Design of a 1 MWth Supercritical Carbon Dioxide Primary Heat Exchanger Test System

Matthew Carlson
Mem. ASME
Sandia National Laboratories,
P.O. Box 5800,
Mail Stop 1127,
Albuquerque, NM 87185-1127
e-mail: mdcarlso@sandia.gov

Francisco Alvarez
Mem. ASME
Sandia National Laboratories,
P.O. Box 5800,
Mail Stop 1127,
Albuquerque, NM 87185-1127
e-mail: falvare@sandia.gov

A new generation of concentrating solar power (CSP) technologies is under development to provide dispatchable renewable power generation and reduce the levelized cost of electricity (LCOE) to 6 cents/kWh by leveraging heat transfer fluids (HTFs) capable of operation at higher temperatures and coupling with higher efficiency power conversion cycles. The U.S. Department of Energy (DOE) has funded three pathways for Generation 3 CSP (Gen3CSP) technology development to leverage solid, liquid, and gaseous HTFs to transfer heat to a supercritical carbon dioxide (sCO_2) Brayton cycle. This paper presents the design and off-design capabilities of a 1 MWth sCO_2 test system that can provide sCO_2 coolant to the primary heat exchangers (PHX) coupling the high-temperature HTFs to the sCO_2 working fluid of the power cycle. This system will demonstrate design, performance, lifetime, and operability at a scale relevant to commercial CSP. A dense-phase high-pressure canned motor pump is used to supply up to 5.3 kg/s of sCO_2 flow to the primary heat exchanger at pressures up to 250 bar and temperatures up to 715 °C with ambient air as the ultimate heat sink. Key component requirements for this system are presented in this paper. [DOI: 10.1115/1.4049289]

Keywords: concentrating solar power, supercritical carbon dioxide, Brayton cycles

1 Introduction

Efforts to identify and develop novel heat transfer fluids (HTFs) to harvest and store solar energy through concentrating solar power (CSP) technologies are underway. The U.S. Department of Energy (DOE) is currently funding research on Generation 3 CSP (Gen3CSP) technologies to develop technology to transfer heat from solid, liquid, or gaseous media to a supercritical carbon dioxide (sCO_2) Brayton cycle [1]. The sCO_2 Brayton cycle is of great interest as it reduces the footprint (due to smaller component size), cost, and has the potential to increase the thermal efficiency of the power cycle (close to 50%), making it competitive when compared with typical Rankine steam power plants [2,3].

The solid/liquid/gaseous Gen3CSP HTF paths (including primary heat exchangers (PHX) design and thermal energy storage) need to prove the capability and scalability of the different systems and require a cooling system for this task. To reach the goals set by the DOE and prove scalability, a cooling system capable of rejecting more than 1 MWth, and handling temperatures and pressures higher than 700 °C and 250 bar, respectively, is necessary.

This paper describes the design of a 1 MWth-scale sCO_2 support loop to provide cooling to the PHX of any of the three Gen3CSP pathway projects following on previous scoping studies [4–6] and builds on experience gained from the design and operation of many previous systems.

2 1-MWth Heat Removal System

The combination of CSP with sCO_2 Brayton power cycles is a topic of great interest due to the potential for increased efficiencies within the power cycle, reduced capital costs given the compact size of the necessary equipment compared with other commercial power cycles (e.g., steam power cycles), and the compatibility with dry cooling that would decrease the need for cooling water.

The Gen3CSP solid, liquid, and gas pathways, currently in development, require a test setup to evaluate their performance during operation. A system capable of working with any of the three media while supporting a minimum 1 MWth thermal rejection was to be designed.

2.1 Requirements.

2.1 Requirements. A set of system requirements were established for the overall Gen3CSP system and are summarized in Table 1. The PHX requirements listed in Table 1 are deemed essential to meet the goals set by the DOE. At the same time, these requirements must be fulfilled when coupled to the sCO_2 test system.

Additional requirements were derived after discussion with the PHX design teams. These requirements are primarily driven by the temperature and pressure needed at the PHX inlet and the thermal duty of the system. The derived requirements are summarized in Table 2, including the ability to accommodate a PHX pressure drop up to at least 5 bar.

Size, location, and operation of the sCO_2 loop were also considered, and an initial set of size and power requirements were established. These requirements are shown in Table 3. The final location of the sCO_2 test system is not yet defined. For this reason, the system has been designed as a set of modules including the inventory management system, flow management system, recuperation, and PHX flow conditioning modules. These modules can be

Table 1 Supercritical CO_2 test system requirements

Requirement	Value
Operating fluid	Carbon dioxide
PHX outlet pressure	250 bar
PHX outlet temperature	715 °C
Thermal duty	≥1 MWth
Operational time	16 h/day

Contributed by the Advanced Energy Systems Division of ASME for publication in the Journal of Energy Resources Technology. Manuscript received September 1, 2020; final manuscript received December 2, 2020; published online January 15, 2021. Assoc. Editor: Zhiwen Ma.

Table 2 Supercritical CO_2 test system derived requirements

Requirement	Value
Allowable PHX pressure drop	≥5 bar (2% drop)
PHX inlet temperature	≤565 °C (150 °C ΔT min)

Table 3 Supercritical CO_2 test system size and power requirements

Requirement	Value
Weight	≤89,000 N (≤20,000 lbs)
Supply power voltage	480 3-Phase Y
Full load amperage	<600 A
Total footprint	≤2.7 m × 3.4 m (≤9 ft × 11 ft)
Height	≤2.3 m (≤7.5 ft)

disassembled, transported, and reassembled to a new location without requiring any onsite cutting or welding.

2.2 Design. Several options for the sCO_2 loop configuration were considered and are summarized in Table 4.

Both liquid and gas blowdown open systems are not desirable for implementation because they require a constant supply of CO_2, increasing the gas inventory cost and the complexity of the logistics to maintain enough CO_2 available. Also, the liquid blowdown system requires an evaporator for cooling; the use of water for cooling is to be avoided to ensure that the test system can be deployed in areas with limited supply of water and ensure that similar systems can be installed in areas where CSP is typically utilized (i.e., water-scarce areas). Another consideration is that the gas-phase Brayton cycle requires further advancement of turbocompressor technology; this topic is addressed in Sec. 3. A liquid system would allow for the use of pumps. For a liquid sCO_2 system, high-pressure, commercially available water pumps can be used by requiring a minimum pump inlet density. Given the technology readiness of water pumps, the decision to use liquid cycles was taken.

The non-recuperated cycles both require significant investment in compression and heat exchanger equipment in addition to the advancement of low technology readiness level (TRL) components. Recuperated cycle layouts leveraging liquid pumping equipment like that shown in Fig. 1 were preferred because they required smaller equipment and the low TRL equipment has already been demonstrated for a 100 kW_{th}-scale system. The recuperated Brayton cycle was chosen as the path to follow for this test system. Note that this is not an actual recuperated Brayton power conversion cycle, but shares the same flow path as this cycle with a pump instead of a compressor and no turbine. The nickel alloy recuperator is coupled with a stainless steel recuperator to reduce the quantity of nickel alloy needed. The Gen3CSP sCO_2 loop includes throttle, recirculation, recuperator bypass, and pump speed control. The system was designed using the most conservative conditions expected (i.e., minimum PHX temperature rise, maximum PHX outlet temperature, and maximum PHX outlet pressure) in order to maximize margin for any given operating condition.

A summary of the fluid states obtained during the analysis of the recuperated cycle is given in Table 5 and Fig. 2. The model (implemented in Engineering Equation Solver (EES)) includes actual pump performance curves, flowmeter pressure drop behavior, throttle valve C_v, and heat exchanger pressure drops assuming

Table 4 Metrics for different system configurations

Configuration	Compression power (kW (hp))	Total UA (W/K)	Heating (MW)	Required CO_2 (kg)	Primary challenge
Liquid blowdown	164 (220)	38,000	4.3	300,000	CO_2 supply
Gas blowdown	1342 (1800)	0	1.9	300,000	CO_2 supply
Liquid Brayton	5.9 (7.9)	160,000	3.9	Closed	Heat exchange
Gas Brayton	43 (58)	2000	0	Closed	High-temperature compression
Recuperated Brayton	10 (14)	54,000	0	Closed	High-temperature recuperation
Recuperated and mixed Brayton	14 (19)	71,000	0.2	Closed	Mixing assembly

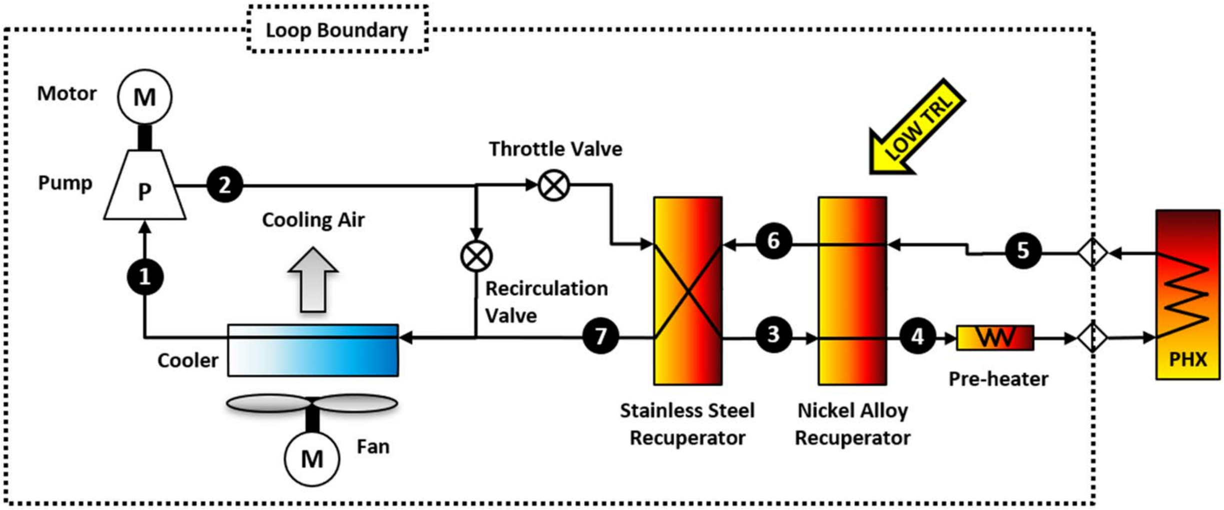

Fig. 1 Recuperated Brayton cycle

Table 5 Supercritical CO_2 fluid states

State	T (°C)	P (bar)	ρ (kg/m^3)
1	56.7	243	800
2	57.6	259	807
3	423	256	190
4	565	254	153
5	715	250	127
6	575	248	147
7	147	245	416

quadratic behavior with mass flowrate. The model assumes 2% pressure drop on PHX, 70% isentropic efficiency, and 27 °C ambient temperature.

An off-design study of the Gen3CSP loop was also performed in EES to understand the range of test conditions attainable through the combination of recuperator bypass and mass flow control. Intermediate combinations of temperature rise and PHX inlet temperature can be achieved by modulating the flowrate and recuperator bypass flow. A summary of this work is shown in Fig. 3. PHX inlet temperatures as low as 440 °C can be provided while still operating with 1 MWth heat transfer duty and a PHX outlet temperature (or turbine inlet temperature, TIT) of 715 °C.

2.3 Key Component Details. The definition of four key components was initiated for the recuperated Brayton cycle as it was expected that lead times for manufacturing would be longer. In addition, final specifications for these key components are needed to complete the design of the rest of the system. The four key components are as follows:

(1) supercritical carbon dioxide circulator,
(2) nickel alloy recuperator,
(3) stainless steel recuperator, and
(4) air cooler/radiator

and are described in this section.

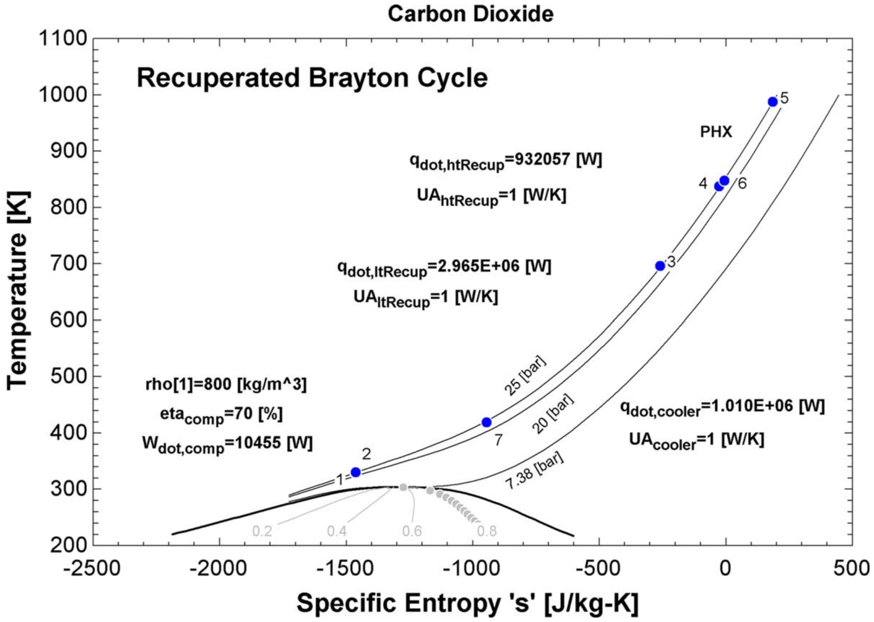

Fig. 2 Recuperated Brayton cycle *T–s* diagram

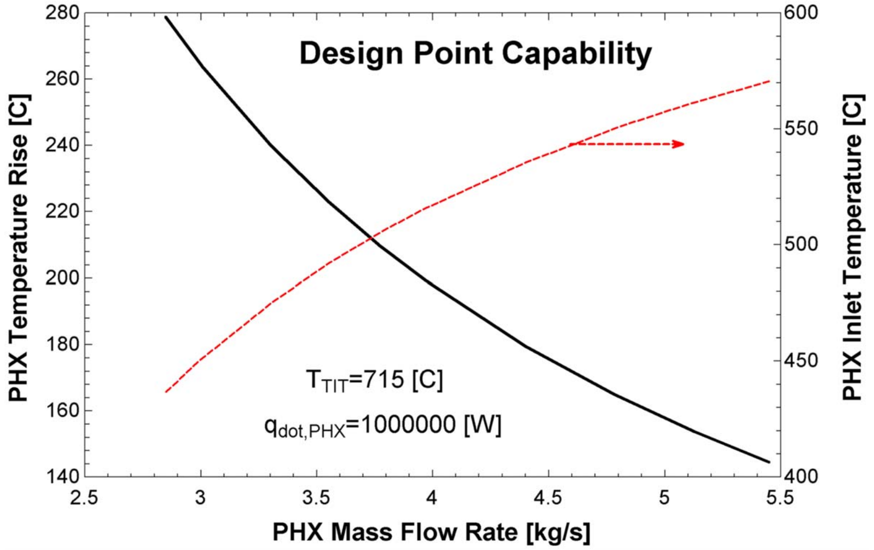

Fig. 3 Results of study to obtain 1 MWth capability over a range of PHX inlet temperature and temperature rise

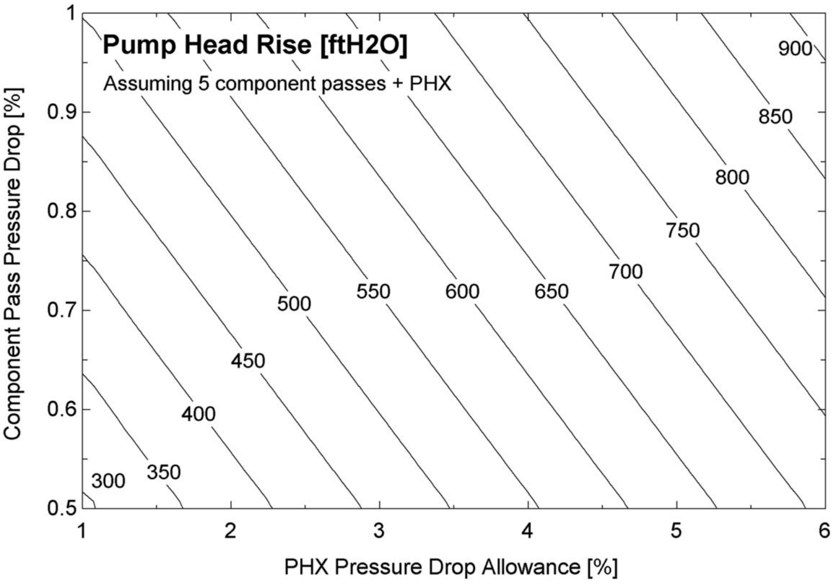

Fig. 4 Map of pump head versus PHX/component pressure drop

2.3.1 Supercritical Carbon Dioxide Circulator. The sCO_2 circulator is the most critical piece of equipment in the Gen3CSP sCO_2 coolant loop because of its high cost, long lead-time, and moderate implementation risk. sCO_2 compressors with significant commercial experience are typically rated for subcritical pressures in refrigeration applications or designed to operate on low-density fluid for gas pipeline compression applications. Several activities are underway to design compressors specifically for sCO_2 applications [7–10], but no reliable and compact commercial option yet exists.

Instead, high-pressure liquid pumps used for boiler feedwater injection and other high-pressure applications are the most reliable option to use for the sCO_2 circulator. Both canned motor and magnetically coupled configurations operate without any rotating shaft seals eliminating the need for a dry gas seal support system and significantly reducing the complexity of operation and amount of leakage from the system. In addition, these configurations rely on bushings lubricated by the process fluid (sCO_2) within the rotor cavity or ball bearings for the coupled motor eliminating the need for a lubricating oil support skid.

The maximum pump head rise required can be estimated from various combinations of primary heat exchanger and individual component pressure drop allowances as shown in Fig. 4. For the baseline assumptions of 1.5% PHX and 1% component pressure drops, a pump head rise of approximately 168 m H_2O (550 ft H_2O) minimum is required. Varying from the baseline assumption for pressure drop allowances requires balancing decreases in component pressure drop with increases in PHX pressure drop depending on achievable pump performance.

The maximum required pump flowrate can be determined for a range of mass flowrates based on the pump inlet density as shown in Fig. 5. For a baseline requirement of 5.3 kg/s, a pump flowrate of 341 lpm (90 gpm) is required for 950 kg/m^3 conditions. This high-density condition is difficult to maintain on hot days using only dry cooling, so it is desirable to reduce the pump inlet density to the lowest value possible. In addition, higher flowrates

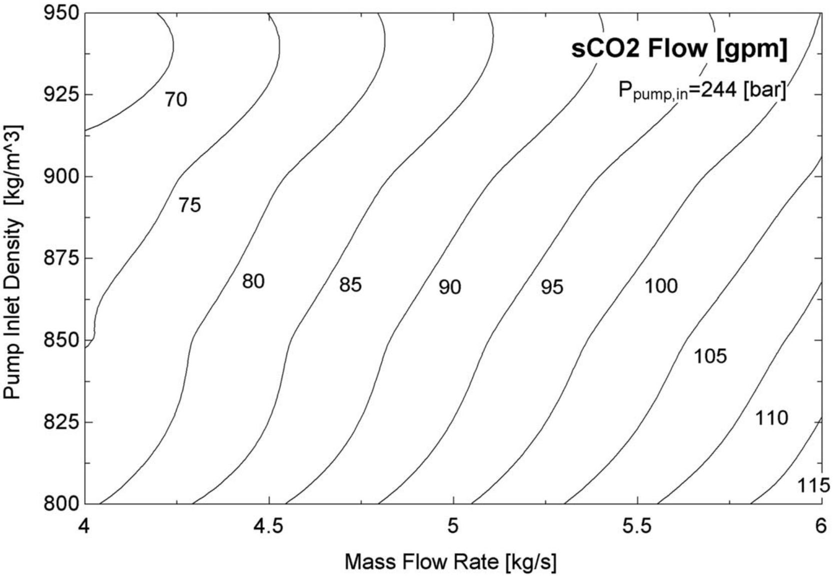

Fig. 5 Map of sCO_2 flow versus pump inlet density and mass flow

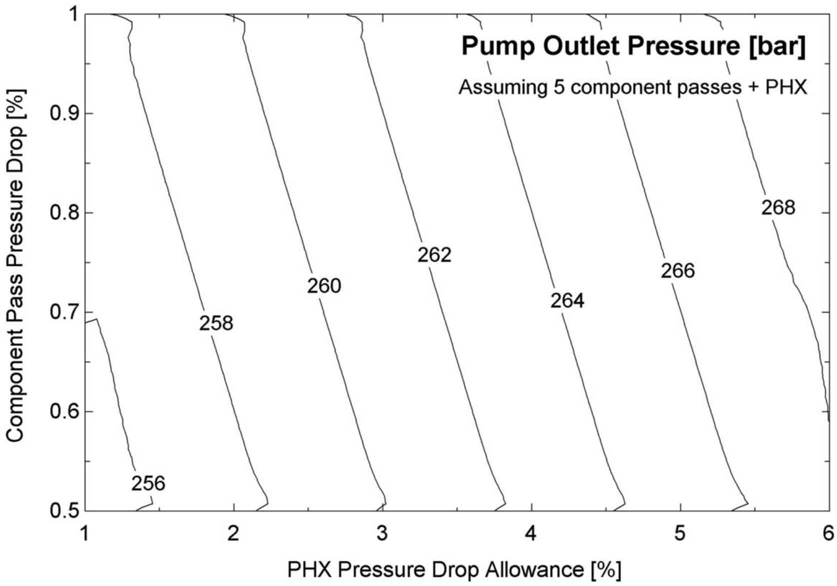

Fig. 6 Map of pump outlet pressure versus PHX/component pressure drop

would potentially provide more capability for the pump, leading to a desire to increase the pump flowrate up to as much as 454 lpm (120 gpm) at low-density conditions.

For a nominal operating pressure of 250 bar at the primary heat exchanger outlet, the pump outlet pressure could range from 258 bar for the baseline assumption of 1% component pressure drop and 1.5% PHX pressure drop up to 270 bar as shown in Fig. 6. The most likely peak pressure expected is 265 bar (3896 psig) for a PHX allowable pressure drop of 4% (6% pressure drop from the pump outlet to the PHX outlet).

A seal-less centrifugal pump suitable for the circulation of supercritical carbon dioxide was selected to serve as the fluid circulator. A high-pressure water pump was determined to be a feasible option to use as a commercially available circulator. The pump must be capable of working with sCO_2 at a specific gravity of 0.9 or lower and a viscosity of 71 μPa·s (0.071 cP) at a design point of 278 lpm (100 gpm) and a head rise of 259 m (850 ft) at 0.9 specific gravity. Requirements are based on thermodynamics analysis performed on EES.

For material compatibility, only austenitic stainless steels or nickel alloys can be used for wetted surfaces and polymer and elastomer materials should be limited to Nylon, Buna-N, urethane, and polyethylene (high-density polyethylene). Since no water will be present during operation, the bearings must be able to function with sCO_2 as lubricant.

Table 6 Centrifugal pump technical specifications

Requirement	Value
Inlet temperature/°C (°F)	37.7 (100)
BEP head/m H_2O (ft H_2O)	259 (850)
BEP flow/lpm (gpm)	378 (100)
Max head/m H_2O (ft H_2O)	287 (942)
Max flow/lpm (gpm)	689 (182)
MAWP/barg (psig)	282.7 (4100)
MDMT/°C (°F)	93.3 (200)
Bearing material	Graphite
Weight/N (lbf)	20,000 (4500)
Motor size/kW (hp)	64.1 (85.9)
Current/A	312
Impellor OD/mm	260
Number of stages	1
Min flow/lpm (gpm)	170 (45)

The specifications for a canned motor pump that closely meets all requirements pump are listed in Table 6. This pump has a vertical configuration (radial load expected to be minimal) and includes a radial bearing wear monitoring coil with remote indictor to track bearing wear. The pump includes a variable frequency drive (VFD) for motor control.

The system curves for different pressure drops overlaid with the pump curves (vendor provided) for the selected option, and other pumps evaluated are shown in Fig. 7. The canned motor pump can provide the needed flowrate of 354 lpm (93.5 gpm) of CO_2 for the 1 MW power system.

2.3.2 Nickel Alloy Recuperator. The nickel alloy recuperator is a printed circuit heat exchanger (PCHE) with both hot and cold sides designed for supercritical carbon dioxide. Key requirements and related fluid properties are listed in Table 7. Note that the hot side inlet and outlet temperature corresponds to a PHX outlet temperature of 715 °C and a PHX temperature drop of 150 °C. Given the location within the system, the nickel recuperator is exposed to the highest temperature and pressure within the system as it is the component in the test system closest to the PHX and therefore must be constructed from nickel alloys to avoid excessive corrosion even in a short time as discussed later. During operation, the recuperator will be insulated to maintain a thermal efficiency of 95% or above (i.e., maximum allowed loss of 50 kW_{th}). The overall heat transfer coefficient-area product (UA) has been approximated to be 6630 W/K.

The nickel alloys considered for construction were unified numbering system (UNS) N08810, UNS N06625, UNS N06617, UNS N06230, and UNS N07740. The material selected was UNS N06625 as a suitable diffusion bonding procedure had been developed in a previous project. Diffusion bonding procedures for the other alloys are also underway but are not expected to be completed in time for this system.

2.3.3 Stainless Steel Recuperator. The stainless steel recuperator is a PCHE with both hot and cold sides designed for supercritical carbon dioxide. Key requirements and related fluid properties are listed in Table 8. The temperature drop across the stainless steel recuperator is more dramatic since it interfaces with the nickel recuperator and the pump. Since the pump can only handle sCO_2 close to density conditions near to those of water, the stainless steel recuperator must have a much higher heat transfer coefficient (approximated as UA = 26,900 W/K) to handle such different densities.

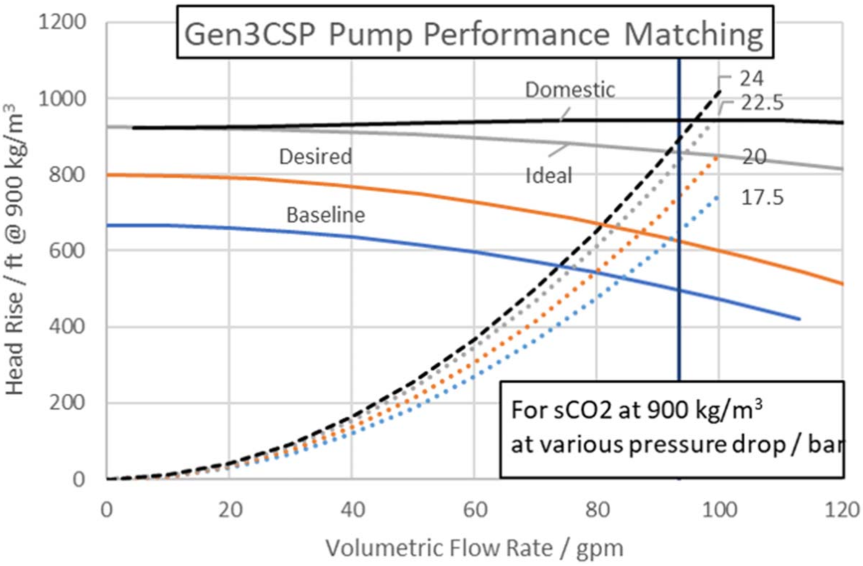

Fig. 7 Head and flow curves for canned motor pumps and system curves at different pressure drops

Also, the nickel recuperator size was to be minimized to decrease the amount of nickel alloy needed, hence reducing the cost of the recuperation subsystem. During operation, the recuperator will be insulated to maintain a thermal efficiency of 95% or above (i.e., maximum allowed loss of 150 $\mathrm{kW_{th}}$).

2.3.4 Radiator. A 1 MWth cooler/radiator is used as the heat sink to support the full duty of the test system need. For this heat exchanger, the hot side is designed for carbon dioxide and the cold side for ambient air. Key requirements and parameters for the radiator are listed in Table 9. The temperature range needed for the radiator allows for use of stainless steel to minimize the cost of the exchanger. Finally, the calculated "UA" is approximately 27,600 W/K.

2.4 Minor Component Details. Other important considerations for the design of the Gen3CSP and that are described in this section.

2.4.1 Inventory Management. The Gen3CSP $\mathrm{sCO_2}$ loop will require an inventory control system to provide for filling, pressurization, venting, and inventory recovery. The baseline design for this system is shown in Fig. 8 to leverage commercially available two-phase $\mathrm{CO_2}$ dewars, ambient temperature vaporizers, $\mathrm{CO_2}$ compression equipment, and remote-actuated regulators and valves for automation. The dewar tanks require only intermittent filling with liquid $\mathrm{CO_2}$ and power for minor electrical loads and does not rely on facility compressed air or significant electrical power for vaporization or compression.

2.4.2 Piping. Corrosion and high-temperature operation considerations are important to ensure the piping compatibility. Walker et al. [11] compared corrosion rates for several alloys operating in high temperature and pressure $\mathrm{sCO_2}$ environments across a range of studies. Based on these results from sample weight gain measurements, stainless steel alloys are expected to have low corrosion rates up to 550 °C and moderate rates up to 600 °C, but will likely have excessive corrosion rates above 600 °C. High nickel alloys, however, appear to have low corrosion rates up to at least 700 °C. Precise corrosion allowance guidance would require sample thickness reduction measurements which are not yet available for $\mathrm{sCO_2}$ environments, so these general expectations for corrosion were used with industrial guidance for corrosion allowances ranging from 0 to 2.54 mm (0–0.1 in.) with a value of 0 used for materials with low expected rates of corrosion, 1.27 mm for moderate rates, and 2.54 mm for high corrosion rates given the relatively short operating life of the Gen3CSP system.

The pipe strength was evaluated using Eq. (1) per ASME B31.1 requirements where P is the internal pressure, S is the maximum allowable stress, E is the weld joint efficiency factor, OD is the pipe outer diameter, t is the pipe wall thickness, y is a coefficient based on material and temperature read from tables in the B31.1 piping code, and A is the corrosion allowance. A value of 0.4 was used for the y parameter in Eq. (1) based on the expected temperatures observed for the alloys considered (nickel and austenitic steels):

$$\frac{P}{S}=\frac{2E(t-A)}{OD-2y(t-A)}=\frac{2(1)(t-A)}{OD-2(0.4)(t-A)} \tag{1}$$

The pressure containment ratio more intuitively captures the sharp transition for each material from allowable stress ratings

Table 7 Key parameters of the nickel recuperator

	Value			
Requirement	Cold side		Hot side	
Fluid flowrate (kg/s)	5.25		5.25	
Temperature (in/out) (°C)	413	565	715	565
Pressure (in) (MPa)	25.7		25.0	
Density (in/out) (kg/m^3)	194	153	127	149
Viscosity (μPa · s)	34.7	38.6	42.6	38.5

Table 8 Key parameters of the stainless steel recuperator

	Value			
Requirement	Cold side		Hot side	
Fluid flowrate (kg/s)	5.25		5.25	
Temperature (in/out) (°C)	37	413	565	123
Pressure (in) (MPa)	26.0		24.8	
Density (in/out) (kg/m^3)	900	194	149	487
Viscosity (μPa · s)	91.3	34.7	38.5	38.7

Table 9 Key parameters of the radiator

Requirement	Value			
	Hot side (CO_2)		Cold side (air)	
Fluid flowrate (kg/s)	5.25		35 (62,000 cfm)	
Temperature (in/out) (°C)	145	53	38	67
Pressure (in) (MPa)	24.5		Ambient	
Density (in/out) (kg/m^3)	420	814	1.2	1.0
Viscosity (μPa · s)	35	74	27	29

based on yield stress at lower temperatures to those based on creep limits and can be directly compared with the geometric strength ratio. Figure 9 shows P/S ratios at different temperatures based on maximum allowed stress for different materials. Most stainless steels and N06625 quickly lose strength or are not allowed above 537 or 593 °C (1000 or 1100 °F) with pressure containment ratios ranging from 0.15 to 0.4 across several materials. N07740 and N06617 are the only viable code-approved options for significantly higher temperatures with pressure containment ratios around 0.28 for N07740 and 0.48 for N06617 at 735 °C (1355 °F).

Based on the information for the pressure containment ratio presented above, and the pressure containment ratio for different pipe sizes and thicknesses, Table 10 lists pipe schedule sizes that can perform at the high pressures and temperatures required for the Gen3CSP loop. N07740 and N06617 are the only viable B31.1 material options for temperatures above 593 °C (1100 °F), while numerous options are available for temperatures below 315 °C (600 °F) including most common austenitic stainless steels. For temperatures between 315 and 593 °C (600 °F and 1100 °F), N06625, N08800, and S34709 are the most viable options.

Another important consideration for piping design is the minimum pipe size to limit pressure drop. Assuming a total pressure drop limitation of 0.1% and allowing the high-temperature piping greater pressure drop due to the limited selection of pipe sizes expected the pressure drop per foot of straight pipe must range from 0.005 bar/m (0.02 psi/ft) on the cold end to 0.02 bar/m (0.1 psi/ft) on the hot end of the system. This metric is trivial to meet for straight pipe even at the smallest expected pipe sizes of 2 nominal pipe size (NPS) SCHXXS, but the loss for even a small number of pipe fittings could quickly exceed the relatively low target of 0.31 bard (4.5 psid) pressure drop total in the piping for small pipe sizes.

An analysis was performed with the preliminary piping layout as shown in Fig. 10 and summarized in Table 11. This minimum sizing yields average cross-sectional flow velocities ranging from 1 to 17 m/s depending on the flow temperature which is roughly in line with conventional guidelines of 1–2 m/s for liquids and 10–30 m/s for gasses as the density of sCO_2 transitions from liquid-like to gas-like over this temperature range.

2.4.3 Non-Welded Connections. Clamp connections are used for all piping at any temperature and pressure required. Conventional components are only rated to 537.7 °C (1000 °F), but higher temperature and pressure ratings are available on request. Several different seal ring sizes from 1 to 6, equivalent to 1 NPS to 6 NPS pipe, are available up to 537.7 °C in standard 316 and 304 grades of stainless steel at both 281.7 and 298.2 barg (4085 and 4325 psig). Vendors recommend the use of high carbon grades or "H-grades" of austenitic stainless steels or nickel alloys for hubs, blinds, and clamps for process temperatures above 537.7 °C where the hubs, blinds, and clamps are fully insulated together with the process piping. In addition, silver-coated UNS N07718 or another suitable seal ring material must be used in order to aid in sealing, prevent seizing of the hub material at high temperatures, and provide sufficient seal rigidity at high temperature.

For uninsulated connections, the clamp material is generally assumed to be at a temperature below 80% of the process temperature, allowing the use of standard 304 or 316 materials up to 676.6 °C (1250 °F). In addition, clamp connections are rated under the ASME code for long-term service such that the short term operation at higher temperatures will likely not cause acute or permanent damage to the joint. The expected failure mode of clamps at higher temperatures is eventual fatigue cracking, but this has not been seen in practical service according to vendor representatives.

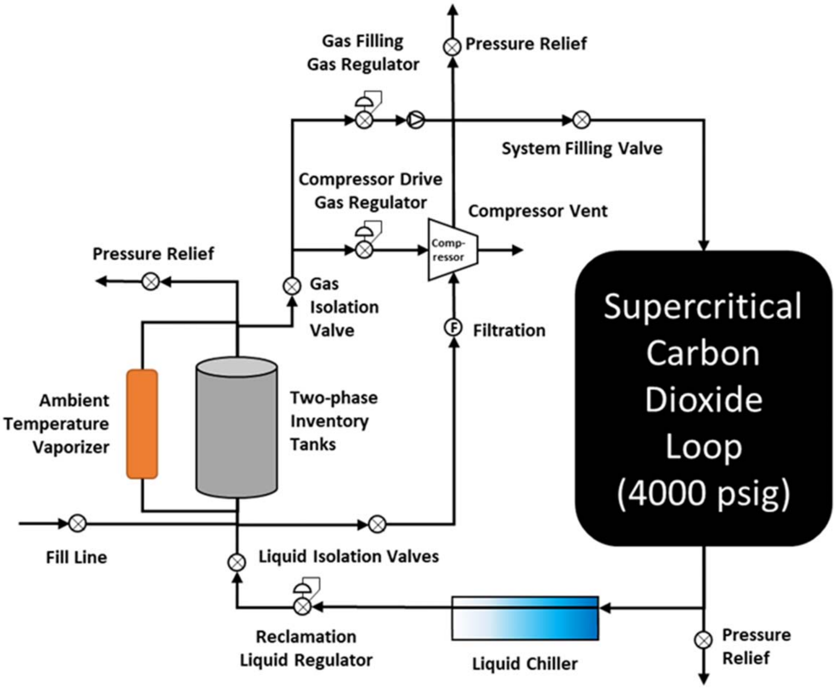

Fig. 8 Diagram of the inventory management system for filling, pressurization, and recovery

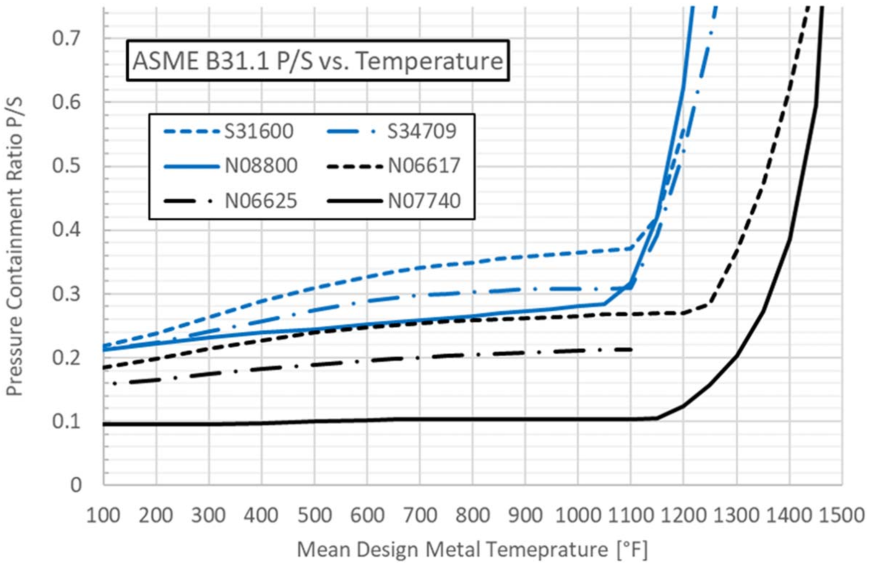

Fig. 9 Pressure containment ratio versus temperature for different alloys

Table 10 Pipe size and schedule of different alloys for use in the Gen3CSP loop

Material/ UNS	MAWP/ bar	MDMT/ °C	*P*/*S*	SCH	Maximum nominal pipe size *A* = 0 mm (*A* = 0 in.)	*A* = 1.3 mm (*A* = 0.05 in.)	*A* = 2.5 mm (*A* = 0.1 in.)
N07740	280	735	0.27	Various	3.5 SCH160	≥6 SCHXXS	4 SCHXXS
N06617	280	726	0.45	XXS	3	2.5	NA
N06625	280	590	0.21	Various	≥6 SCH160	≥6 SCH160	≥6 SCHXXS
N08800	280	590	0.32	XXS	4	3	3
S34709	280	590	0.31	XXS	4	4	3
S34700	280	315	0.28	XXS	6	5	4
S31600	280	315	0.32	XXS	4	3	3
S30400	280	315	0.33	XXS	4	3	2.5

Threaded connections were not considered because no satisfactory thread sealant material has been found for long-term service in sCO$_2$ at elevated temperatures and threaded connections larger than 1/2; NPS are not allowed under B31.1 piping code.

Inspection ports and instrumentation feedthroughs will be required throughout the system to assess fluid conditions, inspect for corrosion, wear, and contamination, and to provide flexibility to change out connections over time. Due to the small pipe diameters used for this system, standard thermowells are often not available or cannot meet the temperature requirements of a given location and custom thermowells must be designed. Clamp or ferrule connections are utilized for inspection ports depending on their size with ferrule connections limited to temperatures below 537.7 °C (1000 °F) after accounting for thermal standoff effects. Gland-based feedthroughs are used for instrumentation where welded thermowells are not practical. Several sizes provide sufficient pressure ratings with feedthrough ports ranging from 1/8 NPS to 3/8 NPS.

2.5 Implementation and Modularity. The Gen3CSP sCO$_2$ loop is currently being designed as a modular system to provide additional layout options to the teams currently developing the rest of the CSP system and to ease in transportation once final location for the system is selected. Given the size of the components (based on initial size estimates and experience with previous

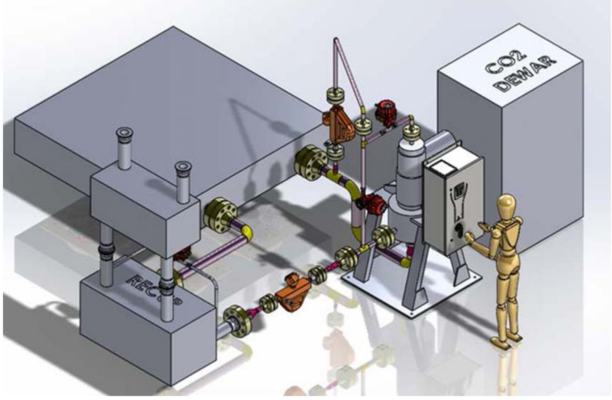

Fig. 10 Preliminary layout for the Gen3CSP sCO$_2$ loop

Table 11 Fittings and flow resistance for operation of the Gen3CSP loop

Piping	Above 593.3 °C (1100 °F)	Between 593.3 °C and 315.5 °C	Below 315.5 °C (600 °F)
Elbows	1	1	4
Run tees	0	2	2
U-bends	0	0	0
Allowable pressure drop/kPa (psi)	5.5 (0.8)	10 (1.5)	14 (2.0)
Minimum pipe size	3 NPS SCHXXS	3 NPS SCHXXS	3 NPS SCHXXS
Flow velocity (m/s)	14–17	9–14	2–9

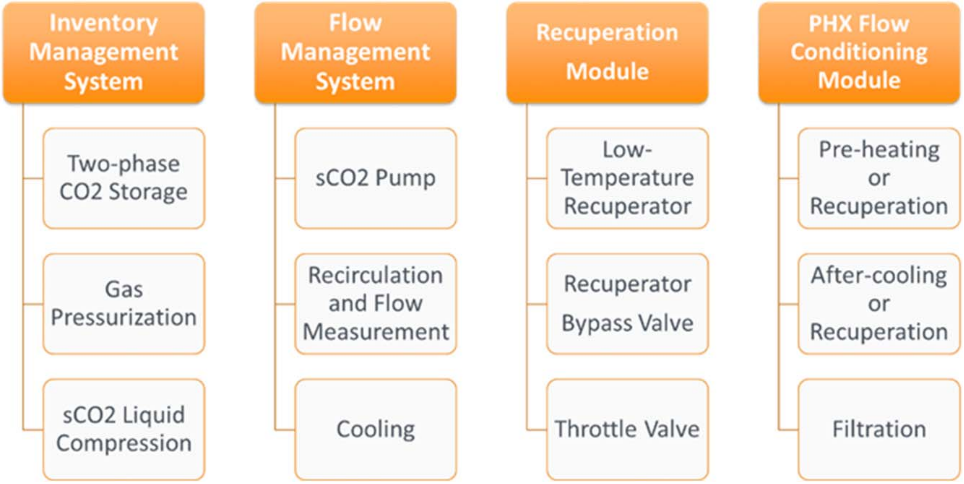

Fig. 11 Gen3CSP sCO_2 loop modules

similar systems) and the function they serve, the loop is split into four modules as shown in Figs. 10 and 11.

3 Conclusion

This work summarizes the design of a 1 MWth-scale sCO_2 test system to provide up to 5.3 kg/s of sCO_2 flow to the primary heat exchanger of any Gen3CSP thermal storage system operating at pressures up to 250 bar and temperatures up to 715 °C. This system is critical to validate design expectations for performance, lifetime, and operability of a CSP PHX with full or near-full scale modules to de-risk their application in commercial plants. A set of high-level requirements based on conservative numbers have been established to ensure delivery of a suitable system, while the potential to accommodate various PHX temperature rises, power levels, and alternative system components has been designed in from the beginning. Finally, the use of ASME codes and standards for design lifetime and reasonable allowances for corrosion provides confidence that this system can be leveraged for future testing after the Gen3CSP program to demonstrate a complete, integrating CSP pilot facility.

Acknowledgment

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government. SAND2020-13464 J.

Conflict of Interest

There are no conflicts of interest.

Funding Data

- U.S. Department of Energy Solar Energy Technologies Office under Award No. DE-EE0001697 34151.

Nomenclature

y = coefficient accounting for temperature
A = corrosion allowance
E = weld joint efficiency factor
P = pressure
S = maximum allowable stress
T = pipe wall thickness
OD = outer diameter

References

[1] Mehos, M., Turchi, C., Vidal, J., Wagner, M., Ma, Z., Ho, C., Kolb, W., Andraka, C., and Kruizenga, A., 2017, "Concentrating Solar Power Gen3 Demonstration Roadmap," NREL, Golden, CO, NREL/TP-5500-67464.
[2] Crespi, F., Gavagnin, G., Sánchez, D., and Martínez, G. S., 2017, "Supercritical Carbon Dioxide Cycles for Power Generation: A Review," Appl. Energy, **195**, pp. 152–183.
[3] Fang, L., Li, Y., Yang, X., and Yang, Z., 2020, "Analyses of Thermal Performance of Solar Power Tower Station Based on a Supercritical CO_2 Brayton Cycle," ASME J. Energy Resour. Technol., **142**(3), p. 031301.
[4] Carlson, M., 2019, "Design and Implementation of a 1-3 MWth sCO_2 Support Loop for Gen3 CSP Primary Heat Exchangers," Presented at the Solar Energy Technologies Office CSP Program Summit 2019, Oakland, CA, Mar. 19.
[5] Carlson, M. D., 2019, "Guidelines for the Design and Operation of Supercritical Carbon Dioxide R&D Systems," Proceedings of SolarPACES 2019, Daegu, South Korea, Oct. 2.
[6] Carlson, M. D., 2018, "sCO_2 Test Loop and Heat Transfer Facility, A 1 MWth-Scale sCO_2 System for Any Gen3CSP Heat Transfer Pathway," Presented at the DOE Gen 3 CSP Kickoff Meeting, Orlando, FL, June 25.
[7] Pasch, J., Conboy, T., Fleming, D., Carlson, M., and Rochau, G., 2014, "Steady State Supercritical Carbon Dioxide Recompression Closed Brayton Cycle Operating Point Comparison With Predictions," Proceedings of the ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, Düsseldorf, Germany, June 16, pp. 1–10.
[8] Rapp, L., and Stapp, D., 2019, "Experimental Testing of a 1MW sCO_2 Turbocompressor," Presented at the 3rd European sCO2 Conference, Paris, France, Sept. 20.
[9] Moore, J., Cich, S., Day, M., Allison, T., Wade, J., and Hofer, D., 2018, "Commissioning of a 1 MWe Supercritical CO_2 Test Loop," Presented at the 6th International Supercritical CO2 Power Cycles Symposium, Pittsburgh, PA, Mar. 27.
[10] Allison, T. C., Smith, N. R., Pelton, R., Jung, S., and Wilkes, J. C., 2018, "Experimental Validation of a Wide-Range Centrifugal Compressor Stage for Supercritical CO_2 Power Cycles," Proceedings of ASME Turbo Expo 2018 Turbomachinery Technical Conference and Exposition, Oslo, Norway, Paper No. GT2018–77026.
[11] Walker, M., Kruizenga, A., Weck, P., and Withey, E., 2016, "Progress in Overcoming Materials Challenges With sCO_2 RCBCs: Final Report," Sandia National Laboratories, Albuquerque, NM, SAND 2016-9774.