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Design and Implementation of a 1-3 MW_{th} sCO_2 Support Loop for Gen3 CSP Primary Heat Exchangers

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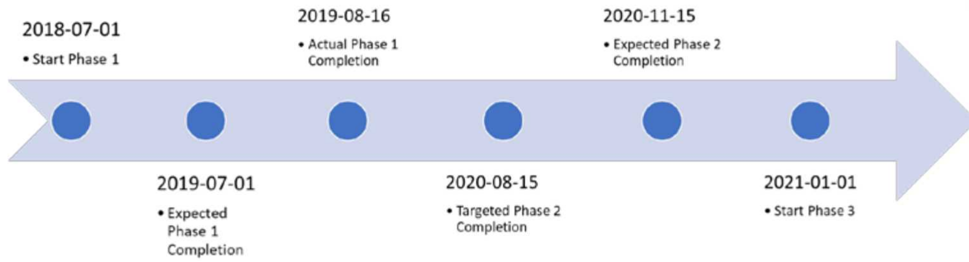
Project Schedule



Project Overview

The generation 3 concentrating solar power, or Gen3CSP, campaign seeks to de-risk and deploy a CSP pilot plant through three parallel project tracks focused on solid, liquid, and gas-phase primary heat transfer fluids. Although the components between the sun and the primary heat exchanger from the thermal storage system differ with each track, the supercritical carbon dioxide (sCO_2) coolant system required to cool the primary heat exchanger in place of a complete power conversion system has very similar requirements regardless of the primary heat transfer fluid. In order to avoid duplicative efforts, this project will design, assemble, perform acceptance testing, and deploy a single sCO_2 coolant system design meeting the needs of any Gen3CSP topic 1 pathway pilot plant design.

Project Goals

If one of the Gen3CSP topic 1 teams is successful in their application to continue to phase 3 and deploy a CSP pilot plant the sCO_2 coolant loop developed under this project will be used directly in the pilot plant. The sCO_2 coolant loop will be available from the start of the topic 1 phase 3 work in order to allow incremental or phased deployment and testing of the CSP pilot plant equipment. In addition, the broader CSP and sCO_2 research and industrial community will benefit from the development and deployment of commercial-grade sCO_2 equipment in an integrated system.

Project Objectives

This project seeks to design, assemble, perform acceptance testing, and deploy a 1 MW_{th}-scale sCO_2 support loop to provide cooling to the primary heat exchanger of any of the three Gen3CSP topic 1 pathway projects operating up to temperatures of 700 °C and 250 bar. Under phase 1 of this work, system design requirements were developed in coordination with the topic 1 project teams and reviewed by Gen3CSP stakeholders, a preliminary design study was completed to evaluate alternative system designs and equipment, and detailed procurement plans were developed. Under phase 2 of this work a detailed design will be developed, equipment will be procured, and the system will be assembled and tested to verify key performance requirements have been met including operating temperatures, pressures, and flow rates.

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Project Justification

There are currently no commercial offerings of high temperature and pressure sCO_2 equipment suitable to operate reliably as the coolant system for the primary heat exchanger of the Gen3CSP effort. Research and development must occur simultaneously on both the CSP thermal transport system and sCO_2 Brayton power cycles without imposing technology risks on either system. Federal funds have supported previous smaller-scale coolant systems and are required to scale up to the 1 MW_{th} level until commercial power cycles are available.

Project Organization and Responsibilities

The work for this project will be conducted by personnel at Sandia National Laboratories in consultation with Gen3 CSP topic 1team representatives to communicate and coordinate requirements and numerous subcontractors to specify and procure equipment.

The Challenges

Executing on this project requires overcoming three key challenges; designing a flexible, modular, and mobile sCO_2 coolant system to satisfy multiple potential customers, specifying and procuring a high reliability sCO_2 pump, and commissioning the system for turnkey operation at full temperature and pressure to ease integration with the Gen3CSP pilot plant. Tackling the first challenge has required a robust system engineering approach to develop and manage requirements with multiple project stakeholders. The second challenge has required evaluation and validation testing of commercially available pumps for use with sCO_2 and collaboration with original equipment manufacturers to understand operating limitations. This step has taken considerable time and challenged the project schedule but planning for sufficient margin in the project has allowed us to absorb the delay. Finally, commissioning a turnkey system will require modeling, simulation, controls development, and verification and validation testing to ensure every mode of system operation is understood and automated to the extent possible.

Milestone Status

Phase 1 of this project has been completed including the development of a requirements tracking database, preliminary design report, and procurement plan to manage our first key challenge and prepare to procure a reliable pump. The requirements database was implemented to allow easy modification and inspection by key project stakeholders from an initial 'landing zone' of metrics to ensure the level of conservatism in the requirements is inversely proportional with the amount of definition developed to support them; that they start highly conservative and are shifted toward more aggressive targets as alternatives and design options are analyzed. The preliminary design report captures a series of alternative and design analyses undertaken to identify equipment options and the impact of key design decisions such as the overall loop configuration and flow circulation technology. Finally, the procurement plan laid out the expected prices, lead-times, and size, weight, and power (SWAP) metrics based on one or more quotes to identify the most viable procurement method to use with each item. The procurement plan led to a one month delay in the schedule as vendors quoting on key equipment needed more time to develop a response, but this delay was accommodated in the project schedule.

Under phase 2 of this project our key milestones include procurement of critical long lead-time and customized components, development of a final design report, and commissioning of the coolant loop as a turnkey system. We have completed 3 of our 5 critical procurements including both our low- and high-temperature recuperators and pilot-operated pressure relief valve. Procurement of the pump is nearly complete but has been delayed by three months from our target date due to negotiations around terms and conditions between Sandia and the vendor. This delay impacts our targeted completion date but could be accommodated by the schedule buffer established in our project schedule. The primary air cooler will be procured following completion of the pump procurement as the design requirements for the cooler are dependent on the final operating requirements of the pump, but discussions with the OEM are underway in parallel. The final design report is in progress with key analyses for the operating envelope and coolant system drafted and can be completed once all critical equipment has been procured. Finally, the commissioning plan will include a failure modes and effects analysis (FMEA), operational logic diagrams, an automated control system and advanced programmer interface (API), and an installation and operations manual to support use by any of the topic 1 teams.

Scalability / Replicability / Impact

The principal impact of this project will be to support the Gen3CSP pilot plant by providing power cycle fluid conditions to the primary heat exchanger to increase the technology readiness and market receptivity of the CSP heat transport system. CSP plants operating at high temperature with an efficient power conversion system will enable power generation at less than 5 ¢/kW-hr unsubsidized to be competitive with other power production methods. In addition to this primary purpose, this project will also advance the technology readiness level of key sCO_2 equipment including the inventory management system, canned motor rotating machinery, direct air cooler in collaboration with original equipment manufacturers (OEMs) to allow them to be scaled up and directly provided to customers outside of the research and development community.

Project Results

Recent accomplishments from this project include the completion of a preliminary design report, procurement of the pilot-operated relief valve and recuperators, and completion of a detailed failure modes and effects analysis (FMEA). The preliminary design report captured analyses of key tradeoffs including the overall configuration of the system, equipment alternatives to circulate sCO_2 through the loop, and a preliminary design of a compact inventory control system to provide for rapid filling, stable operating pressures, and inventory recovery to reduce the need for venting and CO_2 deliveries. Procurement of 3 of our 5 critical long lead-time and customized commercial items pulls them off of our critical path and reduces the schedule risk for our project. The pilot-operated relief valve in particular will allow us to safely operate to within 10% of the maximum allowable working pressure (MAWP) of the equipment which reduces the required MAWP and therefore the cost and complexity of equipment operating at high temperatures. Finally, the FMEA captures almost 100 combinations of failure modes and causes and has been integrated with our requirements tracking database to ensure that potential failures to deliver on each performance requirement are captured and that any mitigations planned are added into our list of requirements. This integration also provides for rapid iteration to capture any new issues that arise and expansion from top-level to lower-level requirements as needed.

Several publications have summarized our findings and progress under this project at the Gen3CSP kickoff meeting held as part of the 2018 American Society of Mechanical Engineers (ASME) Energy and Sustainability conference[1], the 2019 SolarPACES conference[2], and has been accepted for inclusion in the 2020 ASME Energy and Sustainability conference[3].

The scope of this project is not expected to produce new intellectual property or patents as we sought to minimize the research and development required on the equipment but may never the less lead to copyrighted software and documentation so that lessons learned in the control and operation of sCO_2 systems can be disseminated to commercial providers.

Budget Tables

Our project is currently tracking under budget because hiring was delayed by almost a year. However, this direct issue did not impact the scope or deliverables of the project. We are expecting to be somewhat overbudget in equipment costs which can be covered by the surplus in labor costs to keep the project within budget overall.

III. Spending Summary by Budget Category						
	Approved Budget per SF-424A			Actual Expenses		
Budget Categories per SF-424a	BP 1	BP 2	Total	This Quarter	Cumulative	%
a. Personnel	$ 178,124.00	$ 294,453.00	$ 472,577.00	$ 44,402.54	$ 110,893.74	23%
b. Fringe Benefits	$ -	$ -	$ -	$ -	$ -	0%
c. Travel	$ 8,000.00	$ 4,000.00	$ 12,000.00	$ 245.35	$ 4,601.28	38%
d. Equipment	$ -	$ 2,000,000.00	$ 2,000,000.00	$ -	$ -	0%
e. Supplies	$ -	$ 50,000.00	$ 50,000.00	$ 1,893.60	$ 5,892.66	12%
f. Contractual	$ 30,000.00	$ 100,000.00	$ 130,000.00	$ -	$ -	0%
g. Construction	$ -	$ -	$ -	$ -	$ -	0%
h. Other	$ 45,455.00	$ 281,818.00	$ 327,273.00	$ 285,285.95	$ 324,938.74	99%
i. Total Direct Charges	**$ 261,579.00**	**$ 2,730,271.00**	**$ 2,991,850.00**	**$ 331,827.44**	**$ 446,326.42**	**15%**
j. Indirect Charges	$ 238,421.00	$ 369,729.00	**$ 608,150.00**	$ 53,913.67	$ 143,479.70	24%
k. Total Charges	**$ 500,000.00**	**$ 3,100,000.00**	**$ 3,600,000.00**	**$ 385,741.11**	**$ 589,806.12**	**16%**
DOE Share	$ 500,000.00	$ 3,100,000.00	$ 3,600,000.00	$ 385,741.11	$ 589,806.12	16%
Cost Share	$ -	$ -	$ -	$ -	$ -	0%
Cost Share Percentage	0.0%	0.0%	0.0%	0.0%	0.0%	0%

[1] Matthew D. Carlson, "sCO2 Test Loop and Heat Transfer Facility, A 1 MWth-scale sCO2 system for any Gen3CSP heat transfer pathway," presented at the DOE Gen 3 CSP Kickoff Meeting, Orlando, FL U.S.A., 25-Jun-2018.

[2] Matthew D. Carlson, "Guidelines For The Design And Operation Of Supercritical Carbon Dioxide R&D Systems," in *Proceedings of SolarPACES 2019*, Daegu, South Korea, 2019.

[3] Matthew Carlson and Francisco Alvarez, "DESIGN OF A 1 MWTH SUPERCRITICAL CARBON DIOXIDE PRIMARY HEAT EXCHANGER TEST SYSTEM," in *Proceedings of the ASME 2020 14th International Conference on Energy Sustainability*, Denver, CO, USA, 2020.

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