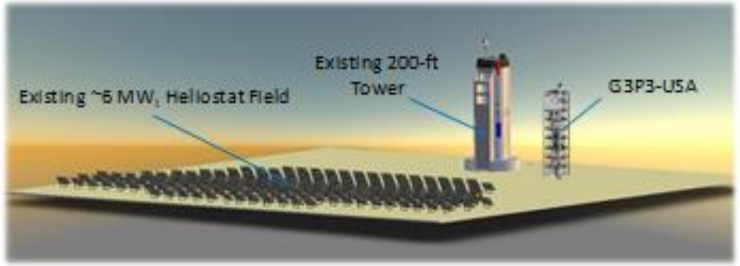
Gen3 Particle Pilot Plant (G3P3) – Next Generation Concentrating Solar Thermal Power



PRESENTED BY

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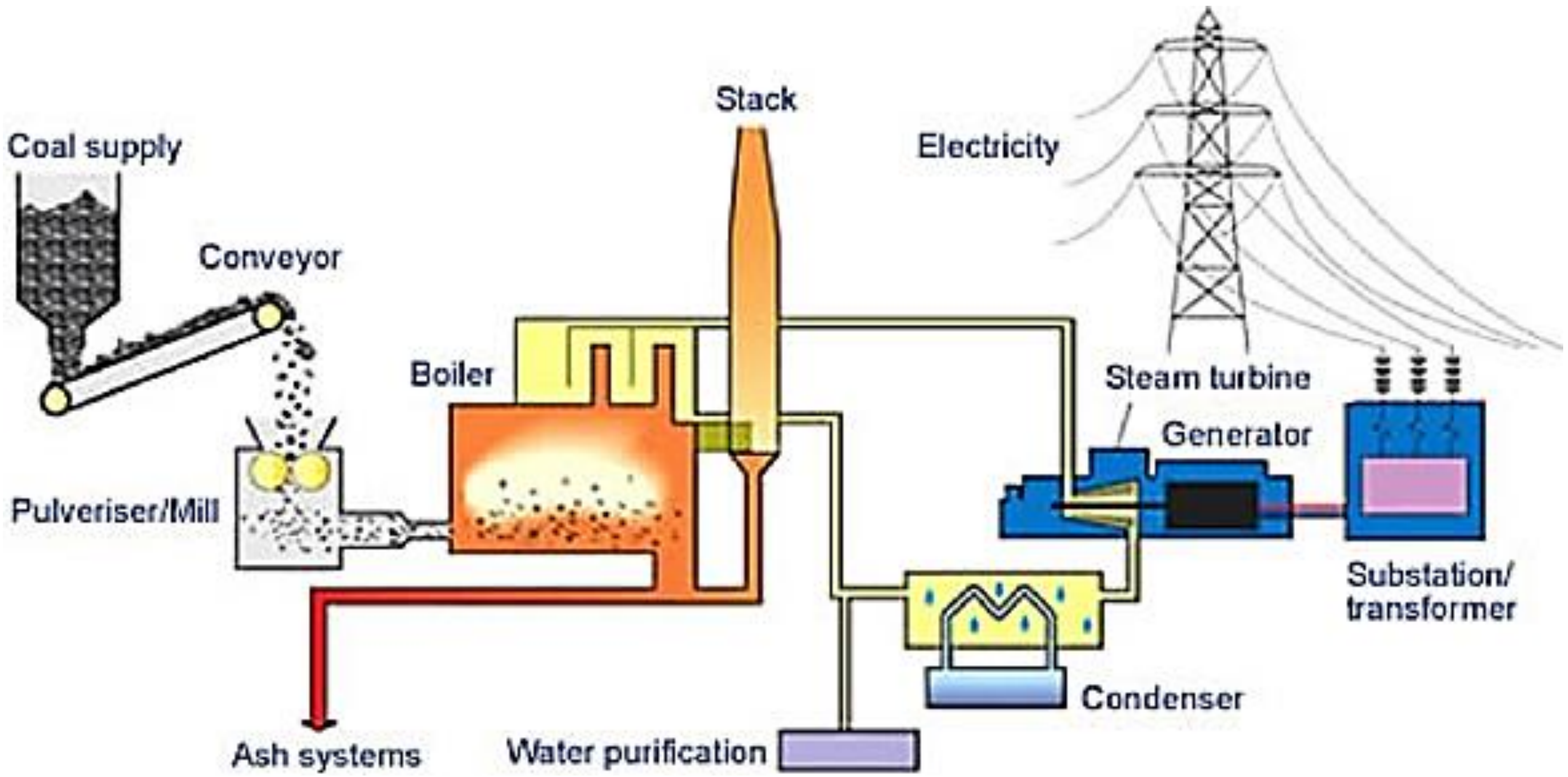
Outline

- Introduction to concentrating solar thermal power (CSP)
- Challenges with CSP and intro to Gen 3
- Gen 3 Particle Pilot Plant overview

What is Concentrating Solar Power (CSP)?

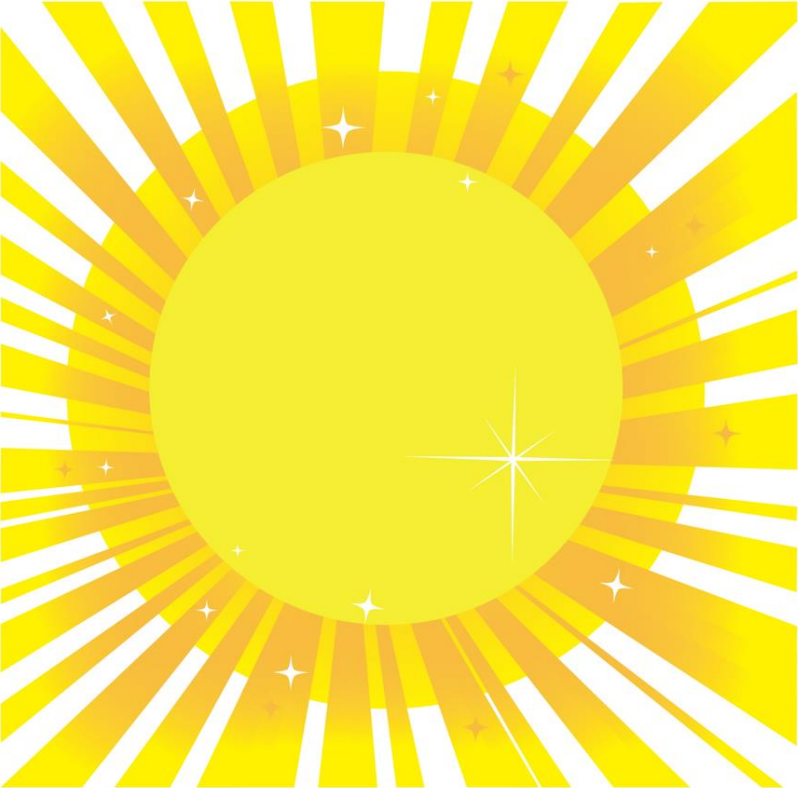
Conventional power plants burn fossil fuels (e.g., coal, natural gas) or use radioactive decay (nuclear power) to generate heat for the power cycle

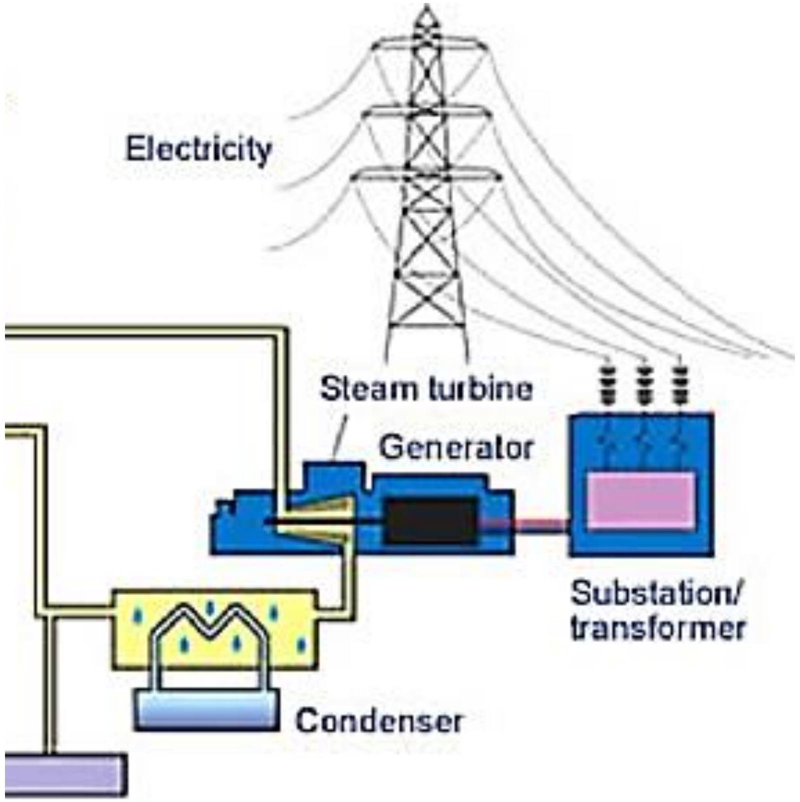


Coal-Fired Power Plant

What is Concentrating Solar Power (CSP)?

CSP uses concentrated heat from the sun as an alternative heat source for the power cycle

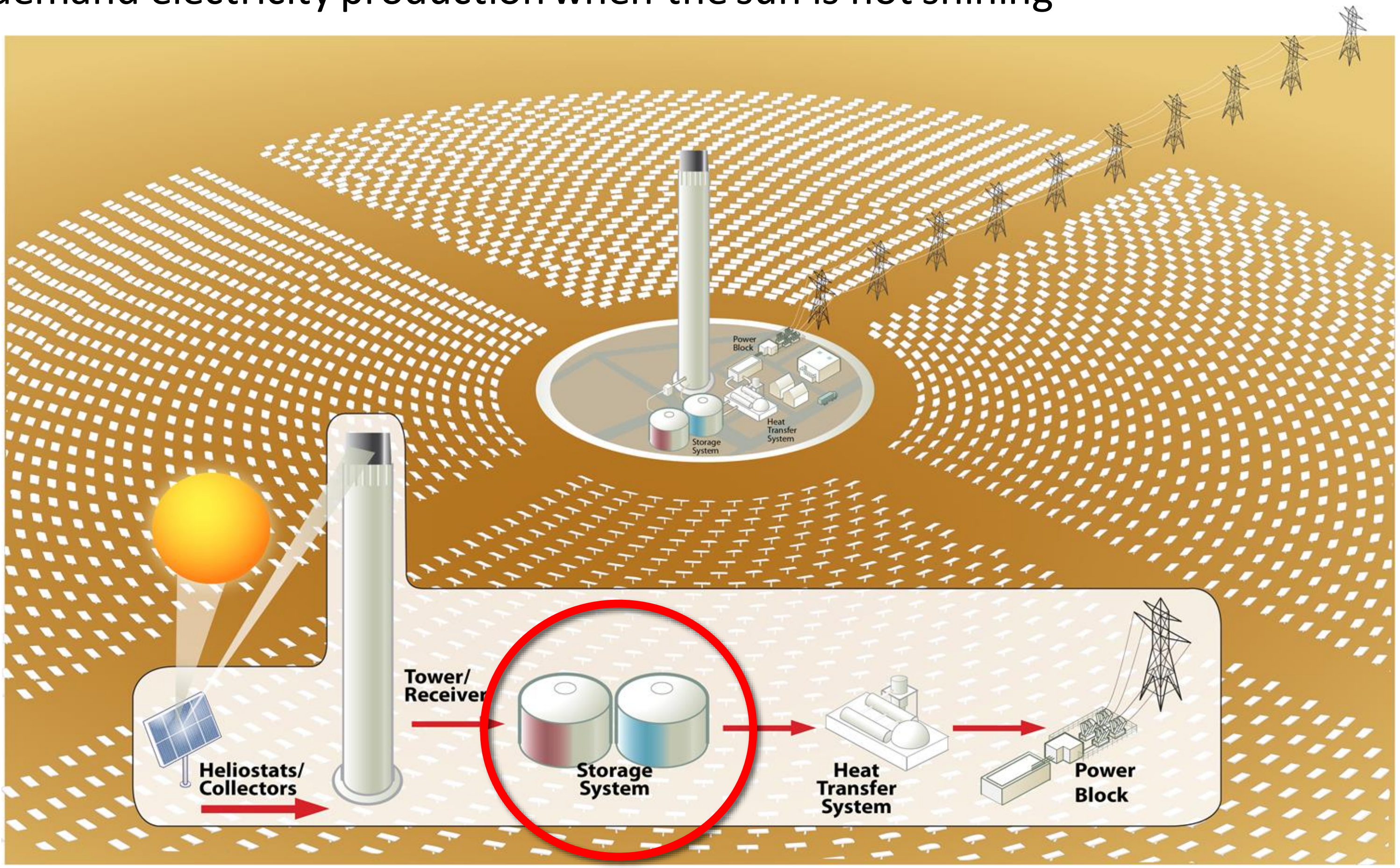




Concentrating Solar Power

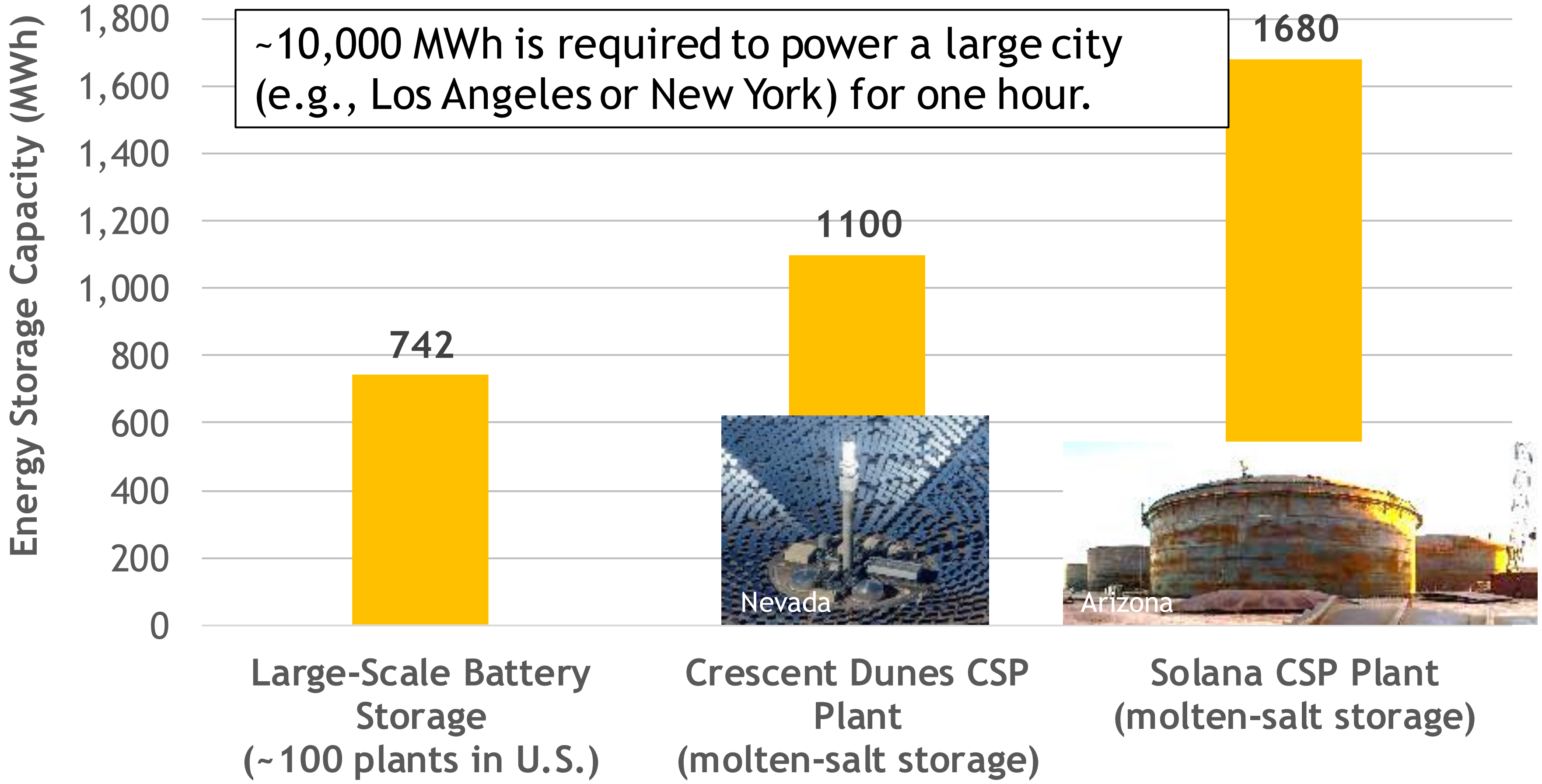
CSP and Thermal Energy Storage

- Concentrating solar power uses mirrors to concentrate the sun's energy onto a receiver to provide heat to spin a turbine/generator to produce electricity
- **Hot fluid can be stored as thermal energy efficiently and inexpensively** for on-demand electricity production when the sun is not shining



Growing Need for Large-Scale Energy Storage

Battery data from U.S. Energy Information Administration (June 5, 2018)
CSP data from https://solarpaces.nrel.gov/projects



Timeline of CSP Development

Solar One and
Solar Two
10 MW_e
Daggett, CA
1980's – 1990's

Stirling Energy Systems
1.5 MW_e, AZ, 2010

Ivanpah, steam, 377 MW_e, CA, 2014

1970's → 1980's – 1990's → 2000's → SunShot 2011 -

National Solar Thermal Test Facility
6 MW_t, Albuquerque, NM, Est. 1976

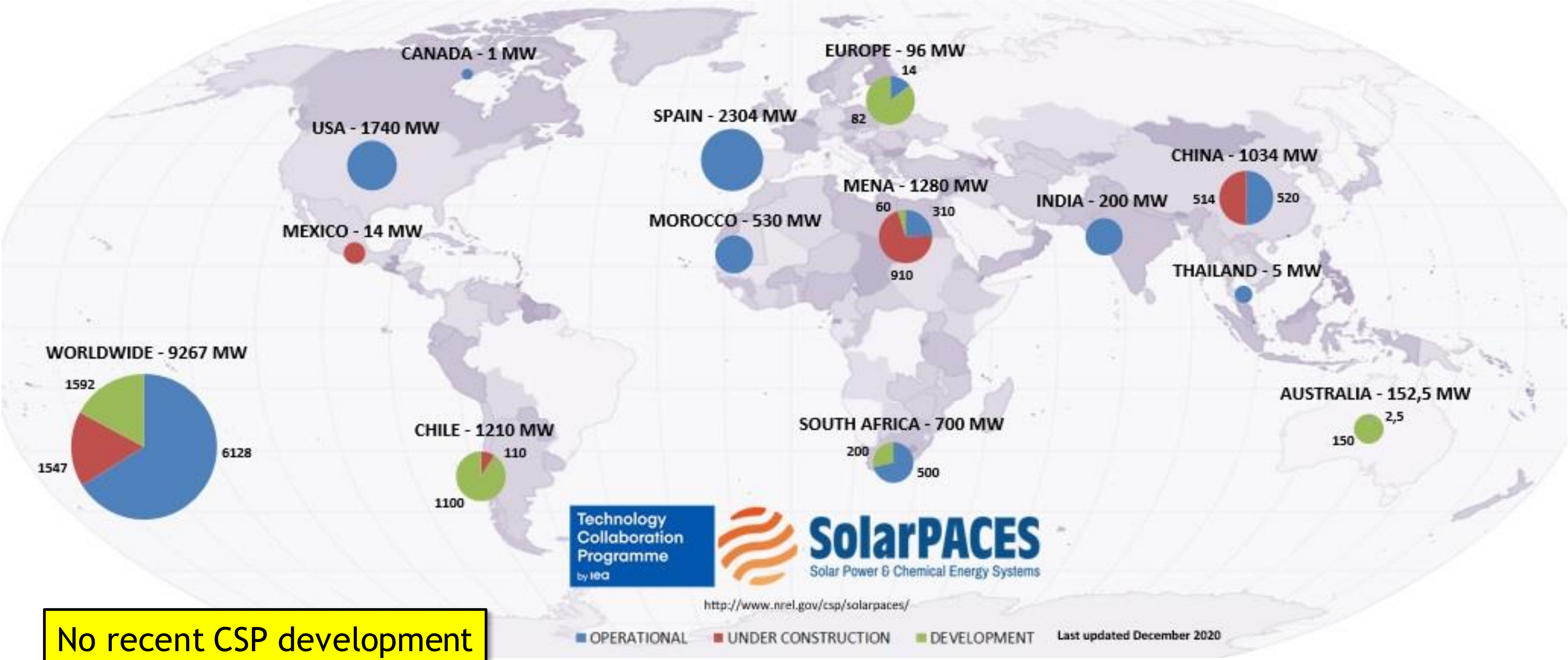
SEGS, 1980's
9 trough plants
354 MW_e, CA

PS10/20, steam, Spain, 2007-2009

Gemasolar, molten salt, 19 MW_e, Spain, 2011

Crescent Dunes, molten salt, 110 MW_e, NV, 2015

Global Concentrating Solar Power Plants



No recent CSP development in the U.S.

Outline

- Introduction to concentrating solar thermal power (CSP)
- Challenges with CSP and intro to Gen 3
- Gen 3 Particle Pilot Plant overview

Challenges Facing CSP

Cost

- CSP is ~$0.07 - $0.10/kWh (levelized cost of energy)
- Solar PV and wind are ~$0.02 - $0.04/kWh (**no storage)**
- Levelized cost of battery systems > ~$0.10/kWh*

Policies/mandates

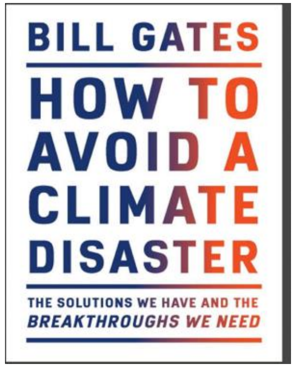
- Meeting renewable portfolio standards driven by "lowest bid"
- States and policies have generally not valued storage (no need for > 4 hours)

"Bankability" (reliability/risk)

- High up-front capital costs for CSP (no fuel cost)
- **CSP and thermal storage for process-heat is nascent**; few demonstrations
- Perceived reliability issues (Crescent Dunes), need for backup fuels (Ivanpah), safety issues ("vaporizing" birds)

Why Now? Higher penetrations of intermittent renewables require economical longer-duration energy storage ⇒ CSP & thermal storage

Why Now? Need to decarbonize heating sector



*For ~4 hrs of daily use
https://www.nature.com/articles/s41467-019-09988-z

Challenges with Current State-of-the-Art CSP

- Current state-of-the-art CSP uses molten salt as storage media
  - Decomposes at temperatures ~600 ˚C
  - Freezes at ~200 ˚C
    - Requires expensive trace heating everywhere the salt touches
- Need higher temperatures to reduce costs
  - More efficient power cycles (supercritical CO_2 Brayton Cycles >700 ˚C)
  - Air Brayton Combined Cycles (>1000 ˚C)
  - Thermochemistry & Solar Fuels (>1000 ˚C)

➡ Need higher-temperature CSP systems (>700 ˚C)

Outline

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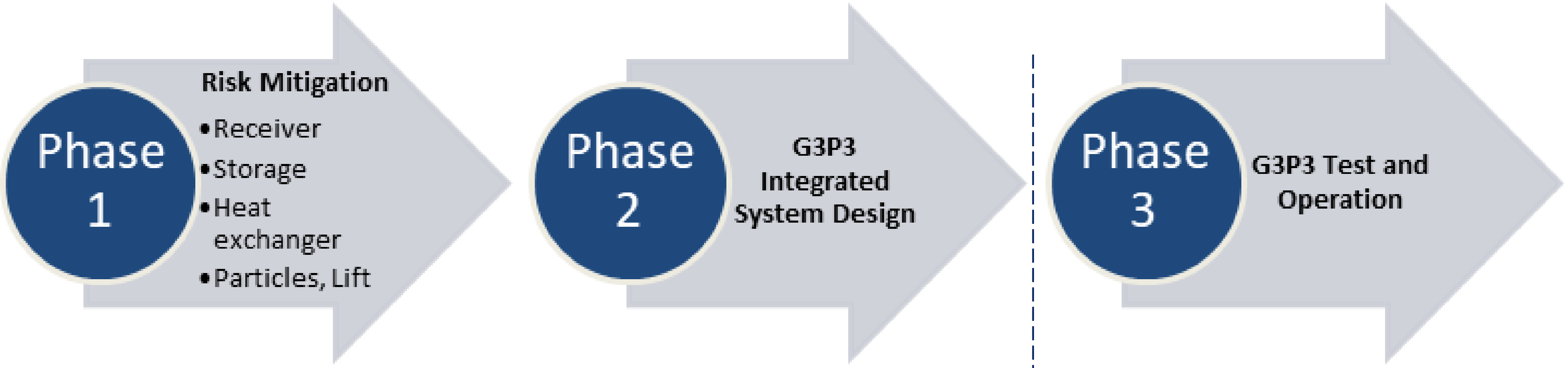
Gen 3 CSP Program (FY19 – FY24)

Achieve higher operating temperatures (>700 °C) for greater efficiency and lower LCOE ($0.05/kWh$_e$)

Brayton Energy	NREL	Sandia
Gas Phase Pathway	Liquid Phase Pathway	Solid Phase Pathway



18 months
FY19 – FY20

6 months
FY20

DOE Downselection (March 2021)

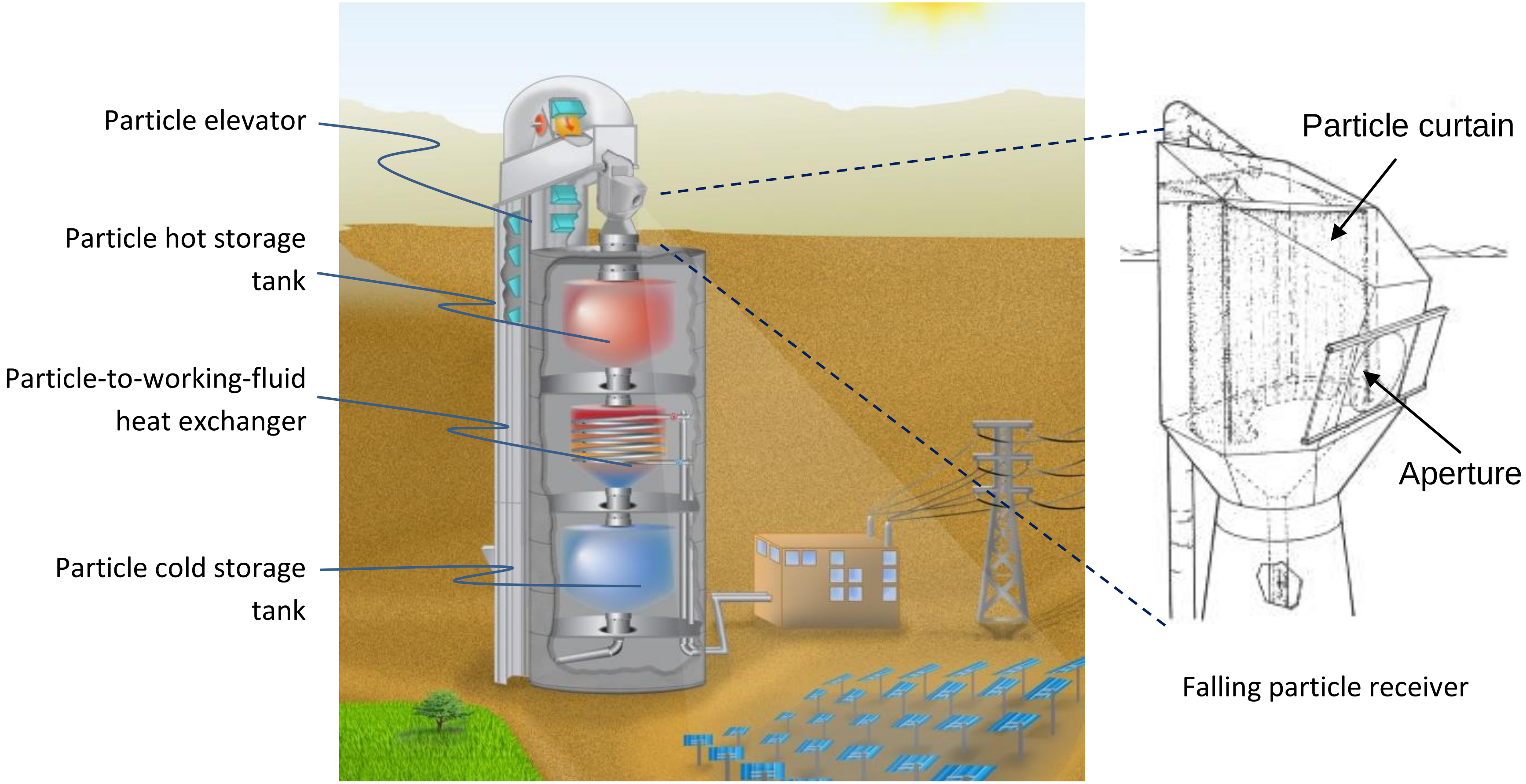
3 years
FY21 – FY23

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	
CSP Developers	• SolarDynamics	
Component Developers / Industry	• Carbo Ceramics • Solex Thermal Science • Vacuum Process Engineering • FLSmidth	• Materials Handling Equipment • Allied Mineral Products • Matrix PDM
Utility	• Saudi Electric Company	

Background and Introduction

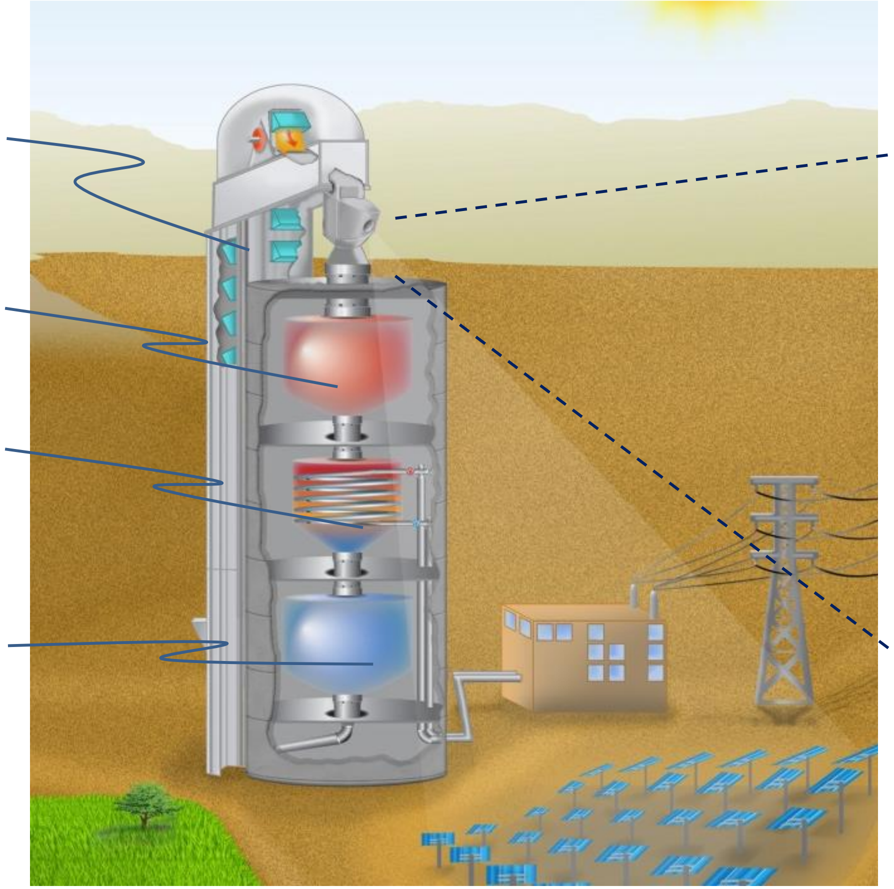
High-Temperature Particle-Based CSP

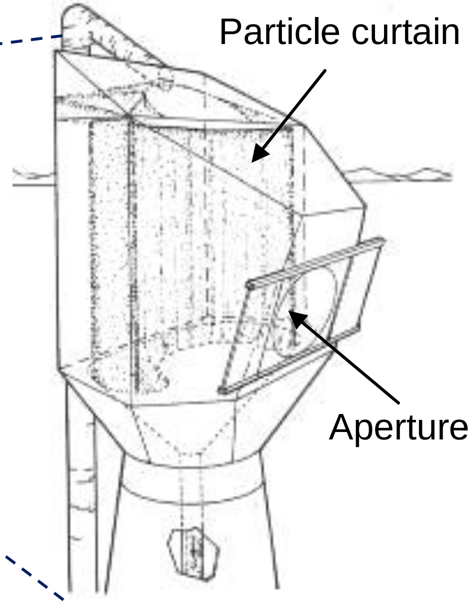


Falling particle receiver

Background and Introduction

High-Temperature Particle-Based CSP



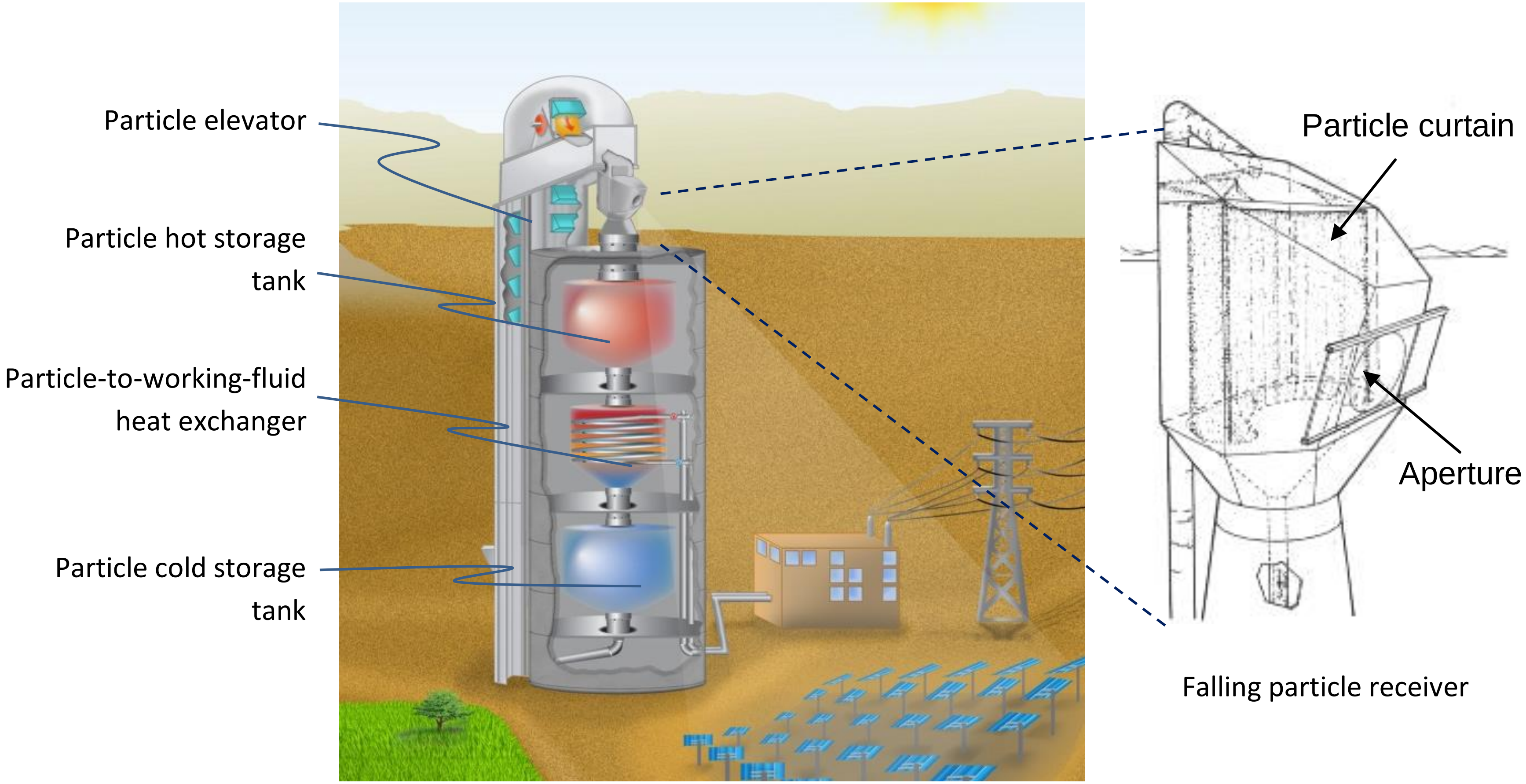


Falling particle receiver

National Solar Thermal Test Facility
Sandia National Laboratories

Background and Introduction

High-Temperature Particle-Based CSP

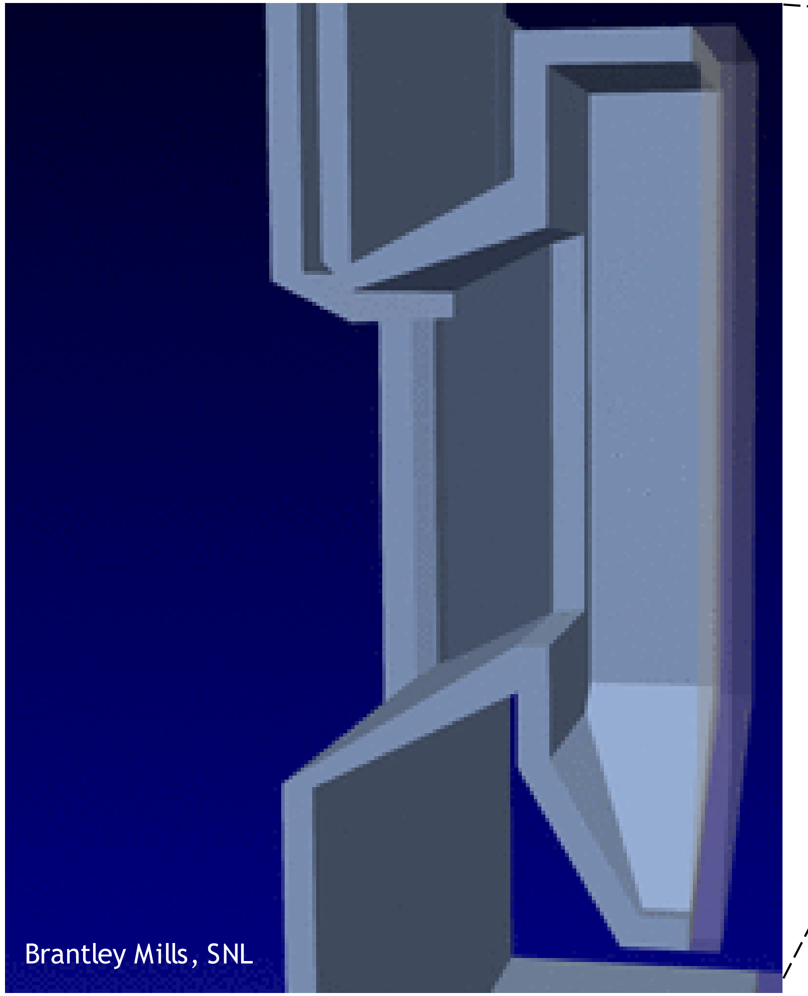


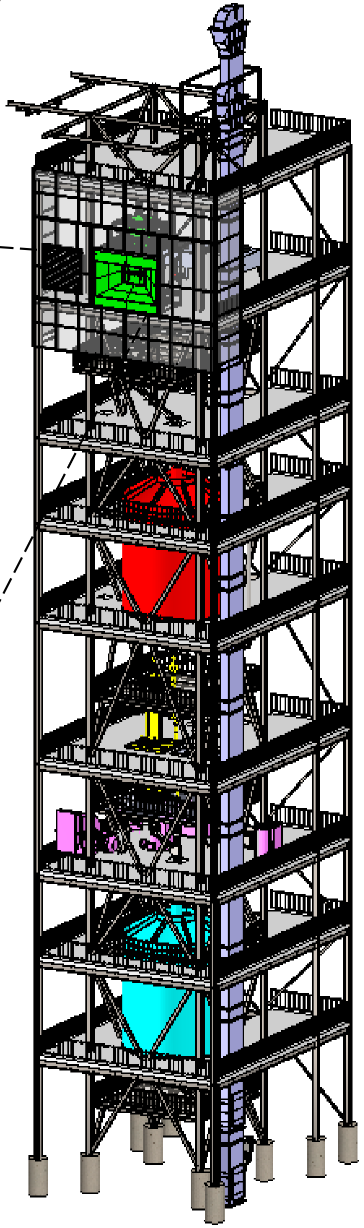
Falling particle receiver

- Higher temperatures (>1000 °C) than molten nitrate salts
- Direct heating of particles vs. indirect heating of tubes
- No freezing or decomposition
  - Avoids costly heat tracing
- Direct storage of hot particles

Gen3 Particle Pilot Plant (G3P3)

Next-Generation High-Temperature Falling Particle Receiver





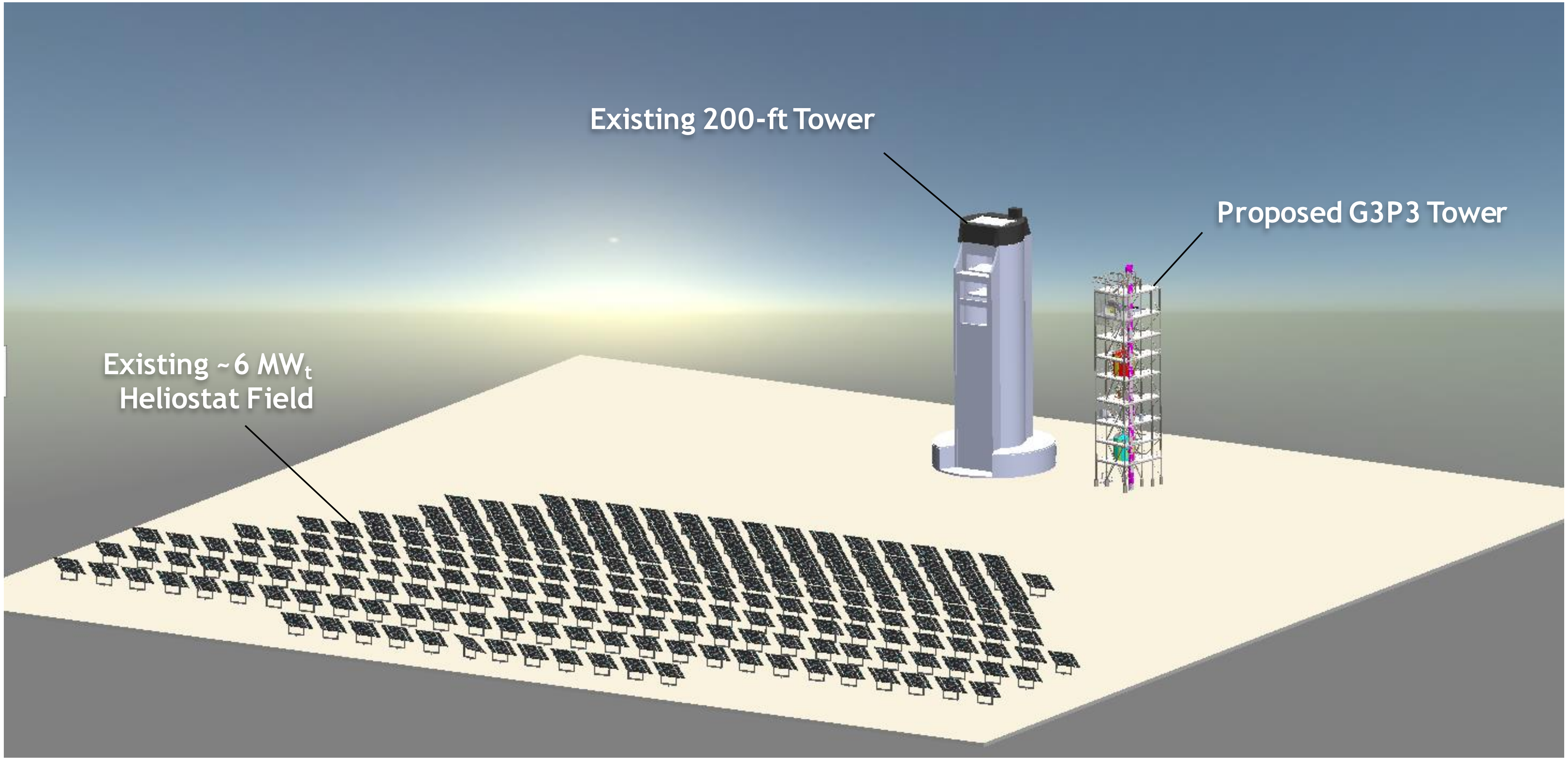
Gen 3 Particle Pilot Plant

- ~1 – 2 MW_t receiver
- 6 MWh_t storage
- 1 MW_t particle-to-sCO_2 heat exchanger
- ~300 – 400 micron ceramic particles (CARBO HSP 40/70)

K. Albrecht, SNL

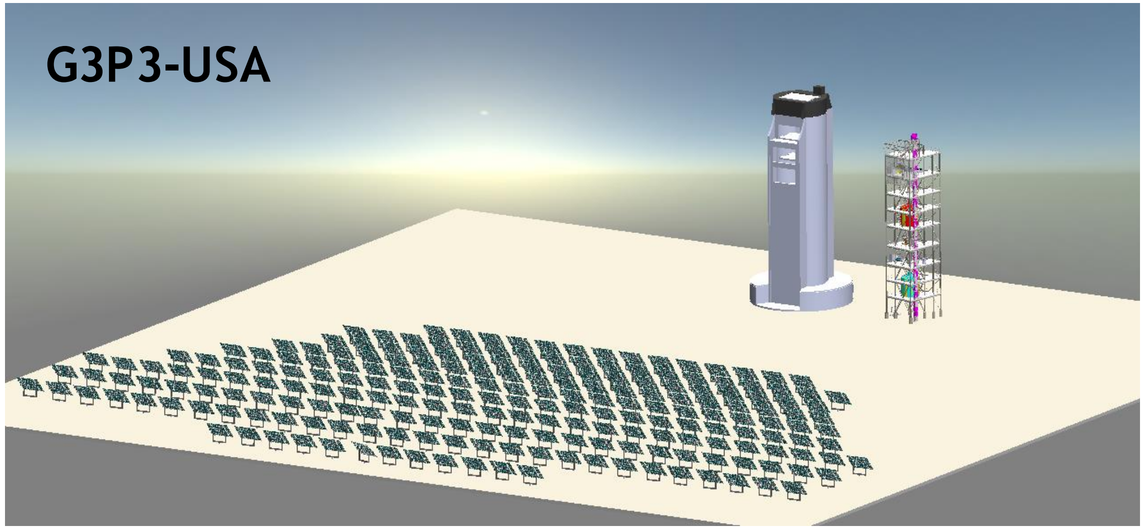
Gen 3 Particle Pilot Plant (G3P3)
Integrated System

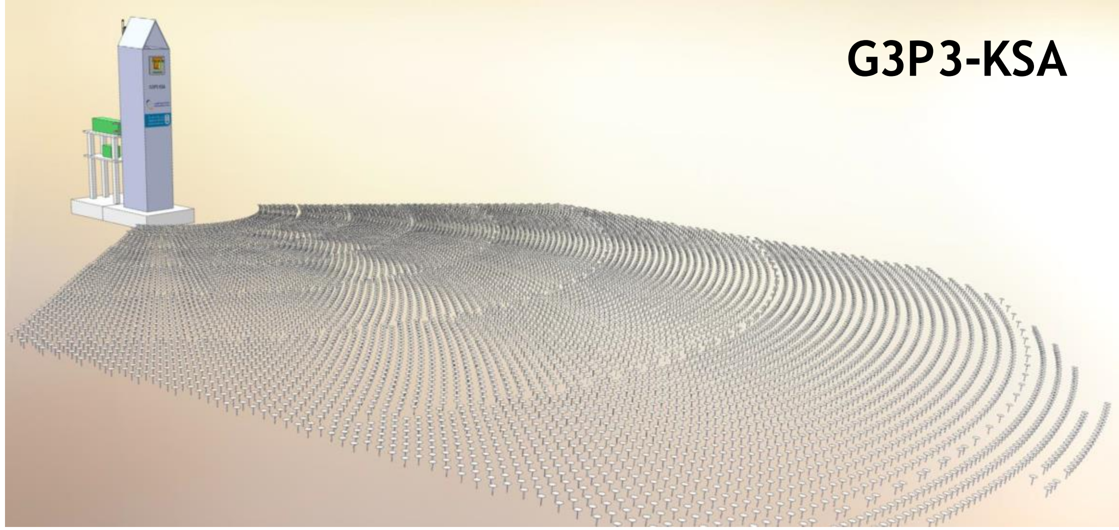
National Solar Thermal Test Facility (NSTTF), Albuquerque, NM

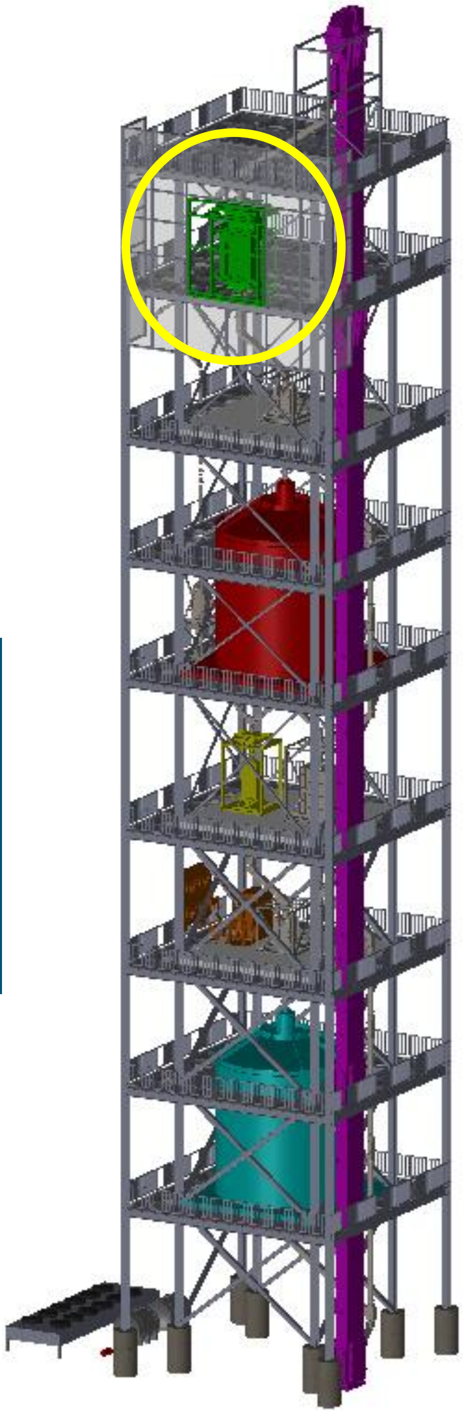


G3P3-USA and G3P3-KSA

Parameter	G3P3-USA	G3P3-KSA
Receiver	~2 MW_t	6 – 7 MW_t
Solar multiple	~2	~2
Particles	CARBO HSP 40/70	Silica sand or Carbobead
Receiver	Multi-stage, 775°C, ΔT=160°C	Obstructed flow; up to 1000°C, ΔT=400°C
Heat exchanger	1 MW_t duty; shell-and-plate; 20-25 MPa sCO2	~3 MW_t duty; shell-and-tube; 400 kPa air
Particle Lift	Bucket elevator	Skip hoist
Power block	~1 MW_t sCO2 flow loop	1.3 MW_e Air Brayton turbine/generator (Aurelia A1300)



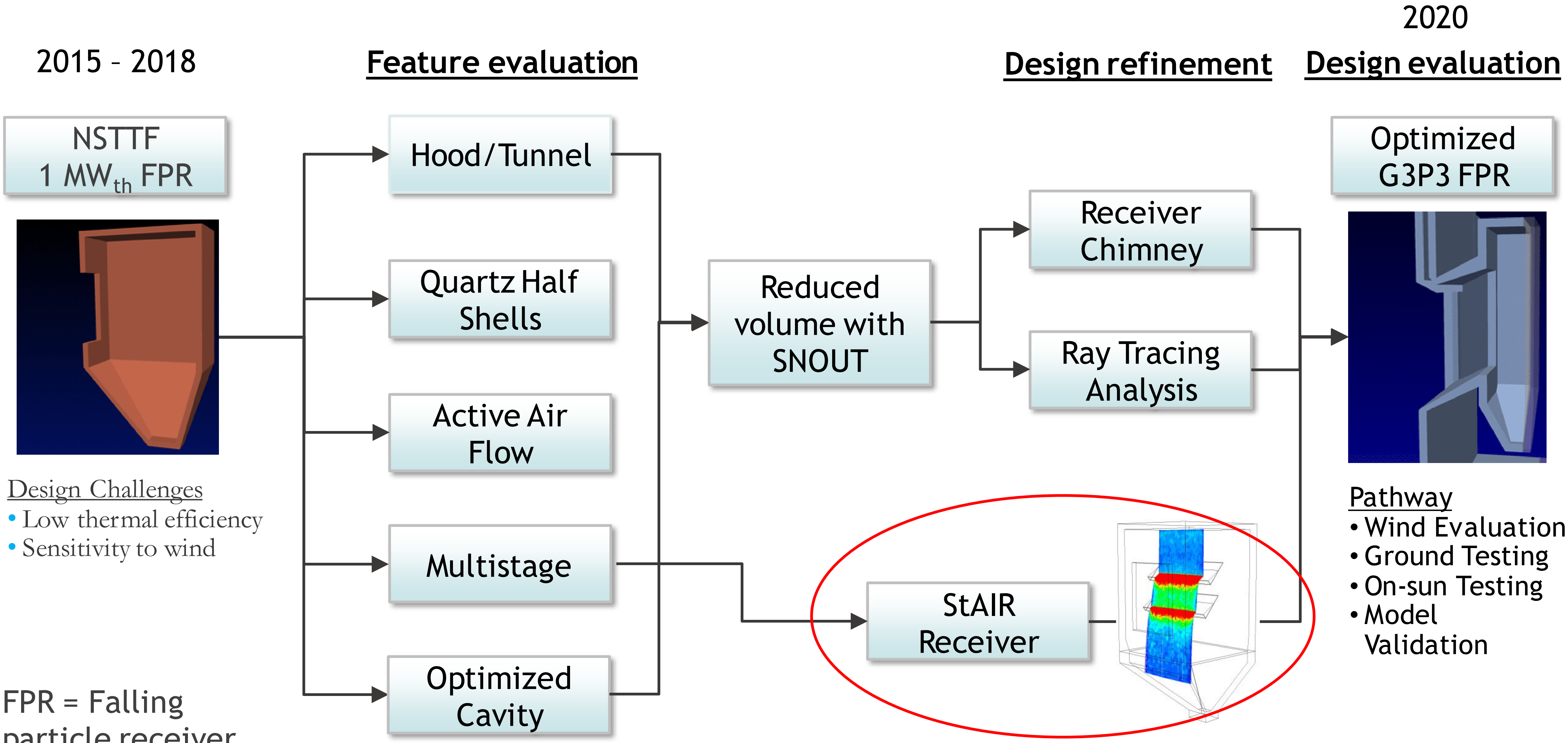




Particle Receiver R&D

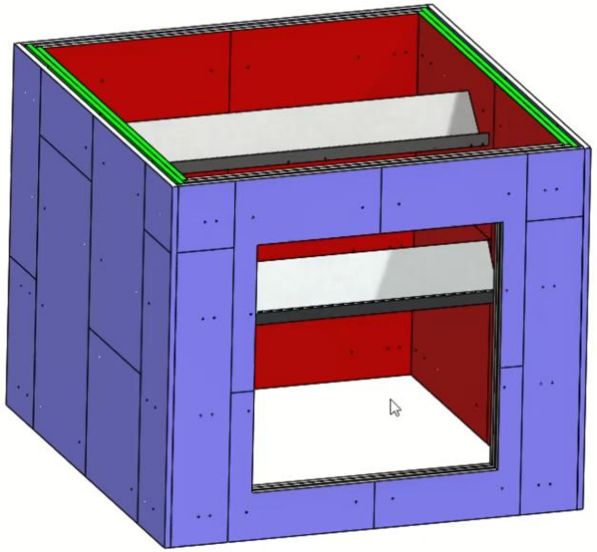
Brantley Mills, Reid Shaeffer, Lindsey Yue

G3P3-USA Receiver Design Evolution



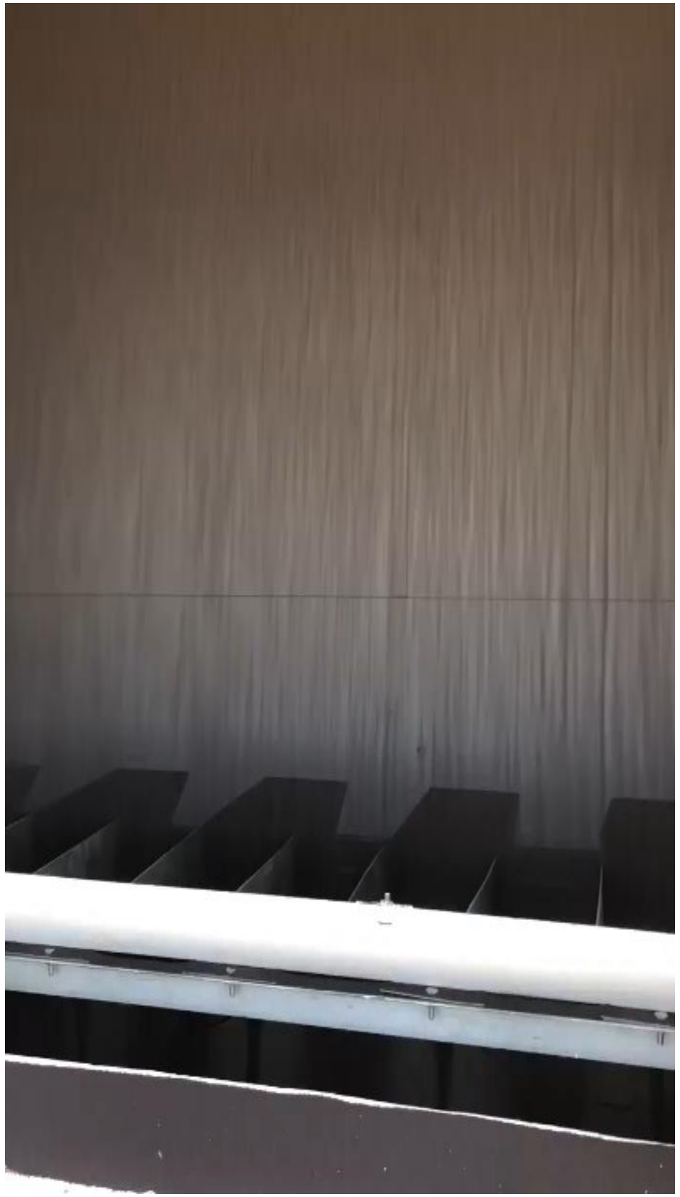
FPR = Falling particle receiver

StAIR (Staggered Angle Iron Receiver) Testing



Drawing of “stairs” in receiver cavity

Particle flow over two-stair configuration (5 – 10 kg/s)

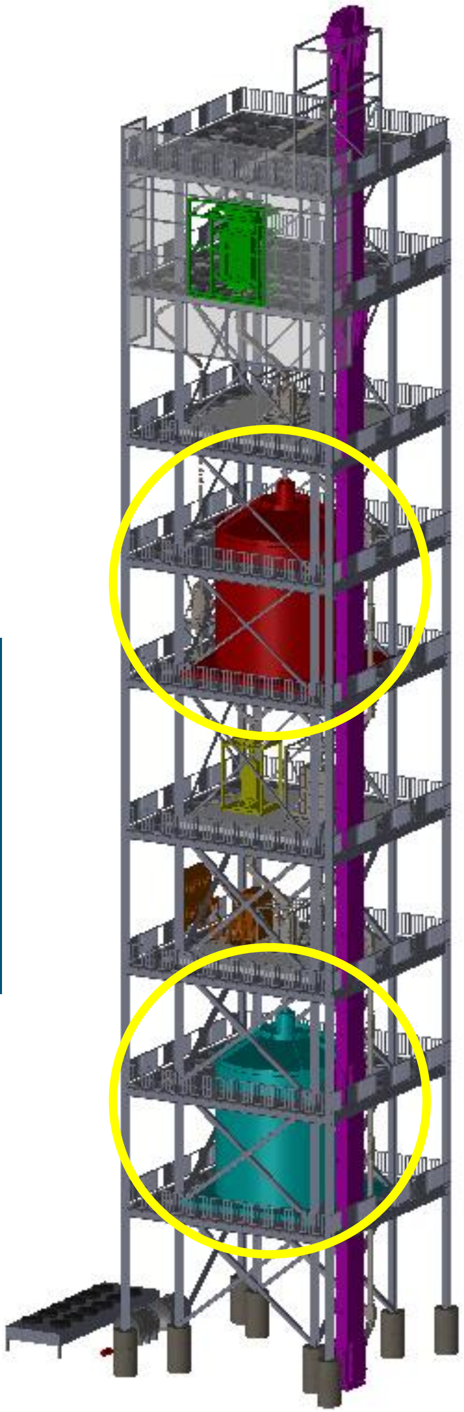


StAIRS create a more uniform and opaque particle curtain for increased solar absorptance

On-Sun Testing at Sandia

On-sun testing of particle receiver with StAIRs and reduced volume

Particle Sampling



Particle Storage R&D

Jeremy Sment

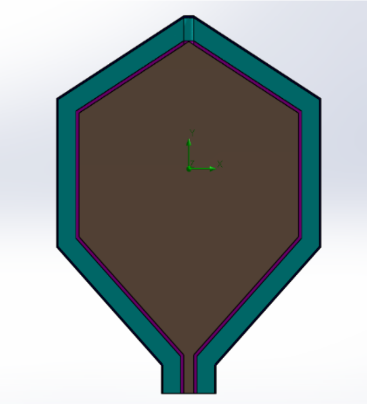
Key Partners:

ALLIED MINERAL PRODUCTS

MATRIX PDM ENGINEERING

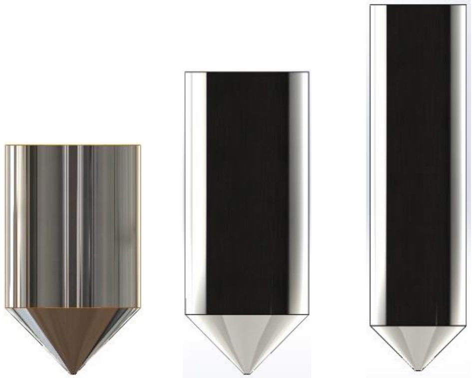
Tulsa University and King Saud University

Storage Design Evolution

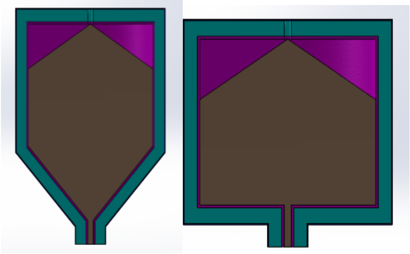


Initial Design

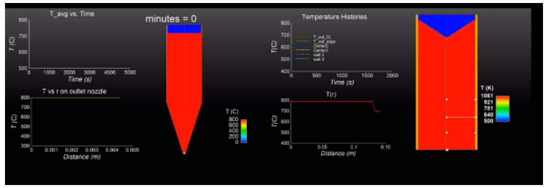
Feature 1: Form Factor



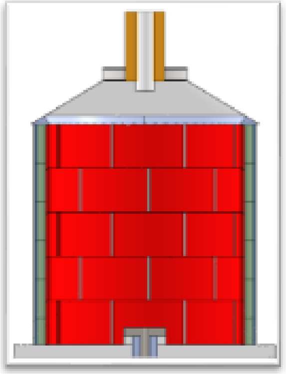
Feature 2: Floor Design

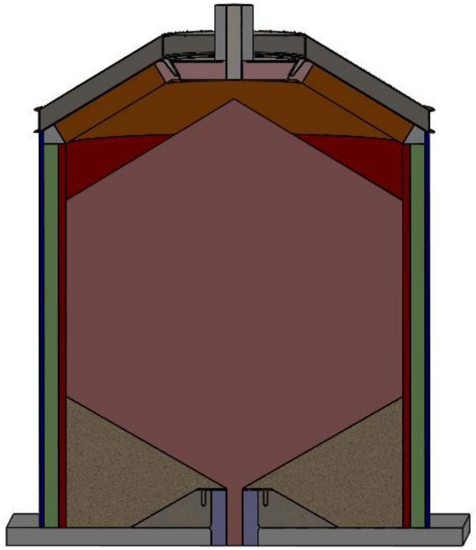


Feature 3: Mass Flow vs. Funnel Flow



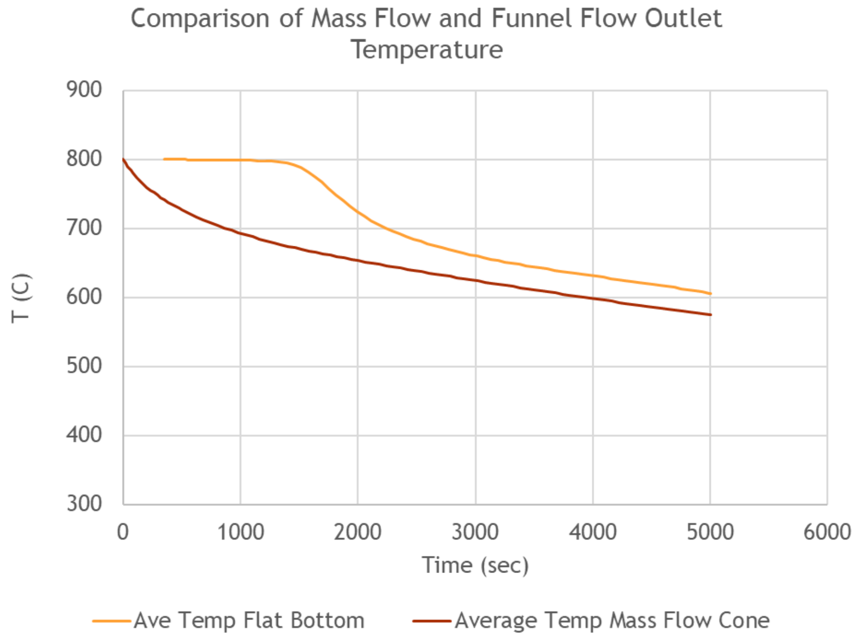
Feature 4: Refractory Insulation Layers





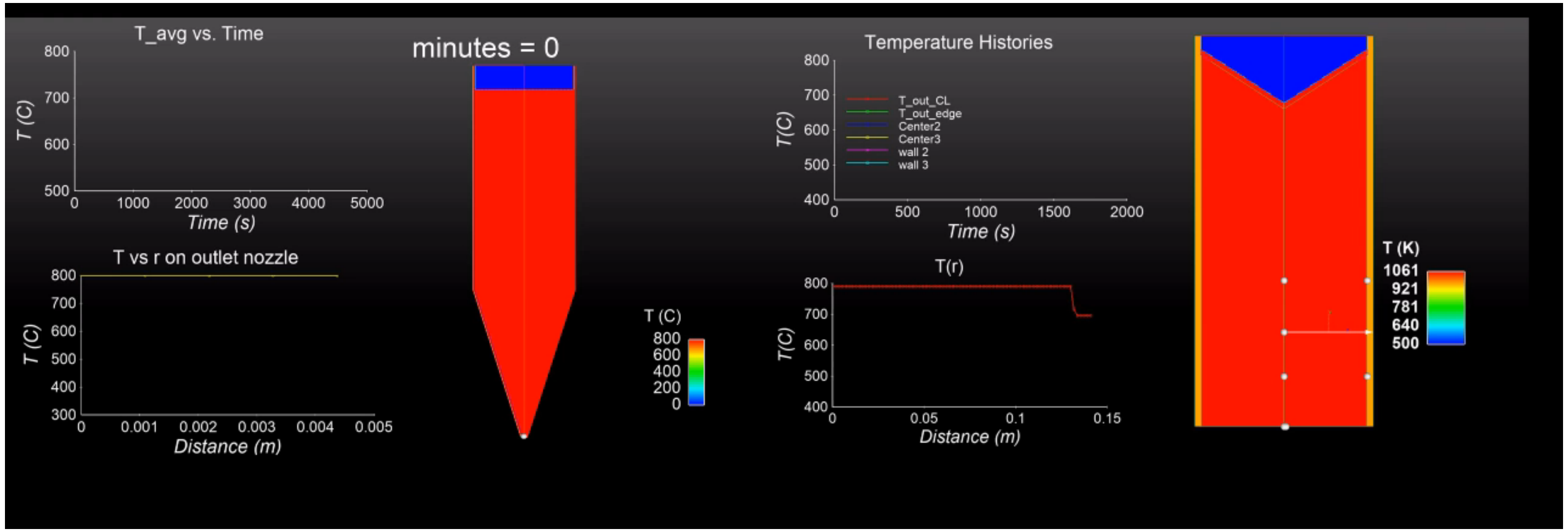
Baseline Design

Dynamic Discharging: Funnel Flow vs. Mass Flow



Mass Flow

Funnel Flow



Funnel-flow bin is expected to yield less heat loss and wall erosion than conventional mass-flow bin

Particle Heat Exchanger R&D

Presented by Kevin Albrecht

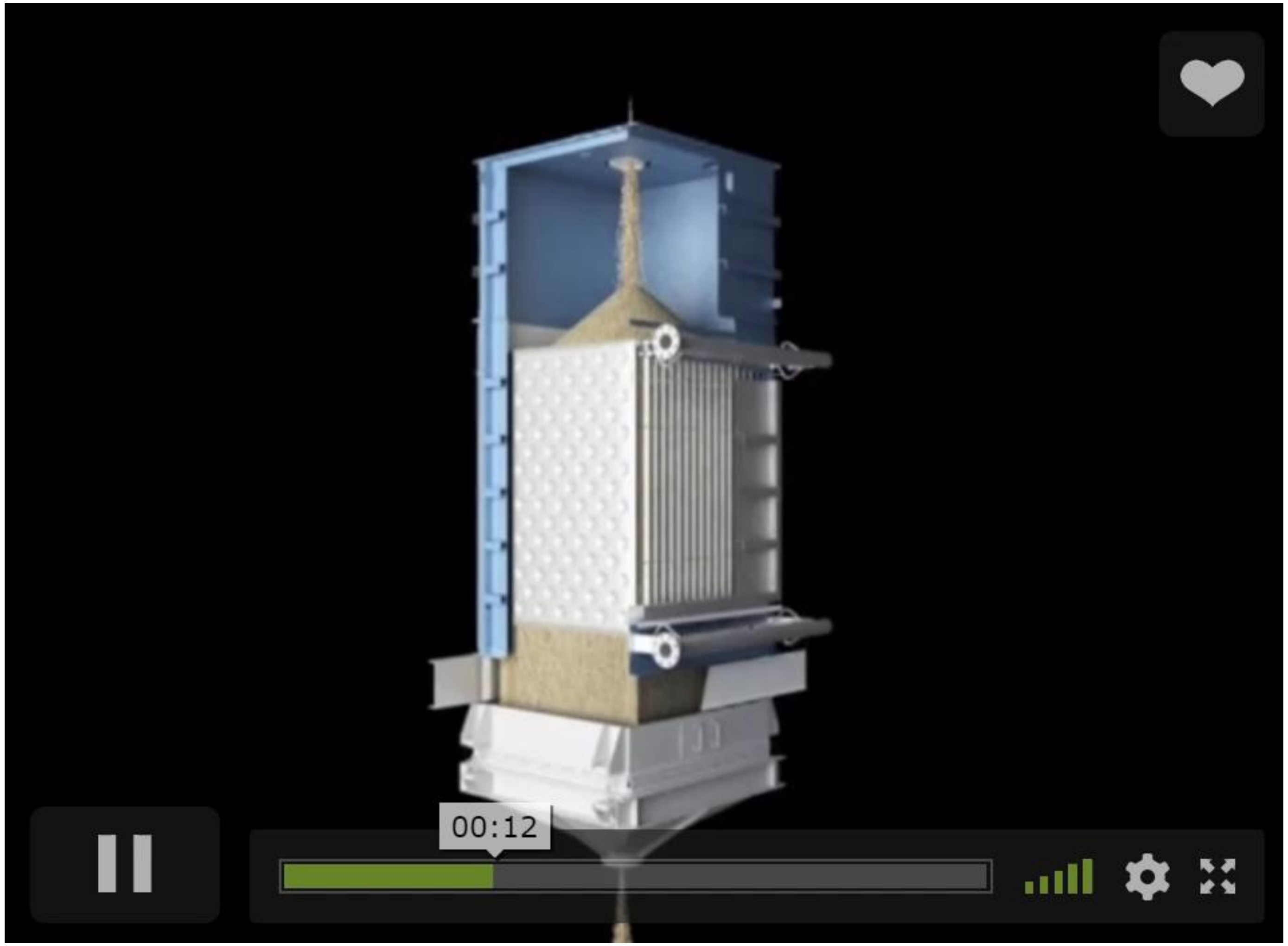
Key Partners:

SOLEX THERMAL SCIENCE

VPE VACUUM PROCESS ENGINEERING

Particle Heat Exchanger

Solex Thermal Science



https://www.solexthermal.com/our-technology/cooling/

High-T, High-P Particle-to-sCO2 Heat Exchanger

100 kW particle-to-sCO2 heat exchanger

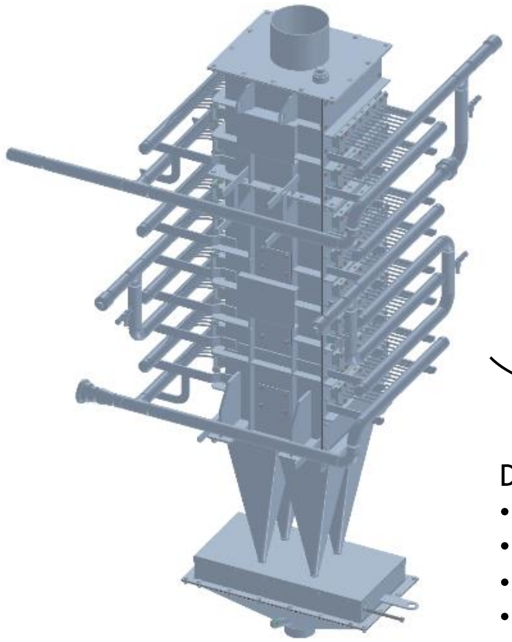
~100 kW sCO2 flow loop

Integration of heat exchanger and sCO2 flow loop in tower

On-sun testing of integrated system with falling particle receiver

G3P3-USA Heat Exchanger Design Evolution

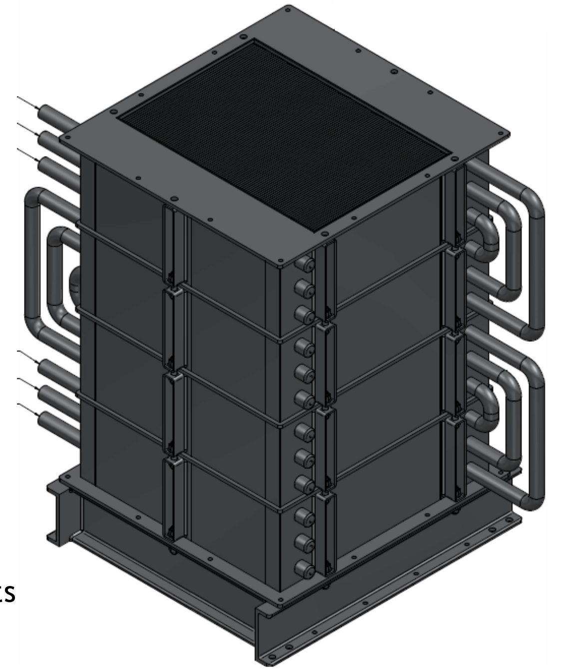
SuNLaMP 100 kW_t Prototype



Design Improvements:
- Closer plate spacing (HTC)
- Remove plate nozzles
- Single outlet cone
- Heat exchanger edge effects
- No particle case

Design Challenges:
- High pressure drop
- Low heat transfer coefficient
- sCO_2 flow maldistribution
- Particle flow nonuniformity
- Particle-side instrumentation
- Heat exchanger edge effects
- High heat loss
- Difficult to manufacture

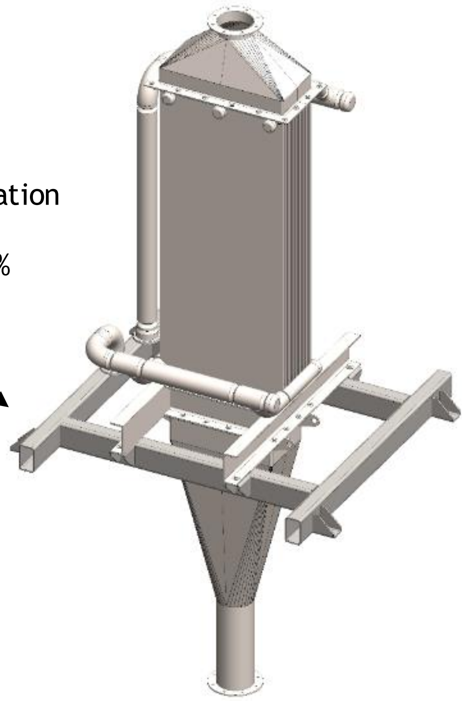
Initial G3P3 Concept



Design Improvements:
- Counterflow configuration
- No interbank piping
- Pressure drop below 2%
- Conceptually scalable

Design Challenges:
- High pressure drop
- Large material wastage
- Substantial sCO_2 external pipe
- Large thermal mass (startup)
- Sharp change in material thickness

Current G3P3 Concept



Design Challenges/Future Work:
- Commercial scale technoeconomics
- Limited ramp rate

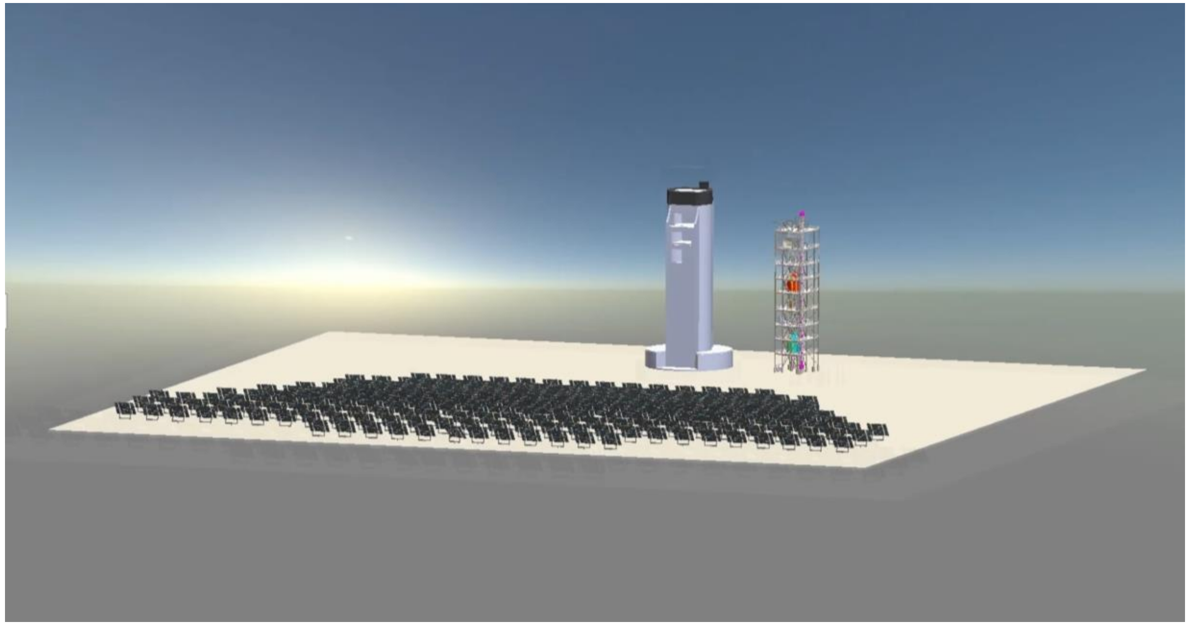
Achieved ~300 W/m^2-K overall heat-transfer coefficient with low pressure drop (0.4%)

CSP Outlook

U.S. Investment in CSP R&D

- DOE Gen 3 CSP (~$70M)
  - Develop next generation high-temperature solar-thermal power generation (FY19 – FY23)
- DOE TESTBED/Heliogen
  - $39M DOE, $30M cost share FY20 – FY24
  - Solarized supercritical CO_2 power cycle with thermal storage; solar fuels
  - **Sandia is a key partner**
- DOE Annual Lab and FOA calls
  - ~$30M - $60M per year in CSP and solar thermal R&D

Sandia Gen 3 Particle Pilot Plant



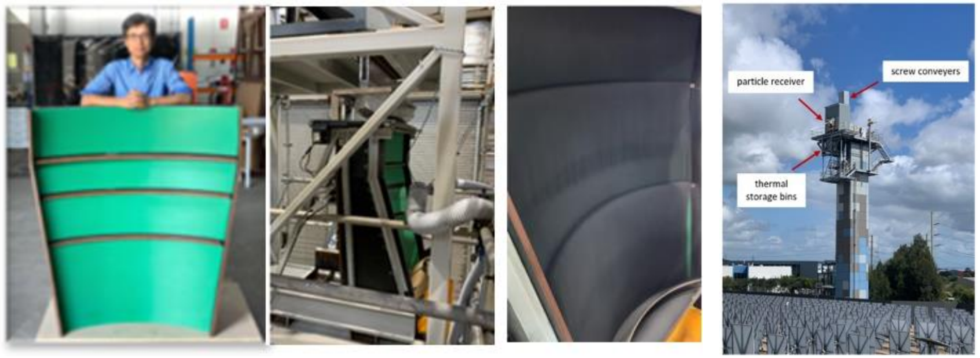
Breakthrough Energy Ventures

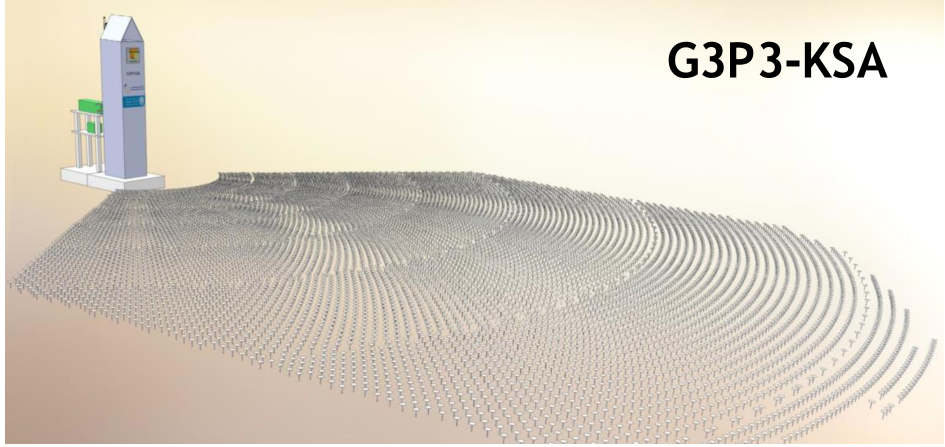
Global Investments in Particle-Based CSP

- International CSP Partners
  - Australian Solar Thermal Research Institute (ASTRI)
    - CSIRO, Australian National University, U. Adelaide
  - Saudi Electricity Company / King Saud U.
  - DLR – German Aerospace Center
    - **Process heat** (HiFlex – **Barilla, drying of pasta using heated particles**, Foggia, Southern Italy)

Millions being invested globally in Sandia & CSP

CSIRO





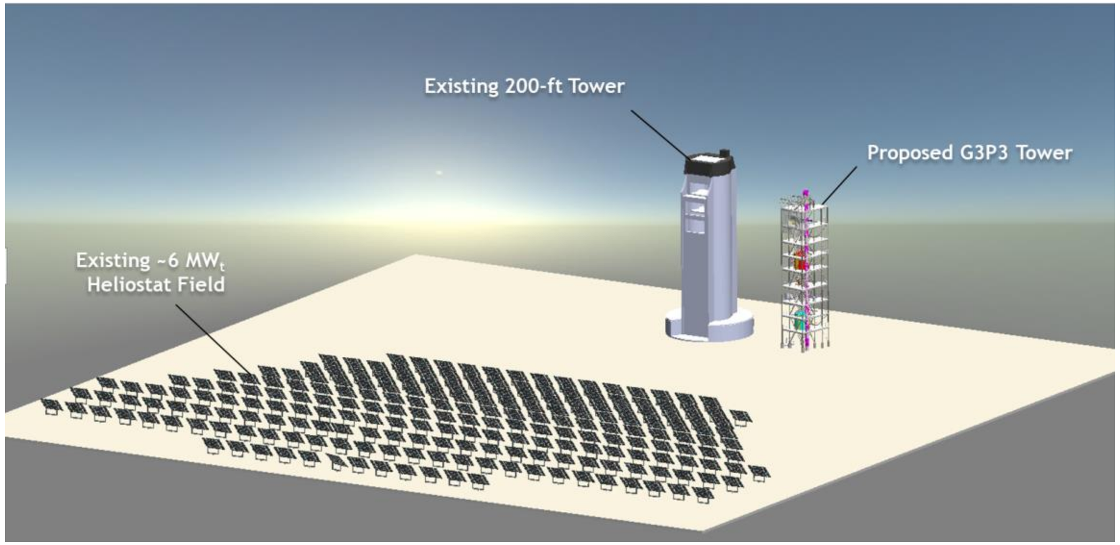
DLR and Sandia received a $1.5M DOE Technology Commercialization Fund award

G3P3 Summary

- 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
- Gaps and risks
  - Extended operation of integrated system over wide range of conditions
  - Heat loss (receiver, storage, heat exchanger, lift)
  - Particle-to-working-fluid heat transfer
  - Thermomechanical stresses in heat exchanger and storage tanks
  - Materials erosion

On-sun testing of the falling particle receiver at Sandia

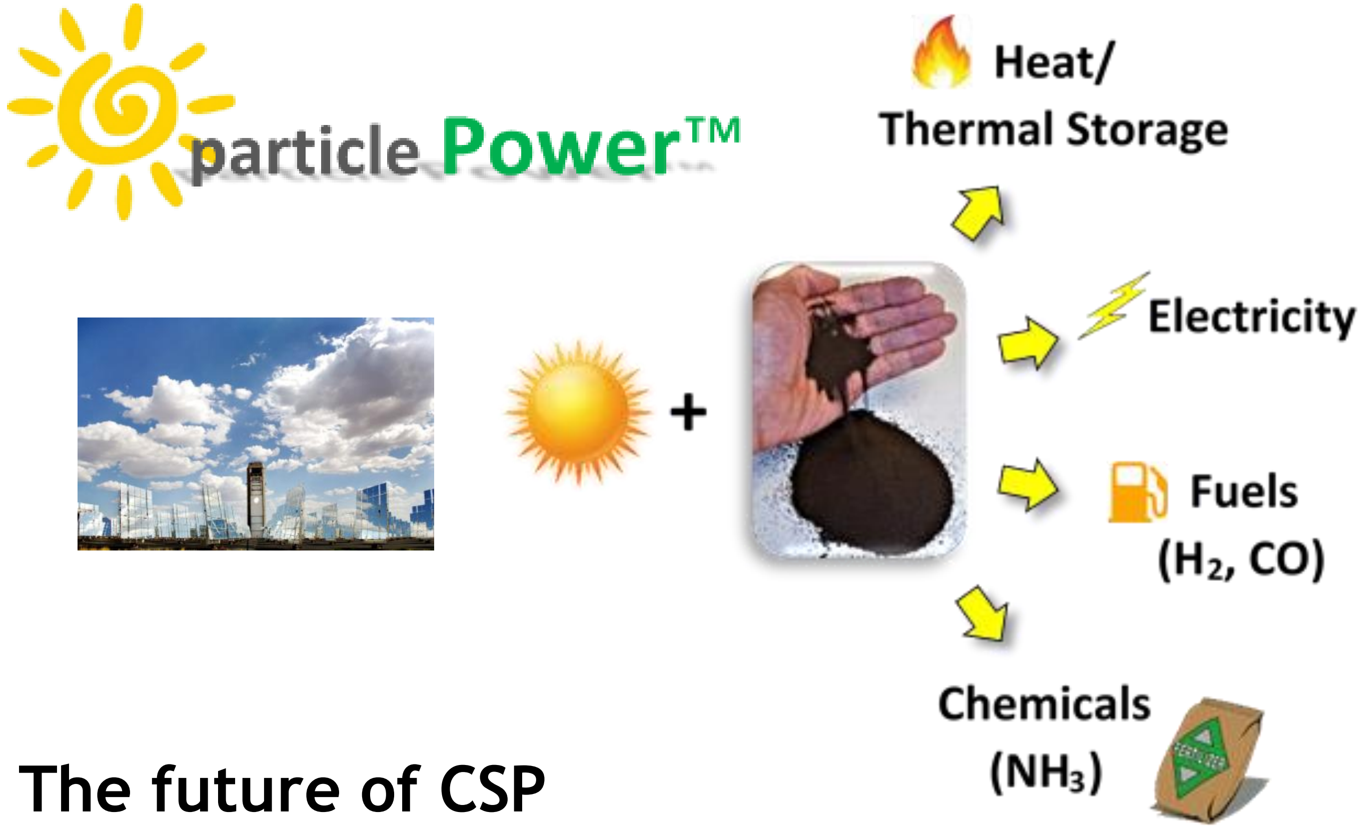
National Solar Thermal Test Facility (NSTTF), Albuquerque, NM



Why CSP?

Economical carbon-free electricity production with large-capacity, long-duration energy storage.

Why particle-based CSP?



The future of CSP

Acknowledgments

- This work is funded in part or whole by the U.S. Department of Energy Solar Energy Technologies Office under Award Number 33869
  - DOE Project Managers: Matthew Bauer, Vijay Rajgopal, Shane Powers, Levi Irwin, Andru Prescod, Mark Lausten, Avi Shultz

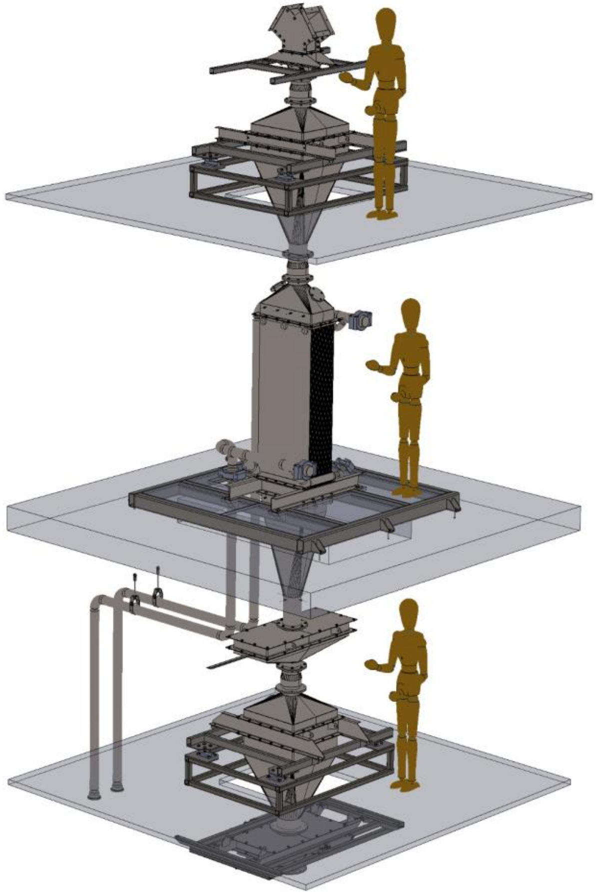
Backup Slides

Summary

- Renewables require energy storage for increased penetration
- Concentrating solar power provides utility-scale electricity AND energy storage for dispatchability when it is most needed
    - Cost of CSP with storage is currently cheaper than photovoltaics with large-scale battery storage

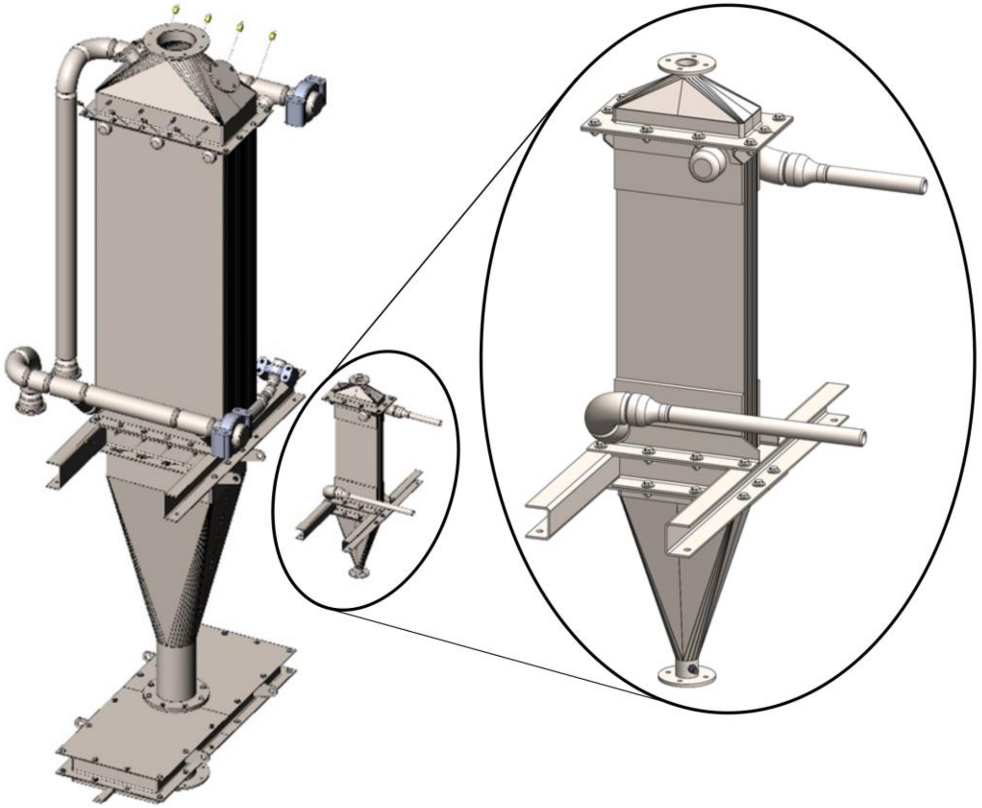
Current 1 MW_t and 20 kW_t Heat Exchanger Design and System Integration

G3P3 Heat Exchanger System Integration

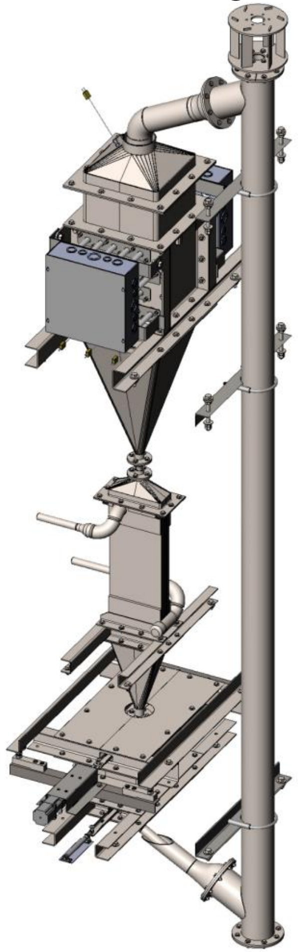


1 MW_t G3P3 Design

20 kW_t Subscale Prototype



20 kW Heat Exchanger Test Stand



Model and manufacturing development is being led by 20 kW_t geometry followed by application to 1 MW_t geometry