1697-1503

Gen 3 Particle Pilot Plant (G3P3):

Integrated High-Temperature Particle System for CSP

Exceptional service in the national interest

Sandia National Laboratories

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SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy

U.S. DEPARTMENT OF ENERGY

NNSA

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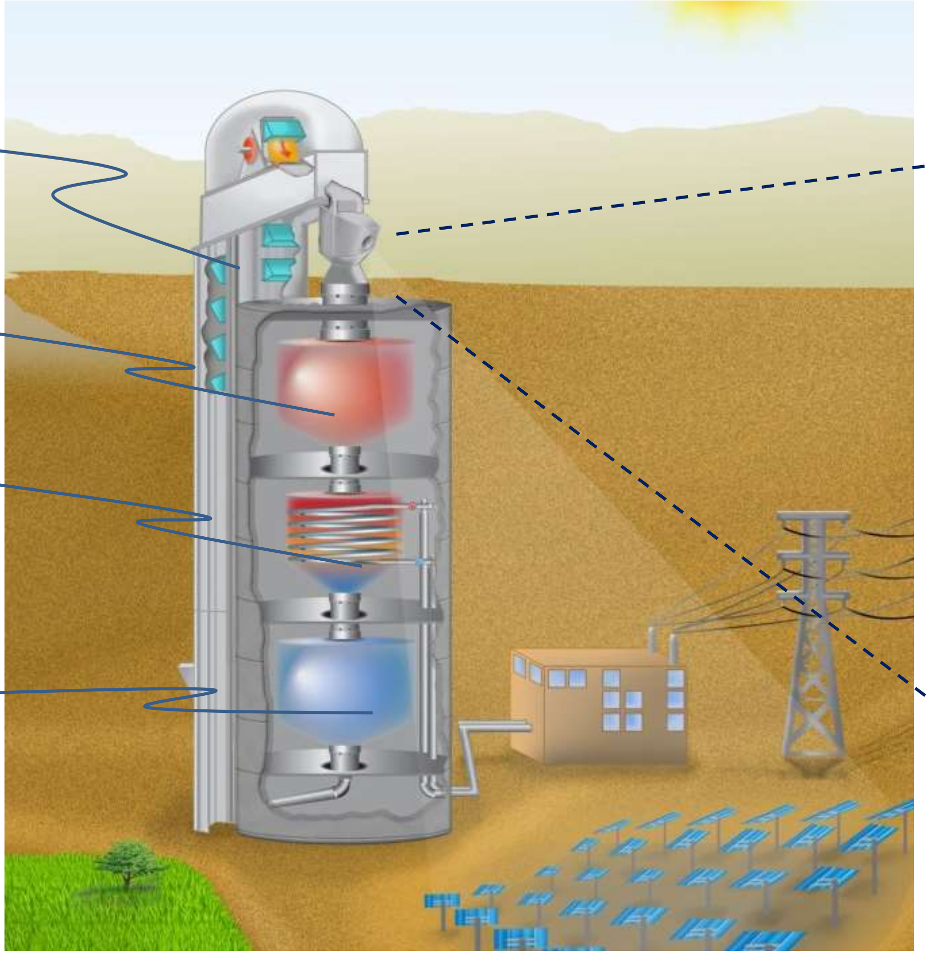
Introduction to the Team

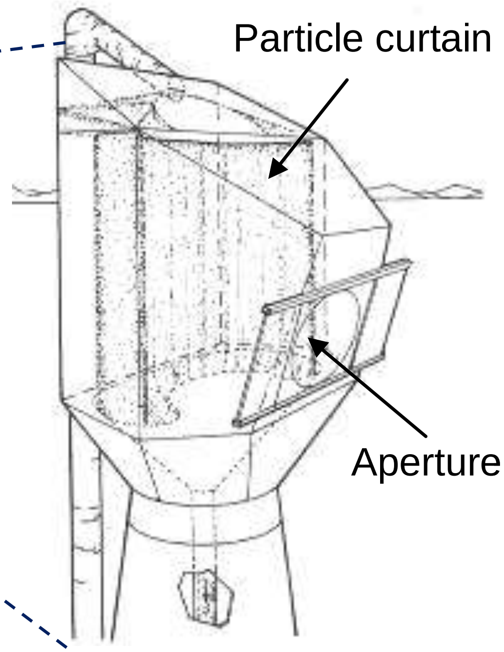
Role	Team Members
PI / Management	• Sandia National Labs (PI, PMP, financial, facilities)
R&D / Engineering	• Sandia National Laboratories • Georgia Institute of Technology • King Saud University • German Aerospace Center • CSIRO • U. Adelaide • Australian National University • CNRS-PROMES
Integrators / EPC	• EPRI • Bridgers & Paxton / Bohannan Huston • INITEC Energia
CSP Developers	• SolarDynamics • SolarReserve (Bruce Kelly)
Component Developers / Industry	• Carbo Ceramics • Solex Thermal Science • Vacuum Process Engineering • FLSmidth • Materials Handling Equipment • Allied Mineral Products • Matrix PDM
Utility	• Saudi Electricity Company

Overview

- Objectives and Value Proposition
- Key Technical Risks (Phases 1 and 2)
- Key Technical Risks (Phase 3)
- Conclusions

High Temperature Falling Particle Receiver



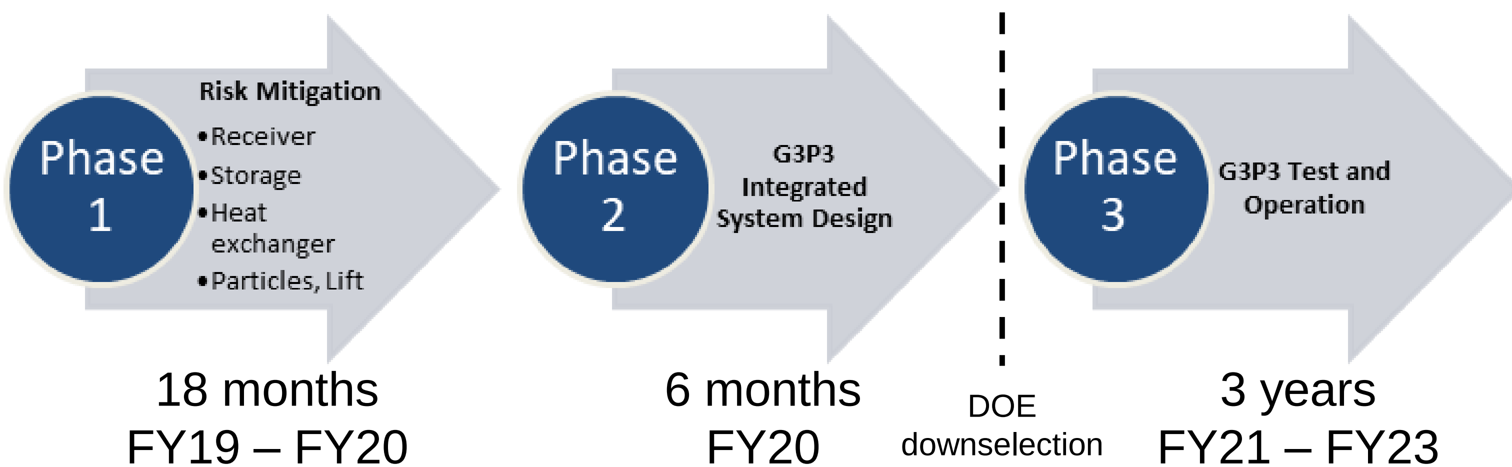


Falling particle receiver

Goal: Achieve higher temperatures, higher efficiencies, and lower costs

G3P3 Objectives

- **De-risk**, **design**, **construct**, and **operate** a multi-MW_t particle receiver system
  - Heat working fluid (e.g., sCO2 or air) to ≥ 700 °C
  - 6 hours of energy storage
  - > 2,000 hours of on-sun operation
  - Meet SunShot cost and performance goals
- **Leverage** international expertise and CSP activity
- Accelerate **commercialization** of G3P3 technology



Advantages of particle Power™

Value Proposition

- Wider temperature range than molten salts (subzero to >1000 ˚C)
  - Enables more efficient power cycles
  - No freezing or decomposition; avoids costly heat tracing
- Use of inert, non-corrosive, inexpensive materials
- Direct heating of particles vs. indirect heating of tubes
  - Higher solar fluxes for increased receiver efficiency
  - Can control particle outlet temperatures instantaneously; no thermal inertia from tubes and headers
- Direct storage of hot particles
  - Reduced costs without extra heat exchangers and separate storage media

CARBO ceramic particles (“proppants”)

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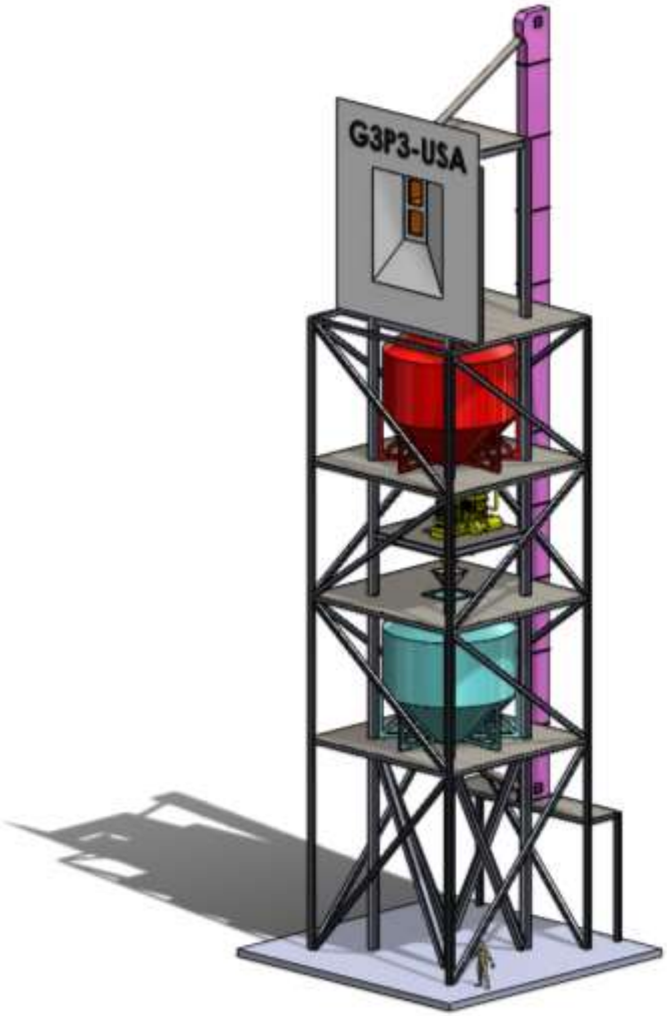
Component Risks and Features

- Particles
- Receiver and Feed Bin
- Particle Storage
- Particle Heat Exchanger
- Particle Lift and Conveyance
- Balance of System



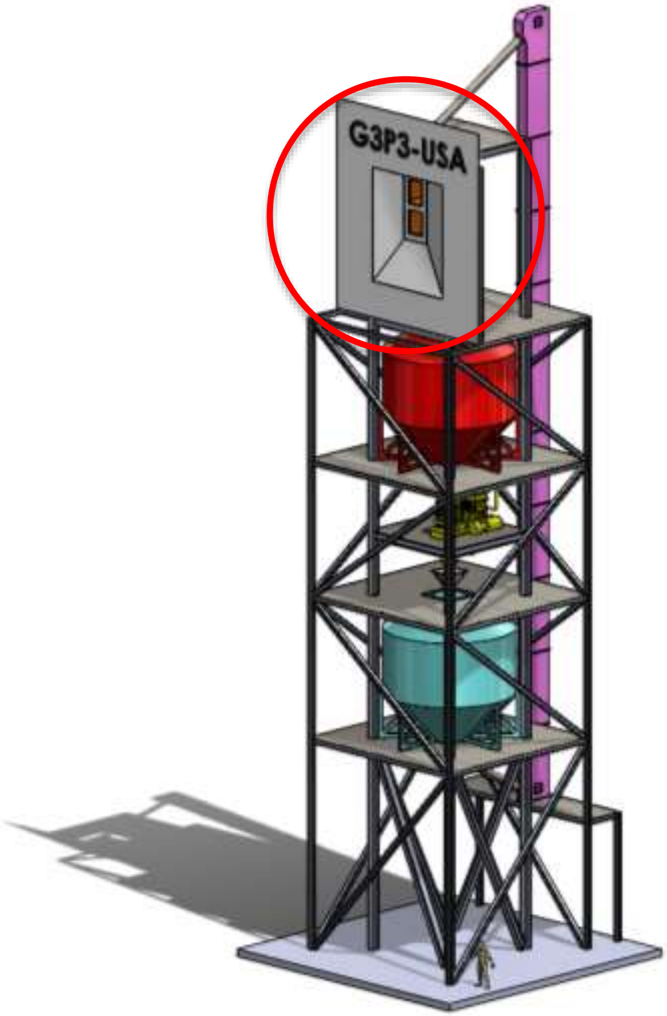
Particles

Sandia National Laboratories

- Cost
  - ≤ $1/kg
- Durability
  - Low wear/attrition
- Optical properties
  - High solar absorptance
- Flowability, low erosion
- Inhalation hazards (e.g., silica, PM2.5)

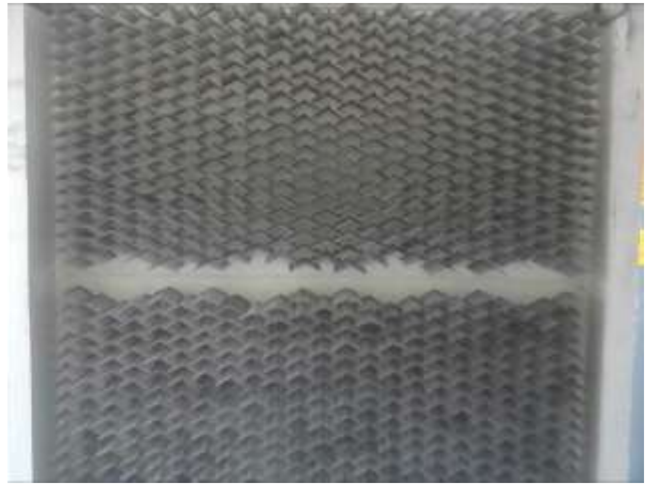
Receiver

- Thermal efficiency
  - Minimize convective/radiative heat loss
- Particle mass flow control
  - Maintain particle outlet temperature
- Damage/overheating of refractory receiver walls
- Particle emissions
  - Inhalation or pollution hazard

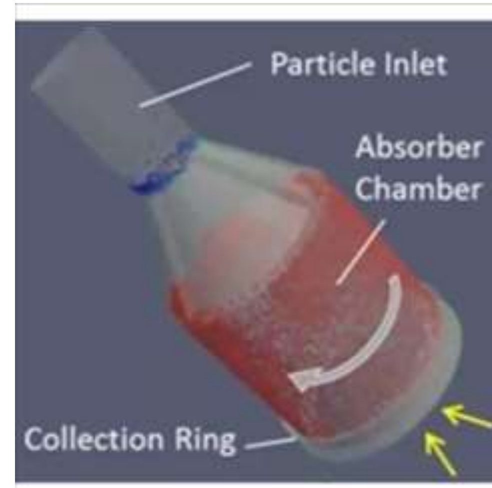


Particle Receiver Designs

Free-Falling (SNL)



Obstructed Flow
(KSU, GT)



Centrifugal (DLR)

Fluidized Bed
(CNRS/PROMES)

Mitigate risks associated with thermal efficiency, cost, and capacity

Receiver Innovations

Multistage Release

- Increases particle curtain opacity
  - Mitigates dispersion with longer drop distances
- Reduces particle loss and impact of wind
- Scalable to commercial systems 10 – 100 MW_e

From Jin-Soo Kim (CSIRO)

Free Falling

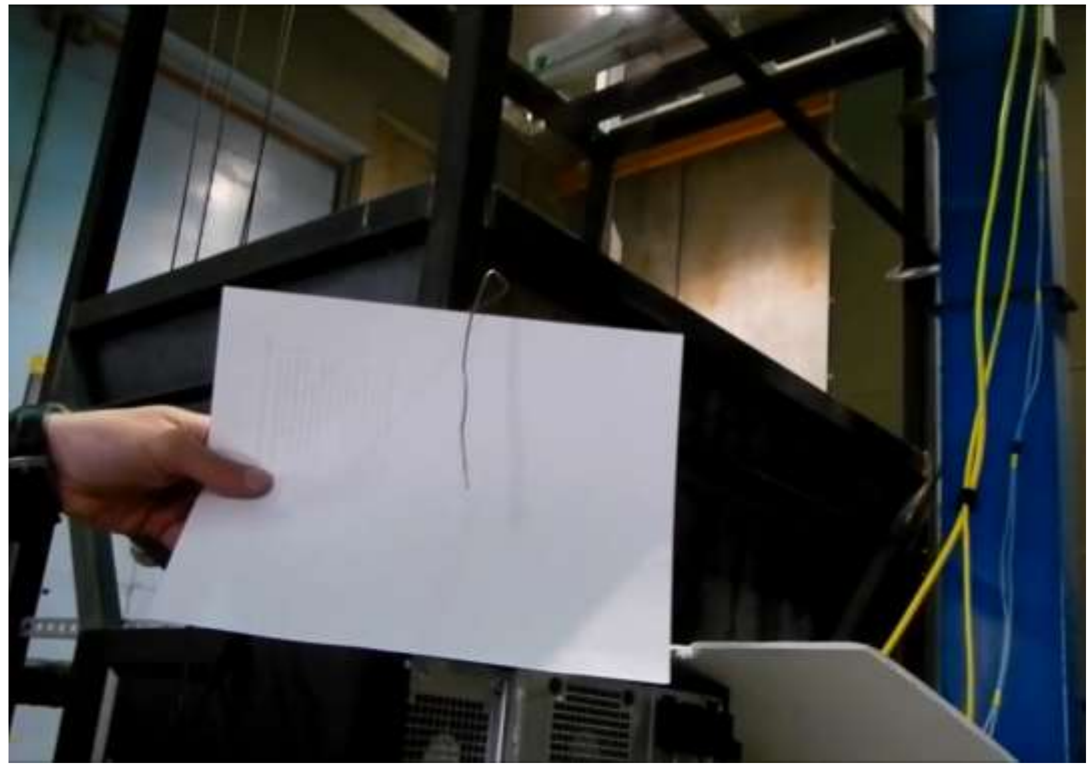
Staged Falling

Patent Pending

Receiver Innovations

Automated Particle Mass Flow and Temperature Control

$$\dot{Q} = \dot{m} c_p \Delta T$$



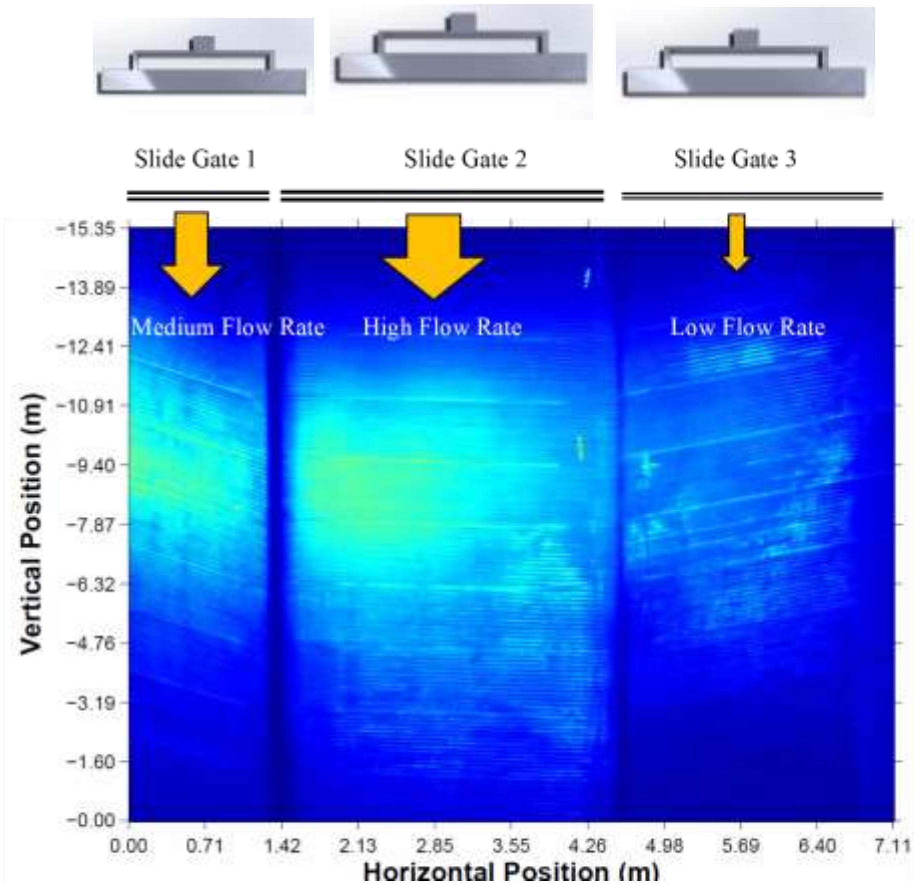
Mitigate risk of variable DNI on particle outlet temperature

Automated Particle Flow and Temperature Control

Patent Pending

Receiver Innovations

Automated Particle Mass Flow and Temperature Control



Multiple Slide Gates

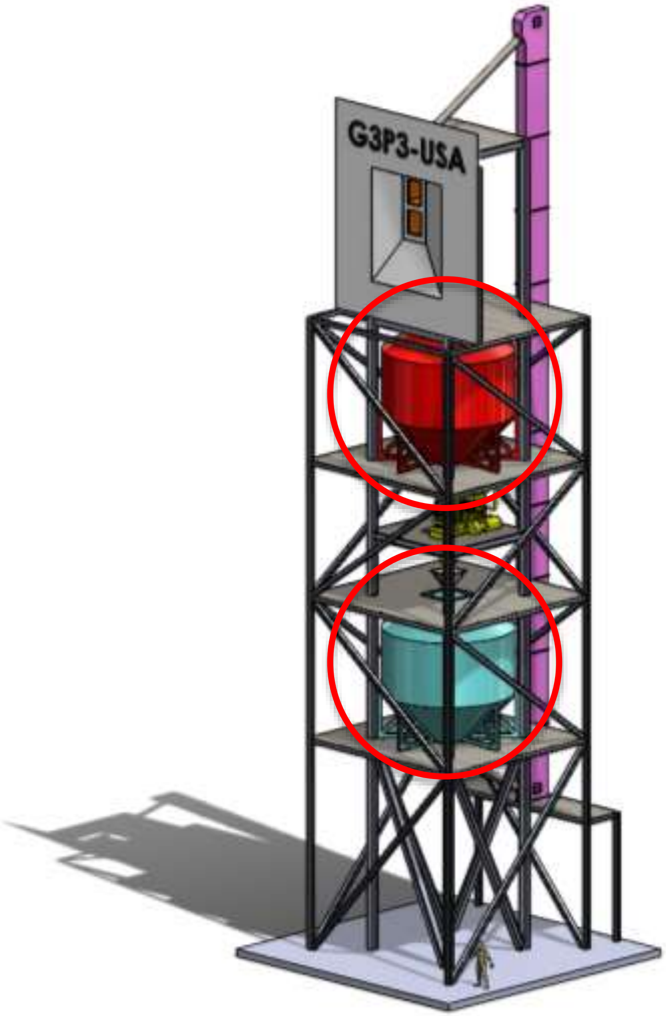
Slide gates can be "numbered up" to scale to larger systems

Mitigate risk of non-uniform and transient irradiance on heating of particles

Patent Pending

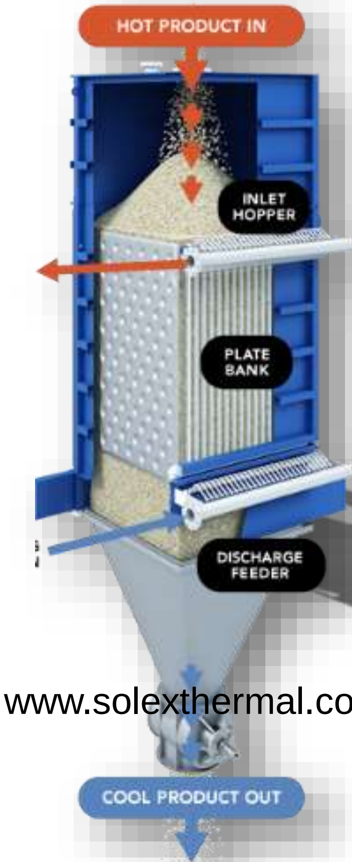
Storage System

- Minimize heat loss during storage, charging, and discharging
  - Robust, cost-effective insulation
- Minimize abrasion on interior of storage bin at temperature
  - Abrasion-resistant materials
  - Low-cost materials
- Minimize thermomechanical stresses
  - Ability to vertically stack at larger scales

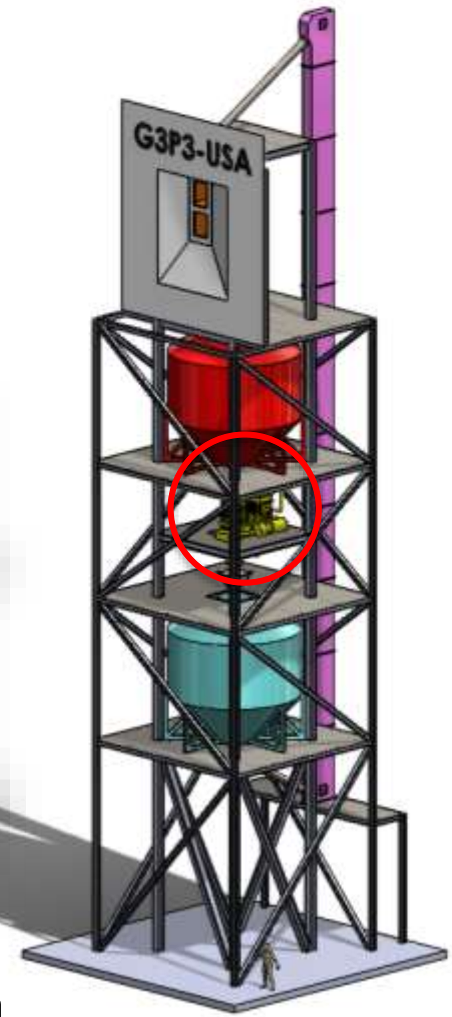


Particle-to-sCO_2 Heat Exchanger

- Heat transfer from particles to high-pressure working fluid
  - Shell-and-plate design
  - Fluidization (G. Jackson)?
- Thermomechanical stresses / fatigue
- Erosion
- Cost
- 100 kW_t prototype
  - Sandia, Solex and VPE have developed a moving packed-bed heat exchanger design for particle-to-sCO_2 heat transfer



www.solexthermal.com



Particle-to-sCO2 Heat Exchanger

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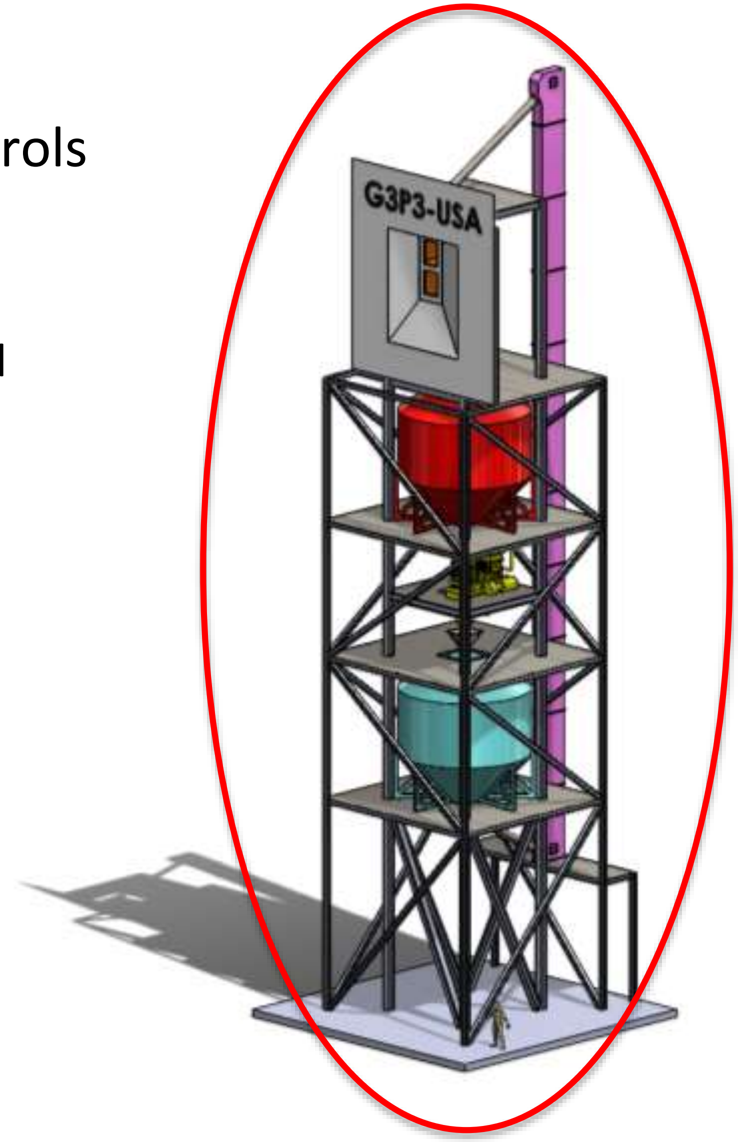
Balance of System

- System instrumentation and controls
  - Diagnostics
  - Bypass valves for startup/shutdown
  - Isolation valves for maintenance and emergency shutdown
  - Particle mass flow monitoring
  - Particle level sensing
- Duct work
  - Differential thermal expansion
  - No need for hermetic seals



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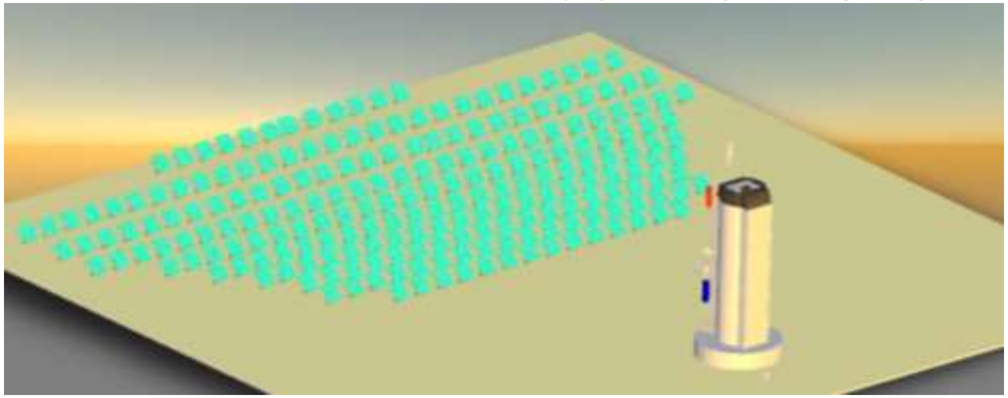
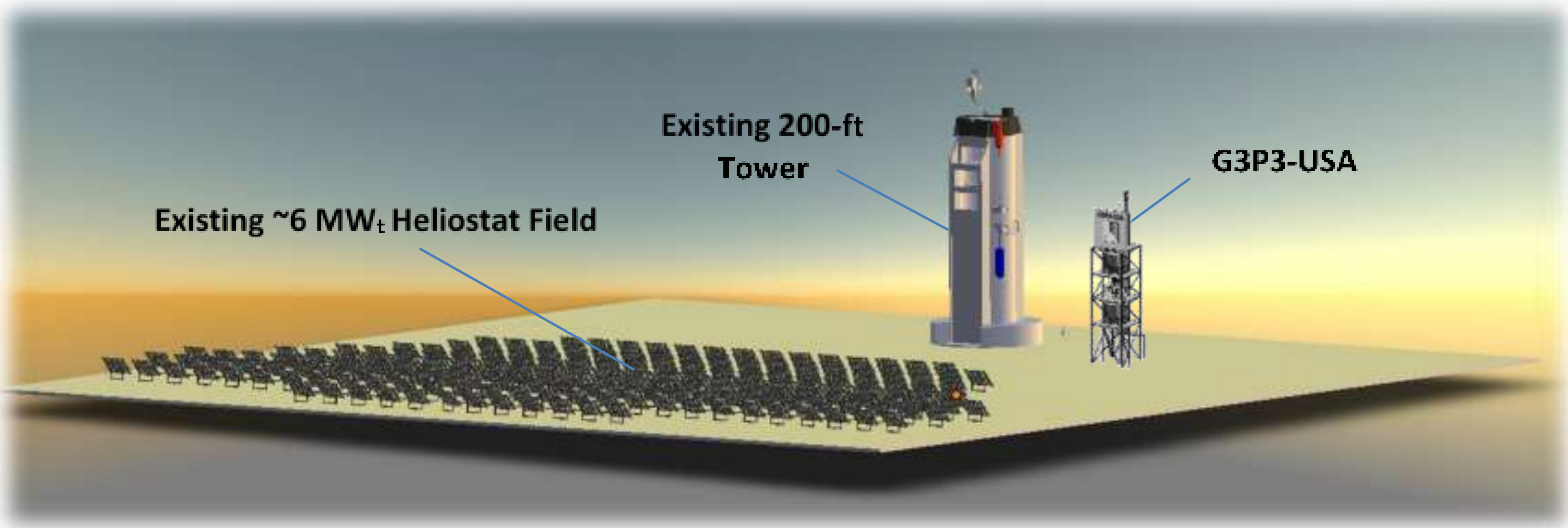
Gen 3 Particle Pilot Plant (G3P3)

Integrated System

National Solar Thermal Test Facility (NSTTF), Albuquerque, NM





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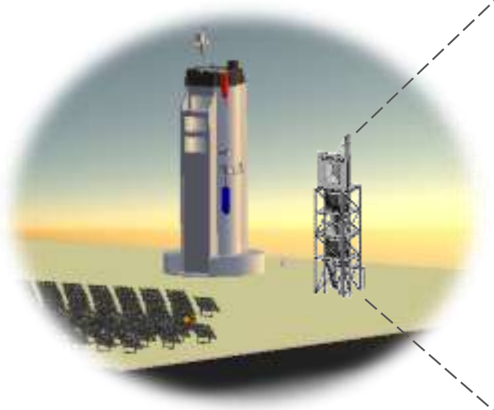
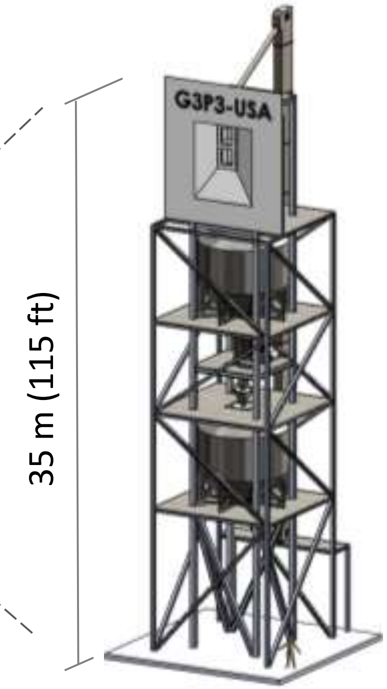
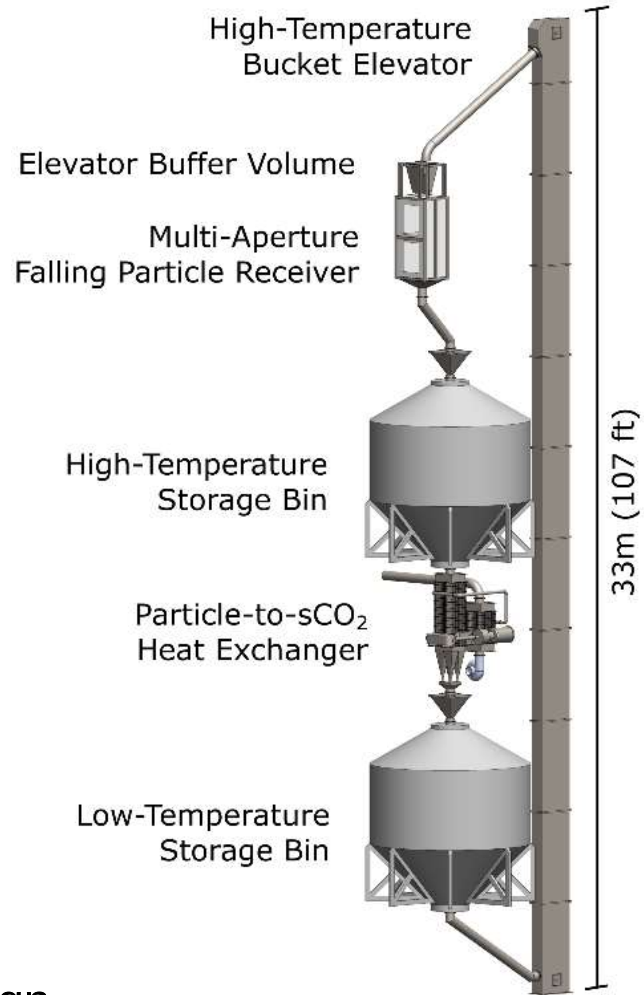
Integrated System



G3P3-USA system next to the existing 200-ft tower at the NSTTF





Baseline Design

Phase 3 Risks to be Retired

- Continuous operation of fully integrated thermal system (up to 10 hours per day)
- Start-up requirements and ramp times with diurnal cycling
- 10 hours of deferred storage with ability to produce 6 MWh of energy using sCO2 at desired turbine inlet temperature of ≥700 °C
- Transient procedures to maintain desired particle-receiver outlet temperatures and sCO2 turbine inlet temperature
- Acceptable levels of particle attrition and loss during long-term operation that meet OSHA and EPA standards and cost metrics
- Sufficient heat transfer coefficient and manufacturing technique capable of achieving heat exchanger cost targets

Construction Challenges

- Timeline (many vendors and novel components coming together in one system)
- Construction sequencing to install components (storage bins, heat exchanger) during the construction process or build in place
- Assembly or construction of the storage tanks on the tower support structure
  - Use of pre-cast refractory sections? Sprayed on site?
- Meeting $25M budget allowance
  - Preliminary cost estimates and quotes are tight

Things we have already demonstrated

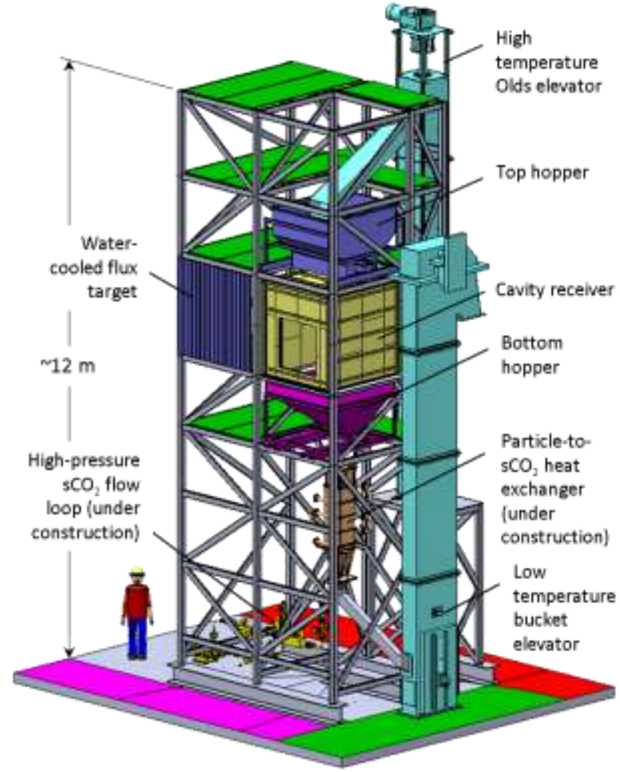
- Ability to continuously operate and recirculate particles through Sandia's falling particle receiver system during hundreds of hours of on-sun tests
  - Reliable high-temperature particle conveyance (commercially available)
  - Reliable and accurate particle flow control
  - High temperature particle valves (isolation and diverter)
  - Accurate measurement of particle mass flow rate
  - Storage and hopper design for particle inventories ~1000 kg
- Ability to heat particles to ~800 °C with fluxes up to 1500 suns
- Ability to achieve receiver thermal efficiencies > 80%
- Excellent durability of particles; no significant wear on equipment
- Good flowability through shell-and-plate heat exchanger with anticipated particle-side heat transfer coefficient > 200 W/m^2-K

Overview

- Objectives and Value Proposition
- G3P3 System Overview
- Gaps and Risks
- Conclusions

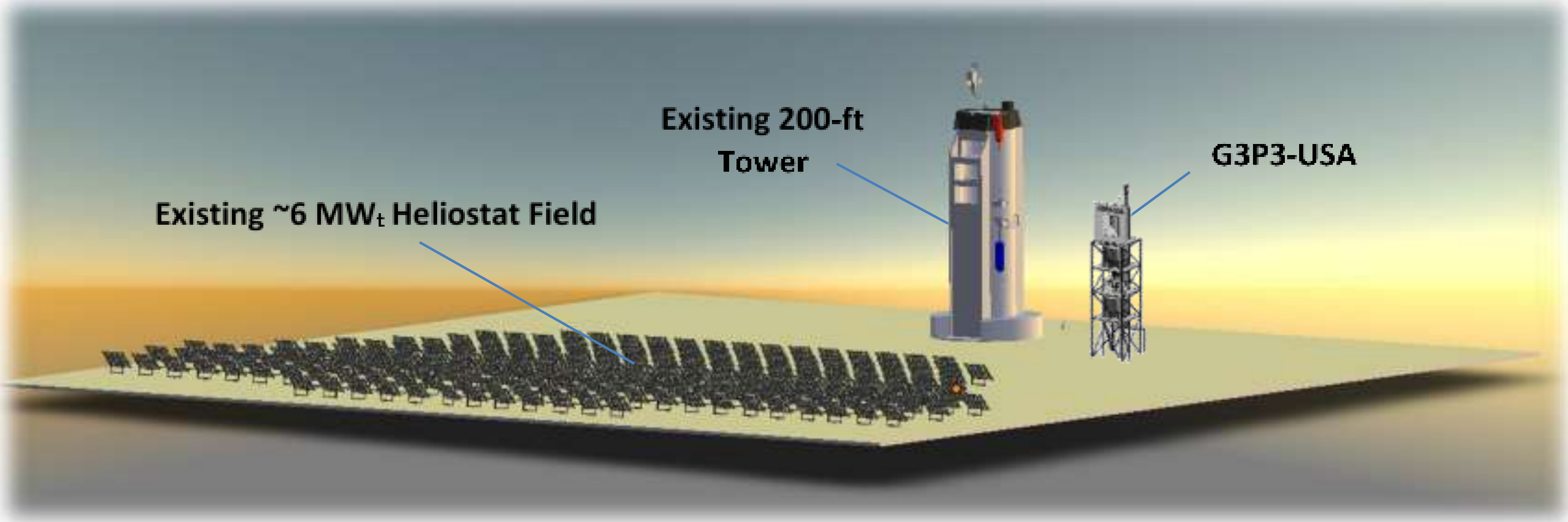
Gen 3 Particle Pilot Plant (G3P3)

- Significant advantages
  - Direct heating of particles
    - Wide temperature range (sub-zero to >1000 °C)
    - Inexpensive, durable, non-corrosive, inert
  - Demonstrated ability to achieve >700 °C on-sun with hundreds of hours of operation
- Technical risks
  - Transient operation of fully integrated system
  - Heat loss and efficiencies (receiver, storage, heat exchanger, lift)
  - Particle-to-working-fluid heat transfer
  - Thermomechanical stresses in heat exchanger and storage tanks
  - Particle attrition and wear; dust formation



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

Questions?



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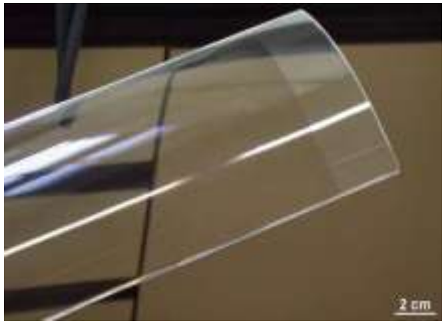
BACKUP SLIDES

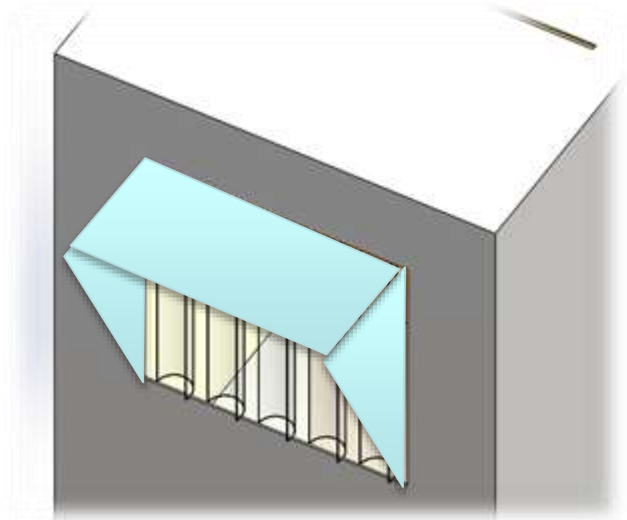
Receiver Innovations

Aperture Covers / Wind Diverters

- Quartz glass transmits solar radiation but creates a barrier to thermal radiation loss, wind, and convection loss
- Soiling of glass windows and reflective losses are challenges
  - Use quartz half-shells with spacing
  - Integrate with air curtain to reduce soiling

Mitigate risks of radiative/convective heat losses and particle losses while reducing reflective losses and soiling

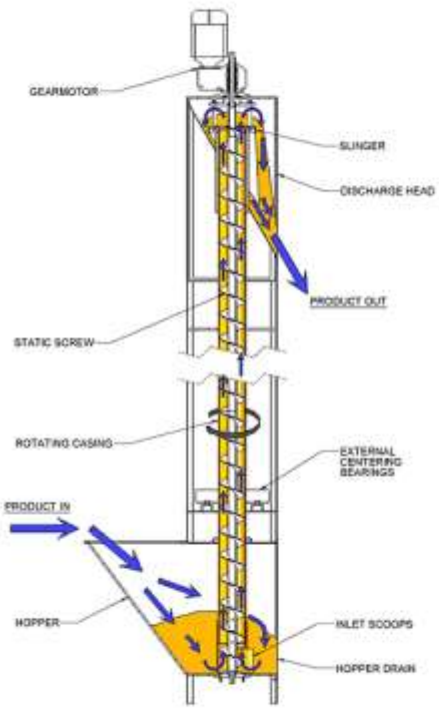


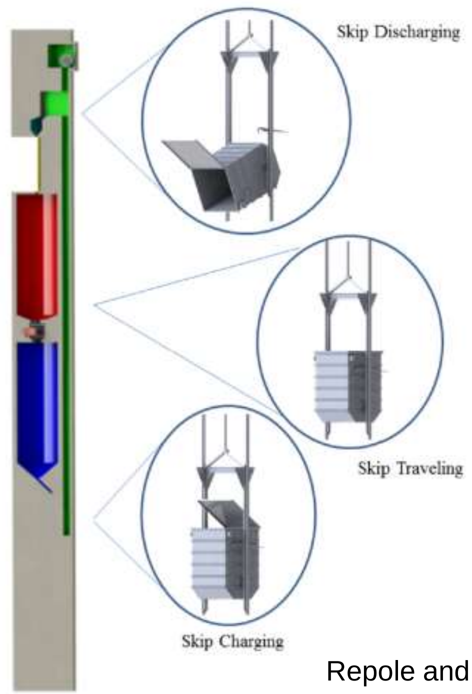


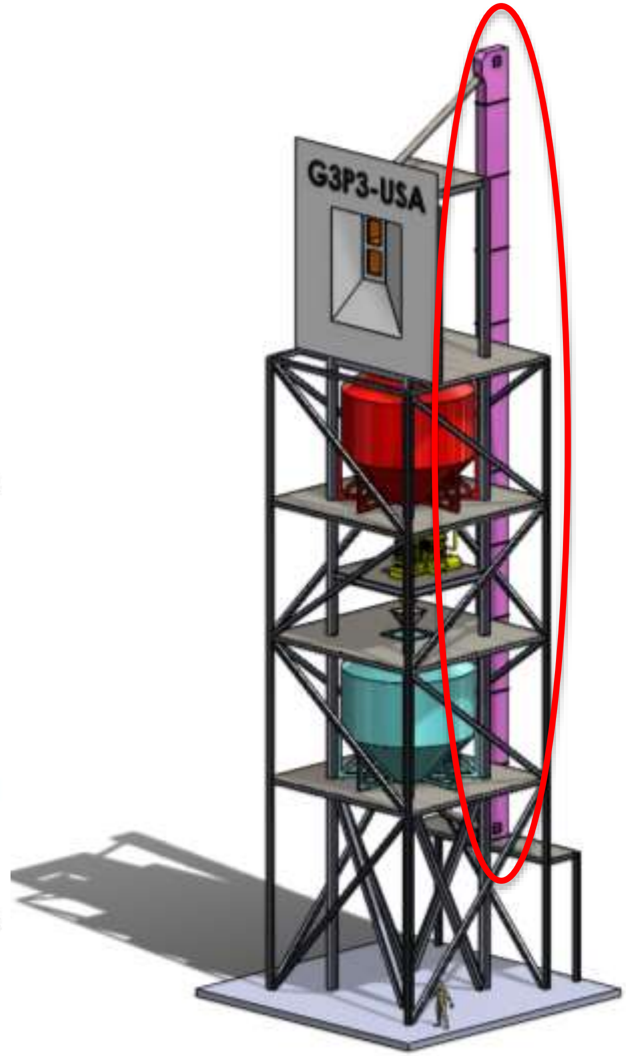
Patent Pending

Particle Lift

- Low particle abrasion and attrition
- High efficiency
- Insulation for minimal heat loss
- Sufficient flow capacity and control





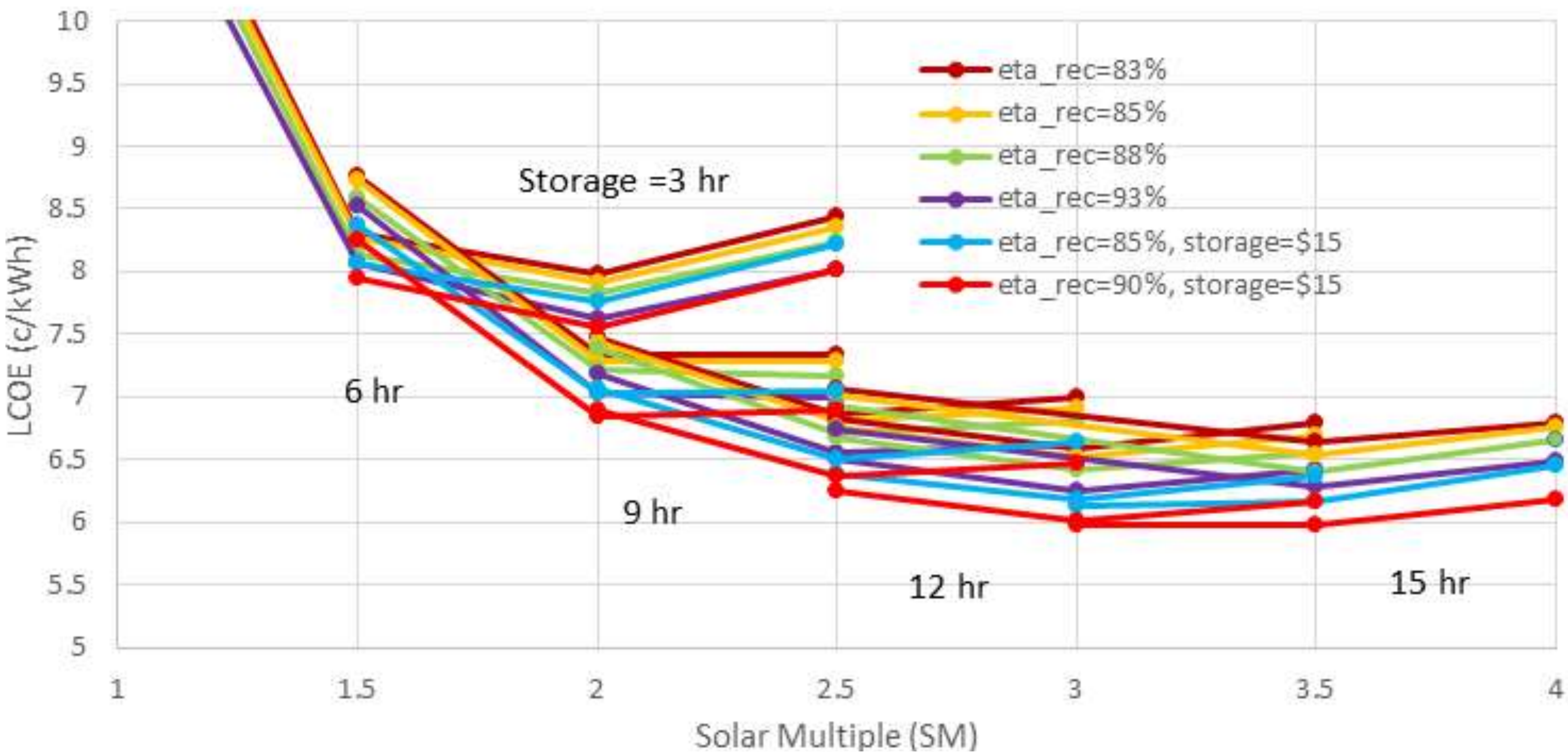


Repole and Jeter (2016)

Economics of Commercial Scale System

SAM Modeling of LCOE for 100 MW_e Particle Power Tower

Particle receiver and storage costs from [15] were used except where noted. All other costs assume SunShot targets.



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G3P3-USA

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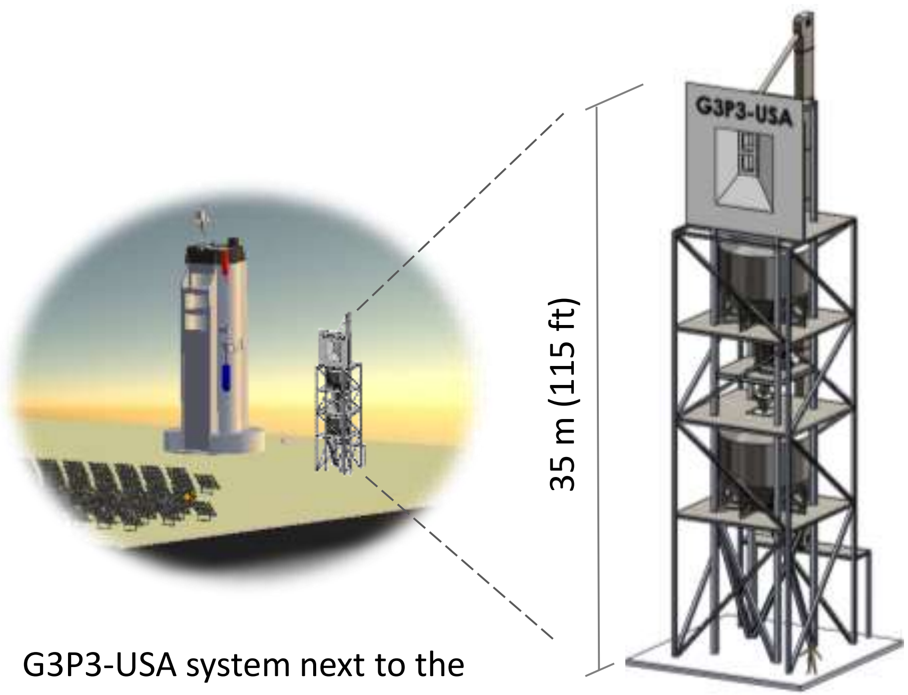

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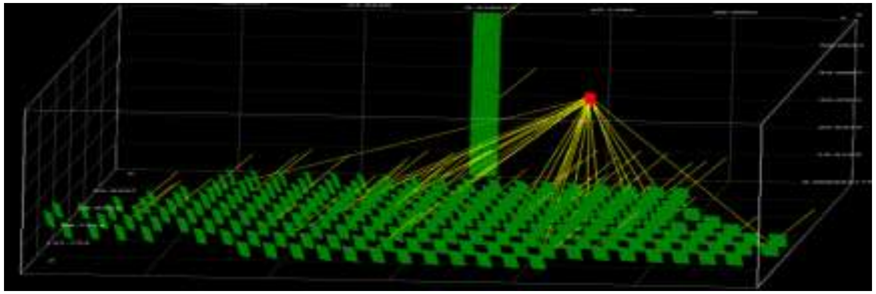

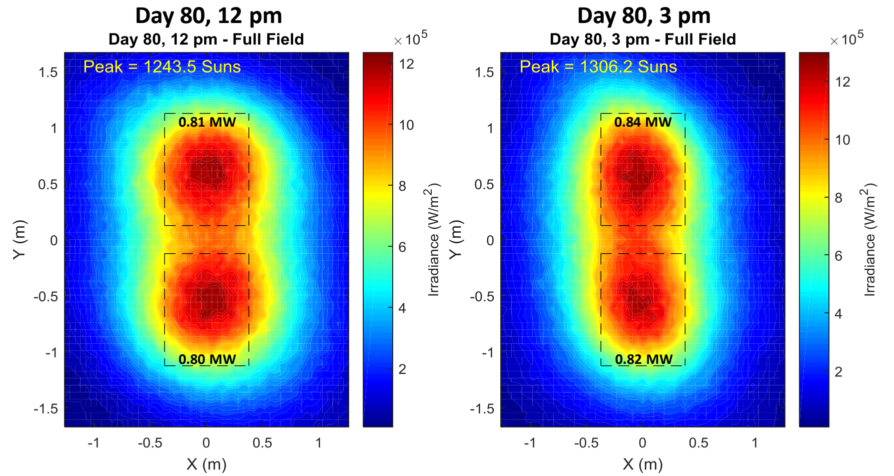

Particle Emissions & Dispersion Modeling

CARBO HSP particle plume dispersion
2 m/s west wind (right to left)

Fines (1-10 microns) emitted as gas at 5e-7 kg/s

350 micron particles emitted at 0.003 kg/s

Properties of Alternative Particles

Material	Composition	Properties		Advantage	Dis-advantage
		Density (kg/m^3)	Specific Heat (J/kg-K)		
Silica sand	SiO_2	2,610	1,000	Stable, abundant, low cost	Low solar absorptivity and conductivity; inhalation risk
Alumina	Al_2O_3	3,960	1,200	Stable	Low absorptivity
Coal ash	SiO_2, Al_2O_3, + minerals	2,100	720 at ambient temperature	Stable, abundant, No/low cost	Identify suitable ash, attrition
Calcined Flint Clay	SiO_2, Al_2O_3, TiO_2,Fe_2O_3	2,600	1,050	Mined abundant	Low absorptivity, attrition
Ceramic particles	75% Al_2O_3, 11%SiO_2, 9%$Fe_2O_{3,}$3%TiO_2	3,300	1,200 (at 700°C)	High solar absorptivity, stable	Relatively higher cost

Mitigate risks of attrition, high cost, and low heat absorption