	$881K	$718K	$2517K

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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Project Objectives

- Goal:
  - Deliver a solar-selective coating for next-gen power tower receiver that out-performs current state-of-the-art
  - Improve efficiency of receiver from <88% to 90% or higher and reduce LCOE to reach the SunShot targets (annual average thermal efficiency of 90% and a cost target of $150/kW_t$ or less)
    - High solar-weighted absorptance (α >0.95)
    - Low emittance (ε <0.40)
    - Operate in air at temperatures ≥ 650 °C without degradation for ≥10,000 cycles

- Innovation:
  - We will develop materials that have tailored intrinsic selective properties and customize the surface morphology to enhance absorption to surpass performance of Pyromark

Technical Approach

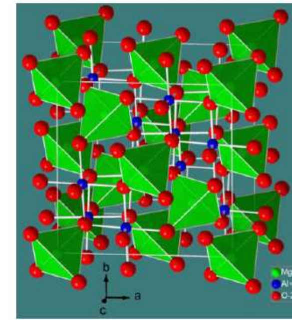
- Three fundamental research approaches are:
  - Development of new materials (e.g., spinel oxides, refractory metals)
  - Innovative application of deposition methods (thermal spray, electrodeposition, PVD)
  - Characterization and comparison to Pyromark 2500 benchmark (optical characterization, cost characterization, durability characterization)
- Conduct durability testing of candidate materials deposited on receiver metal substrates
  - Test in conventional thermal furnaces, solar simulators, and on-sun
  - Understand the degradation mechanisms.
  - Conduct physiochemical characterization of materials post treatment.
  - Improve stability under realistic and simulated environments.
- This work builds on selective coating work currently underway at Sandia and NREL.

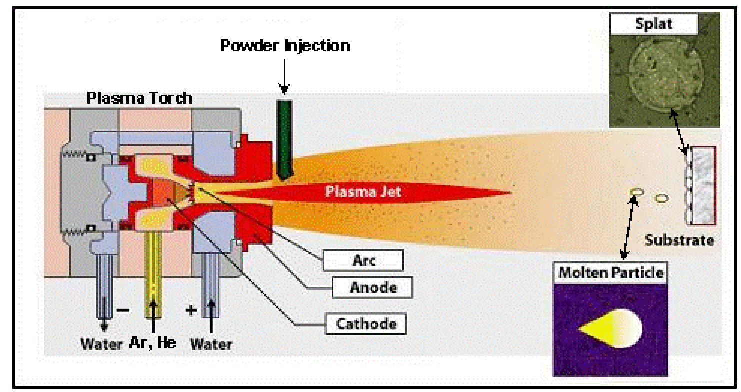
Technical Approach

Materials:

- Metal spinel oxides (AB_2O_4): Inherently stable at high temperature in air, amenable to doping and substitution (e.g. Ni^{2+}, Mn^{2+} and Cu^{2+}), to chemically tailor their properties
- Refractory metal (M) silicides (MSi_2), diborides (MB_2), and their ternary and quaternary compounds: high absorption, low emittance, and high oxidation resistance

Spinel structure

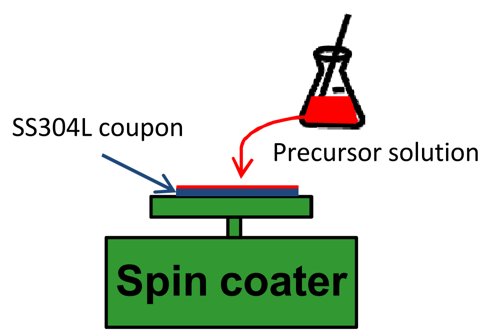


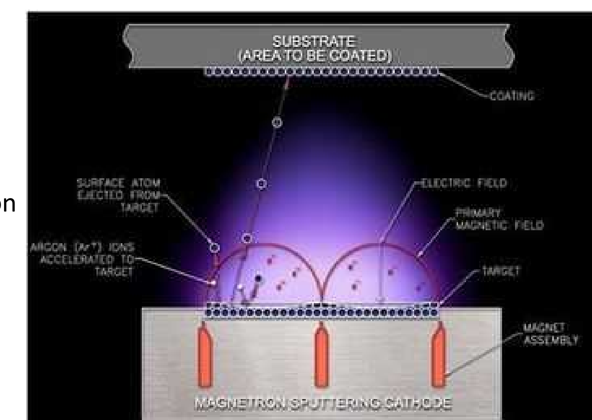


Air-plasma thermal spraying process for absorber coatings

Deposition Methods:

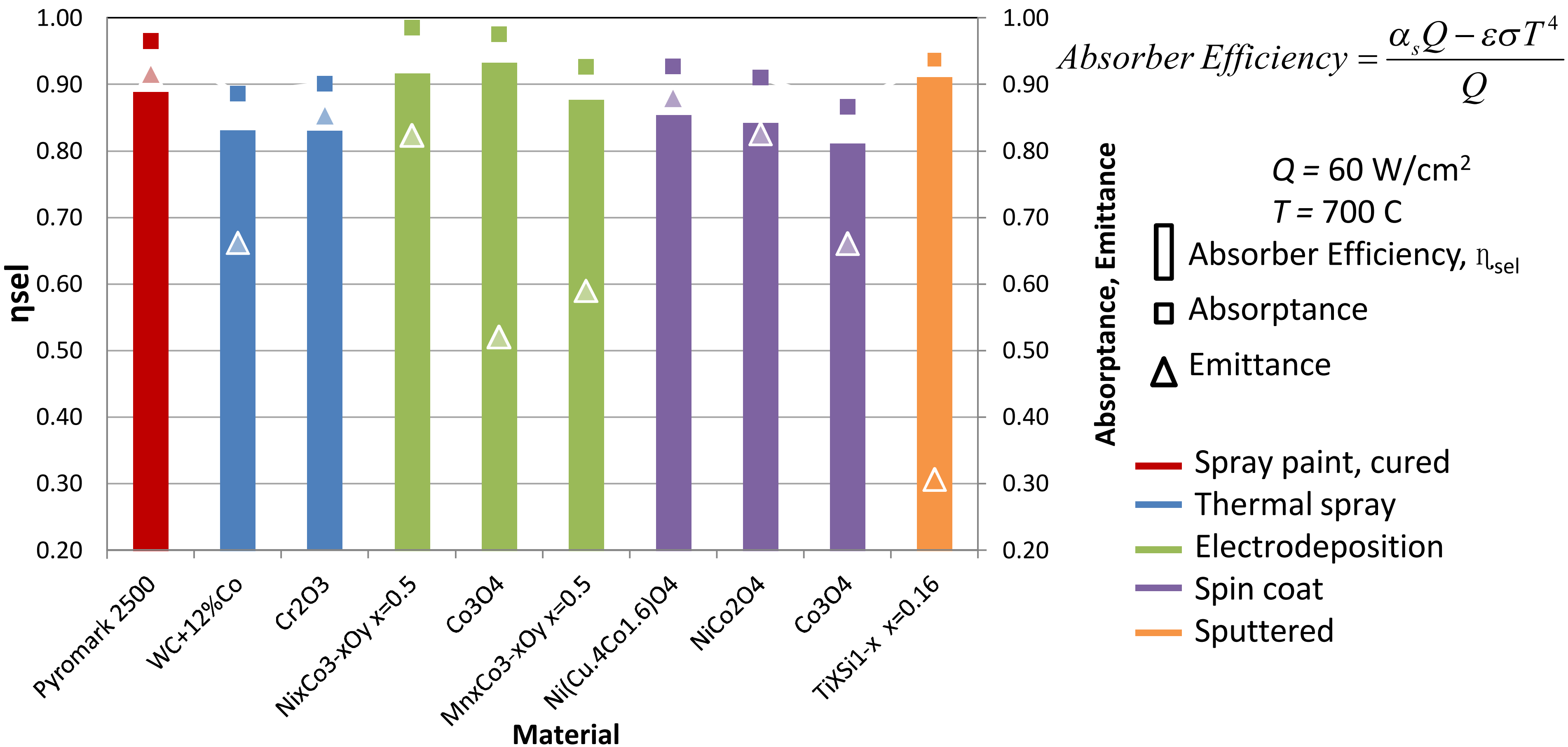
- Spin coating (screening)
- Electrodeposition (screening)
- Thermal Spray (scale-up)
- Physical vapor deposition (scale-up)





Sputtering (PVD) process for absorber coatings

Technical Approach: FY12 Work Results



- Titanium silicides and cobalt oxide-based spinels can have high absorptance, improved emittance, and yield high absorber efficiencies
- Need to improve durability of electrodeposited samples
- Need to assess ability of thermal spray to deposit cobalt-oxide-based spinel

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Intellectual Merit and Impact

- **Scientific advances include:**
  - Novel materials that are intrinsically solar selective: high α, low ε and stable in air and high temperatures for power towers
  - Development of thermal spray techniques to apply pore formers to modify surface morphology in an efficient and cost-effective manner
  - Deposition of the refractory coatings (e.g., silicides, dibromides) by PVD instead of ceramic processes
  - Electrodeposition as a materials development tool is a novel approach to screening solar selective materials
  - Understanding the effect of surface modification on the properties of these new coatings
- **Impact:**
  - At 650 °C, a reduction in the receiver thermal emittance from 0.88 to 0.4 will increase the thermal efficiency by four percentage points
  - At 800 °C, the same reduction in receiver thermal emittance increases the thermal efficiency by seven percentage points
  - Levelized cost of energy (LCOE) estimated to be reduced at least 0.25¢/kWh.
  - Few groups have undertaken such a systematic and materials science-based study of materials coupled with the development of test protocols and real-world cost analysis

Technical Approach

Phase 1: Optimize, evaluate, and characterize coatings

- 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

Phase 2: Initial on-sun and durability testing

- 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

Phase 3: Refine coatings and final on-sun testing

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

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Milestones and Go/No Go Decision Points

Phase 1: Optimize, evaluate, and characterize coatings

M1.1: Quantify parameters which yield optimized solar selective properties or exceed the selective absorber efficiency for Pyromark 2500

M1.2: Enhance the selective surface efficiency of refractory metal compounds

M1.3: Identify microstructure modifications that enhance solar selectivity

M1.4: Document system-level metrics for candidate coatings which incorporates initial and reoccurring costs with performance

Go/No Go Decision Point 1
Develop promising selective surface coating with a selective surface efficiency and LCOE-like metric greater than Pyromark 2500

Phase 2: Initial on-sun and durability testing

M2.1: Quantify degradation rate of candidate samples at elevated temperatures in air and the implications to the selective surface efficiency

M2.2: Quantify performance of candidate coatings. Submit papers to a conference/journal

M3.2: Document results in report

Go/No Go Decision Point 2
Promising selective surface coating has been developed which has been shown to have minimal degradation under high temperature and on-sun conditions

Phase 3: Refine coatings and final on-sun testing

M3.1: Document methods and formulations of coatings that are refined to yield most promising candidates for the on-sun test

M3.2: Complete on-sun testing of most promising coating. Measure performance of selective coating and compare to Pyromark

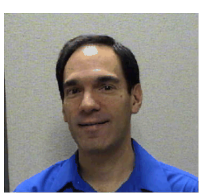
Final Deliverables:

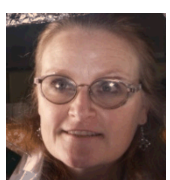
Final Deliverable 1: Samples of most promising selective coatings on receiver substrates (e.g., nickel-based alloys)

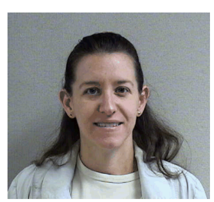
Final Deliverable 2: Journal article and report summarizing formulations, durability, optical performance, and cost results

Proposing Team Qualifications and Roles

Key Research Members	Role	Qualifications
James Pacheco , MS	Principal Investigator, lead systems analysis effort, testing activities. and coordinate project	M.S. Mechanical Engineering, SNL CSP Program Manager, 63 Publications, 1 Patent (4 pending)
Cheryl Kennedy, MS	Lead development and characterization of refractory metal PVD coatings	M.S. Material Science, B.A. Physics, B.S. Chemistry, 3 Patents (1 pending), 78 Publications
Andrea Ambrosini, PhD	Lead development and characterization of metal oxide spinels	Ph.D. Inorganic Chemistry, 30+ Publications, 1 Patent
Aaron Hall, PhD	Lead development of thermal spray coatings	Ph.D. Materials Science and Engineering, 13 Publications
Matthew Gray, PhD	Conduct optical characterization and deposit refractory metal coatings	Ph.D. Physics, 8 Publications
Timothy Lambert, PhD	Lead development of electrodeposition coatings	Ph.D. Chemistry, 30+ Publications, 2 Patents
Clifford K. Ho, PhD	Provide system-level analysis and coordinate on-sun receiver testing	Ph.D. Mechanical Engineering, 140 Publications, 8 Patents


Jim Pacheco


Cheryl Kennedy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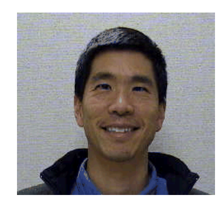

Cliff Ho

Response to Review Panel's Questions/Comments

The proposal lacks a clear description of the scientific advancements that will be made.

- Scientific advances include
  - Novel materials that are intrinsically solar selective: high α, low ε and stable in air and high temperatures for power towers
  - Development of thermal spray techniques to apply pore formers to modify surface morphology in an efficient and cost-effective manner
  - Deposition of the refractory coatings (e.g., silicides, dibromides) by PVD instead of ceramic processes
  - Electrodeposition as a materials development tool is a novel approach to screening solar selective materials
  - Understanding the effect of surface modification on the properties of these new coatings

Response to Review Panel's Questions/Comments

The fundamentals of how the layers of the coating would optimize performance were not discussed in any detail.

- Layering materials will allow light to be trapped due to alternate layers of highly absorptive coatings and lower emittance coatings

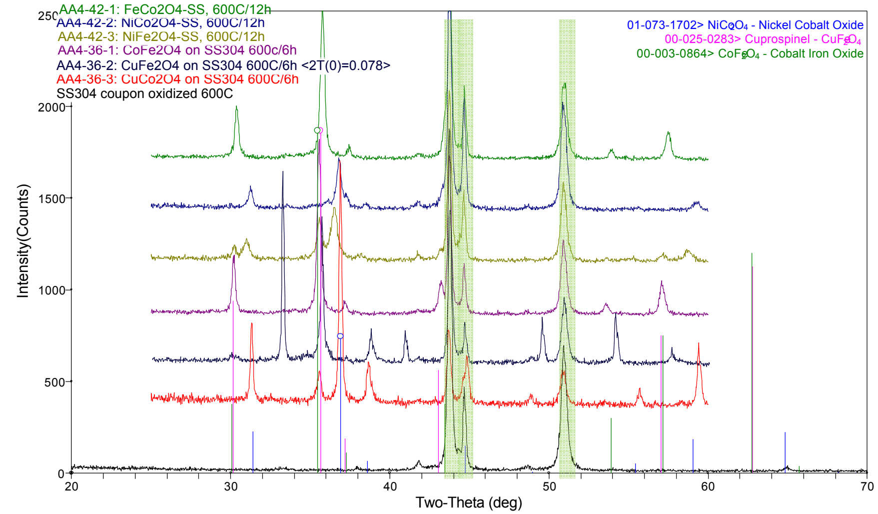
- Layers of coatings enhance solar selectivity by:
  - Increasing absorptivity: Columnar microstructure increases absorptivity by trapping light within the columnar microstructure
  - Surface texturing of a highly stable absorber will improve α (e.g. the superblack idea of porous Si).
  - Additional antireflective layers can increase the α

Multilayer absorbers

Response to Review Panel's Questions/Comments

The proposal does not deal with any mechanical compatibility issues nor has the team indicated that any oxidation analysis will be conducted.

- Mechanical compatibility of the coating with the substrate and coatings is critical. It requires:
  - High thermal and structural stabilities
  - Excellent adhesion
  - Resistance to thermal and mechanical stresses
  - Acceptable thermal conductivities
- Thermal spray coatings are highly stable and have low incidence of spallation and thermal shock issues



- Spinels are already oxidized, therefore air stability is not an issue; the larger concern is compatibility between coating and substrate
- We will conduct thermal stability testing and analyze all deposited coatings before and after testing to determine phase stability and oxide resistance (in the case of silicides and borides) using microscopy, XRD, and TGA

Response to Review Panel's Questions/Comments

The proposal does not blaze new trails but rather offers to apply experience and existing knowledge to higher temperatures.

- Our materials differ substantially from materials developed for lower temperature applications
- Our approach is a systematic development of new materials to fulfill the additional requirements that higher temperature processes demand (e.g. high temperature and oxidization stability, additional thermal stresses, etc…)
- Our approach also includes the modification of known materials (e.g., chromium oxides) from high-temperature protective coatings for gas turbines and hypersonic flight to solar selective coatings
- Leveraging existing knowledge from the field of lower temperatures selective absorber coatings is advantageous to this work. Some of the same fundamental issues exist at high temperatures, such as oxidation resistance, diffusion barriers, adhesion, long-term durability, thermal stability, reliability, manufacturability, and cost.

Response to Review Panel's Questions/Comments

The proposal does not adequately address the issue of adhesion of the coating to different substrate materials in potential receivers.

- Coating adhesion will be measured using ASTM-C633 - the recognized standard for testing coating adhesion strength.
- To control coating adhesion and manage CTE we can investigate:
  - Bond coatings
  - Graded density coatings
- The gas turbine industry has many solutions that can be adapted
  - High-conductivity materials have improved thermal-shock resistance
  - Thermal cycling can result in thermal-stress failures, thus some plasticity and ductility is desired
- Identify effective high temperature coating first, then focus on managing adhesion and CTE as this will be highly dependent upon deposition technique

Response to Review Panel's Questions/Comments

The proposal does not contain a discussion on substrate materials. Additionally, it does not address problems related to compatibility of the coating and substrate as well as cycle induced spallation that results from different thermal expansion or mechanical properties across interfaces.

- We will apply coating to common receiver substrate materials (e.g., Haynes 230, Inconel 625, stainless steel)
- We will test for compatibility and durability at high temperatures during Phase 2 durability tests
- Thermal cycling and spallation is a concern
  - Address with the correct bond coating and graded density coatings.
  - Many solutions from the gas turbine industries
- The right development path is to figure out the absorber first and then deal with the bond coating

Response to Review Panel's Questions/Comments

The team must reproduce results that were achieved at 400-450 degrees at 700 degrees.

- We are not reproducing results achieved at 400 °C, as these are new materials developed specifically for high temperature applications
- Operation at 700 °C introduces additional challenges that are not faced by current coatings
- Emittance requirements do not have to be as low as for parabolic trough; a reduction in emittance from 0.88 to 0.4 results in an increase in receiver efficiency of 4 percentage points
- Long-term durability of the coating will be tested in Phase 2

Response to Review Panel's Questions/Comments

The budget appears to be on the high side.

- Budget reasonable compared to solar selective coating research performed by industry (e.g., BrightSource and Schott)
- Personnel is the major cost in the proposal and the half-time 7-person team is quite modest compared to the 30-person team that developed the PTR-70 receiver coating at Schott
- All deposition equipment is extremely specialized and is expensive to purchase, maintain, and replace consumables
- Additional equipment costs include:
  - Upgrading the Vac-Tec deposition system to Closed Field UnBalanced Magnetron Sputtering (CFUBMS) at NREL. Will enable high density, high adhesion, oxidation resistant coatings with tailored solar selective properties on tubular substrates.
  - Development of On-Sun test fixture and protocols

Summary

The collaborative effort between NREL and SNL produces a multidisciplinary team with complimentary facilities that enable materials research and development, scale-up, real-world testing and demonstration. We will:

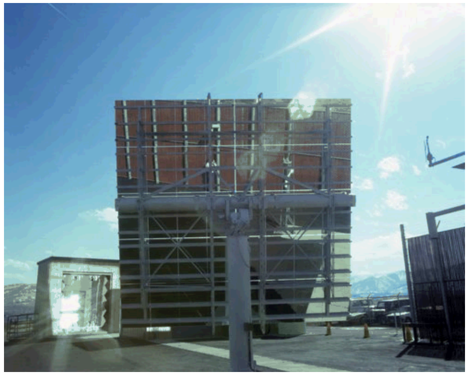
- Develop novel solar selective coatings for next-generation power tower applications that exhibit high absorptance with lower thermal emittance, surpassing the performance of the current benchmark material, Pyromark
  - Materials will be stable in air at high temperature (≥ 700 °C), thermally conductive, and nonvolatile
- Develop deposition methods that can be scaled-up to practical use
- Conduct durability testing of promising materials deposited on receiver metal substrates in conventional thermal furnaces, solar simulators, and on-sun to understand the degradation mechanisms and improve stability under realistic simulated environments

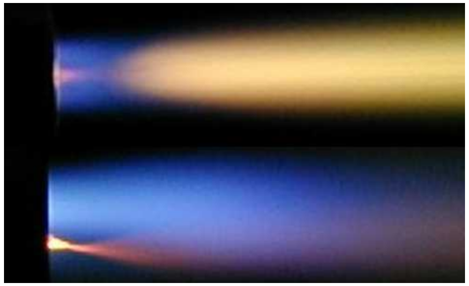
These advances will result will be an improved efficiency of receiver and reduce LCOE to reach the SunShot targets of annual average thermal efficiency of 90% and a cost target of ≤ $150/kW$_t$

BACKUP

Facilities

Facility	Description
Heliostat Field and Solar Tower (SNL)	This facility directly supports the SunShot goals by providing flux levels of greater than 250 W/cm^2 and total power in excess of 6 MWt. The tower is a 61 m high concrete structure with three test locations. The tower can support testing for CSP experiments and large-scale, high-flux materials samples.
High-Flux Solar Furnace (NREL)	The power generated at the 10 kW High-Flux Solar Furnace can be used to expose, test, and evaluate many components—such as receivers, collectors, and reflector materials—used in concentrating solar power systems.
Solar Furnace (SNL)	The peak flux provided is greater than 600 W/cm^2. The furnace is used for selective absorber testing, small-scale receiver testing, and material screening.
Thermal Spray Research Laboratory (SNL)	TSRL is a recognized leader in the development of spray technology and ranks among the best-equipped thermal spray labs in the world. This ~2500 ft^2 facility has four spray stations. In addition, the TSRL maintains a suite of diagnostics equipment on-site for characterizing thermal spray feedstocks, and characterizing coating properties.
Advanced Optical Materials Laboratory (NREL)	AOML has diverse capabilities for the vacuum deposition of thin-film coatings. The system is equipped for reactive co-sputtered physical vapor deposition (PVD) as well as direct and reactive electron beam co-deposition. A five chamber system is currently being retooled and upgraded to include two chambers for plasma enhanced chemical vapor deposition (PECVD) , reactive PVD enhanced with high power pulsed magnetron sputtering (HPPMS), and thermal evaporation.





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Response to Review Panel's Questions/Comments

Criterion:	Strengths
1. Technological and Scientific Merit	•New knowledge of coating processing science and fundamental knowledge of optical properties will be generated. •The proposal indicates considerable heritage research has been done via proof-of-concept work, patent applications, and selective absorber efficiency calculations to establish this path forward. •There is potential for advancing knowledge and understanding of solar selective coatings by considering numerous high temperature and oxidation resistant materials such as refractory metal silicides and diborides and novel microstructures and tailored spinels that may be successful at addressing high temperature and in-air durability needs. •Utilizing a solar selective coating such as the one proposed on receivers may be transformative.
2. Technical Approach	•The fundamental approach and project path have been clearly described. Tasks are well delineated and described. The project milestones are incremental and success-based with suitable go-no go decision points. •The proposers have an understanding of pitfalls in the process and have selected materials systems – including materials that have undergone screening and others that have not yet – and deposition techniques to mitigate high temperature durability issues. •The team has specific goals for absorptivity and emissivity along with temperature limits and cycles.
3. Applicant Qualifications, Prior Accomplishments and Appropriateness of Requested Funds	•The team has extensive experience with solar power systems, coating deposition, and materials characterization. The Sandia group has a strong history of coatings research, some of it for solar energy applications. The group at NREL has developed materials selection criteria to assist in finding suitable candidate materials. •The facilities are world-class and ideal.

Response to Review Panel's Questions/Comments

Criterion 1. Technological and Scientific Merit (Weight: 40%)	
Weakness	Rebuttal
The proposal lacks a clear description of the scientific advancements that will be made.	Scientific advances include new formulations for solar coatings that are intrinsically high α, low ε and stable in air and high temperatures for power towers: the development of thermal spray techniques to apply these coatings in an efficient and cost-effective manner; electrodeposition of these types of coatings is also a new area of research; deposition of the refractory coatings by PVD instead of ceramic processes; gaining a fundamental understanding of the composition-property relationship of these new formulations through systematic study; the effect of surface modification on the properties of these new coatings. Few groups have undertaken such a systematic and materials science-based study of materials coupled with the development of test protocols and real-world cost analysis.
The fundamentals of how the layers of the coating would optimize performance were not discussed in any detail.	High α is dependent on low reflectance (ρ) in the UV-Vis-NIR and low ε is dependent on high ρ in the IR. Modifying deposition conditions to give columnar microstructure increases α because more light is trapped within columnar space. Sputtering is line-of-sight PVD process allowing very complex microstructures to be deposited by changing the deposition parameters (e.g., cathode or substrate incidence angle, reactive gas mixture, argon pressure, and substrate temperature). Surface texturing of a highly stable absorber (Cr_2O_3, refractor metal compound, or some other dark oxide) will improve α (e.g. the superblack idea of porous Si). Additional antireflective layers can increase the α. Emittance is a surface property that can change with surface roughness, substrate smoothness, surface films and oxide layers, thermal load (oxidation), high humidity or water condensation on the solar selective surface (hydratization and hydrolysis), atmospheric corrosion (pollution), diffusion processes (interlayer substitution), chemical reactions, and poor interlayer adhesion. Stable nanocrystalline or amorphous materials are the most desirable (and practical) for diffusion-barrier (oxidation resistant) applications. However, there will be a trade-off in the microstructure between a highly oxidation-resistant coating (i.e., amorphous or nanocrystalline) and a solar-selective coating with both high absorption (i.e., columnar or porous microstructure) and low emittance (i.e., smooth or highly dense).

Response to Review Panel's Questions/Comments

Criterion 1. Technological and Scientific Merit	
The proposal does not deal with any mechanical compatibility issues nor has the team indicated that any oxidation analysis will be conducted.	Achieving a solar-selective coating that is stable in air at high temperatures requires high thermal and structural stabilities for both the combined and individual layers, excellent adhesion between substrate and adjacent layers, suitable texture to drive nucleation and subsequent growth of layers with desired morphology, enhanced resistance to thermal and mechanical stresses, and acceptable thermal and electrical conductivities. Important coating considerations are long-term durability, thermal stability, reliability, manufacturability, and cost. Other desirable properties are good continuity and conformability over the tube, as well as compatibility with fabrication techniques. Mechanical issues are dependent on deposition methods. For Sandia coatings, the ED coatings are still relatively fragile, the TS samples are quite durable and the SC films are in-between. This is something we are keeping in mind and working towards (1) making coatings that are stable and (2) testing the durability of such coatings. Thickness is less of an issue than adhesion. The TS process creates highly bonded coatings. The NREL PVD sputtered coatings are quite durable and adherent. The need for high-temperature materials for gas turbines and hypersonic flight has motivated significant research into very low oxidation rate materials. One way to anticipate corrosion reactions and to select oxidation resistant materials is to employ established chemical thermodynamics and the kinetic properties of their compounds. For oxidation resistance the melting point temperature, Gibbs free energy, resistivity, diffusion, and several other properties are considered. Materials that form multicomponent oxide scale with a low vapor pressure composed of a refractory oxide skeleton and an amorphous (glass) oxide component provide good oxidation performance. One of the reasons we are looking at oxides and oxide spinels is that they are already fully oxidized and temperature-stable. We will conduct TGA-DSC and XRD of Co_3O_4 and refractory metal samples. We will analyze the deposited coatings before and after thermal testing to determine phase stability.

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Response to Review Panel's Questions/Comments

Criterion 1. Technological and Scientific Merit	
The proposal does not blaze new trails but rather offers to apply experience and existing knowledge to higher temperatures.	Some of our materials may have been suggested but never applied to lower temperature applications. Many other materials are being modified from high-temperature protective coatings for gas turbines and hypersonic flight to solar selective coatings. Applying lessons learned from lower temperatures selective absorber coatings is advantageous to this work. Some of the same fundamental issues exist at high temperatures, such as oxidation resistance, diffusion barriers, adhesion, long-term durability, thermal stability, reliability, manufacturability, and cost. At higher temperatures high absorption is favored more than low emittance .
The proposal does not adequately address the issue of adhesion of the coating to different substrate materials in potential receivers.	Oxide materials are intrinsically resistant to oxidation but generally have low thermal-shock resistance and adhesion. High-conductivity materials have improved thermal-shock resistance. Higher conductivity allows more energy to be conducted away from the stagnation point where the concentrated solar energy is incident on the receiver tube and allows the energy to be radiated into the lower-temperature regions of the tube. Thermal cycling can result in thermal-stress failures, thus some plasticity is desired and materials that possess ductility at room temperature may be valuable. The coating adhesion will be measure using ASTM-C633; the recognized standard for testing coating adhesion strength. As for controlling coating adhesion and managing coefficient of thermal expansion issues, many techniques exist including bond coatings and graded density coatings. The gas turbine industry provides many solutions that can be adapted for our needs. The task of managing adhesion and CTE is something that should only be undertaken after an effective high temperature stable absorber coating is demonstrated because it is critical to know what the final top coat is before designing the bond coats and CTE management coatings.

Response to Review Panel's Questions/Comments

Criterion 2. Technical Approach	
The proposal does not contain a discussion on substrate materials. Additionally, it does not address problems related to compatibility of the coating and substrate as well as cycle induced spallation that results from different thermal expansion or mechanical properties across interfaces.	We are applying coating to common receiver substrate materials (e.g., Haynes 230, Inconel 625, stainless steel). We will test for compatibility and durability at high temperatures. Diffusion of cations between the substrate and coating is a concern; we will determine if and at what temperatures this occurs and address it if necessary. Thermally cyclic inducted stresses become an issue on thick coatings when the CTE of the coating is significantly different than the substrate. Thinner coatings will help with CTE, but there are other ways to deal with CTE (e.g. bond coats, and graded density coatings). The right development path is to figure out the absorber first and then deal with the bond coating.
The team must reproduce results that were achieved at 400-450 degrees at 700 degrees.	This is challenging, we acknowledge. But the emittance requirements do not have to be as low as for parabolic trough applications because the concentration ratio in a power tower is much higher. Even a reduction in emittance from 0.88 to 0.4 results in an increase in receiver efficiency of 4 percentage points. An important attribute is long-term durability of the coating. We are currently working with a thermal spray coating material (Cr_2O_3) and the refractory compounds that are routinely used in gas turbine engines at temperatures above 700^{o}C. If it can be modified to be an effective absorber we are confident that it will survive at 700^{o}C and that it can be adhered to the receiver tubes. We will test the coatings at temperature in Phase 2.

Response to Review Panel's Questions/Comments

Criterion 3. Applicant Qualifications, Prior Accomplishments and Appropriateness of Requested Funds	
The budget appears to be on the high side.	In comparison to solar selective coating research performed by industry (e.g., BrightSource and Schott), this budget is very to moderately low when compared to. Personnel is the major cost in the proposal and the half-time 7-person team is quite modest compared to the 30-person team that developed the PTR-70 receiver coating at Schott. Aside from personnel, a major cost is upgrading the Vac-Tec deposition system to Closed Field UnBalanced Magnetron Sputtering (CFUBMS) at NREL which will enable high density, high adhesion, oxidation resistant coatings with tailorable solar selective properties on tubular substrates. The use of the Closed Field and unbalanced magnetrons creates a magnetic confinement that extends the electron mean free path leading to high ion current densities. The combination of high current densities with ion energies in the range ~30 eV creates optimum thin film growth conditions. CFUBMS is perfectly situated to deposit the solar selective coatings on short prototype receiver tubes. Also in general, deposition equipment is extremely specialized and fairly expensive to purchase maintain.

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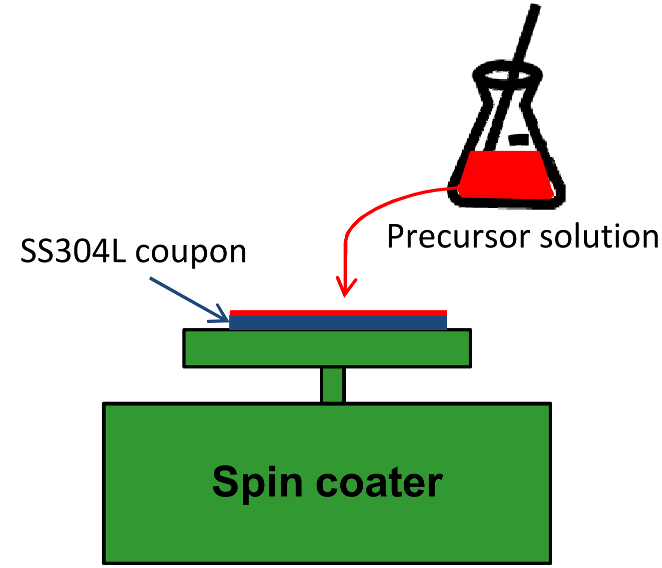
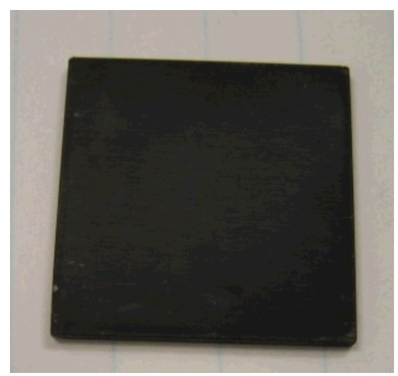
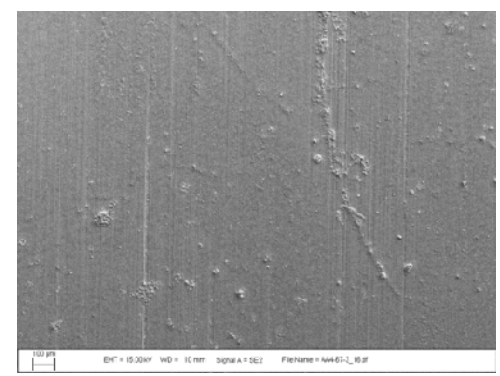
Spin Coating

- Provides a facile and inexpensive method of coating metal coupons
- Easily screened for stability and optical properties
- Solutions are deposited onto cleaned, but untreated coupons (e.g., stainless steel (304L) or nickel alloys)
- Precursor solutions of a 1M aqueous solution of metal nitrates, Triton X (wetting agent) and citric acid (complexing agent) applied
- Solution deposited onto a coupon, spun at 2000 rpm for 30 seconds, and dried on a hot plate
    - After 10 layers, coupon was sintered in a box furnace at 600 °C
    - Process repeated to form coatings of 40-50 total layers







$FeCo_2O_4$ coating (left) and SEM of $FeCo_2O_4$ surface (right). Scale bar = 100 µm.

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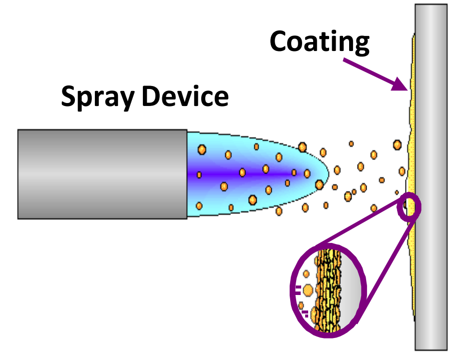
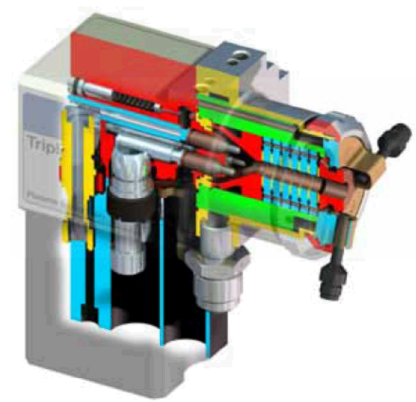
Cr_2O_3 Air Plasma Sprayed Coatings

Chrome Oxide (Cr_2O_3)

- Melts at 2435°C (4415°F)
- Boils at 4000°C (7232°F)
- Extreme
  - thermal stability
  - chemical stability
  - hardness
  - wear resistance
- Insoluble in water, acids, alkalis, and alcohol
- Commonly plasma sprayed
  - Pump seals
  - Textile manufacturing components
  - Printing rolls
  - Wear surfaces
- Can be alloyed with SiO_2 & TiO_2
  - increased toughness
  - Increased mechanical shock resistance

- Initial optical measurements on air plasma sprayed Cr_2O_3 coatings show 0.80-0.83 solar efficiency
- 600°C is a low temperature for Cr_2O_3
  - 25% of melting temp
  - Service temperatures of 815°C (1500°F) are normal for Cr_2O_3 coatings
  - *Surface texturing expected to improve solar efficiency*.
  - *No sintering of Cr_2O_3 expected at 700°C*





Triple cathode design

Triplex®Pro-200 Sulzer-Metco Inc.

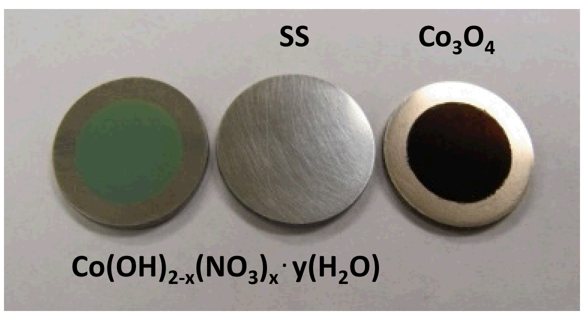
Cr_2O_3 coatings represent a high technical readiness level solution!

Electrochemical Deposition

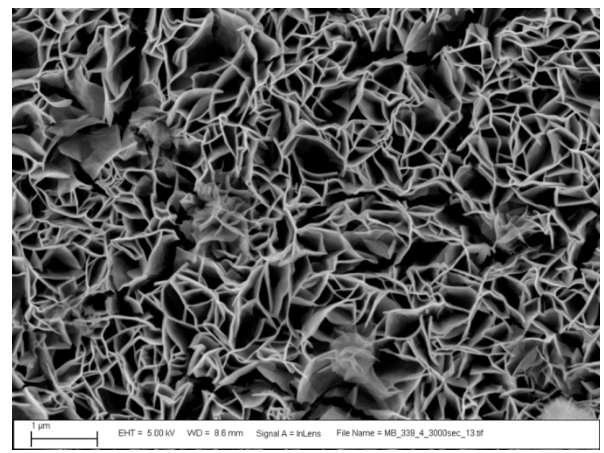
- Cobalt hydroxide is precipitated at surface of stainless steel sample submerged in cobalt nitrate by applying electrical current
- Resulting cobalt hydroxide is thermally annealed to form Co_3O_4

$$[Co(OH)_{2-x} \cdot (H_2O)_x]^{x+} + xNO_3^- \longrightarrow Co(OH)_{2-x}(NO_3)_x \cdot y(H_2O) \xrightarrow{\Delta\ 300^oC} Co_3O_4$$

Formation of Co_3O_4 is then followed up with aging at 600 ^oC or 800 ^oC



Visual appearance of as deposited and heated stainless steel film.



Scanning electron micrograph of the surface of Co3O4 (from electrodeposition/thermal annealing) on SS304L pucks.

SunShot U.S. Department of Energy