Gen3 Gas Phase System Development and Demonstration

The Gen3 Gas Phase System Development and Demonstration program proposes Construction, Commissioning, Testing of a Phase 3 Test Facility capable of de-risking an integrated commercial Concentrating Solar Power (CSP) system with Thermal Energy Storage (TES) for dispatchable power day or night.

The commercial system being developed leverages critical elements that will appear familiar to end users and financiers, thereby reducing barriers to adoption. A tubular receiver design absorbs concentrated sunlight from a field of heliostats and uses it to heat supercritical carbon dioxide (sCO_2). This hot fluid then delivers its heat into a flowing bed of low-cost silica sand, which is thermally stable to high temperatures and can retain that heat for extended periods. The heated sand may then be used immediately to power an electricity-producing engine cycle, or it may be stored nearly indefinitely until it is needed.

Within this system there are several technology innovations and elements that operate in regimes well beyond the state-of-the-art. These elements are being captured in the Test Facility at suitable scale and operational similitude to retire their risk and enable rapid adoption of the full-scale commercial system. The overall Phase 3 Test Facility, including the surround field of heliostats, is depicted in Figure 1.

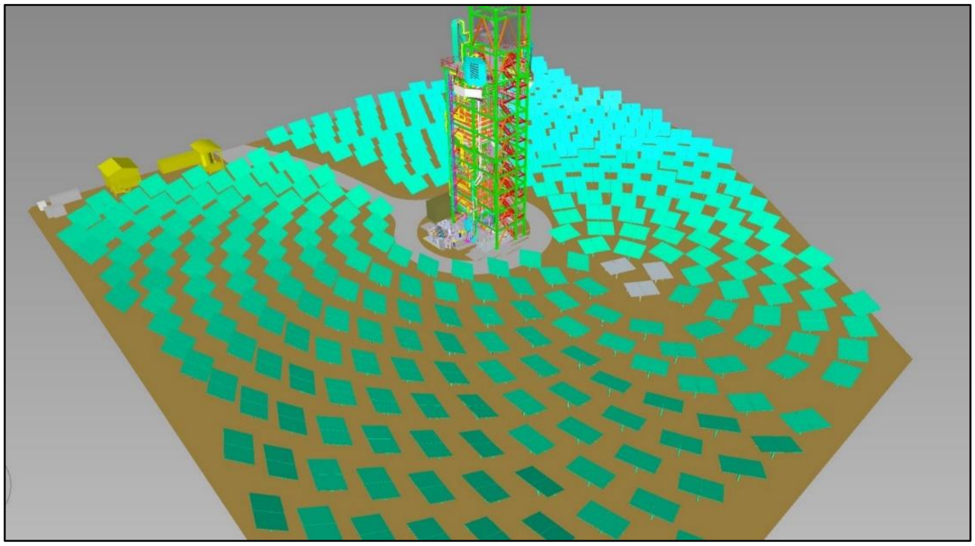


Figure 1 – The integrated Phase 3 Test Facility, consisting of a central receiver tower surrounded by a field of heliostats.

The proposed Phase 3 Test Facility design incorporates the following key elements:

- A 5 MW_t field of heliostats collect incoming solar energy and focus it on three receiver sections located atop a central tower, shown in Figure 2.
- The first receiver absorbs 1 MW_t of incoming solar energy and transmits it into sCO_2 at 575 °C flowing into its tubes.
- Hot sCO_2 exiting the receiver at 730 °C enters a 1 MW_t gas-to-particle charge heat exchanger, where it delivers its heat into a flowing bed of silica sand. The hot silica sand, now at 715 °C, is collected in a hot storage silo mounted mid-tower where it can be stored indefinitely or used immediately.
- The cooled sCO_2 exiting the heat exchanger then flows into the second receiver, where it repeats the same heat-and-deliver cycle in a second charge heat exchanger. The outlet flow from this unit then flows into one more coupled receiver/heat exchanger pair.
- The cooled fluid then flows down to ground level. To simulate interaction with a coupled power block, the cool sCO_2 at 575 °C passes through a primary heat exchanger, this time *absorbing* 1 MW_t from hot sand flowing out of the hot storage silo. Once heated to 700 °C the fluid is conveyed to a circulator that simulates a 0.5 MW_e power-producing gas turbine engine, after which it will return up-tower to repeat its circuit.
- Having donated its heat, the cooled sand is collected in a cold storage silo located near the bottom of the tower. From here it will be carried back up to the top of the tower via an insulated skip hoist.

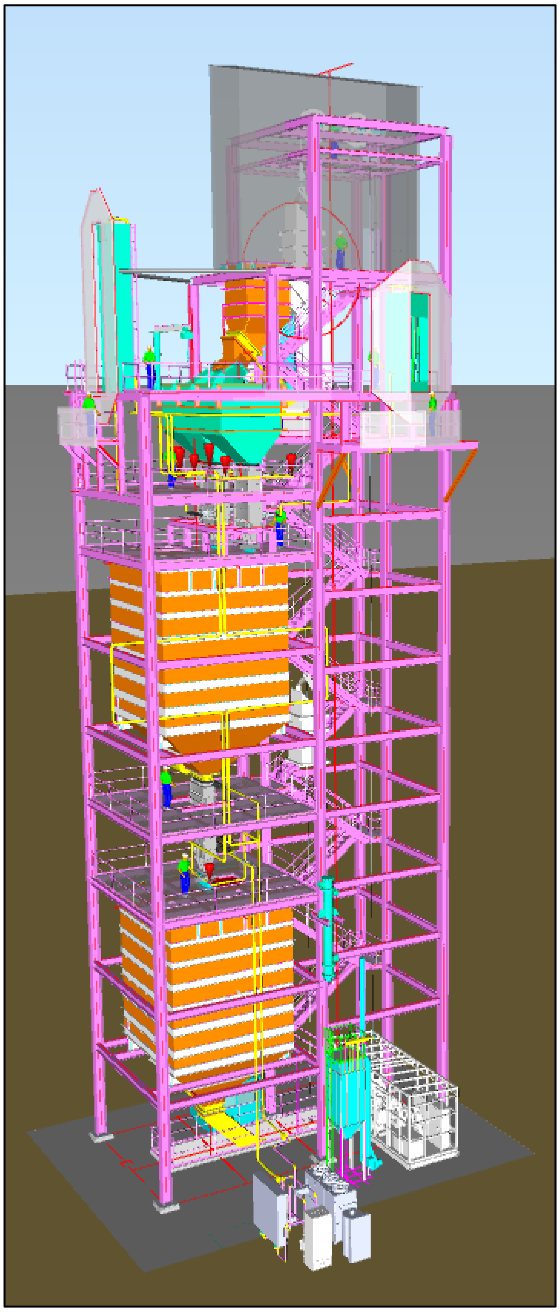


Figure 2 – The Phase 3 Test Facility central tower.

Within the full integrated system described above, 3 MW_t is absorbed into sand while 1 MW_t is discharged from the sand whenever the sun is shining. This 3 to 1 store to discharge ratio corresponds to a baseload power generating system; during 8 hours of sunshine one third of the absorbed energy is used to run the engine, while the other 2/3 is stored. After the sun goes down, the hot sand can continue to run the turbine for an additional 16 hours, completing the daily cycle.

RISK MITIGATION EFFORTS

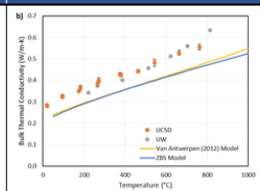
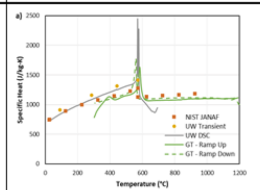
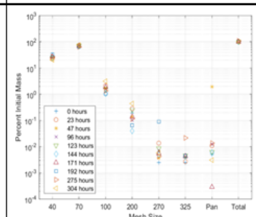
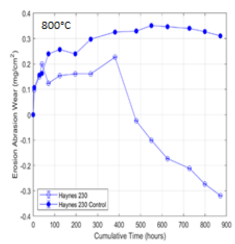
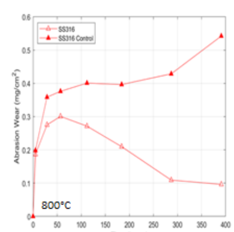
Several key elements of the integrated system described above were identified for risk reduction activities. These included:

1. Ensuring the flowability of the silica sand through the heat exchangers and valves over the full range of operating temperatures, and validating that erosion induced by flowing particles would not induce a failure
2. Confirming the manufacturability, operability, thermo-hydraulic performance, durability, and cost of the thermal energy storage heat exchangers, which exchanger energy between flowing particles on one side and sCO_2 at up to 25 MPa on the other side
3. Validating the manufacturability, operability, thermo-hydraulic performance, durability, and cost of the receiver sections

A series of detailed analyses and empirical test campaigns were performed to de-risk the items listed above. These efforts included:

1. To address particle-related risks subject matter experts were engaged to evaluate the silica sand particles for operability in the proposed system. Wherever possible the Gen3 Gas Phase program has leveraged other Department of Energy-funded efforts that may provide valuable learnings or guidance, thereby intensifying the value of government investment. Four such programs with specific relevance are presented in detail in Table 1, along with their results relevant to the Gas Phase program.
2. TES heat exchanger risk mitigation efforts included:
    a. Detailed creep, fatigue, and coupled creep-fatigue lifing analysis to produce a design that has a 100,000 hour operational life even under the strenuous conditions
    b. Subjecting as-manufactured heat exchanger cell sections to creep and fatigue testing at temperature in an sCO_2 environment to confirm that they exhibit the anticipated life

Table 1 – Other Department of Energy-funded research with direct application to the Gen3 Gas Phase system.

TEST NAME	OBJECTIVE	PARTNER	RESULTS	CONCLUSIONS
Bulk Effective Thermal Conductivity	Determine temperature-dependent effective thermal conductivity of candidate particle beds	UCSD		Measurements indicate an increase in bulk effective thermal conductivity with increasing temperature
Specific Heat	Determine temperature-dependent specific heat of candidate particle beds	Georgia Tech		Specific heat measurements agree with data for silica published in the NIST JANAF tables. The quartz phase change occurring at 573°C is visible through a peak in specific heat
Particle Attrition	Assess particle attrition rates	Boise State		Results at room temperature suggest negligible attrition after 300 hours
Particle-Wall Abrasion	Determine rates of wall abrasion in moving particle conditions at ambient (25°C) and elevated temperatures (800°C)	Boise State / U. of Tulsa	 	Erosion testing with silica sand and Haynes 230 (heat exchanger material) and SS316 (silos) indicate minimal abrasion wear at 800°C operating temperatures. Increase in wear is attributed to oxidation formation.

c. Performing heat transfer and pressure drop testing on the internal geometry of the heat exchanger cells to measure their thermo-hydraulic performance characteristics

d. Manufacturing a 16 kW_t subcore assembly (shown in Figure 3) to demonstrate manufacturability and measure in-situ performance between flowing particles and sCO2 at full operating conditions

e. Performing a series of manufacturing scale-ups to demonstrate that the commercial scale heat exchanger cell geometry is achievable

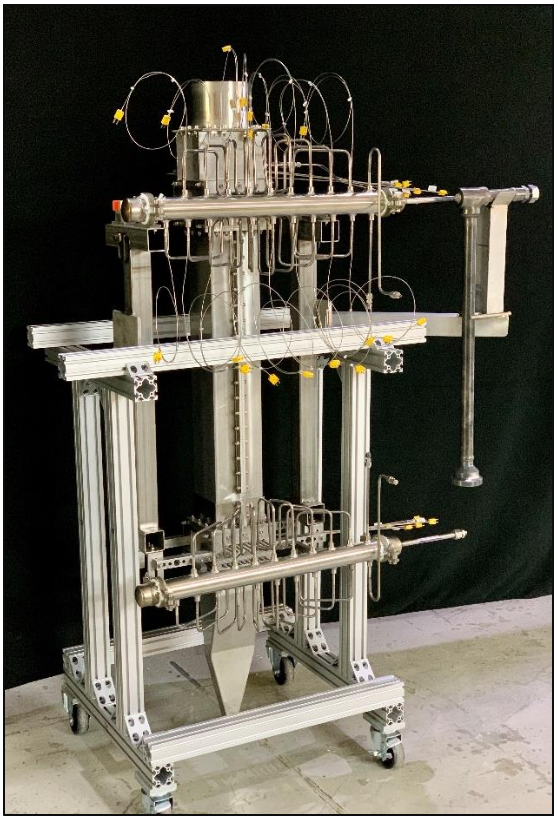


Figure 3 – The 16 kW_t TES subcore test article.

Figure 4 – On-sun testing of the 100 kW_t receveir test article.

3. The receiver assembly de-risk efforts included:
    a. Designing the receiver to ASME code
    b. Designing the receiver such that even when exposed to over-temperature and over-pressure conditions the receiver will achieve a 100,000 hour (30 year) operational lifetime, even assuming -3σ material properties within the receiver structure
    c. Fabricating a 100 kW_t receiver test article (shown in Figure 4) for on-sun testing

LEVELIZED COST OF ELECTRICITY

The primary metric by which the proposed commercial system may be evaluated is through the cost of the electricity it produces. To compete favorably with fossil fuels power must be delivered for at rates well below 6 ¢/kWh_e.

The Gen3 program considers power generation in two application or market structures. The first is a baseload market in which the objective is to minimize the levelized cost of energy (LCOE) produced by the system, and the second is a so-called “peaker” design whose objective is to maximize production during a limited time window associated with high-value electricity. The Gen3 gas pathway team has undertaken design and analysis of systems operating in both hypothetical market spaces.

The analysis begins with a fully integrated system model capturing the schematic and operational characteristics of the commercial power plant. In order to accurately reflect the full system a network of constituent sub-models were developed to simulate the cost, performance, availability, and any other key characteristics for the components and subsystems that comprise the overall power plant. More than 20 governing correlations were developed, including a bottom-up O&M model extrapolated from a commercial CSP facility to the design under consideration. Other inputs not pertaining to the technical design of the proposed commercial system (i.e. site location, financial terms, etc.) conformed to the prescribed inputs of the Gen3 program or, where appropriate, the default values in NREL’s System Advisory Model (SAM).

The system design assumes a fixed design receiver CO_2 outlet temperature of 730°C regardless of particle or heat exchanger design assumptions. This constraint ensured that the worst-case conditions for which the receiver and TES heat exchangers had been designed were not exceeded, thereby preserving its long-life operation.

The resulting economic results indicated that the commercial systemic achieves an LCOE of 5.03 ¢/kWh_e. This conclusion came out of a multivariate optimization of the integrated system model, in which key design parameters (such as power block scale, heat exchanger approach temperatures, etc.) were allowed to vary and the configuration corresponding to the lowest LCOE results was identified. A plot showing the outputs from the optimization routine is shown in Figure 5. The lowest LCOE case – corresponding to the aforementioned value – occurred around 65 MW_e.

A comparable analysis was performed on a peaker system, in which the on-sun components are not couple to the power block and are instead connected to a warm sCO_2 circulator. The corresponding LCOE-vs-Power Block scale graph is shown in Figure 6. The resulting LCOE and PPA are both very good. Applying the Department of Energy-defined pricing schedule results in an LCOE of 2.83 ¢/kWh_e and a PPA price of 3.40 ¢/kWh_e.

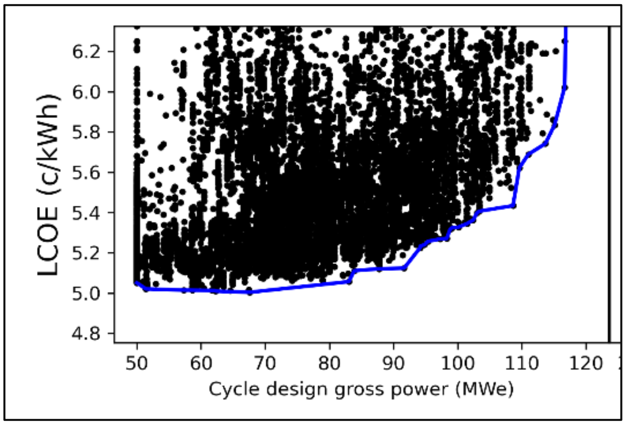


Figure 5 – Pareto front showing the optimal (lowest-LCOE) baseload case occurring at ~65 MW_e power block size

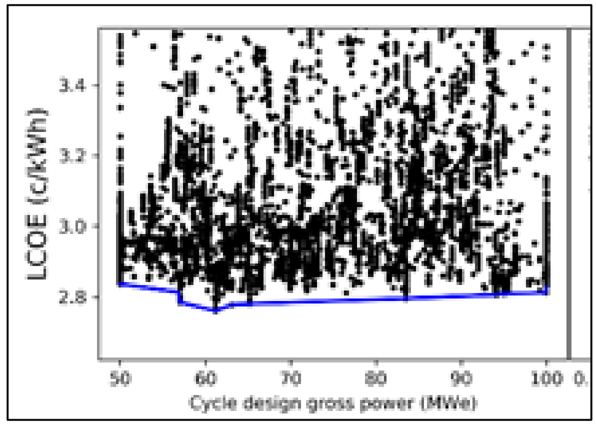


Figure 6 – Pareto front showing the optimal (lowest-LCOE) baseload case occurring at ~65 MW_e power block size

SUMMARY

Phases 1 and 2 of the Gen3 Gas Phase program were executed with a continuous philosophy of end-use-based risk mitigation. In Phase 1 a rigorously modeled commercial design was defined for robust long-life operation; from this a Phase 3 system was defined that incorporated commercial-scale elements wherever possible and employed them in a system with operational similitude to the full-scale system. The Phase 3 design was itself de-risked in Phase 2 via component and subsystem test campaigns. The result is a Phase 3 Test Facility proposal that has been substantially de-risked through manufacturing trials and test campaigns, and which will in turn de-risk the economically-compelling commercial design .