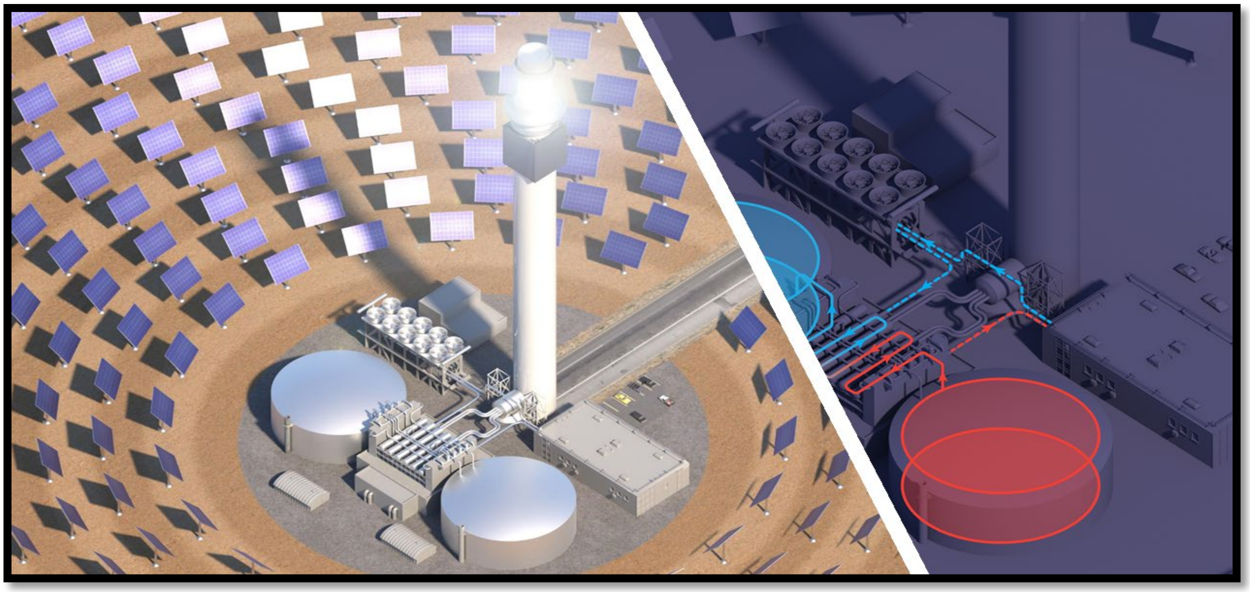

CSP Gen3 Liquid Pathway Continuation Application
Executive Summary

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1. Executive Summary

The U.S. Department of Energy (DOE) established the Concentrating Solar Power Generation 3 (CSP Gen3) program to promote the development of advanced CSP systems capable of producing electricity at a levelized cost of energy (LCOE) less than \$60/MWh. This goal was based on criteria published in the CSP Gen3 Roadmap [1] and a subsequent funding opportunity announcement (Gen3 FOA) [2]. This report summarizes the progress and potential of the “Liquid Pathway” to meet these objectives. The Liquid Pathway proposes the use of low-cost molten chloride salts for energy storage, mated with a solar receiver that employs liquid-metal sodium for heat capture and transfer to the storage salt. This approach leverages molten-salt technology from the current state-of-the-art CSP power towers embodied by plants such as Gemasolar, Crescent Dunes, Noor III, and the DEWA 700 CSP project. Furthermore, the design builds on the knowledge gained over decades of use of liquid-metal sodium as a high-temperature heat transfer fluid (HTF) in solar tests and nuclear-power applications.

The commercial representation of the proposed Gen3 design incorporates a high-efficiency sodium receiver operating at ~740°C, with a liquid-liquid heat exchanger feeding a two-tank, molten-chloride storage system, as depicted in Figure 1. Chloride salt is dispatched to a supercritical CO_2 (sCO_2) power cycle to provide electric power to the grid. The design integration is a conceptual match for the current sodium receiver → solar salt storage → steam-Rankine power cycle promoted by CSP-developer Vast Solar, which will facilitate commercial acceptance and development.

The Liquid Pathway leverages an extensive list of suppliers and developers in CSP and nuclear industries. This market presence will shorten the timeline to commercial deployment of the proposed Gen3 technology.

To advance this sodium/salt Gen3 system, the Liquid Pathway team proposes the design and construction of an integrated 1-MW_{th} pilot-scale system, per the goals of the DOE Gen3 Program. The Liquid Pathway team is led by the National Renewable Energy Laboratory (NREL) and includes industry, academic and national laboratory contributors. Sandia National Laboratories, working closely with Bridgers & Paxton (B&P), serves as the host site and system integrator. Industrial and academic partners provide expertise related to system components such as valves, tanks, and heat exchangers designed to work with the high-temperature fluids. Partners of the Australian Solar Thermal Research Institute (ASTRI) lead the development of the sodium receiver and sodium handling system and have provided research amounting to an approximate 34% in-kind cost share over the span of project Phases 1 and 2.

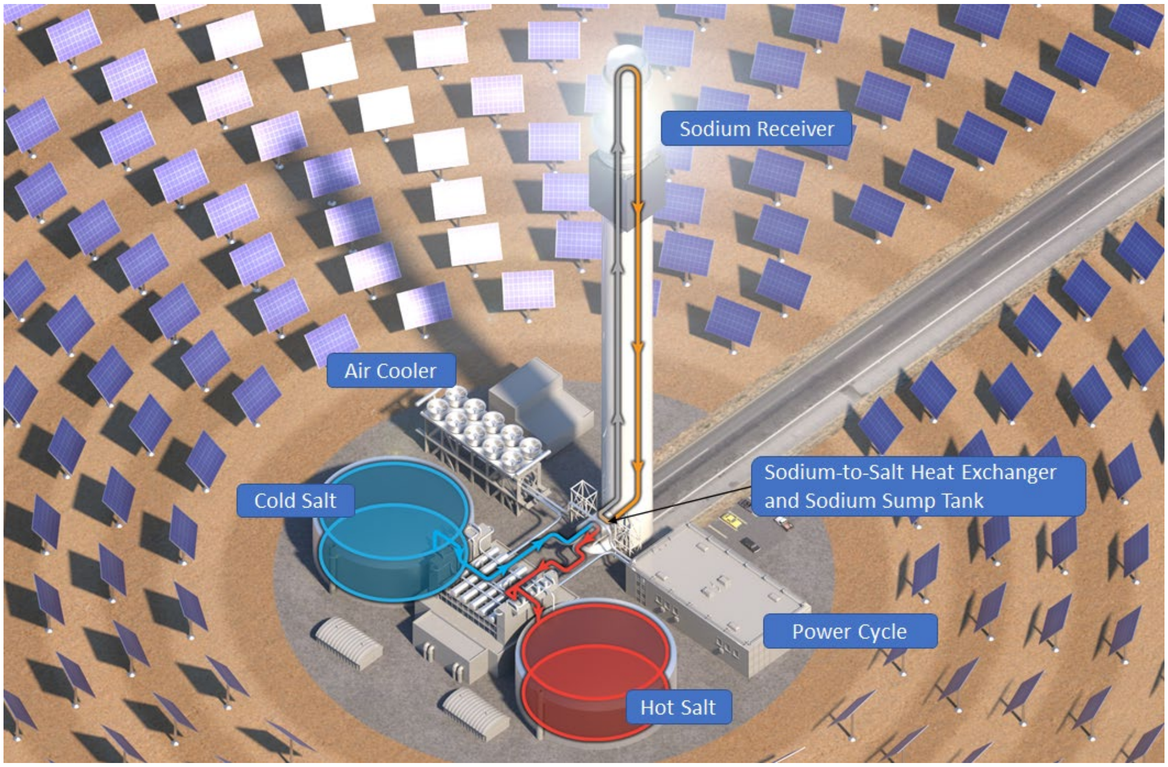

Figure 1. Sodium/Salt Gen3 system showing on-sun charging of the salt storage system.

In addition to the official project team, the Liquid Pathway benefits greatly from an ecosystem of industrial suppliers and developers working with these liquid HTFs. In particular, Vast Solar has provided guidance on sodium handling and components, while receiver manufacturer John Cockerill has given the team significant help on receiver design, construction, and cost. Molten salt component suppliers Flowserve (pumps and valves), Sulzer (pumps), Flexitallic (gaskets and seals), Guichon (valves) and Gosco (valves) have shared information and/or hardware with the project team. Questions regarding sodium handling and system design have been guided by experts at Creative Engineers, Inc. (USA), Argonne National Lab and CEA France. Materials selection and compatibility with these fluids has leveraged work in the wider DOE "Salt Collective" research arena, with specific engagement from Electric Power Research Institute, EPRI, and Special Metals (alloy properties), Powdermet (protective cermet coatings), Liquid Metal Holdings (protective thermal-spray coatings), Argonne National Lab (salt chemistry sensor), Oak Ridge National Lab (corrosion and small-scale testing), and Universities of Wisconsin and Arizona (salt chemistry). This research and supply-chain network, and the similarity of design with the existing CSP fleet of power towers, facilitates the route to commercial implementation once the technology has been demonstrated.

The Liquid Pathway has been further aided by engagement with our project Technical Advisory Committee (TAC), led by Cara Libby of EPRI. The TAC has attended quarterly reviews and was essential to the receiver selection process. New TAC members were brought onboard at the end of Phase 1 to bolster the team's knowledge of sodium systems after the sodium receiver was selected in the down selection.

1.1. Liquid Pathway Commercial System Design and Advantages

During project Phase 1 the team compared the benefits and risks of salt storage mated to a salt receiver or a sodium receiver. This review was undertaken via a structured analytic hierarchy process (AHP) facilitated by EPRI [3]. The AHP participants, which included the project's leadership team and TAC, concluded that the sodium receiver had both a significantly higher benefit (19.3%) and a lower LCOE (11.4%), with only a slightly higher risk (3%) than the salt alternative. Key observations included:

- While the score for criterion *Minimize risk to people and the environment* was the primary factor that resulted in a higher risk for sodium, it did not seem to impact the score for *Minimize the risk of obtaining bank financing and insurance for a commercial plant*, which received roughly the same score for both receiver types. The group concluded that even with the added risk from sodium, it would be feasible to educate bank engineers and the public about sodium as a safe technology.
- In the benefit hierarchy, the sodium alternative scored higher than the salt alternative across all six criteria. The three biggest differentials between the salt and sodium criteria scores were (i) accommodate different plant sizes and configurations, (ii) maximize efficiency and performance, and (iii) maximize long-term reliability and availability.

The sodium receiver's operational benefits are due to sodium's superior thermophysical properties versus the chloride salt, such as lower melting point (98°C vs. 400°C), lower volume change on freezing/melting (3% vs. ~20%), lower viscosity (~10x lower), and greater thermal conductivity (64 vs. 0.4 W/m-K). These attributes lead to greater operational flexibility and greater allowable flux on the receiver (i.e., a smaller, cheaper and more efficient receiver), as showcased by developer Vast Solar in their SolarPACES 2019 Innovation Award acceptance presentation and at their 5-MW$_{th}$ Jemalong facility (Figure 2). The overall result is a lower projected LCOE, despite the need for a sodium/salt heat exchanger. While the current Vast Solar design operates at less than 600°C, the proposed Gen3 design will endeavor to move the technology to higher temperatures and efficiencies.

Figure 2. Vast Solar's 5-MW$_{th}$ Jemalong pilot plant has derisked sodium handling in preparation for their proposed Mt. Isa project. Vast's commercial system will operate at sodium temperatures up to about 600°C and employ thermal energy storage with nitrate solar salt. Photo: Vast Solar

Importantly, the dual-fluid design allows each HTYF to operate where best suited. The unparalleled properties of sodium are dedicated to the solar receiver, leading to higher receiver efficiency and lower freeze risk. Sodium inventory is kept at a minimum and confined to the receiver, tower, and close proximity to the tower base in the Gen3 design. The Gen3 design uses low-cost chloride salt as sensible-heat thermal storage media capable of operation at temperatures exceeding 700°C. Both media are available in bulk quantities from existing commercial suppliers. The ternary salt blend is provided to this project by ICL as anhydrous carnellite, a feedstock used by the magnesium industry.

1.1.1. Commercial-scale system LCOE estimate

In the team's Phase 1 comparison of a salt-only and salt/sodium design, both units were modeled as 100-MW$_e$ single-tower systems. As noted above, the salt/sodium design was selected. The versatility offered by a sodium receiver opens the design space to include modular or multitower systems as evidenced by the Vast Solar system design. Accordingly, in Phase 2, the team explored multitower designs, examining the tradeoff between economy-of-scale and benefit of smaller size systems. This analysis led to the selection of a 50-MW$_e$ unit, which is duplicated to form a 100-MW$_e$ power facility to meet the DOE FOA requirement for a 100-MW$_e$ system. Advantages of the 50-MW$_e$ unit design include significant optical efficiency benefit, ability to utilize smaller towers (with potential cost savings), smaller salt tanks (allowing for a single pair of salt tanks per tower), better capacity match to the nascent sCO$_2$ power cycle, adaptability to fringe-of-grid and small-grid markets (e.g., Australia, which is perceived as a likely early adopter), easier financing and shorter construction times, and learning-by-doing replication. The twinned facility also offers operational redundancy where 50% generation can be maintained while maintenance is performed on the second unit. Bigger facilities can employ a "power park" design that allows for shared staff and support infrastructure [4]. These advantages overwhelmed the negative effects of the smaller plant capacity, namely higher cost-per-kW capacity and slightly lower efficiency of the power cycle.

Performance and capital cost estimates for the proposed commercial-system design were developed by the team during Phase 2 (Table 1). The SolarTherm CSP system model was used to generate LCOE estimates for the proposed design with a reference case of best-estimate costs and a parametric study that statistically varied each cost input, typically +/- 25%. This analysis resulted in a probability distribution of **LCOE as shown in Figure 3 with a mean of \$58/MWh$_e$ (USD), meeting the FOA target of \$60/MWh$_e$**.

Table 1. High-level performance and cost parameters for the 50-MW_e unit.

Item	50 MW_e module
Energy per year (MWh):	391,982
Capacity factor (%):	89.5
Receiver thermal input at design point (MW_{th}):	385
Receiver thermal output at design point (MW_{th}):	350
Annual field efficiency (%)	48.0
Annual solar to thermal efficiency (%):	41.3
Annual solar to electric efficiency (%):	19.3
Power block gross rating at design point (MW_e):	55.6
Power block efficiency at design point (%):	47.9
Full load hours of storage (h):	12.0
Storage capacity (MWh_t):	1,393
Total salt inventory, working and heel (tonnes):	22,925
Solar multiple:	3.0
Receiver diameter (m):	14.0
Receiver height (m):	14.5
Tower height (m):	150
Number of heliostats:	14,461
Single heliostat mirror area (m^2):	50.0
Total field area (m^2):	722,832
Total capital (installed cost, USD)	$ 324,800,000

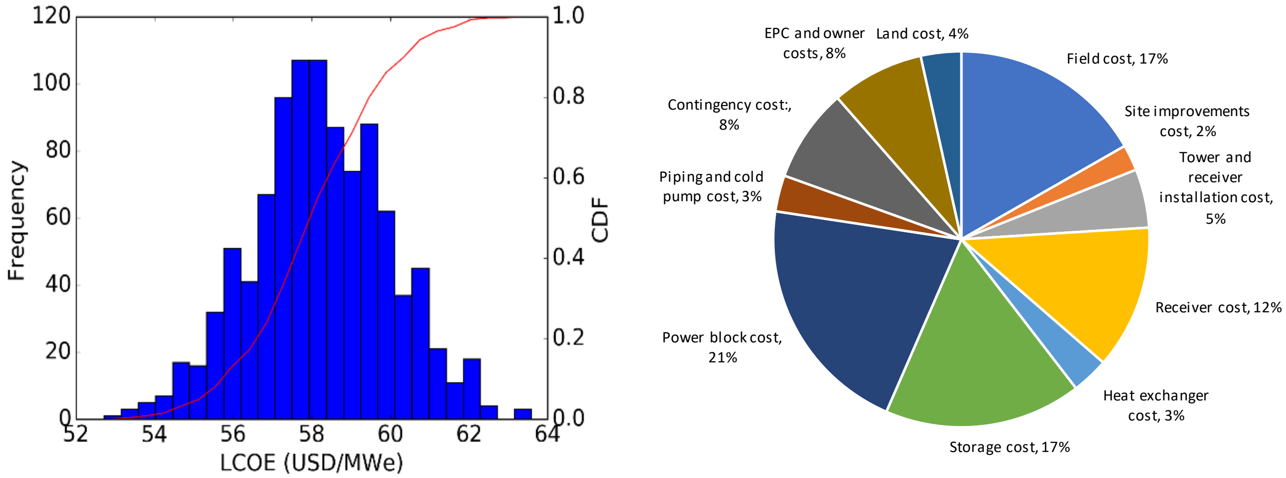

Figure 3. Left: Probability distribution for the LCOE of the 50-MW_e commercial system. The FOA target value for Gen3 is \$60/MWh_e. Right: Breakdown of total capital costs for the 50-MW_e system.

1.2. Summary of Major Accomplishments of Phases 1 & 2

During the project's Phase 1 & 2 research periods, significant knowledge was gained to derisk the technology. The tank design and liner materials were investigated, and a refractory liner defined that withstands the temperature and corrosion challenges of the salt. This design built on knowledge from the magnesium and refractory industries. The salt tank design employs a hot-face brick liner shown to be resistant to salt attack and that forms a protective forsterite phase in the presence of magnesium salt. This design insulates and protects the tank shell so that carbon steel can be used for the shell itself.

Melting and purification of the salt was demonstrated at the laboratory and bench scale. Building on research from DOE's wider research program in molten chloride salts (aka, the *Salt Collective*), the team developed a protocol for melting the multi-ton quantity of salt required for the pilot scale system. This protocol has been tested with the melting of a 200-kg batch of salt at Oak Ridge National Laboratory.

Prior to the sodium vs. salt comparison and down selection, the project evaluated multiple salt and sodium receiver designs, work which has been submitted for publication by the project teams. Two designs were selected for the head-to-head down selection, which concluded that a sodium receiver design could achieve a lower LCOE and had greater operational benefits versus the salt design.

The proposed pilot-scale sodium receiver design is representative of the selected commercial-scale receiver. The pilot-scale receiver is estimated to have a thermal efficiency of approximately 84%, not accounting for intercept losses, which are negatively influenced by the small receiver size and large heliostats at the test site. The exit sodium temperature is 740°C. The commercial-scale design is estimated to have an overall receiver efficiency of 88%, accounting for all thermal and intercept losses.

Maximum allowable flux on the receiver is limited by creep-fatigue damage of receiver tubes. Detailed inelastic analysis explored the design constraints for the receiver in collaboration with experts at Argonne and Idaho National Labs. A protocol was developed for estimating receiver lifetime in the creep-fatigue regime that avoids the conservativism inherent in simpler (elastic) design procedures. Testing of the pilot-scale system will provide confidence in estimated receiver lifetime and a means to further calibrate the protocol. The high flux allowances currently under consideration translate to lower cost and higher efficiency in a commercial design.

The primary salt-to-sCO_2 heat exchanger (PHX) will use a printed circuit heat exchanger design (PCHE). Etching and bonding tests during Phase 2 confirmed the ability to fabricate such a unit out of Inconel 617 and H230. The high-nickel alloy PCHE design allows for a compact heat exchanger that can withstand both the sCO_2 pressure and differing corrosive effects of the two fluids. The commercial availability of PCHE technology gives a high degree of confidence to the estimated performance of these units.

1.2.1. Relevant accomplishments under Topic 2 or other R&D

The Liquid Pathway project has benefited from several complementary projects funded under Topic 2 of the Gen3 CSP FOA, alloy materials research funded by EPRI and the DOE nuclear program, and other research around the world. These include projects examining chloride salt chemistry, salt-chemistry sensors, salt pumps, salt valves, coatings to protect against salt corrosion, and the prototype test Facility to Alleviate Salt Technology Risks (FASTR) at Oak Ridge National Lab.

Projects led by Powdermet [5] and Liquid Metal Holdings [6] have developed and tested protective coatings for use in chloride salts. Other research has examined the potential of cladding as a protective liner in pipes and tanks. The cermet coatings developed by Powdermet are applicable as a wear-protective layer in pumps, valves, and fittings and have been quoted to the team for use in the project. The thermal spray coatings developed by Liquid Metal Holdings can be applied to tanks and large-diameter piping. Both of these approaches allow for use of lower-cost substrate alloys and longer life components.

Monitoring of the salt chemistry is essential for corrosion control and Argonne National Lab has developed an electrochemical sensor shown to effectively measure salt redox potential and corrosion indicators in laboratory and bench scale testing. This technology will be deployed and tested at the pilot system to monitor salt conditions.

Pump suppliers Sulzer, Flowserve, and Hayward Tyler engaged with the Liquid Pathway team on the design of molten-chloride salt pumps. These pumps leverage extensive knowledge of long-shaft, vertical-turbine salt pumps used in current CSP plants. Changes are made to adjust for the differing corrosion, salt property, and temperature conditions of the Gen3 molten chlorides. Sulzer and Flowserve provided pump designs, performance specifications, and pricing for the pilot scale salt pumps, as well as budget estimates for the commercial scale.

Similarly, chloride salt valve technology borrows heavily from the knowledge of current molten salt valves. High-nickel alloys, globe-valve design, and bellows seals are recommended for dealing with chloride salts. The Liquid Pathway project consulted with valve suppliers Flowserve, Guichon, Trillium, Gosco, and Jarecki, during Phases 1 and 2. Both Flowserve and Gosco have supplied valves for bench-scale testing, although these tests have been delayed due to pandemic-related issues.

Recognizing the value in preliminary prototype component testing, DOE funded the FASTR project. This chloride-salt test facility provides similar piping size, temperature, and flow rates as expected in the proposed 1-MW_{th} pilot scale system. Hampered by pandemic related delays, FASTR's anticipated start in summer 2020 was pushed back into late fall. Recently, the FASTR team successfully melted their 200-kg batch of salt and charged the system. However, the delays mean FASTR is unlikely to inform the Gen3 down select decision, although the facility is key to derisk components prior to potential integrated-system demonstration.

1.3. Remaining Major Risks

Risks associated with the proposed Liquid Pathway were identified and tracked throughout the project in a formal Risk Registry. The risk registry captured project risks across over 17 component and subsystem categories and currently tracks over 400 identified risks associated with design, operation, and performance of the pilot-scale system. Current significant risks include the integrity of the tank liner, the performance of the salt valves, the impact of salt vapor on system components, salt piping freeze recovery, pressure and chemical sensor performance, online corrosion control, 740H alloy compatibility with sodium, and risk of fire from hot and reactive fluids. Addressing these risks and demonstrating reliable operation is the goal of the pilot-scale demonstration system.

1.4. Objectives of the Phase 3 Demo

The overall goal of the integrated system demonstration is to derisk the Liquid Pathway approach and facilitate the development of the liquid pathway technology for Gen3 CSP. The general system layout is shown in Figure 4. Specific objectives include:

Operational Performance

- Demonstrate operational modes including dynamic and steady-state conditions.
- Demonstrate safe operation of a sodium receiver and sodium loop. While sodium provides superior heat transfer capabilities in the receiver, the safety and reactivity concerns surrounding sodium can have significant implications on perception and acceptance of the technology.
- Demonstrate operation at the target thermal rating of 1 MW_{th} and outlet temperature of 740°C. Many failure modes for the receiver system arise from operation at target outlet temperatures that are well above those encountered in current commercial CSP systems. Thus, operating the receiver and sodium-salt heat exchanger at the target conditions is critical to derisk the functionality and survivability of the technology.
- Demonstrate thermal ramp rates for all three fluid loops and quantify limits of dynamic performance. CSP receiver systems operate under inherently dynamic conditions owing to variability in solar flux and weather. Responsiveness, controllability, and survivability under dynamic conditions are paramount to successful system performance.
- Demonstrate safe operation and survivability of components in response to emergency conditions including power loss for heliostat control or receiver flow control, simulated critical component failures, or excursion of properties including receiver flux and temperature conditions from the desired set point.

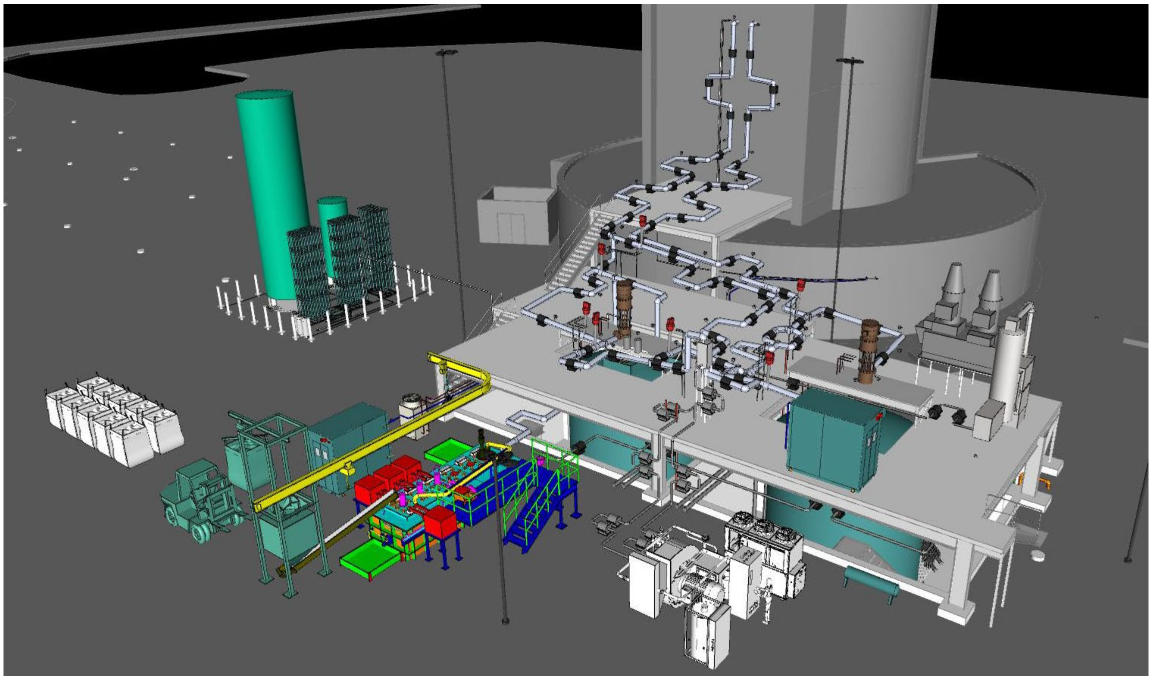

Figure 4. System layout at the tower base of Sandia's National Solar Thermal Test Facility: Melter in color at front left, N_2 ullage gas supply in left rear, scrubber in right rear on the elevated deck, and PHX with sCO_2 system in foreground at right. Receiver level not shown.

Model Validation

- Characterize heat loss and receiver thermal performance. Validated pilot-scale performance models will provide confidence in commercial-performance projections.
- Characterize salt tank heat loss and thermal performance.

Salt Tank

- Characterize the performance of foundation cooling in the pilot-scale tanks to refine performance models for air cooling of commercial-scale tank foundations. Successful implementation may point to cheaper designs for large salt tanks.
- Demonstrate tank liner integrity and performance.

Pumps, Valves and Piping System

- Demonstrate salt and sodium pump and valve operational capabilities at Gen3 conditions.
- Assess impact of salt vapors on system components and tank headspace.
- Demonstrate operation and durability of heat tracing in the valve and piping network and sodium and salt freeze recovery.

Materials and Corrosion

- Demonstrate receiver panel fabricability. Fabrication of the 1-MW_{th} pilot-scale receiver system will provide a detailed assessment of the workability of the materials, ease of manufacturing for the 740H alloys and tube dimensions, and fabrication cost.
- Demonstrate sodium cold trap operation and salt corrosion control. Maintaining purity levels in the sodium and salt fluids is essential to their long-term performance and the durability of the system.
- Test corrosion rates and compatibility of alloys and coatings with sodium and salt at the hot-side and cold-side temperature conditions.
- Complete sampling and post-test evaluations to validate material degradation and gain confidence in the ability to predict damage and degradation, and thereby to design components to a specified commercial-scale service life.

1.5. Estimated Cost of the Phase 3 Demo

The estimated budget for the Phase 3 project as calculated by the team's 90% Design Report is approximately $57 million dollars (estimated range $52 to $68 million). This estimate is roughly double the $31.2 million funding target set by the DOE program (federal share of $25 million plus 20% minimum cost share).

Should the Liquid Pathway project not be selected for construction of the full integrated 1-MW_{th} demonstration system under the Gen3 FOA, the team suggests that the DOE Solar Office consider partnering with other stakeholders for continued development of the chloride-salt thermal energy storage technology.

Liquid Pathway receiver down selection meetings held in February 2020 were hosted by nuclear-power developer TerraPower in Bellevue, Washington. TerraPower is developing both a molten chloride fast reactor (MCFR) and a sodium-cooled reactor design for future power generation. Their Natrium reactor combines a sodium-cooled reactor with energy storage in nitrate salt. The design was recently selected for an $80 million DOE demonstration award with the plan for a reactor to be operational within the next seven years (https://www.terrapower.com/doe-natrium-demonstration-award/). The MCFR design uses a binary $MgCl_2$/NaCl salt coolant with properties very similar to the ternary salt promoted by the Liquid Pathway team. Both systems currently interface with nitrate salt for thermal energy storage to facilitate reactor stability and load-following dispatchability. Transition to a chloride salt for energy storage offers significant benefits if the technology can be demonstrated to be reliable and cost effective.

The Liquid Pathway team sees value in combining the knowledge gained by the DOE Solar program's salt and sodium development research with other stakeholders, where development and demonstration could derisk chloride salt energy storage for both nuclear and CSP applications. Shared test objectives would include many of the same objectives listed for the CSP Liquid Pathway Gen3 program, namely:

- Demonstrate robust, affordable high-temperature salt storage tanks
- Demonstrate reliable pressure and flow sensors
- Demonstrate reliable and affordable flow control, isolation, and check valves
- Demonstrate the ability to monitor and control corrosion in chloride-salt systems
- Demonstrate the durability of alloys and coated-alloy samples in flowing chloride salt
- Characterize the performance of sodium-to-salt heat exchangers (relevant to the Natrium and CSP systems)

In short, the development for sodium/salt power systems from the Nuclear and Solar perspectives could be accelerated by cooperation in the development and demonstration of many of the objectives in the current proposal under such a cross-program partnering agreement.

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