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Assessment of Particle Candidates for Falling Particle Receiver Applications Through Irradiance and Thermal Cycling

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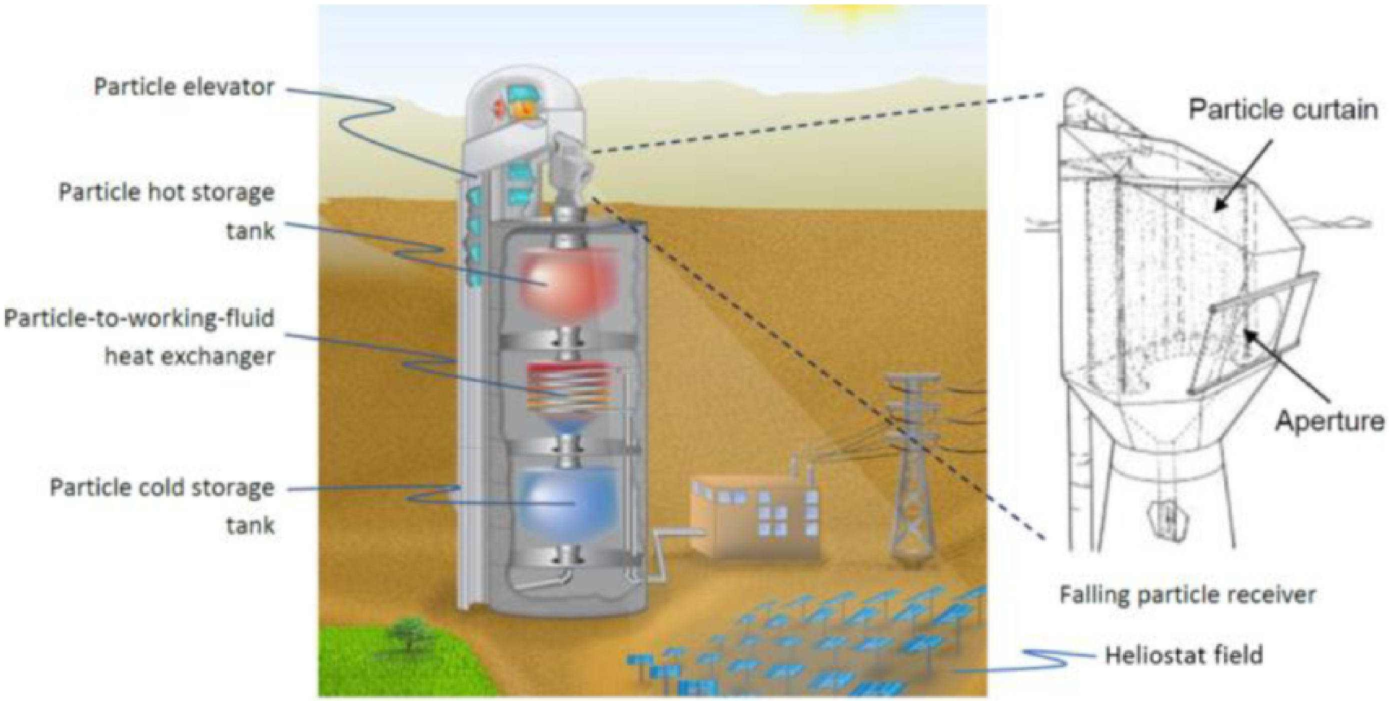
Falling Particle Receivers

- Falling Particle Receivers (FPR) utilize solid particles as the heat transfer fluid (HTF) and thermal energy storage (TES)
- Sand-like particles are dropped through a cavity receiver to directly absorb thermal energy from the concentrated solar heat flux
- Particles are should be highly absorptive and in the size range of 100-700 μm
- Particles must maintain absorptive properties following repeated exposure to solar flux and extended time at high temperatures, >700°C



Source: Sandia National Labs

Novel and Previously Tested Particle Candidates

CARBOBEAD HSP 40/70 (A)

- Previously tested through isothermal aging
- Utilized in a protype 1 MW falling particle receiver
- High absorptivity
- 350 µm median particle size

CARBOBEAD CP 40/100 (B)

-Previously tested through isothermal aging

-300 µm median particle size

CARBOBEAD HD 350 (C)

- Novel particle
- Highly absorptive

-350 µm median size

CARBOBEAD MAX HD 35 (D)

-Novel particle

- High sphericity (decreased material erosion)
- 690 µm median particle size

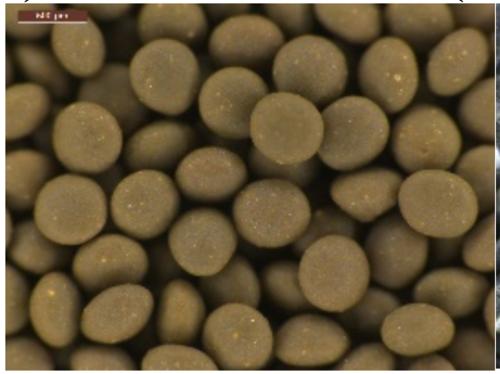
WanLi DiamondBlack (E)

- Novel particle
- High absorptivity
- Low sphericity
- ~650 µm median particle size

(A)

(B)

(C)



(D)

(E)

Irradiance Cycling and Thermal Aging

Samples were held in 25 mm x 25 mm stainless steel crucible forming a 1 mm thick packed bed

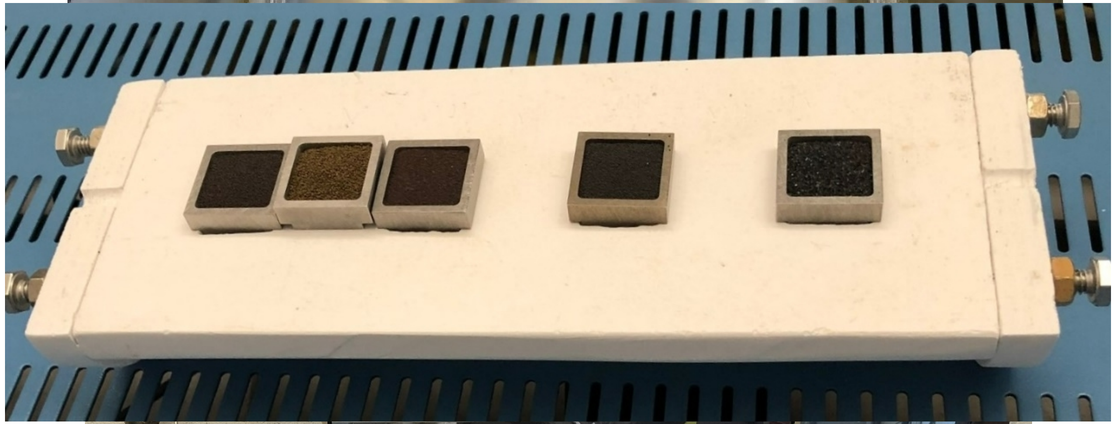
Particle samples were exposed to high flux thermal cycling using a solar simulator

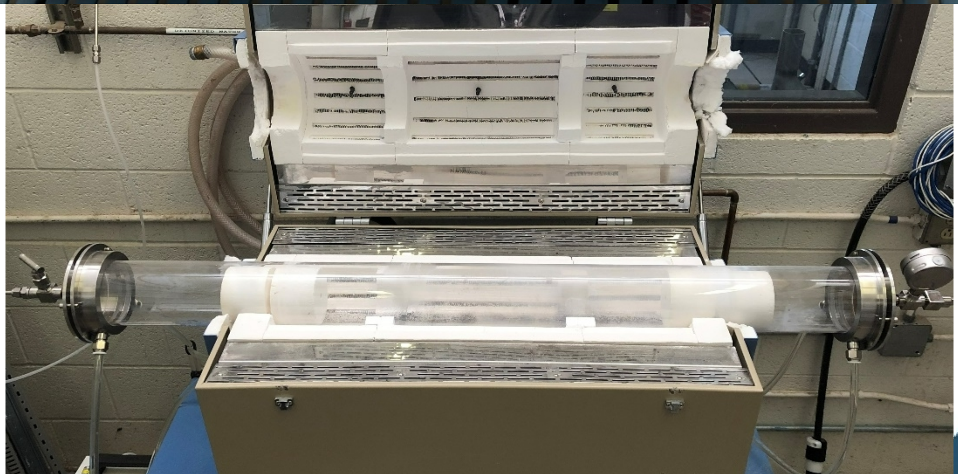
- The solar simulator utilizes metal halide lamps that produce a spectrum similar to sunlight
- Elliptical silver coated reflectors concentrate the light onto the sample
- High flux exposure creates high thermal gradients

Particles were held at high temperature for extended periods in a quartz tube furnace

- An unpurified air cover gas purged potential off gasses

Particle samples were aged using a solar simulator and tube furnace





Measurement

A Solar 410 reflectometer was used to measure the particle reflectance in the solar spectrum. Solar absorptivity was obtained by subtracting the solar reflectance from one.

An ET 100 handheld emissometer was used to determine the particle emissivity at 970°C

An optical microscope was used to determine particle surface degradation

Changes in particle absorptivity, emissivity, and appearance were observed

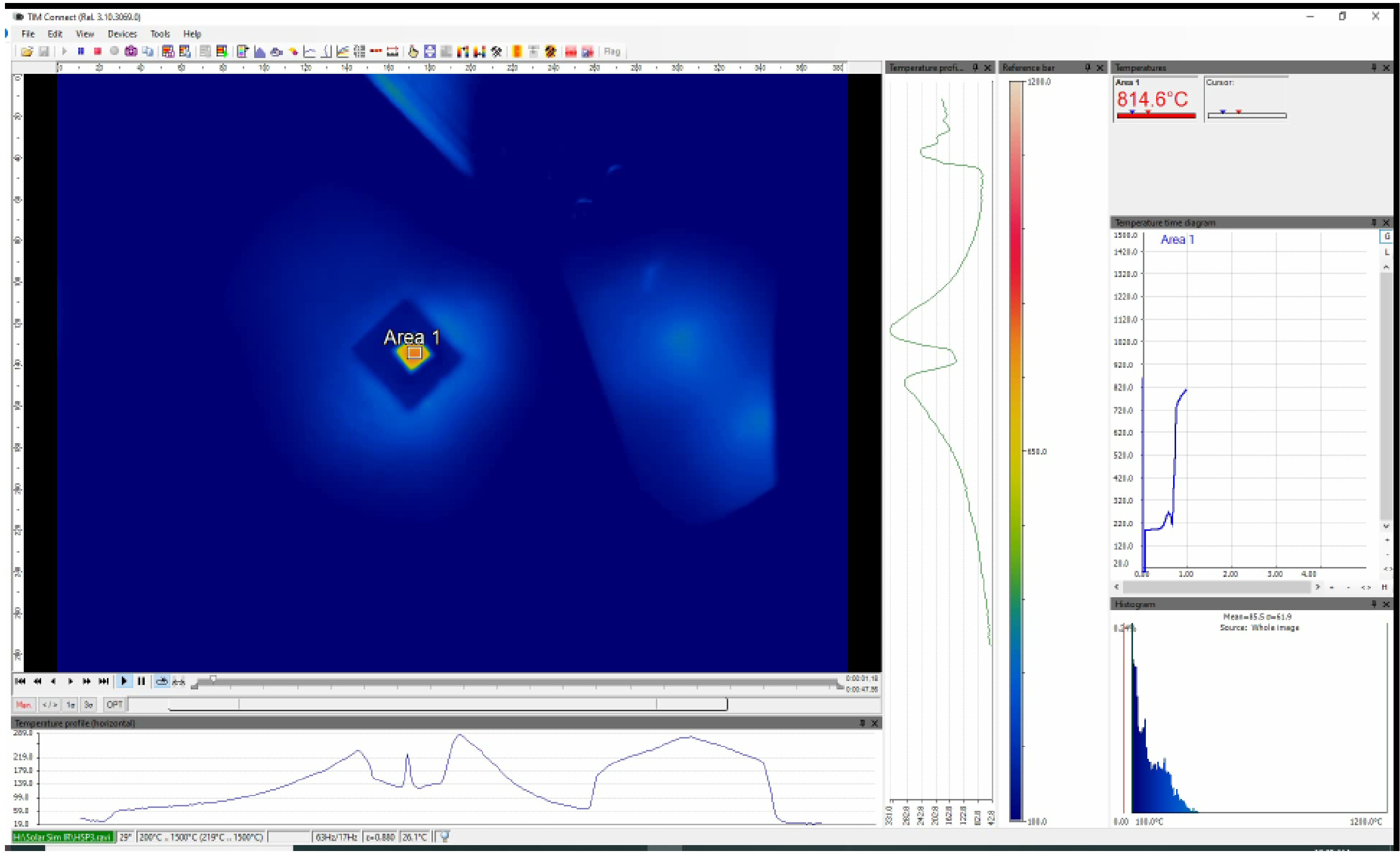
Irradiance Cycling Test Procedure

Particles were exposed to the concentrated solar flux for 10,000 cycles representing repeated flux exposure during a 30-year lifetime of a commercial solar power plant

Three separate experiments were conducted. Individual cycles were concluded based on three cycle ending criterion

- Particle temperature = 775°C, 35 W/cm^2
- Particle temperature = 975°C, 35 W/cm^2
- Freefall simulations, 70 W/cm^2
  - Particles were heated to the inlet temperature of a falling particle receiver (615°C)
  - Particles are then exposed to flux for 1.7s corresponding to the time it would take a particle to fall through a 30 MW receiver

Measurements are taken in 2000 cycle intervals



Cycle End Criterion	615 °C + 1.7 seconds	Final Temp. 775 °C	Final Temp. 975 °C
Measurement Intervals (Cycles)	0, 2k, 4k, 6k, 8k, 10k	0, 2k, 4k, 6k, 8k, 10k	0, 2k, 4k, 6k, 8k, 10k

Three irradiance cycling experiments were conducted

Tube Furnace Procedure

Particle were exposed to 800°C for 400 hours and 900°C and 1000°C for 300 hours.

Furnace temperature was ramped at a rate of 300°C/hr

Measurements were taken in 100 hour intervals

Tube Furnace Temperature	**800 °C**	**900 °C**	**1000 °C**
Measurement Intervals (Hours)	100, 200, 300, 400	100, 200, 300	100, 200, 300

Three isothermal aging experiments were considered

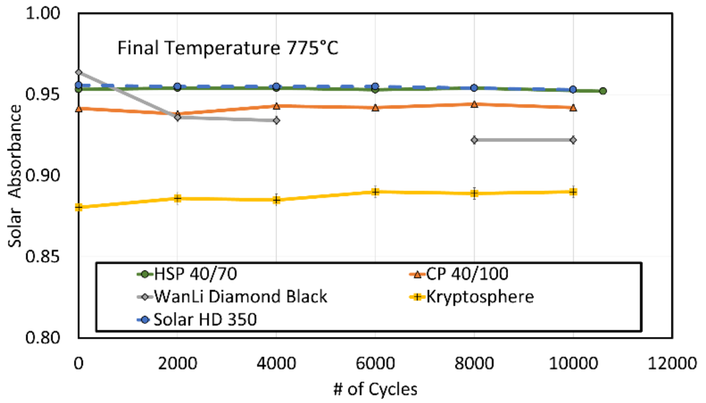
Irradiance Cycling Results

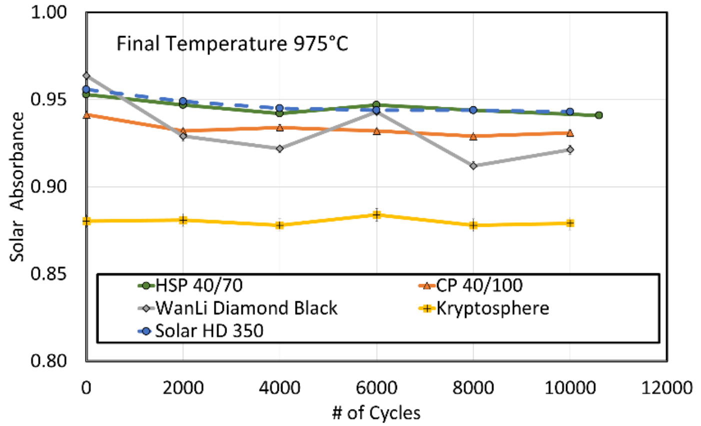
Particle	As Received Particle Absorptance	615 °C + 1.7 seconds	Final Temp. 775 °C	Final Temp. 975 °C
HSP 40/70	95.3%	-1.3%	-0.12%	-1.3%
CP 40/100	94.1%	-1.2%	0.06%	-1.1%
MAX HD 35	88.0%	-1.7%	1.1%	-0.16%
HD 350	95.6%	-1.7%	-.29%	-1.3%
WanLi Diamond Black	96.4%	-2.6%	-4.3%	-4.4%

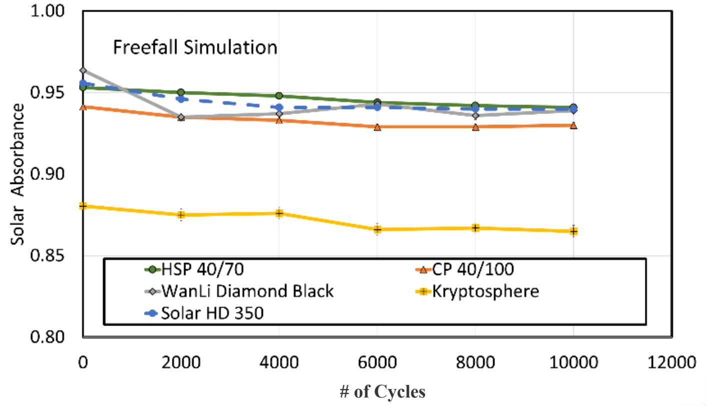
WanLi DiamondBlack particles experienced the largest decrease in absorptivity, 4.4%, after 10,000 cycles at 975°C peak cycle temperature

HSP 40/70 and HD 350 particles had the highest absorptivity following 10,000 following each scenario

HSP 40/70 and HD 350 were the most stable







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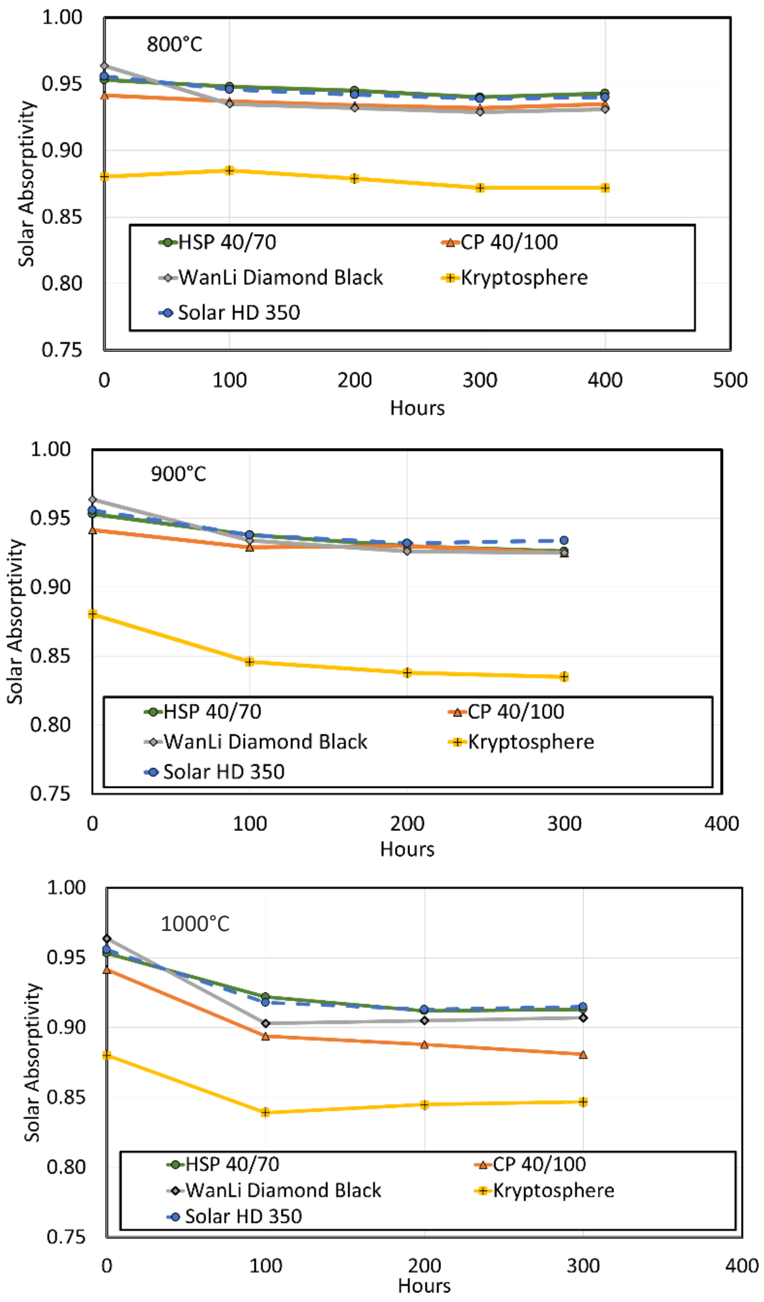
Isothermal Hold Results

Particle	As-Received Particle Absorptance	400 hours @ 800 °C	300 hours @ 900 °C	300 hours @ 1000 °C
HSP 40/70	95.3%	-1.1%	-2.9%	-4.2%
CP 40/100	94.1%	-0.7%	-1.8%	-6.4%
MAX HD35	88.0%	-1.0%	-5.2%	-3.8%
HD 350	95.6%	-1.7%	-2.8%	-3.8%
WanLi Diamond Black	96.4%	-3.4%	-4.0%	-5.9%

WanLi DiamondBlack particles experienced the largest decrease in absorptivity, 5.9%, after 300 hours at 1000°C

HSP 40/70 and HD 350 particles had the highest absorptivity following each isothermal hold

HSP 40/70 and HD 350 were the most stable



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Conclusion

- Five particle candidates, CARBOBEAD HSP 40/70, CP 40/100, MAX HD 35, HD 350, and WanLi Diamond Black, were tested for stability at high temperatures through irradiance cycling and sustained elevated temperatures.
- HSP 40/70 and HD 350 particles experience the smallest change in absorptivity following thermal cycling and isothermal holds of the particle candidates.
- WanLi Diamond Black particles experience the greatest change in absorptivity for all the irradiance cycling experiments and the majority of the sustained heating experiments
- CP 40/100 and HD 35 particles had maximum decrease of 6% and 5% respectively.
- Particle emissivity following each of the experiments was recorded
- Microscopy revealed particle cracking for the WanLi particles
- The HSP 40/70 particles that will be utilized in the generation 3 particle pilot plant experienced a maximum of a 1.3% decrease in absorptivity for the plants expected operating conditions
  - A 1.3% decrease in packed bed absorptivity does not correspond to a 1.3% decrease in particle curtain absorptivity due to the curtains light trapping effects