Gen 3 Particle Pilot Plant (G3P3): Integrated High-Temperature Particle System for CSP

G3P3 Down-Select Continuation Application

Executive Summary

1. Background

Particle receivers are being pursued to enable higher temperatures (>700 °C) with direct storage for next-generation dispatchable concentrating solar power (CSP) plants, process heating, thermochemistry, and solar fuels production [1]. Unlike conventional CSP receivers that use fluids flowing through tubes, the proposed particle-receiver system uses solid particles (ceramic or sand) that are heated directly as they fall through a beam of concentrated sunlight. Because the solar energy is directly absorbed by the particles, the flux limitations associated with tubular receivers are mitigated, enabling higher concentration ratios. Once heated, the particles are stored in an insulated bin before passing through a particle-to-working-fluid heat exchanger (HX) to power a high-efficiency Brayton cycle (e.g., sCO2 or air). The cooled particles are collected and then lifted back to the top of the receiver. Aside from the particle lift, the entire process is based on gravity-driven flow of the particles through each component, which can reduce parasitic power consumption.

Sandia National Laboratories has successfully developed and demonstrated a 1 MW_t high-temperature directly irradiated falling particle receiver system that has achieved particle temperatures over 800 °C with continuous recirculation [2, 3]. Key findings from those studies indicated that direct irradiance of falling particles enabled very high heating rates (up to several hundred degrees Celsius over ~ 1 – 2 m of drop height with ~1 – 7 kg/s and up to ~1800 kW/m^2 peak irradiance), but additional methods to reduce heat losses (convective and radiative) and particle losses are needed to increase receiver thermal efficiencies and reduce costs. A key partner, King Saud University, has also tested a complete falling particle-based CSP system at the 300 kW_t scale [4]. Other particle receiver designs besides direct irradiance free-falling receivers have been considered by researchers, including obstructed flow [2, 5], centrifugal [6, 7], flow in tubes with or without fluidization [8-10], and multi-pass recirculation [11, 12].

Until now, DOE SETO funding has focused primarily on component-level research that developed new particle-receiver designs, process and performance models, and small-scale proof-of-concept demonstrations. However, integration with other required subsystems such as storage, heat exchangers, and particle-lift systems remains to be demonstrated at larger scales and for significant durations. The next step (and the purpose of the Gen 3 program) is to move towards demonstration of larger-scale integrated particle-based systems and address risks associated with receiver thermal efficiency, particle heat exchanger performance and cost, material erosion, minimization of heat loss, and particle attrition and conveyance.

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2. Objectives

The objective of this work is to first mitigate key risks associated with the particle-based CSP system through focused R&D efforts (Phases 1 and 2), and then design, construct, and operate a multi-MW_t falling particle receiver system that can operate for thousands of hours, provide 6 hours of energy storage, and heat a working fluid (e.g., sCO2 or air) to ≥ 700 °C (Phase 3) (Figure 1). This first-of-a-kind Gen 3 Particle Pilot Plant (G3P3) is being led by Sandia National Laboratories and coordinated with leading international particle-technology researchers to accelerate deployment and commercialization.[1] **To increase our chances of success, we plan to develop two G3P3 systems in parallel**: (1) a G3P3-USA system deployed at Sandia's NSTTF, and (2) a G3P3-KSA system deployed in the Kingdom of Saudi Arabia with support from Saudi Electricity Company (SEC). Both systems will feature vertically integrated thermal components that meet the desired Gen 3 metrics. Success metrics for each component and the overall G3P3 system are shown in Table 1.

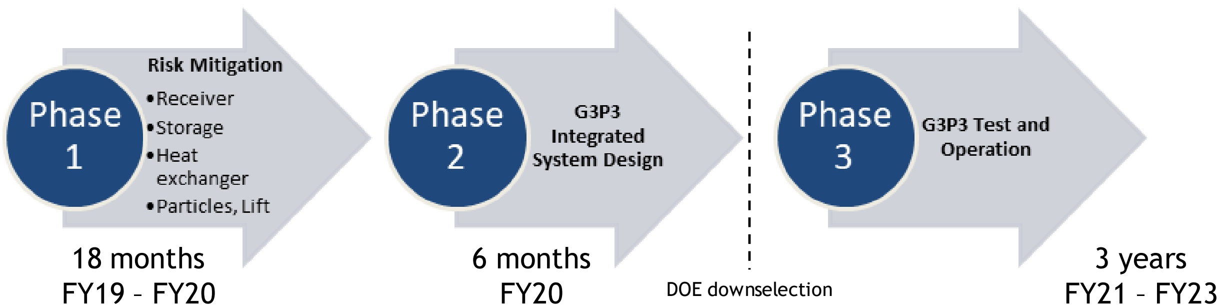


Figure 1. Project phases for the proposed Gen 3 Particle Pilot Plants (G3P3). Phase 2 was extended to ~9 months due to the COVID-19 pandemic.

Table 1. Summary of target performance metrics for each component and the overall G3P3 system. Cost targets are for the commercial scale (~100 MW_e).

Component	Target Metrics	Basis
Particles	Cost ≤ \$1/kg Attrition ≤ 0.001% of flow	• Cost target based on price competitiveness with molten salts • Attrition target related to cost metrics for storage and LCOE
Receiver	Thermal duty: ≥ 1 MW_t Cost ≤ \$150/kW_t Thermal eff. ≥ ~80 - 85% (pilot), 85-90% (commercial) T_{out} ≥ 775 °C $\dot{m}$ ≥ 5 kg/s	• Thermal duty meets FOA goals and matches capability at NSTTF • Cost and outlet temperature meet SunShot goals • Recent simulations show that a commercial receiver efficiency of 85-90% can still yield \$0.06/kWh_e; pilot-scale efficiency scales down with receiver size [13] • Mass flow based on required thermal duty
Thermal Storage	T_{out} ≥ 765 °C Capacity ≥ 6 MWh_t Cost ≤ \$15/kWh_t	• Particle temperature based on heat-exchanger approach temperature of 50 °C and desired sCO2 outlet T ≥ 715 °C

[1] Georgia Institute of Technology, King Saud University, CSIRO, Australian National University, U. Adelaide, PROMES-CNRS, DLR, EPRI, Bridgers & Paxton, Solar Dynamics, SolarReserve, Carbo Ceramics, Solex Thermal Science, Vacuum Process Engineering, Allied Mineral Products, Matrix PDM, Saudi Electricity Company

Component	Target Metrics	Basis
		• Capacity and duration meets 6 hours of storage (deferred 10 hours) for 1 MW_t heat exchanger per FOA
Heat Exchanger	Particle mass flow ≥ 5 kg/s U ≥ 300 W/m^2-K $T_{sCO2,out}$ ≥ 715 °C	• Mass flow rate enables ≥ 1 MW_t as required by FOA • Overall heat transfer coefficient (U) and temperature targets designed to meet cost and performance requirements [14]
Particle Lift	Mass flow rate ≥ 5 kg/s Lift efficiency ≥ 50% (commercial) T_{max} ~600 °C	• Mass flow rate enables ≥ 1 MW_t • Lift efficiency required to reduce particle attrition and parasitics; can be achieved with preliminary design of hoist system [15] • Temperature of "cold" particles will be up to ~600 °C
System	LCOE ≤ $0.06/kWh	• From FOA for 100 MW_e system

The G3P3 system will consist of a ~2 MW_t particle receiver situated on top of a tower to heat the particles from ~600 °C to nearly 800 °C in a single pass. The particles will be collected in an insulated high-temperature particle storage tank capable of holding ~160,000 kg (~160 tons) of particles for 6 hours of storage before being passed through a 1 MW_t particle-to-working-fluid heat exchanger. The heat exchanger will be connected to a flow system capable of providing pressurized working fluid (e.g., sCO2) that will be heated from ~550 °C to ≥700 °C. The particles are then collected in a "low-temperature" insulated storage bin, and an insulated particle lift system will carry the particles (~580 – 615 °C) to the top of the receiver. A control system will maintain a constant working-fluid outlet temperature, even with varying particle inlet temperatures.

3. Results of Phases 1 and 2

In Phases 1 and 2, we successfully de-risked key elements of the proposed Gen 3 Particle Pilot Plant (G3P3) by improving the design, operation and performance of the G3P3 system through both modeling and testing of critical components (Figure 2). Modeling and test results have led to optimized designs of each component that meet desired performance metrics. Detailed drawings, piping and instrumentation diagrams, and process flow diagrams were generated for the integrated system, and structural analyses of the assembled tower structure were performed to demonstrate compliance with relevant codes and standards. Instrumentation and control systems of key subsystems were also demonstrated.

Together with Bridgers & Paxton, Bohanan Huston, and Sandia Facilities, we have completed a **100% G3P3 tower design package with signed and sealed engineering drawings** suitable for construction bid in Phase 3. The G3P3 continuation application also addresses all five Phase 3 downselection criteria as illustrated in Figure 2. Key findings from the G3P3 Phases 1 and 2 activities are summarized below.

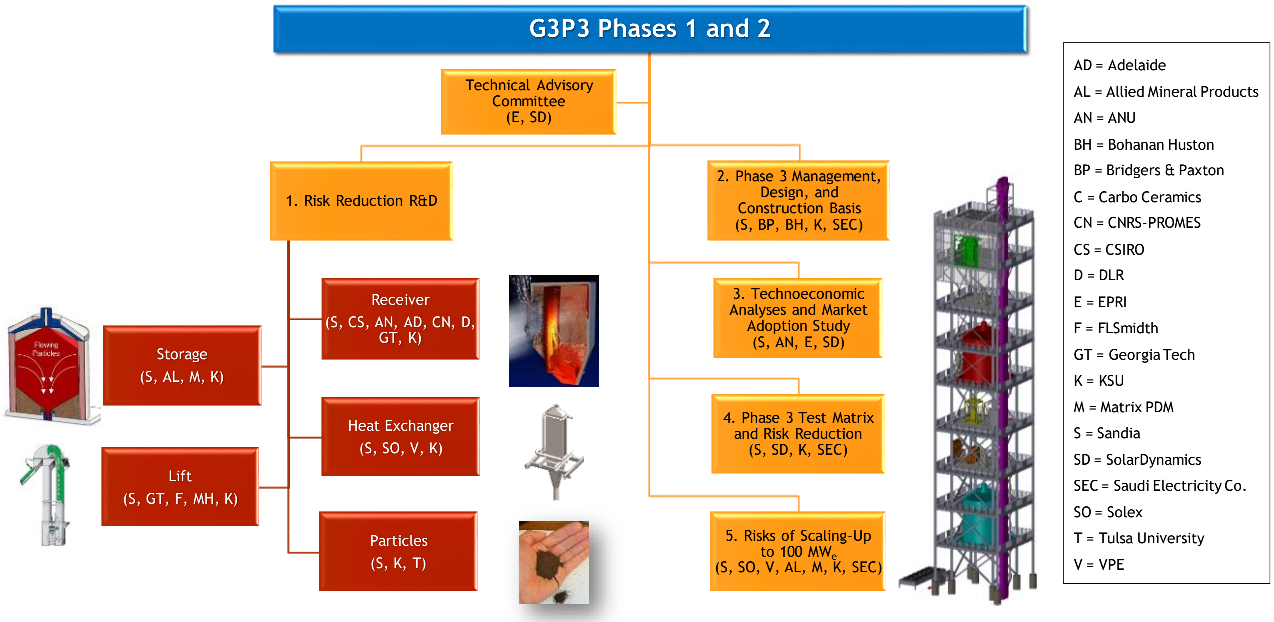


Figure 2. Overview of key G3P3 R&D activities in Phases 1 and 2 categorized by the five Phase 3 downselection criteria (in orange).

3.1. Phases 1 and 2 Risk Reduction

3.1.1. Particle Receiver

- Advective losses and wind were found to be the primary loss mechanisms in lowering thermal efficiencies in our previous receiver designs
- Seven new features (hood, quartz aperture covers, active airflow, multistage release, reduced volume receiver, SNOUT, and chimney) were simulated and/or tested in Phase 1 to reduce heat loss, mitigate wind impacts, reduce particle emissions, and minimize damage from high fluxes. Of these, three features (multistage release, reduced volume, and SNOUT) were shown to have significant impact (increasing receiver efficiency by over 10 percentage points in some cases) and are being implemented in the G3P3-USA receiver design.
- Rigorous optimization was applied to a 2 MW_t G3P3-USA receiver geometry; simulated efficiencies expected to approach ~85 - 90%
- Over 250 hours of on-sun and ground-based testing were performed to investigate the impact of multistage release, reduced volume receiver, and automated particle flow control (PID) to regulate the particle outlet temperature
  - Receiver efficiencies up to ~80 – 90% were achieved with new features
  - PID controls were effective at maintaining particle outlet temperatures up to ~780 °C
  - Multi-stage release was effective at cooling backwall temperatures
  - Reduced cavity volume was effective at reducing advective heat loss

  - Emission of particle dust was below EPA and NIOSH standards
- 100 MW_e three-receiver tower design simulated with good wind resilience and efficiencies (> ~80%)

3.1.2. Particle Storage

- Flat-bottomed G3P3 storage bins were designed to induce funnel flow, reducing wall erosion and heat loss via stagnant self-insulating particles
- Small-scale tests were performed to validate particle flow and heat-transfer models
- Pre-cast refractory liner materials were tested for erosion and thermal expansion; shotcrete application methods were investigated and tested
- Methods for cooling of concrete slab were investigated
- Tower-integrated and ground-based storage bins designs were evaluated for commercial systems with capacities from 10 - 100 MW_e with consideration of heat loss (<1%) and the structural limitations of tower-integrated systems in regions with high seismicity
- Cost models for ground-based and tower-integrated storage were developed

3.1.3. Particle Heat Exchanger

- Simulations and testing of 100 kW_t SuNLaMP HX and shell-and-tube KSU heat exchanger provided lessons learned and informed design of G3P3 HX
- Shell-and-plate G3P3 HX design with integral headers, closer plate spacing (~3 mm), and counterflow design provided >300 – 400 W/m^2-K with <2% (500 kPa) pressure drop based on modeling
- Subscale (20 kW_t) prototype was manufactured from stainless steel with novel design features to understand manufacturing steps and verify performance
- Subscale prototype was tested up to 500 °C at 17 MPa, which yielded overall heat transfer coefficients of >300 W/m^2-K and pressure drop <7 kPa (0.04%)
- Particle flow testing was performed at 650 °C with varying plate spacing (1.5-6 mm) to demonstrate reliable and uniform particle flow in narrow vertical channels at operating temperature
- Bonding, brazing, and chemically etching of IN740H was conducted, but bond strength has not yet met ASME code requirement. Parallel efforts provided the bond, braze, and etch development for constructing the heat exchanger from IN617 and HR230.
- sCO2 corrosion of 800H was larger than expected; corrosion testing is being planned for 800H, 740H, IN617, and/or HR230.

3.1.4. Particle Lift

- Bucket elevator selected for G3P3-USA due to excessive costs for small-scale skip hoist; skip hoist was designed and evaluated for 100 MW_e plant

- Heat loss from the G3P3 bucket elevator was modeled, and insulation was designed to minimize heat losses and particle temperature drops to < 3 °C
- Transient heat loss and costs were evaluated for commercial-scale skip hoist

3.1.5. Particles

- CARBO HSP 40/70 selected for G3P3-USA based on demonstrated solar absorptance, durability and flowability at high temperatures
- CARBO HSP 40/70 particles were exposed to 10,000 irradiance cycles reaching 1000°C per cycle which resulted in a 1% decrease in absorptivity. Particles held at a constant temperature of 800°C for 400 hours also resulted in a 1% decrease in absorptivity
- Particle flow processes and alternative low-cost particles were evaluated
- Impact of particle properties on LCOE and other solar thermal applications were evaluated

3.2. Phase 3 Management, Design, and Construction Basis

- Project Execution Plan was completed to manage Phase 3 scope, schedule, and budget as detailed in MS Project file (Figure 3)
- G3P3 equipment lists, costs, timeline, process flow diagrams, P&ID, and engineering drawings were completed (Figure 4)
- G3P3 tower design and drawings were signed/sealed by Bridgers & Paxton/ Bohannan Huston and reviewed by Sandia Facilities (ready for construction bid)

3.3. Technoeconomic Analyses and Market Adoption Study

- LCOE Analysis
    - EES model of 100 MW_e system were developed to evaluate sensitivity of LCOE to key component costs and processes. Probabilistic analyses showed up to 85% probability of real LCOE ≤ \$0.06/kWh using published cost and performance models (Figure 5)
    - SolarTherm/Modelica model developed to evaluate transients and alternative component designs to optimize system performance, reduce LCOE, and optimize dispatch strategies with peaker plant designs
    - Alternative particle-based CSP systems evaluated by partners (DLR, centrifugal particle receiver; CNRS-PROMES, fluidized particle receiver) were also independently estimated to yield LCOE < \$0.06/kWh_e
- Market Adoption Study
    - Key differentiators for particle-based vs. alternative Gen3 systems identified and implemented in market adoption study
    - EPRI and SolarDynamics performed production-cost modeling to evaluate market opportunities for particle systems around the world

- G3P3-KSA is being sponsored by Saudi Electricity Company with direct path for commercialization; Heliogen wants to collaborate on G3P3-USA

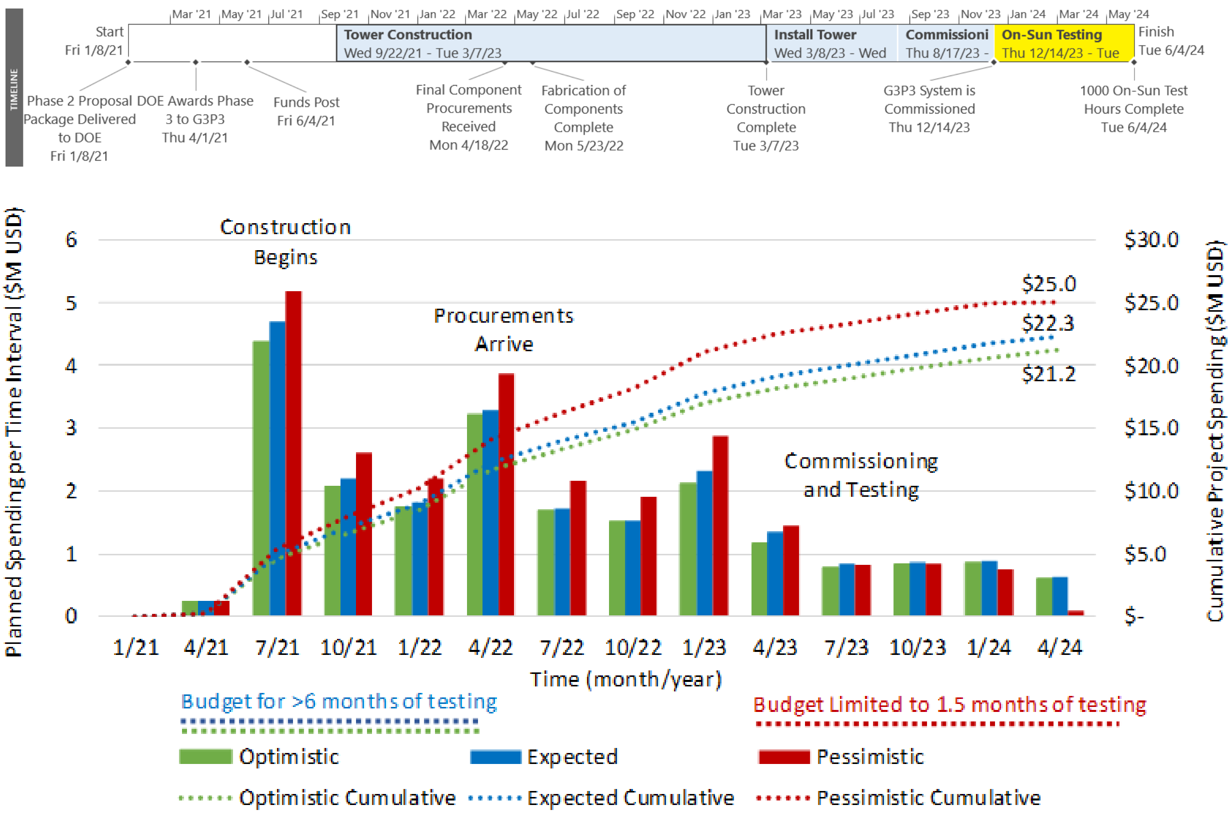


Figure 3. Proposed G3P3 Phase 3 timeline and planned spending over three-year project.

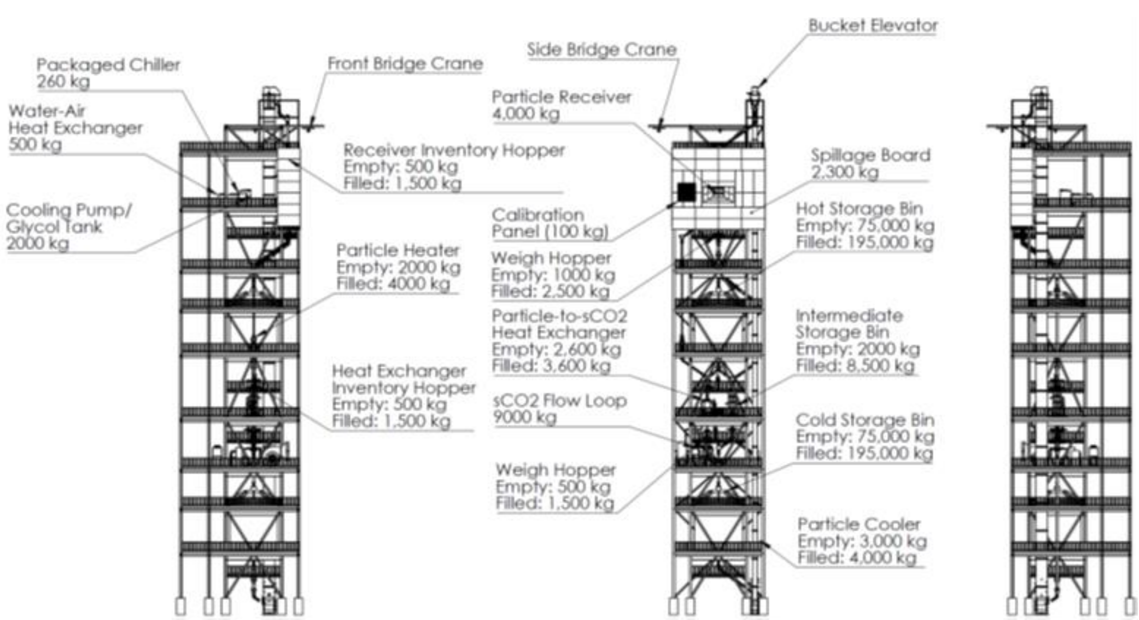
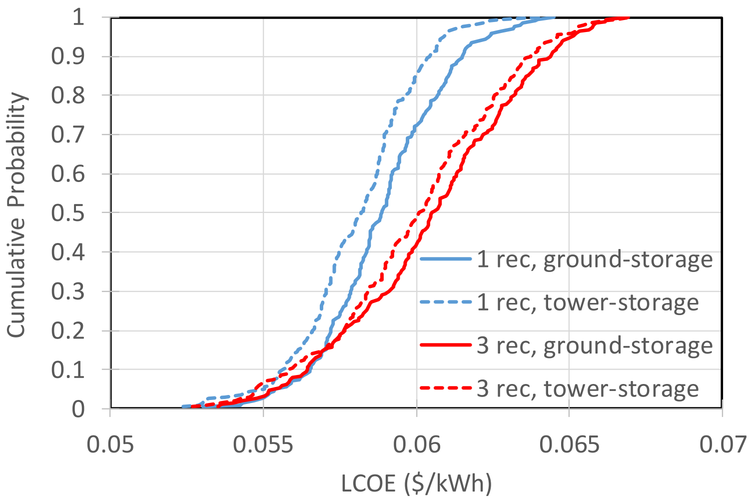


Figure 4. Front and side views of the G3P3 tower and components.



Configuration	Probability of LCOE ≤ $0.06 kWh
1 receiver, ground storage	72%
1 receiver, tower storage	85%
3 receivers, ground storage	42%
3 receivers, tower storage	49%

Figure 5. Left: Cumulative probability of LCOE for four 100 MW$_e$ particle tower configurations (ground storage vs. tower storage, one receiver vs. three receivers). Right: Probability of achieving LCOE ≤ $0.06/kWh. Note: 3-receiver system not optimized.

3.4. Phase 3 Test Matrix and Risk Reduction

- Phase 3 test plan and risk register was completed; scope, schedule, and cost were detailed in MS Project file. See Figure 6 for illustrated overview of Phase 3 testing and opportunities to further reduce G3P3 risks in Phase 3.

3.5. Risks of Scaling Up to 100 MWe

- Risks of scaling G3P3 to 100 MW$_e$ commercial system were compiled with associated mitigation measures in risk register.
- See Figure 7 for commercial-scale design and associated risks and mitigation opportunities based on discussions with industry and commercial vendors.

4. Conclusions

In Phases 1 and 2, G3P3 component and system designs were developed, tested, and optimized to reduce risks associated with particle-based CSP technology. Simulations and testing were performed to inform the design of the receiver, storage, heat exchanger, and particle-lift components. In addition, stamped engineering drawings of the integrated components and tower system were completed. Process flow diagrams detailing various operational and maintenance scenarios were developed, along with piping and instrumentation diagrams that provided a basis for equipment lists and costs bases. Technoeconomic analyses were performed using published models and cost curves, and probabilistic modeling was performed to evaluate important factors and uncertainties impacting LCOE. Phase 3 test plans were detailed along with scope, schedule, and cost for Phase 3 activities in a MS Project file. Finally, risk registers were drafted for both the Phase 3 testing and scaling up from G3P3 to 100 MW_e commercial plants.

In conclusion, we feel that the proposed G3P3-USA and G3P3-KSA systems will create a marketable pathway for next-generation high-temperature CSP systems.

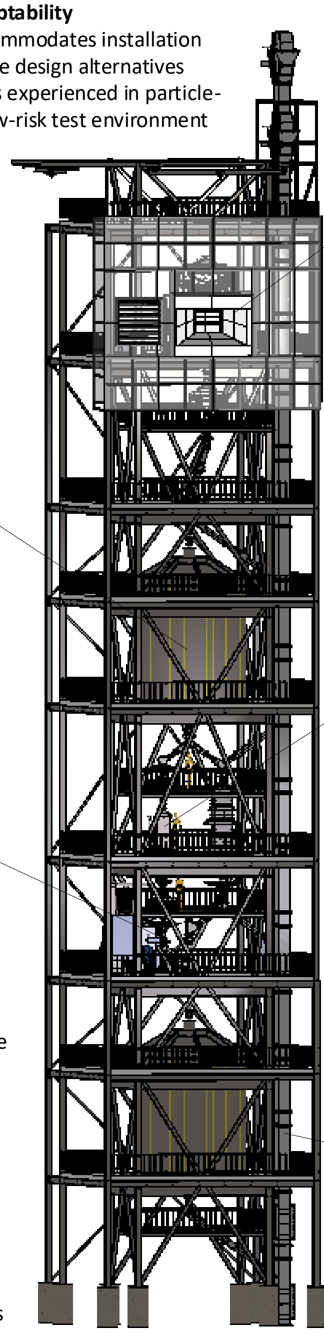


Figure 6. G3P3 Phase 3 testing and risk-reduction opportunities by component.

System

Risk – Reliability will not have been demonstrated for required service life:
- G3P3 USA and KSA will be operated for thousands of hours to identify reliability issues.
- Ongoing development of alternative designs
- Use of commercially established components whenever possible

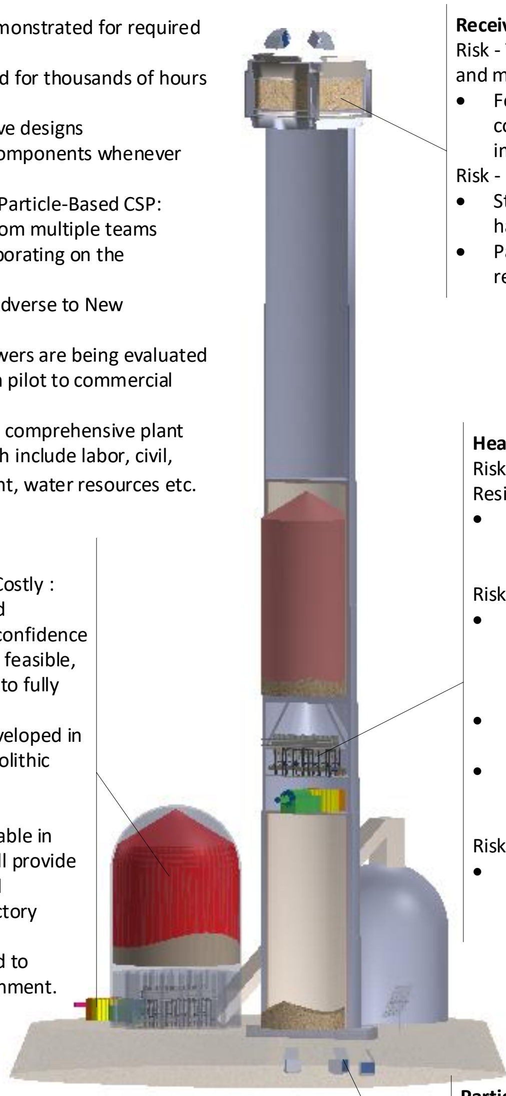
Risk – Labor Force Lacks Experience in Particle-Based CSP:
- Established team of researchers from multiple teams around the world have been collaborating on the development of components.

Risk – Commercial Investors Are Risk-Adverse to New Technologies
- Modular systems with multiple towers are being evaluated to reduce the technology gap from pilot to commercial scale.
- Probabilistic cost models based on comprehensive plant cost studies by NREL and SBP which include labor, civil, electrical, piping, cables, equipment, water resources etc.

Receiver

Risk - Thermal efficiency is lower than expected and more vulnerable to wind impacts at 100 MWe
- Features such as nods or multi-stage release components may reduce wind effects and improve particle curtain opacity.

Risk - Particle loss through aperture:
- Studies performed do not show inhalation hazard from lost particles
- Particle loss is reduced with multi-stage release features



Heat Exchanger

Risk – Manufacturing and Scale-Up with Corrosion-Resistant Etched and Diffusion-Bonded Materials:
- Diffusion-bonded modular banks of 32 MWt units have been designed to accommodate multi-megawatt thermal duties

Risk – Low Particle-Side Heat-Transfer Coefficient:
- Detailed modeling studies and tests are being performed to improve particle-side heat-transfer coefficient and overall heat transfer performance.
- True-counterflow and cross-counterflow designs are being designed
- Alternative fluidized bed heat exchangers are being developed that show higher heat exchange coefficients

Risk – Low reliability and increased failure modes
- Detailed modeling studies are being performed to evaluate and mitigate thermomechanical stress

Storage

Risk – Tower-Integrated Storage is too Costly :
- Consultation with silo designers and construction managers resulted in confidence that the tower-integrated system is feasible, but detailed design work is needed to fully understand logistics and costs.
- Storage in external bins is being developed in parallel using well-established monolithic dome construction.

Risk – Excessive Heat Loss:
- Modeling shows heat loss is acceptable in large capacities. Phase 3 testing will provide improved understanding of thermal resistance and capacitance in refractory materials.
- Experimentation is being performed to understand the effects of air entrainment.

Particle Lift and Conveyance

Risk – Heat losses and Adequate Insulation :
- FLSmidth has experience at relevant capacities and believes they can accommodate thermal requirements.
- G3P3-KSA will test a small-scale skip hoist

Risk – Excessive Particle Temperatures on External Conveyors:
- Vendors of high-temperature particle conveyance equipment have been consulted and are participating in solutions to meet capacity and temperature requirements.
- Vertically integrated hot storage and heat exchanger system configurations are being designed for both tower-integrated and externally integrated systems.

System Controls

Risk – Ability to Control Both Flow Rate and Temperature of Particles Through Receiver
- Computer learning techniques can couple optics with flow rate controls to stabilize temperature variability.
- KSA will test a cogenerative system with a natural gas heating element
- Load-Follow operations will be tested in G3P3
- Supervisory control algorithms operational control response to stochastic weather events

Figure 7. Commercial-scale particle-based CSP system displaying alternative tower-integrated vs. external storage configurations and associated risks/mitigations.

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