Comparison of Solar Thermal Receiver Technologies

	Solar Thermal Receiver Technology				
	Falling Particle Receiver	Steam Receiver	Molten Salt Receiver	Liquid Sodium Receiver	Volumetric Air Receiver
Direct energy storage (> 6 hours)?	Yes	No	Yes	No	No
Maximum irradiance[1] (kW/m^2)	Unlimited (>2,000)	600	600	1,500 – 2,500	900
Maximum temperature[1] (°C)	>1000 °C up to melting point of particles (2000 °C)	650 °C	<600 °C	800 °C	800 – 900 °C
Thermal efficiency[2] (%)	80 – 90%	80 – 90%	80 - 90%	90 - 96%	50 – 80%
Cost[3] ($/$kW_t$)	125	~140 – 200	~140 – 200	140 - 200	no data
Restrictions/limitations	N/A	High pressure steam requires thicker tubing and more expensive materials	Salt freezes at 200 °C; requires trace heating	Sodium reacts violently with water and spontaneously ignites in air above 115 °C	N/A

[1]Falcone, P.K., 1986, A Handbook for Solar Central Receiver Design, SAND86-8009, Sandia National Laboratories, Livermore, CA; Hoffschmidt, B., F.M. Tellez, A. Valverde, J. Fernandez, and V. Fernandez, 2003, Performance evaluation of the 200-kW(th) HiTRec-II open volumetric air receiver, *Journal of Solar Energy Engineering-Transactions of the Asme*, 125(1), p. 87-94.

[2]Ho, C.K., J.M. Christian, J. Yellowhair, K. Armijo, and S. Jeter, 2016, *Performance Evaluation of a High-Temperature Falling Particle Receiver*, in *ASME Power & Energy Conference*, Charlotte, NC, June 26-30, 2016 (particle receiver); Ho, C.K. and B.D. Iverson, 2014, Review of high-temperature central receiver designs for concentrating solar power, *Renewable & Sustainable Energy Reviews*, 29, p. 835-846 (steam, molten salt, and volumetric air receivers); Rockwell International, *Final Report Sodium Solar Receiver Experiment*, SAND82-8192, Dec. 1983 (liquid sodium receiver).

[3]Ho, C.K., A Review of High-Temperature Particle Receivers for Concentrating Solar Power, *Applied Thermal Energy*, 109(Part B), p. 958-969.; Kolb, G.J., Ho, C.K., Mancini, T.R., Gary, J.A., 2011, Power Tower Technology Roadmap and Cost Reduction Plan, SAND2011-2419, Sandia National Laboratories, Albuquerque, NM.

Comparison of Energy Storage Technologies

	Energy Storage Technology					
	Solid Particles	Molten Nitrate Salt	Batteries	Pumped Hydro	Compressed Air	Flywheels
Levelized Cost[1] ($/$MWh_e$)	10 – 13	11 – 17	100 – 1,000	150 - 220	120 – 210	350 - 400
Round-trip efficiency[2]	>98% thermal storage ~40% thermal-to-electric	>98% thermal storage ~40% thermal-to-electric	60 – 90%	65 – 80%	40 – 70%	80 – 90%
Cycle life[3]	>10,000	>10,000	1000 – 5000	>10,000	>10,000	>10,000
Toxicity/environmental impacts	Potential dust formation	Reactive with piping materials	Heavy metals pose environmental and health concerns	Water evaporation/ consumption	N/A	N/A
Restrictions/limitations	Particle/fluid heat transfer can be challenging	< 600 °C (decomposes above ~600 °C)	Very expensive for utility-scale storage	Large amounts of water required	Unique geography required	Only provides seconds to minutes of storage

[1]Ho, C.K., A Review of High-Temperature Particle Receivers for Concentrating Solar Power, *Applied Thermal Energy*, 2016; Kolb, G.J., Ho, C.K., Mancini, T.R., Gary, J.A., 2011, Power Tower Technology Roadmap and Cost Reduction Plan, SAND2011-2419, Sandia National Laboratories, Albuquerque, NM; Akhil et al., 2015, DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA, SAND2015-1002, Sandia National Laboratories, Albuquerque, NM. For solid particles and molten salt, we assume a 30 – 50% thermal-to-electric conversion efficiency and 10,000 lifetime cycles for the thermal-to-electric storage and conversion systems; the cost includes the storage media (bulk ceramic particles and sodium/potassium nitrate salts ~$1/kg with ΔT = 400 °C and 9 hours of storage), tanks, pumps/piping/valves, other parts and contingency, and the power block at $1000/$kW_e$ with 19 operating hours per daily cycle (including 9 hrs of storage) and 90% availability. For batteries, cost is based on sodium-sulfur, vanadium-redox, zinc-bromine,lead-acid, and lithium-ion batteries capable of providing large-scale electricity.

[2]Roundtrip efficiency defined as ratio of energy in to energy retrieved from storage; Djajadiwinata, E. et al., 2014, Modeling of Transient Energy Loss from a Cylindrical-Shaped Solid Particle Thermal Energy Storage Tank for Central Receiver Applications, Proceedings of the Asme 8th International Conference on Energy Sustainability, 2014, Vol 1.; Siegel, N.P., 2012, Thermal energy storage for solar power production, Wiley Interdisciplinary Reviews-Energy and Environment, 1(2), p. 119-131.; http://energystorage.org/energy-storage/energy-storage-technologies; http://energymag.net/round-trip-efficiency/

[3]Siegel, N.P., 2012, Thermal energy storage for solar power production, Wiley Interdisciplinary Reviews-Energy and Environment, 1(2), p. 119-131.

*Patents and Patents Pending. This technology may be available for licensing. For more information, please contact ip@sandia.gov.

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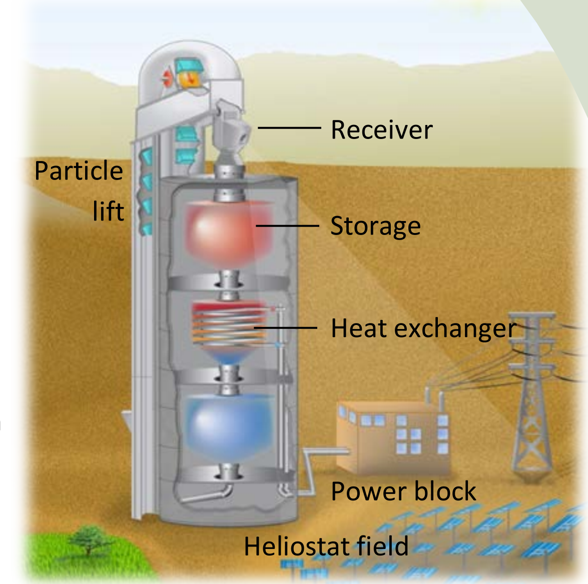
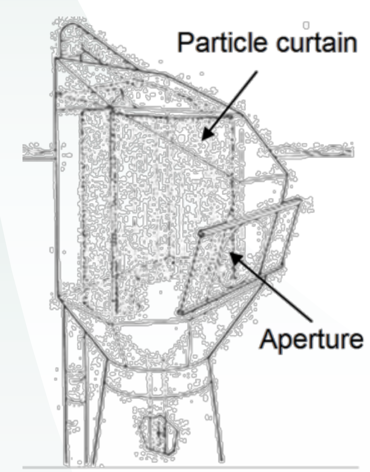
Sandia National Laboratories

High-Temperature Falling Particle Receiver

Technology Description

Falling particle receivers for concentrating solar power (CSP) systems enable clean, on-demand energy production using concentrated sunlight with highly efficient and inexpensive thermal storage. The falling particle receiver uses sand-like particles that fall through a beam of highly concentrated sunlight focused by an array of mirrors. The particles are heated very efficiently, increasing in temperature by over 100 °C in just a fraction of a second, and are capable of reaching temperatures over 1,000 °C. Once heated, the hot particles are stored and used to generate electricity in a power cycle or to create process heat.





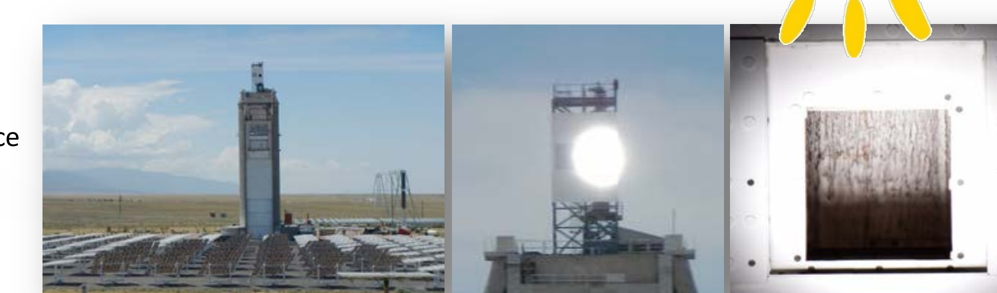
Falling particle receiver

Pushing the Limits

The world's first continuously recirculating high-temperature falling particle receiver has been tested on-sun at Sandia National Laboratories. Unlike conventional receivers that employ flowing fluids, particle receivers heat particles directly, enabling higher solar concentrations and consequently higher temperatures, higher efficiencies, and lower costs. For example, current conventional solar receivers use molten salt, which decomposes at less than 600 °C, thus limiting the operating temperature and efficiency of the power cycle. Recent on-sun tests with Sandia's 1 MW_t falling particle receiver have achieved peak particle temperatures over 900 °C and thermal receiver efficiencies approaching 80% at 1000 suns with particle mass flow rates of 1 – 7 kg/s. Efficiencies of ~90% are expected for larger-scale (>100 MW_t)

particle Power

- Higher operating temperatures (>1,000°C)
- No freezing or need for trace heating
- Lower receiver cost
- Direct heating and storage

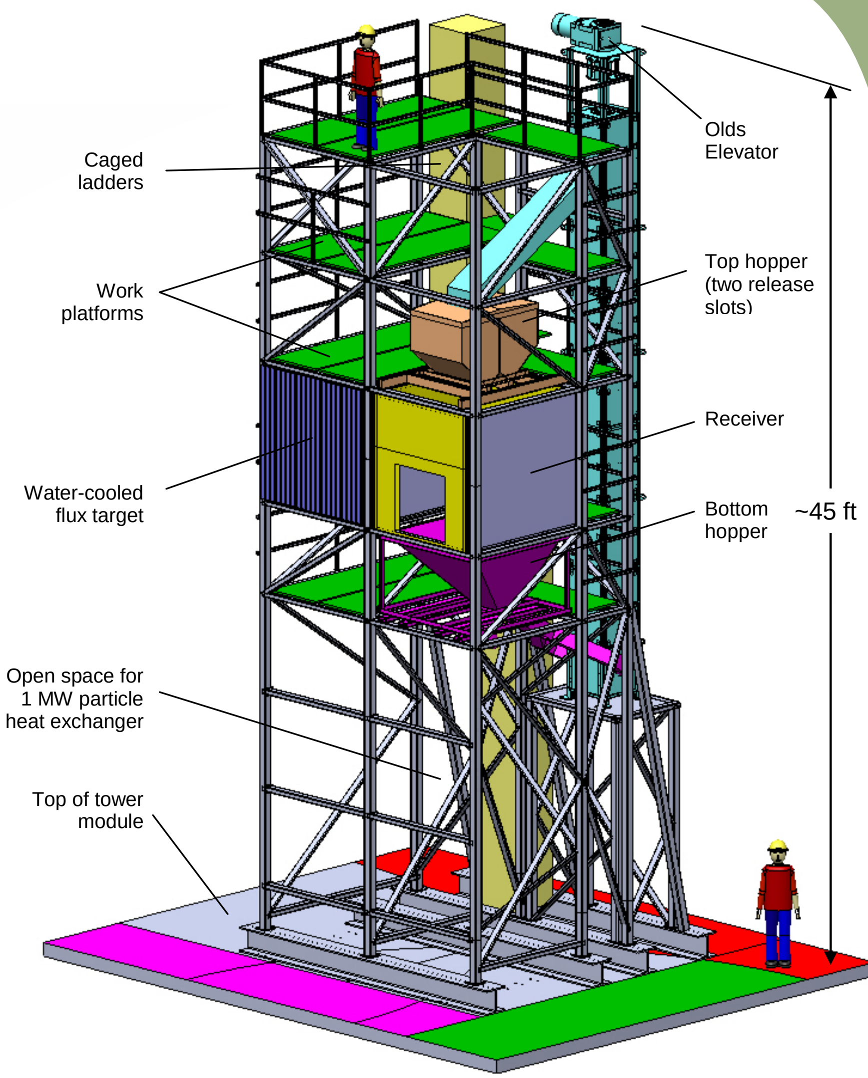


On-sun testing of the 1 MW_t falling particle receiver at Sandia National Laboratories

Particle Receiver*

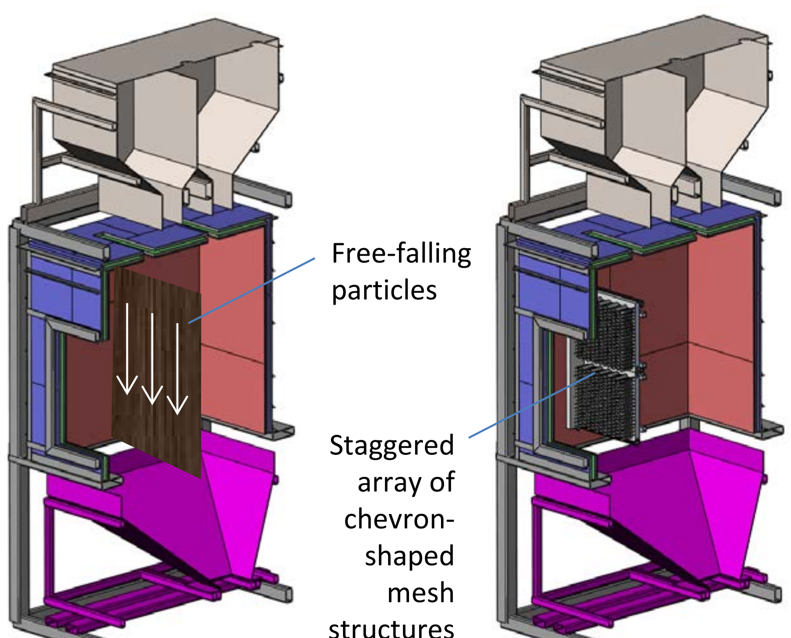
The 1 MW_t falling particle receiver prototype fielded at Sandia National Laboratories includes a particle elevator, cavity receiver, and top and bottom hoppers. The cavity receiver can accommodate either a free-falling curtain of particles or a staggered array of porous chevron-shaped mesh structures that slow the particle flow through the concentrated solar flux for increased temperatures and efficiency. A water-cooled flux target next to the receiver aperture is used to characterize the irradiance from the heliostat field. Nearly 200 hours of on-sun testing have been completed.

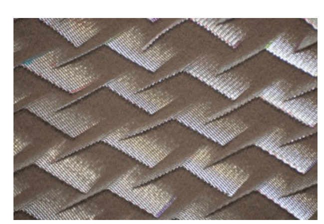
- **~300 – 1000 kW/m^2**
- **~1 – 7 kg/s per meter of particle curtain width**
- **>700 ˚C average particle outlet temperature**
- **>900 ˚C peak particle outlet temperature**
- **ΔT = 25 – 200 ˚C/m (free-fall)**
- **ΔT = 50 – 300 ˚C/m (obstructed flow)**
- **~80% thermal efficiency**



1 MW_t prototype falling particle receiver system, which sits on top of a 60-m (200-ft) central receiver tower at Sandia National Laboratories, NM

Free-falling particle curtain



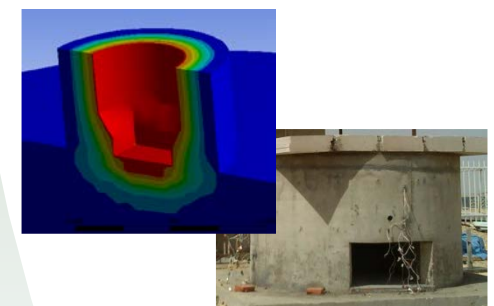


Obstructed-flow using a staggered array of chevron-shaped mesh structures

*Patents and Patents Pending. This technology may be available for licensing. For more information, please contact ip@sandia.gov.

Particle Thermal Storage

The particle collection hopper used in the prototype system consists of a stainless-steel liner with layers of insulation on the outside. Studies were also performed to evaluate storage systems comprised of insulating firebrick, insulating concrete, and reinforced concrete for use in larger-scale systems operating at potentially higher temperatures (~1,000°C). The reinforced concrete design was modeled and tested at a small scale, and results showed that the heat loss in these systems was less than 4% per day, which corresponded to ~1% per day for larger-scale systems, with costs less than $15/kW$_t$.



Particles

Spherical sintered-bauxite particles were found to be the best candidate material because of their high solar absorptance (>0.9) and resistance to abrasion and sintering at high temperatures and pressures. These particles are commercially available (used as proppants for hydraulic fracturing in oil and gas industry) and inexpensive (~$1/kg for bulk pricing).

Ceramic particles from CARBO Ceramics

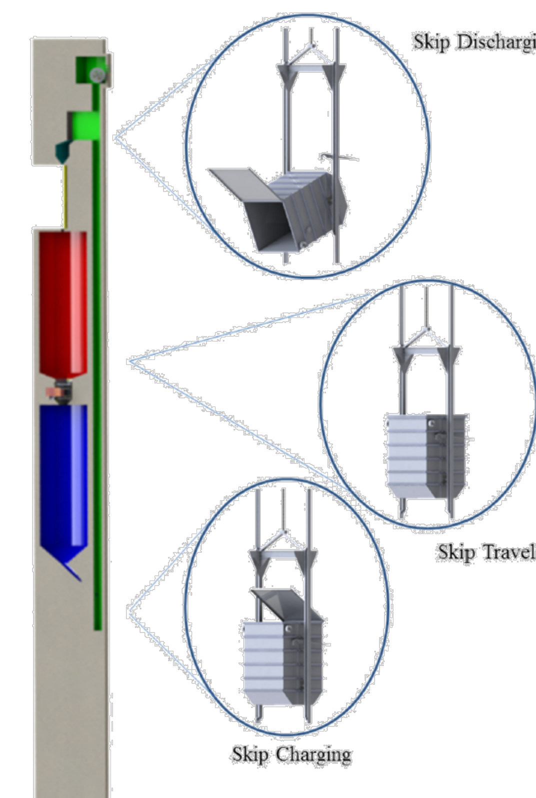
Particle Heat Exchanger

Moving-packed-bed heat exchanger designs were investigated to heat a working fluid up to ~700 °C. Tests showed that the particle-side heat transfer coefficient was limiting, but could achieve ~100 W/m^2-K with proper design and spacing of the tubes and fins. Fluidized-bed designs were also characterized from the literature, which yielded higher particle heat transfer coefficients (up to ~600 W/m^2-K) but with higher parasitic power consumption and heat loss associated with particle fluidization. Sandia is currently working with industry (Babcock & Wilcox, Solex Thermal Science, and Vacuum Process Engineering) to design and construct a particle-to-sCO2 heat exchanger operating at >700 °C and 20 MPa that can be integrated with our on-sun particle receiver system. Fluidized-bed and moving packed-bed heat exchanger designs are being considered.

Example of moving packed-bed particle heat exchanger

Particle Lift

The particle lift used in the prototype system is a stainless-steel Olds elevator that can operate at over 800 °C. A cylindrical casing rotates about a stationary screw to lift particles up ~8 m at a variable controlled rate of up to ~10 kg/s. Because the particles are lifted by friction between the particles and the rotating casing, the lift efficiency is low (~5%). For larger-scale systems, an insulated skip hoist system was designed that can achieve ~80% lift efficiency with a parasitic power consumption less than 1% of the rated electrical output of the CSP plant.



Skip hoist designed to lift "cold" particles to the top of the receiver (Est. cost ~$9K/MW$_t$) (Repole & Jeter, 2016)

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