Overview and Design Basis for the Gen 3 Particle Pilot Plant (G3P3)

Clifford K. Ho,[1, a)] Kevin J. Albrecht,[1] Lindsey Yue,[1] Brantley Mills,[2] Jeremy Sment,[1] Joshua Christian,[1] and Matthew Carlson[1]

[1]*Concentrating Solar Technologies, Sandia National Laboratories, P.O. Box 5800, MS-1127, Albuquerque, NM 87185-1127, USA*

[2]*Thermal Sciences & Engineering, Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185, USA*

[a)]Corresponding author: ckho@sandia.gov

Abstract. This paper provides an overview of a next-generation particle-based concentrating solar power (CSP) system. The Gen 3 Particle Pilot Plant (G3P3) will heat particles to over 700 °C for use in high-temperature air or supercritical CO_2 Brayton cycles with 6 hours of storage. The particles, which are inert, non-corrosive, durable, and inexpensive, are used as both the heat-transfer and storage media. Details of the operation, requirements, and design basis for the G3P3 system are presented, including a description of expected operational states and major components. Operational states include start-up, transients, steady-state operation, off-design conditions, and idling. The key components include the particle receiver, storage bins, heat exchanger, lift, and tower structure subsystems. Design bases and innovative features of each component are presented that will aid in achieving the desired cost and performance metrics.

INTRODUCTION

Particle-based systems 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 and heating rates.

Once heated, the particles are stored in an insulated bin before passing through a particle-to-working-fluid heat exchanger to power a high-efficiency Brayton cycle (e.g., supercritical CO_2 (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 falling particle receiver system that has achieved particle temperatures over 700 °C [2, 3]. Key findings indicated that direct irradiance of falling particles enabled very high heating rates (up to several hundred °C over ~ 1 – 2 m of drop height with ~1 – 7 kg/s and up to 1000 kW/m^2), but additional methods to reduce heat (convective and radiative) and particle losses are needed to increase receiver thermal efficiencies, reduce costs, and mitigate potential health risks from inhalation of particle fines. In addition, a 100 kW_t particle-to-sCO2 heat exchanger and sCO2 flow loop are currently being tested to study high-temperature particle flow and heat transfer in a shell-and-plate heat exchanger.

Other particle receiver designs besides direct irradiance free-falling receivers have also been considered by researchers, including obstructed flow [2, 4], centrifugal [5, 6], flow in tubes with or without fluidization [7-9], and multi-pass recirculation [10, 11]. Each technology has advantages and challenges that need to be assessed for scalability and long-term operation with consideration of cost, performance, reliability, and manufacturability.

Until now, research on particle-based systems has focused primarily on individual components and related subsystems such as new particle-receiver designs, process and performance models, and small-scale proof-of-concept demonstrations. However, integration with storage bins, heat exchangers, and particle conveyance subsystems remains to be demonstrated at larger scales and for significant durations. The next step is to move towards demonstration of larger-scale integrated systems utilizing designs and components that show promise based on previous research studies.

This paper describes the Gen 3 Particle Pilot Plant (G3P3), a proposed next-generation CSP system that can achieve desired cost and performance metrics using solid particles as the heat-transfer and storage medium. We believe the proposed particle receiver system has significant advantages over current state-of-the-art molten nitrate salt systems and other proposed Gen 3 technologies, including a much greater range of operational temperatures (subzero to over ~1,000 °C); no freezing or need for expensive trace heating; use of inert, non-corrosive materials; direct storage of the particles (no need for expensive gas-to-storage heat exchanger); and direct heating of particles for rapid heating rates and response times. **TABLE 1** provides a comparison of CSP technologies using different heat-transfer/storage media.

TABLE 1. Comparison of CSP technologies using different heat-transfer/storage media.

Feature	Solid Particle Technology	Molten Nitrate Salt Technology	Molten Chloride Salt Technology	Gas Receiver Technology
Operating temperatures	Ambient to >1000°C	~300°C – 600°C	~400°C – 800°C	Ambient to >1000°C
Solar flux	No flux limitations on particles	Limited to tube-wall fluxes of 800-1200 kW/m^2	Limited to tube-wall fluxes of 800-1200 kW/m^2	Limited to tube-wall fluxes of 800 kW/m^2 or less depending on gas-side heat-transfer coefficient
Freezing	No freezing	Freezing below 200 – 300 °C; requires trace heating	Freezing below 200 – 300 °C; requires trace heating	No freezing
Corrosion	Inert materials, non-corrosive	Corrosive to the containment materials	Extremely corrosive to the containment materials in the presence of air or water	Potentially corrosive depending on gas
Storage	Direct thermal storage	Direct thermal storage	Direct thermal storage	No direct thermal storage; requires intermediate heat exchanger
Ducting and containment	No hermetic seals required	Hermetic seals required	Hermetic seals required	Hermetic seals required
Conveyance	Particle lift (bucket elevator or skip hoist)	Long-shafted pumps	Long-shafted pumps	High-temperature blowers; lifts for particles if used as storage media

Objectives

The objective of the G3P3 project, which began in 2018, is to develop a >1 MW_t particle-based CSP thermal system that will integrate key components and heat a pressurized working fluid to >700 °C, enable 6 hours of direct thermal storage, and provide long-term operation to retire primary risks associated with particle-based CSP systems. Key innovations and risk-mitigation measures being pursued by Sandia and international and industry partners include developing novel designs to increase receiver efficiency, reduce heat losses in low-cost storage systems, increase heat transfer coefficients and durability in particle heat exchangers, reduce particle wear/attrition/erosion and heat losses in all components, and lower costs to achieve the DOE goals of \$0.05 – \$0.06/kWh_e. The proposed work is scheduled to occur in three phases over five years (the last phase is contingent upon the results of the first two phases): (1) design, modeling, and testing activities to reduce risks in remaining key particle-based components, (2) development of integrated designs and technoeconomic analyses for the G3P3 and commercial-scale systems, and (3) construction and long-term testing and operation of the G3P3 system. G3P3 is being developed through coordinated efforts with leading international researchers, industry, and utilities to accelerate technology advancements and commercial deployment for particle-based CSP systems. To increase our chances of success, we plan to develop two G3P3 systems in parallel: (1) a G3P3-USA system deployed at Sandia's National Solar Thermal Test Facility (NSTTF), and (2) a G3P3-Saudi system deployed near Riyadh, Saudi Arabia (primarily through cost share). Both systems will feature vertically integrated thermal components that meet the desired metrics. The remainder of this paper focuses on results from the first two phases of the G3P3-USA project.

SYSTEM OVERVIEW

The G3P3 system will consist of a ≥1 MW_t particle receiver situated on top of a tower to heat the particles directly via concentrated sunlight to nearly 800 °C in a single pass. The particles will be collected in an insulated storage bin capable of holding ~100,000 kg (~100 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 ~565 °C to ~715 °C. The particles are then collected in a "low-temperature" insulated storage bin, and a high-efficiency insulated particle lift system will carry the particles (~580 - 615 °C) back to the top of the receiver. A control system will maintain a constant working-fluid outlet temperature, even with varying inlet conditions (e.g., solar resource, particle and working-fluid inlet temperatures, mass flow rates). **FIGURE 1** shows a drawing of the proposed integrated G3P3-USA system, which will be co-located at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories in Albuquerque, New Mexico.

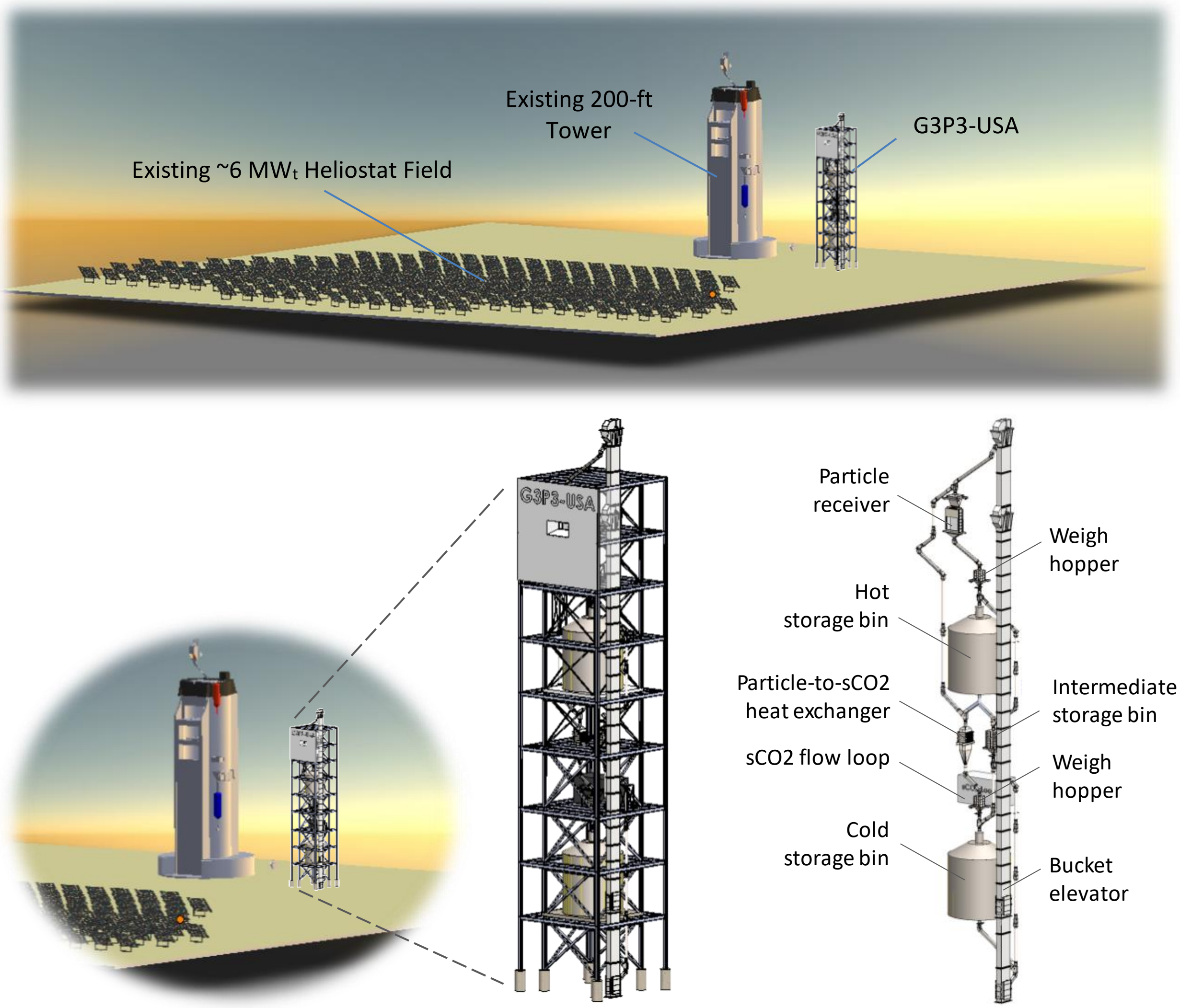


FIGURE 1. Location and baseline design of the G3P3-USA system at the NSTTF.

The G3P3-USA system will be situated next to the existing tower at the NSTTF and will utilize the existing ~6 MW_t heliostat field. Different locations at the NSTTF were considered, and the minimum height of the receiver was determined based on optical ray-tracing simulations of the heliostat field to ensure sufficient solar flux at different times of the day and year that could produce the desired ~200 °C particle temperature rise with a particle flow rate of ~5 kg/s to deliver 1 MW_t. Based on the current design and optical simulation results, the location due west of the tower (~40 m) was found to be best, and the minimum height of the receiver was >30 m (100 ft).

Process Flow and Operational States

Process flow diagrams and piping & instrumentation diagrams for the G3P3 system have been developed. The process flow diagrams show the major components, including the bucket elevator, receiver and feed hopper, storage bins, and heat exchanger, along with diverter valves, weigh hoppers, and slide gates to accommodate the anticipated operating states. Interfaces, instrumentation, and controls systems for each subsystem are shown in the piping & instrumentation diagrams.

The anticipated operating states of the G3P3 system that will be demonstrated in Phase 3 include: (1) Receiver Startup/Transients, (2) Receiver Steady-State, (3) Intermediate Storage Drain, (4) Receiver Shutdown/Idle, (5) Heat Exchanger Maintenance Heating, (6) Heat Exchanger Startup, and (7) Heat Exchanger Steady-State.

Receiver Startup/Transients. During receiver start-up and significant transients that prevent the particles from being heated to the desired temperature range of ~775 – 800 °C, the particles will flow through the receiver and weigh hopper and then be diverted around the hot-storage bin to an intermediate storage bin. During this transient period, the particles in the cold-storage bin will be discharged (at a desired temperature of ~565 – 615 °C) at a controlled flow rate to maintain a constant level of particles in the receiver feed hopper. The purpose of the intermediate storage bin is to hold the particles, which may be too hot to divert directly to the bucket lift (currently rated at ~600 °C), until the particles can be slowly released and mixed with the particles from the low-temperature bin for a more consistent temperature at the receiver inlet during steady receiver operation.

Receiver Steady-State. During steady-state operation of the receiver when particles are being heated to their desired temperature range of ~775 – 800 °C, the particles flow through the receiver, hopper, and into the hot storage bin. The cold-storage bin releases particles at a controlled flow rate to maintain a constant particle level in the receiver feed hopper.

Intermediate Storage Drain. While the receiver is operating under steady-state conditions, any particles accumulated in the intermediate storage bin will be slowly drained (<1 kg/s), diverted around the cold-storage bin, and mixed with the particles discharged from the cold storage bin. This slow blending is intended to minimize receiver inlet temperature deviations while enabling temporary storage of hot particles that are either too cold for hot storage or too hot for the bucket lift.

Receiver Shutdown/Idle. When the hot storage bin is full, or when there is insufficient solar flux, the system can be idled by removing the solar flux from the receiver while recirculating the particles through the receiver and bypassing both the hot and cold storage bins until the particle temperature decreases to the acceptable cold storage temperature (< 600 °C), at which point the particles can flow into the cold storage bin. If the particles leaving the receiver are diverted around the hot storage bin after the solar flux has been completely removed from the receiver, it is anticipated that those particles will be less than ~600 °C and can be sent directly to the cold storage bin.

Heat Exchanger Maintenance Heating. If the heat exchanger is not in use (i.e., sCO2 is not flowing), we wish to hold the heat exchanger at an isothermal elevated temperature condition that is within temperature limits of all the banks for quicker startup and ramping. Particles from the cold storage bin will be recirculated through the lift and heat exchanger at a very low flow rate (0.l – 0.5 kg/s), well below the design point, while being diverted around the receiver.

Heat Exchanger Startup. During heat exchanger startup, it may be necessary to mix particles from the cold storage bin with the particles from the hot storage bin to control the temperature ramp rate within the heat exchanger. However, an alternative may be to flow the particles from the hot storage bin into the heat exchanger at a very low flow rate while the sCO2 is also flowing through the heat exchanger. This may yield acceptable temperature ramp rates in the heat exchanger without the need to mix particles from the cold storage bin.

Heat Exchanger Steady-State. During steady-state operation of the heat exchanger, which can occur simultaneously with the receiver steady-state operation, particles are directed from the hot-storage bin to the heat exchanger at a controlled particle mass flow rate via a slide gate or rotary valve at the base of the heat exchanger. The cooled particles are then stored in the cold storage bin. This is the typical operating mode when electricity would be produced from the power plant.

Design Requirements

Performance and cost requirements for each of the major components of G3P3 are summarized in **TABLE 2**.

TABLE 2. 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 [12]
Receiver	Thermal duty: ≥1 MW_t Cost ≤ $150/$kW_t$ Thermal eff. ≥ ~80 - 85% (pilot), 85-90% (commercial) T_{out} ≥ 750 °C Particle mass flow ≥ 5 kg/s	• Thermal duty meets FOA goals and matches capability at NSTTF • Cost and outlet temperature meet SunShot goals • Recent System Advisor Model 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	Cost ≤ $15/$kWh_t$ Heat loss ≤ 1%/10hrs Capacity ≥ 6 MWh_t	• Preliminary cost and heat loss performance studied previously by our partner, KSU [14] • Capacity and duration meets 6 hours of storage (deferred 10 hours) for 1 MW_t heat exchanger per FOA
Heat Exchanger	Cost ≤ $150/$kWh_t$ Particle mass flow ≥ 5 kg/s U ≥ 100 W/m^2-K T_{out} ≥ 700 °C	• Cost target enables desired cost of $900/$kW_e$ for entire power cycle • 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 [15]
Particle Lift	Mass flow rate ≥ 5 kg/s Lift efficiency ≥ 50% (commercial) Heat loss ≤ 5% 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 [16] • Temperature of "cold" particles being lifted will be up to 600 °C • Cost included as part of the receiver component
System (~100 MW_e)	LCOE ≤ $0.06/kWh	• Estimated from preliminary technoeconomic analysis [1], which will be updated based on new designs and results in Phases 1 and 2.

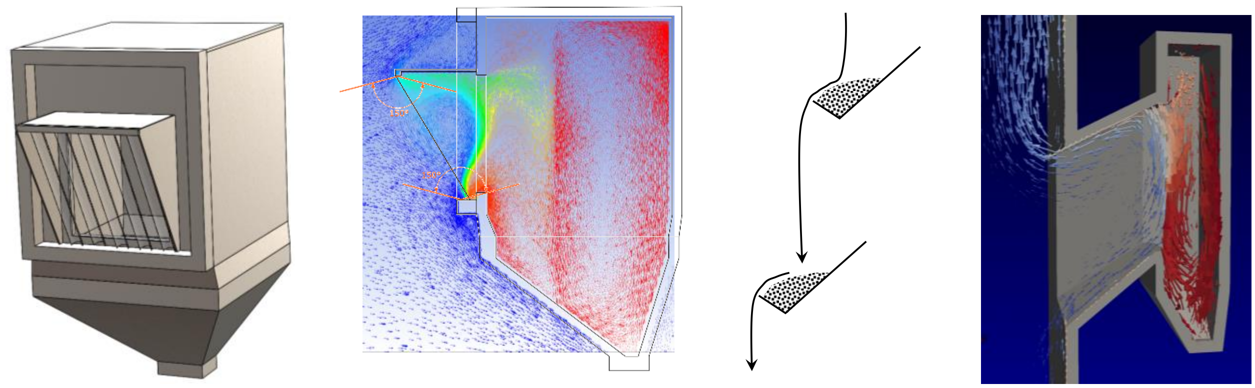
DESGIN BASIS AND INNOVATIVE FEATURES

The first two phases of the G3P3 project are focused on identifying component and subsystem designs that can meet the desired performance metrics in **TABLE 2**. The following sections describe the designs being considered and associated studies for each of the major G3P3 components.

Receiver

The baseline receiver design to accommodate required heating and mass flow rates is a directly-irradiated falling particle receiver system [17], but additional novel designs (centrifugal, obstructed, fluidized) and innovative patent-pending features (aperture covers, suction/recirculation, multistage release) are being considered in Phases 1 and 2 through partnership with international team members to reduce risks associated with achieving a 90% receiver thermal efficiency (commercial scale) at particle temperatures between ~580 and 775 °C. The receiver must be able to accommodate >5 kg/s of particle flow (≥1 MW_t) and irradiances of 1 MW/m^2 or greater from the NSTTF heliostat field. Automated particle mass-flow control methods to maintain constant particle outlet temperature and address risks associated with temporally and spatially varying solar flux are also required [18]. The following sections describe innovative receiver features that are being pursued in Phases 1 and 2.

Quartz Half-Shell Aperture Covers. A challenge associated with falling particle receivers is the reduction of advective and radiative heat losses from the open aperture of the cavity receiver. One option being pursued to mitigate these losses (first proposed by the German Aerospace Center (DLR) [19]) is the use of segmented glass tubes that partially or completely cover the aperture. The use of quartz half-shell tubes provides additional rigidity and strength (relative to flat glass panes) and allows concentrated solar irradiance (~0.4 – 2.5 microns) to pass through the glass into the receiver for particle heating. The transmissivity of quartz glass decreases significantly at ~2.5 – 3 microns, which prevents a significant amount of thermal reradiation from escaping through the aperture. In Phase 1, we performed computational fluid dynamics (CFD) simulations of quartz half-shell tubes that partially or completely cover the particle receiver aperture (**FIGURE 2**a) to evaluate their impact on particle receiver performance [20]. Results showed that, contrary to expectations, the quartz aperture covers can increase radiative losses by becoming hot and reradiating directly to the environment. Advective losses could also be increased in the partially covered case. Proposed mitigation measures included active cooling (e.g., air curtain) and proper materials selection with high transmissivity. It was also determined that upscaling the quartz aperture covers to sizes required by 10 – 100 MW_e CSP systems (~tens of meters in size) would be difficult.



(a) (b) (c) (d)

FIGURE 2. (a) Quartz half-shell tubes placed over the receiver aperture with a hood, (b) side-view of simulated air flow patterns colored by temperature resulting from varying angles of air injection across the aperture, (c) multistage catch-and-release particle receiver concept, (d) example of receiver geometry design from optimization process to reduce advective heat losses.

Active Airflow. CFD simulations were performed in Phase 1 to investigate active airflow (e.g., air curtains) across the aperture and suction-recirculation methods to reduce advective heat and particles losses, and to potentially cool and clean the quartz aperture covers. Previous studies have shown that air curtains can reduce heat losses in cavity and particle receivers [21, 22]. In this study, the magnitude and direction if air flowing across the aperture were varied, and the impact on receiver efficiency was simulated (**FIGURE 2**b). Results showed that under quiescent conditions, air curtains could improve the efficiency under certain configurations. However, the air curtains could not reliably mitigate the adverse impacts of wind, even with air-jet speeds of up to 30 m/s. Upscaling of air curtains over tens of meters of distance is also expected to be a challenge. Additional CFD models of air suction at different locations within the receiver were also simulated, but results did not show a significant decrease in advective losses.

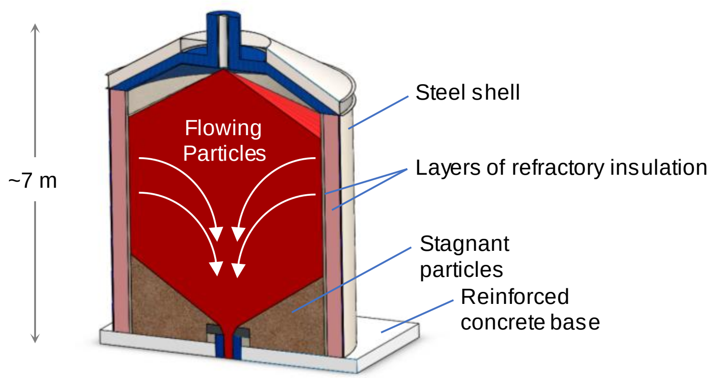
Multi-Stage Release. A patent-pending multi-stage catch-and-release system has been developed and tested to reduce the particle velocity and advective losses and to increase particle-curtain opacity for increased receiver thermal efficiency. Several catch-and-release designs have been considered. **FIGURE 2**c shows a simple design that allows particles to accumulate in a trough or angle-iron that spans the width of the receiver. Particles that fall from the upstream trough impact the mound of particles and are slowed before spilling over to the trough below. This design accommodates variable particle mass flow rates and minimizes direct irradiance to the troughs. Tests are ongoing to optimize the shape, orientation, and dimensions of the troughs that maximize particle opacity and stability while minimize particle bouncing and loss. Modeling studies have demonstrated appropriate spacing of the troughs for different size and power requirements [23].

Geometric Optimization. A suite of CFD simulations was performed to optimize the geometry of the G3P3 receiver to minimize advective heat losses. A simplified model that included the release of hot particles through the receiver without radiation was used in ANSYS FLUENT. Turbulent particle-air interactions and advective losses through the aperture were simulated while changing the dimensions and shape of the receiver. The optimization tool DAKOTA was used to vary these dimensions with the objective of minimizing advective heat losses. Once an optimized geometry was obtained, a full-physics model including irradiance was simulated to ensure desired particle temperatures were achieved with reasonable power levels. **FIGURE 2**d shows a cross-section of an optimized design which contains a "snout" that reduces the advective loss of entrained hot air that recirculates within the receiver. The impacts of external wind were also simulated, as well as loss of particle fines.

Particles and Storage System

The particle storage bins in the G3P3 system are designed to hold hot particles between ~600 – 800 °C with a storage capacity of 6 MWh_t (6 hours at a thermal duty of 1 MW_t) (**FIGURE 3**). As shown in **FIGURE 1**, the storage bins are vertically located in-line with rest of the G3P3 system so that the particles can flow through all of the principal components solely by gravity drainage. The storage bins will exhibit unique features that include particle funnel flow (vs. "mass flow" in which all particles in the cylindrical section flow downward at a uniform velocity) in a refractory-lined cylindrical tank to minimize erosion, heat loss, and costs. The unique design of a flat-bottomed tank (instead of a conical feed hopper), is intended to induce funnel flow and reduce particle flow and friction along the walls of the tank, thereby reducing erosion of the containment and insulation materials. The bins will each hold up to ~160,000 kg (~160 metric tons) particles (particle bulk density ~2000 kg/m^3). The inventory consists of ~120,000 kg of flowing particles and ~40,000 kg of stagnant particles. Small-scale tests are being performed to evaluate the funnel-flow concept and its impact on average particle outlet temperatures during draining after 10 hours of deferred storage. In addition, the stagnant particles create a self-insulating layer that protects the concrete base. Candidate particles include commercial sintered bauxite proppants (e.g., from Carbo Ceramic) that have desired optical/thermal/mechanical properties based on previous on-sun tests [3]. CARBO high-strength proppant (HSP) 40/70 materials have been found to have superior optical and durability characteristics (**FIGURE 3**).

Scalable particle storage systems that utilize tower-integrated or ground-based storage tanks will be designed and evaluated in Phases 1 and 2 with industry partners that consider costs and structural viability for 100 MW_e systems.



CARBO HSP 40/70	
Composition	Al_2O_3 (83%), SiO_2 (5%), Fe_2O_3 (7%), TiO_2 (3.5%)
Median particle diameter (μm)	~350
Specific gravity	3.6
Bulk density (kg/m^3)	~2,000
Roundness	~0.9
Sphericity	~0.9
Specific heat (J/kg-K) at 700°C	1,250
Bed solar absorptance	0.93
Bed thermal emittance	0.86

FIGURE 3. Left: design of the G3P3 hot storage bin with 6 MWh of storage capacity. Right: properties of CARBO HSP [24, 25].

Heat Exchanger and sCO2 Flow System

Design requirements for the G3P3 particle-to-sCO2 heat exchanger include 1 MW_t duty, overall heat transfer coefficient ≥ 300 W/m^2-K, working-fluid pressures up to 25 MPa, particle and fluid mass flow rates of ~4 and ~5 kg/s, respectively, and particle and sCO2 temperatures discussed above. Designs consider approach temperatures on the cold side of the heat exchanger between 15 – 50 °C. Counter-flow and counter-crossflow packed-bed shell-and-plate particle-to-sCO2 heat exchangers are being investigated for G3P3 using multiple banks of diffusion-bonded plates to contain the high-pressure sCO2 [26] (**FIGURE 4**). High-temperature banks near the top of the heat-exchanger will utilize nickel-based alloys, while the lower banks can be made of less expensive stainless-steel.

Our previous studies have measured particle-wall heat-transfer coefficients of ~200 W/m^2-K with 4 mm vertical channels in a simulated shell-and-plate design at low temperatures. In addition, uniform particle drawdown through 6-mm-wide vertical channels in between 316 stainless-steel plates was achieved with particle flow rates of ~5 mm/s at temperatures up to 600 °C [26-28]. Required ramp rates, turndown ratio, and controls are also being considered. Additional component testing and analysis are being performed to better understand and mitigate risks of erosion, flowability, and heat transfer from the particles to the sCO2.

The sCO2 loop will be designed for ≥1 MW_t, mass flow rate of ≥5.3 kg/s, a heat-exchanger outlet pressure of 25 MPa, a pressure drop of 0.5 MPa (2%), outlet temperature of 715 °C, and inlet temperature of 565 °C. The sCO2 loop will consist of an sCO2 inventory management system (two-phase CO_2 storage, gas pressurization, sCO2 liquid compression), a flow management system (pump, recirculation and flow measurement, cooling), a recuperation module (low-temperature recuperator, recuperator bypass valve, throttle valve), and particle heat-exchanger flow conditioning module (pre-heating or recuperation, after-cooling or recuperation, filtration).

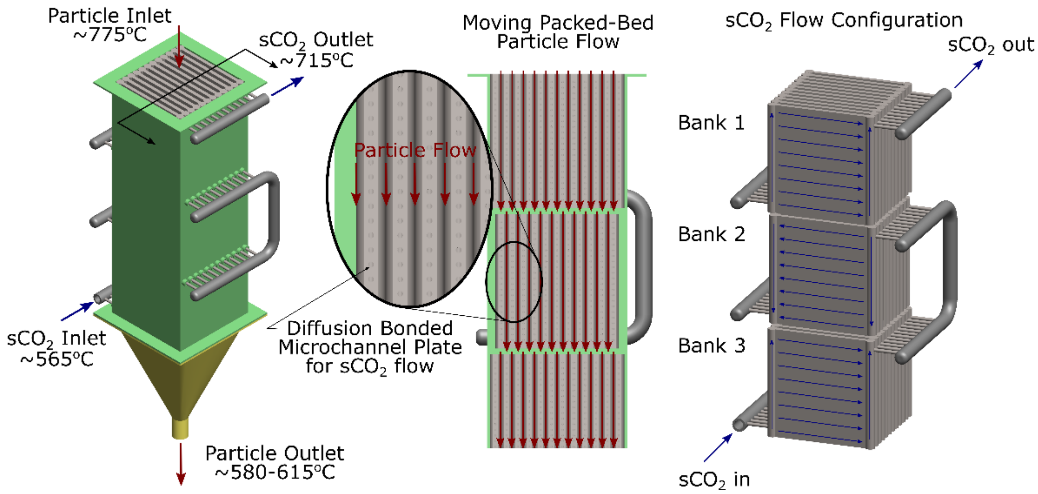


FIGURE 4. Illustration of a moving packed-bed, shell-and-plate, particle-to-sCO2 heat exchanger with multiple banks (adapted from [29]).

Particle Lift

High-temperature bucket elevators and skip hoists are being designed and evaluated for G3P3 and commercial (100 MW_e) scales, respectively. Design considerations include mass flow rate (up to 10 kg/s for G3P3 and up to ~2000 kg/s for a 100 MW_e plant with 15 hours of storage), particle temperatures up to ~600 °C, and minimization of heat loss, particle attrition, and cost. Although the skip hoist is expected to be the most suitable system for commercial scales [16], quotes obtained from a major mine-hoist supplier were extremely costly at the small scale of the G3P3 system. Therefore, a previously demonstrated bucket elevator is being pursued for G3P3. Previous on-sun tests at Sandia have also used the screw-type Olds Elevator, but high-friction between the particles and the rotating casing of the elevator was suspected of causing significant particle wear and attrition [3].

FIGURE 1 shows the current baseline design of the G3P3 system with a ~50 m tall bucket elevator to lift the particles from the base of the cold storage bin to the top of the receiver. A significant challenge is the minimization of heat loss through the large surface area of the casing of the bucket elevator, which is expected to be ~150 m^2. Steady-state internal temperatures of the bucket elevator are expected to reach up to ~600°C. Two metrics are critical for the design: (1) the casing temperature must stay below 350°C to avoid creep failure at high temperatures and (2) the heat loss should be minimized (<5% of the thermal duty of the system). Various internal and external insulation designs are being considered to meet these metrics.

CONCLUSIONS

A next-generation particle-based CSP system (G3P3) has been proposed to demonstrate the ability to achieve higher temperatures for advanced power cycles (>700 °C), 6 MWh_t of thermal storage, ≥ 1 MW_t of thermal duty, and thousands of hours of operation with consideration of start-up, transients, steady-state, off-design, and idling processes. Design requirements and novel features of the key components were described, including those of the receiver, storage bins, heat exchanger, and particle-lift subsystems. Increasing the thermal efficiency of the receiver was pursued using aperture covers, active airflow, multistage release, and optimized geometries. The storage bin was designed with consideration of minimization of wall erosion, heat loss, and wall stress. The particle-to-sCO2 heat exchanger consists of a moving packed-bed shell-and-plate design with particles flowing through narrow channels between diffusion-bonded plates that contain flowing high-pressure sCO2. Design of the particle lift considered minimization of heat loss and particle attrition. While the skip hoist is believed to be best suited for commercial scales, a bucket lift was selected for G3P3 due to cost limitations and its previous use during on-sun tests at Sandia.

The G3P3-USA system is focused on the sCO2 Brayton cycle while partners in Saudi Arabia are developing a G3P3-Saudi system in parallel that is focused on a hybridized air-Brayton system. Development of both systems in parallel will increase chances of success and accelerate de-risking of key components and system operation. In addition, the G3P3 project is being developed with key international and industry partners* to accelerate deployment and commercialization of particle-based CSP technologies.

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