

# Behavior of a Solid Fuel Fired Primary Heat Exchanger in a 1.5 MW<sub>TH</sub> Closed Loop Brayton Cycle Using sCO<sub>2</sub>

DOE Award: DE-FE0031928

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2026 International sCO<sub>2</sub> Energy Technologies Symposium  
Pittsburgh, PA  
March 2-5, 2026



# Project Team & Responsibilities

Responsibilities	
	Project Management, Furnace Integration, Fundamental Studies on Deposition, Corrosion
	Technology Holder, sCO <sub>2</sub> Compression Skid, Technoeconomic Analysis
	CFD/Process Modeling, Primary Heater Design, Corrosion Monitoring
	Host Site, Furnace Reconfiguration, Furnace Operation
	Primary Heater Design, Construction, Fabrication (RPI is a vendor to BYU)
	CO <sub>2</sub> Expertise, Cost Share CO <sub>2</sub> and Storage Tank



# Project Overview

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- *Objective:* To perform the R&D necessary to mitigate the risk associated with the design of the primary heater by utilizing large lab-scale / small pilot-scale testing and advanced modeling to optimize the conceptual design process for a coal-fired heater intended for use in an indirectly fired sCO<sub>2</sub> power cycle
- *Budget:* \$5.3M program (\$4.2M DOE, \$1.1M cost-share)
- *Period:* October 1, 2020 through September 30, 2024
- *Team:* Brigham Young University (BYU), Echogen Power Systems Inc. (Echogen), Reaction Engineering International (REI), Riley Power, Inc. (RPI), San Rafael Energy Research Center (SRERC), Linde / Praxair (Linde)



# Project Overview

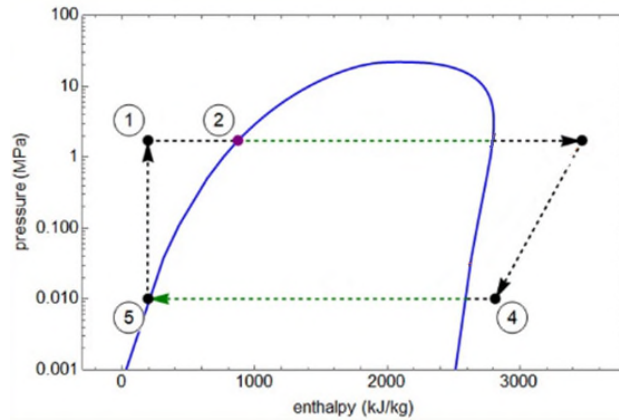
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- **Objective:** To perform the R&D necessary to mitigate the risk associated with the design of the primary heater by utilizing large lab-scale / small pilot-scale testing and advanced modeling to optimize the conceptual design process for a coal-fired heater intended for use in an indirectly fired sCO<sub>2</sub> power cycle
- **Project Crux:** Managing tube metal temperatures in the radiative section of the PHX
  1. The sCO<sub>2</sub> working fluid does not undergo phase change in the PHX as in Rankine Cycle
  2. Solid fuel flames strongly radiate to HX panels in the near flame region
  3. Heat release distribution from a solid-fuel flame is a function of flame aerodynamics

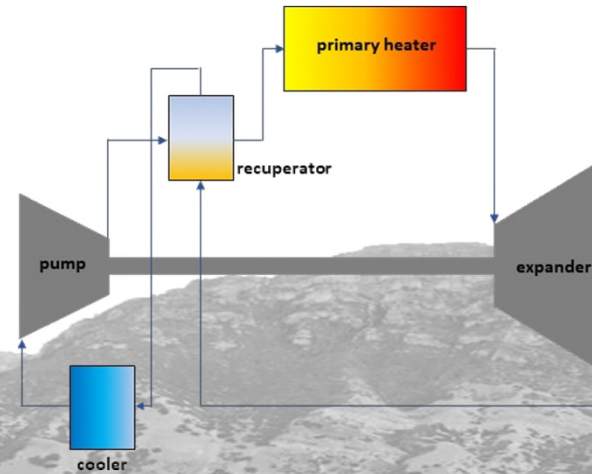
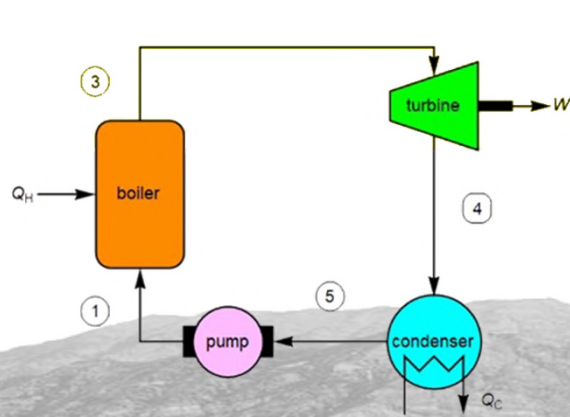
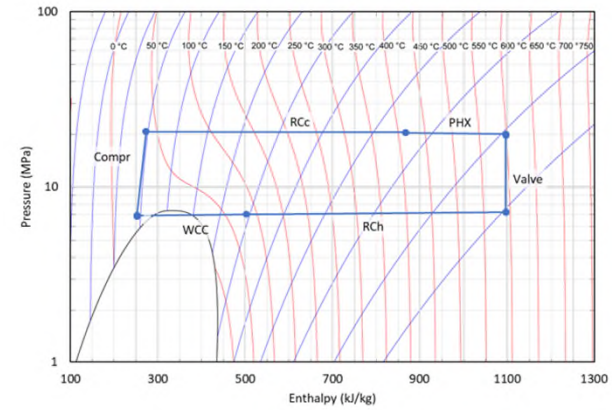


# Closed Loop Supercritical CO<sub>2</sub> vs. Rankine Cycles

Rankine



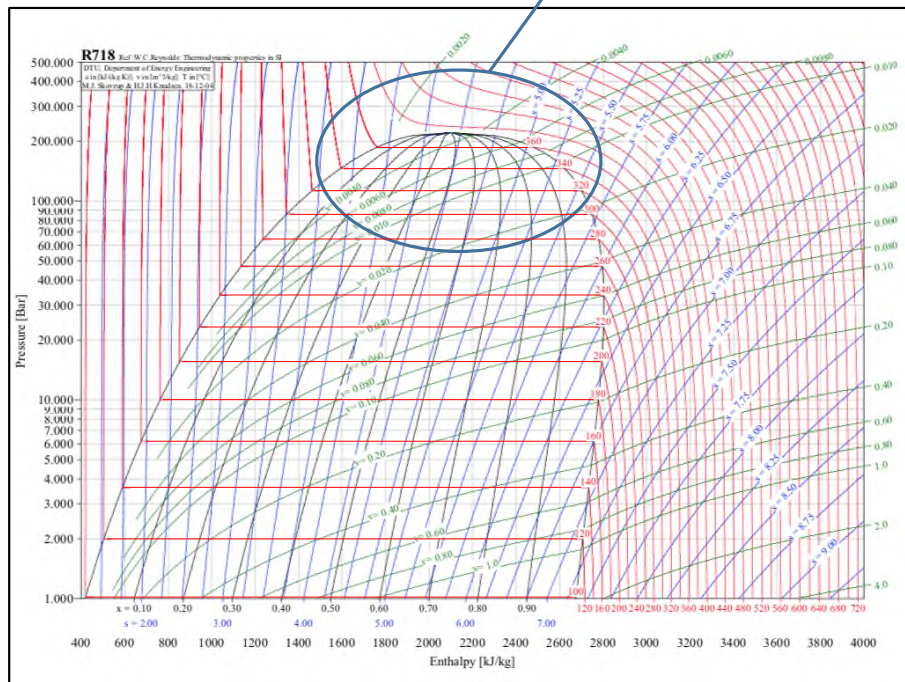
Brayton



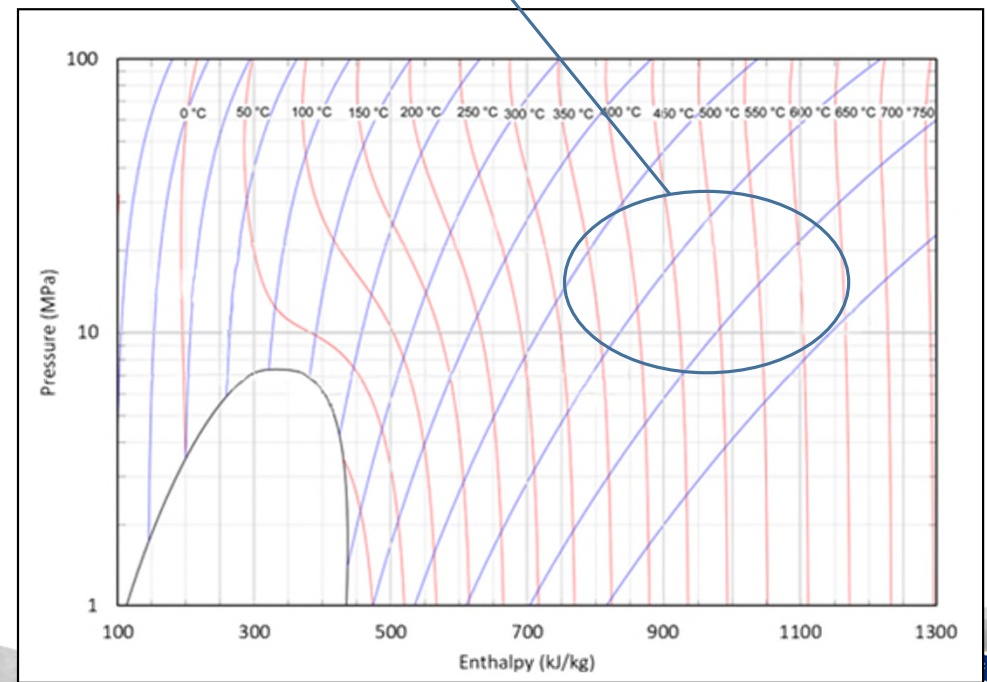
# Closed Loop Supercritical CO<sub>2</sub> vs. Rankine Cycles

Region of Radiative Heat Transfer

Steam / Rankine



CO<sub>2</sub> / CL Brayton



Which direction are the red lines going?

# Approach (Road Mapping)

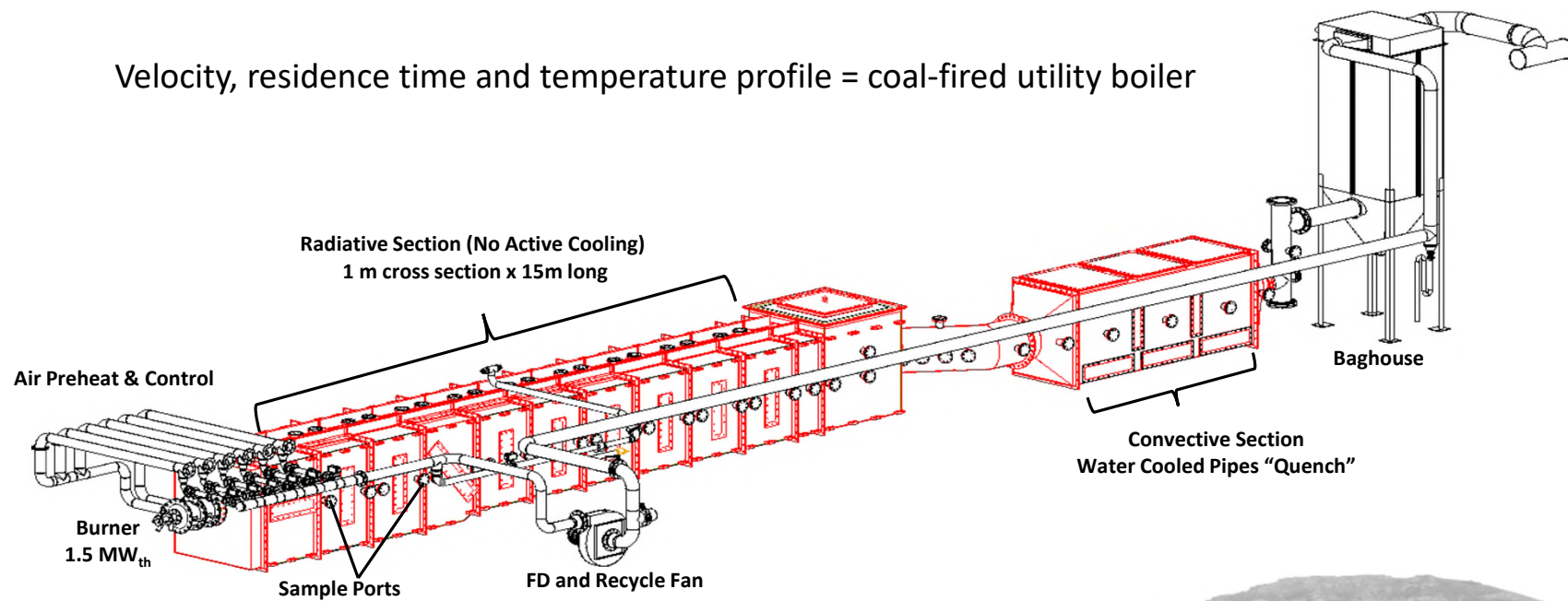
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1. Development of an sCO<sub>2</sub> primary heat exchanger (PHX) for an existing coal combustion furnace
2. Integration with an existing/modified sCO<sub>2</sub> flow loop
3. Shakedown and operation of the integrated system
4. Evaluation of the PHX performance and tube metal conditions

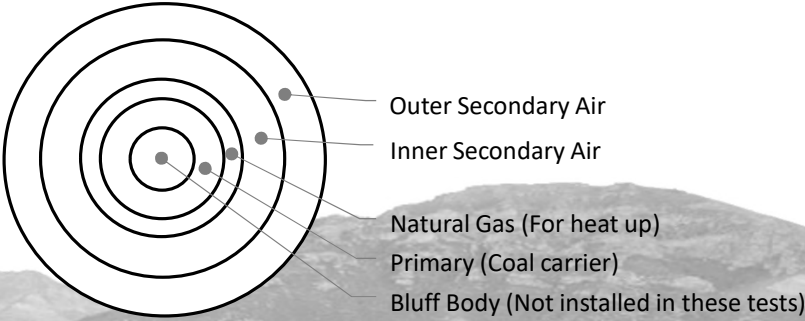
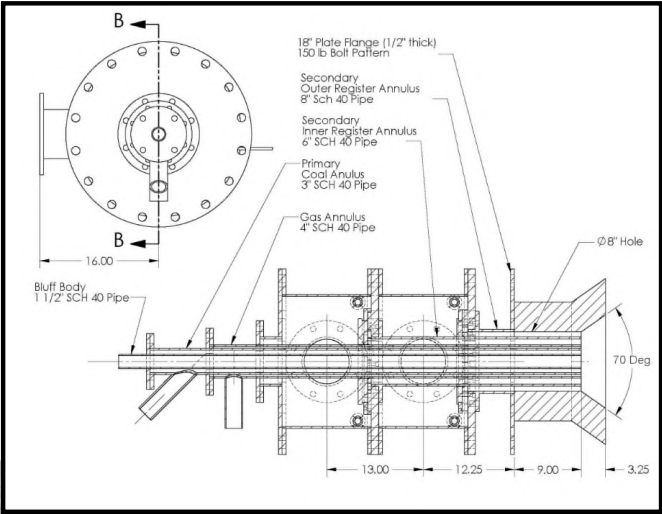


# Entrained Solid Fuel Furnace (L1500)

Velocity, residence time and temperature profile = coal-fired utility boiler



# L1500 Burner



# Design, Const. & Install of Solid Fuel Primary Heater

CFD Modeling was performed to evaluate the effect of flame shape on tube heat flux

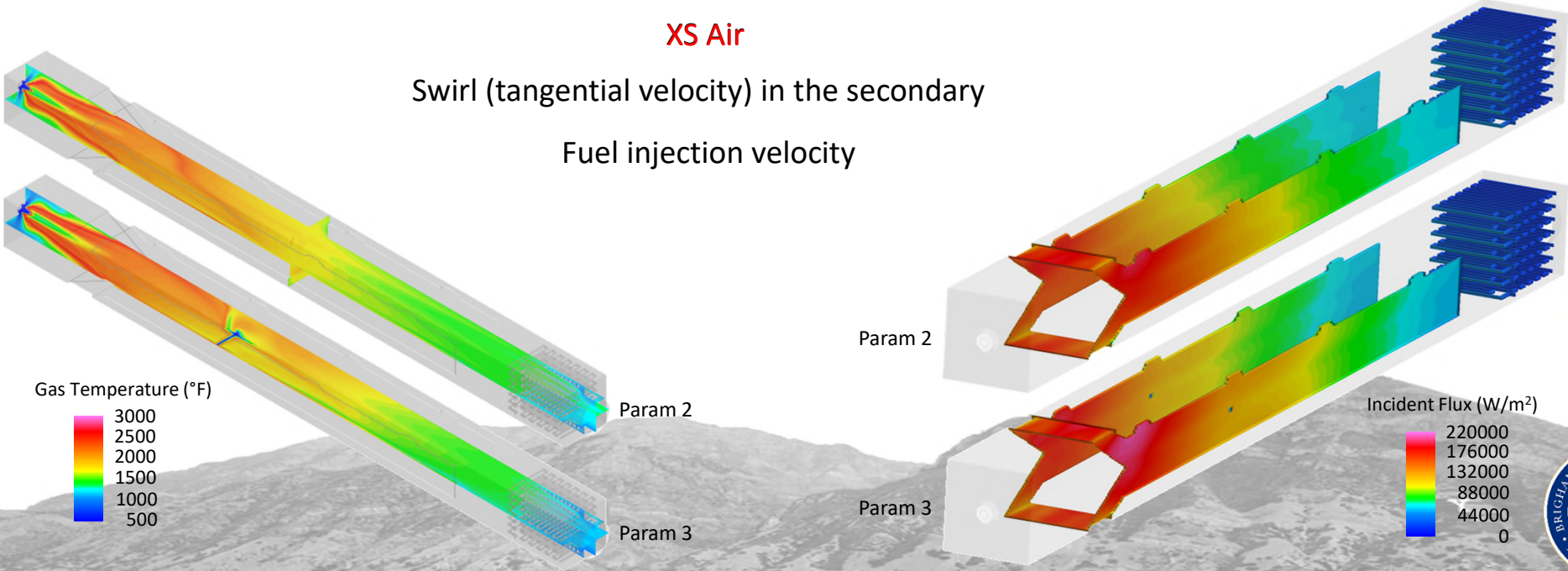
Relative position of crossover tubes to burner

Staged vs unstaged flame

XS Air

Swirl (tangential velocity) in the secondary

Fuel injection velocity



# Design, Const. & Install of Solid Fuel Primary Heater

PHX Detailed Design & Construction by RPI

## Convection Module:

1.625" O.D. x 0.380" M.W. Tubes  
SA 213 S30432 Super 304H  
Stainless Steel  
6.625" O.D. x 1.25" M.W. Headers  
SA321 TP316 SS  
Supports, + Attachments  
A304 SS

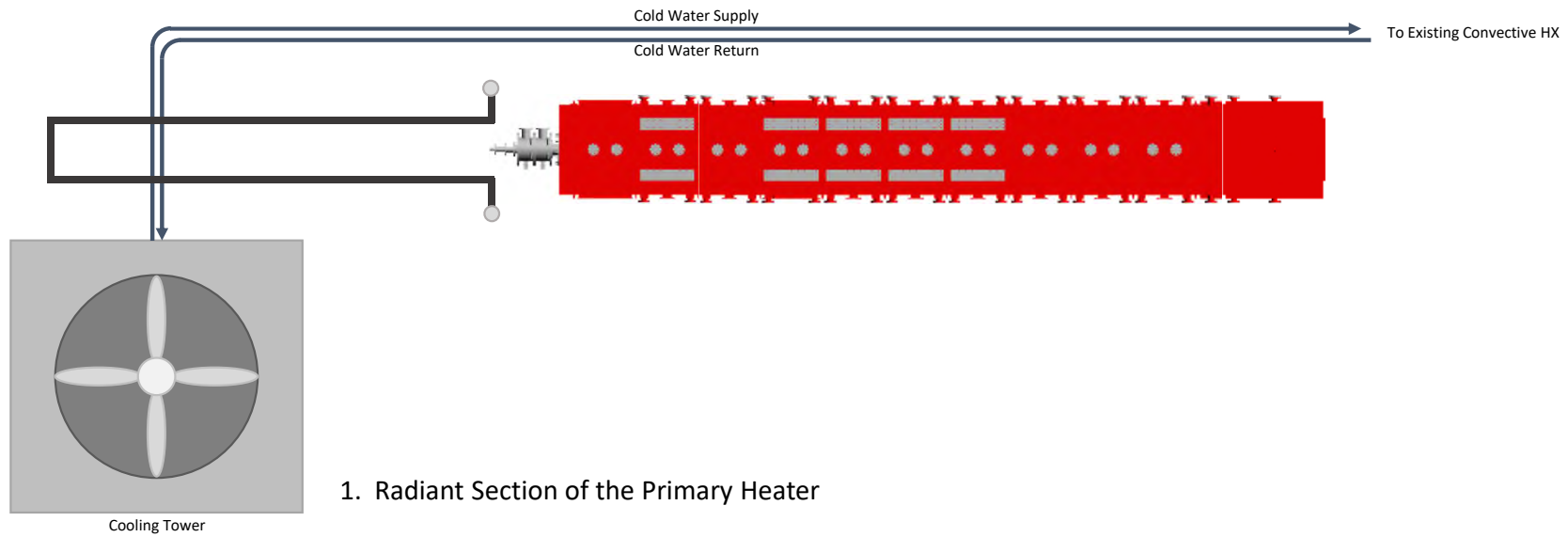
## Radiant Module:

1.625" O.D. x 0.380" M.W. Tubes  
SA 213 S30432 Super 304H  
Stainless Steel  
6.625" O.D. x 1.25" M.W. Headers  
SA321 TP316 SS  
Membranes, Supports, +  
Attachments  
A304 SS



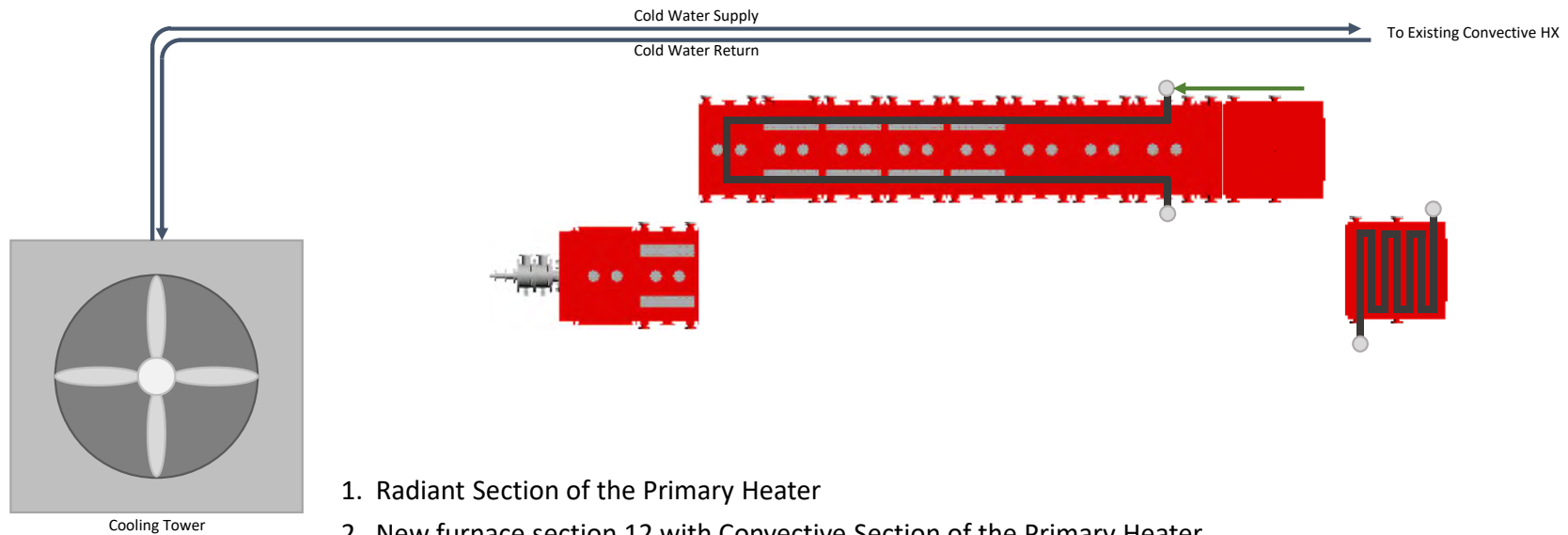
# Adding an sCO<sub>2</sub> Closed-Loop Brayton Cycle to the L1500

## Installation Steps



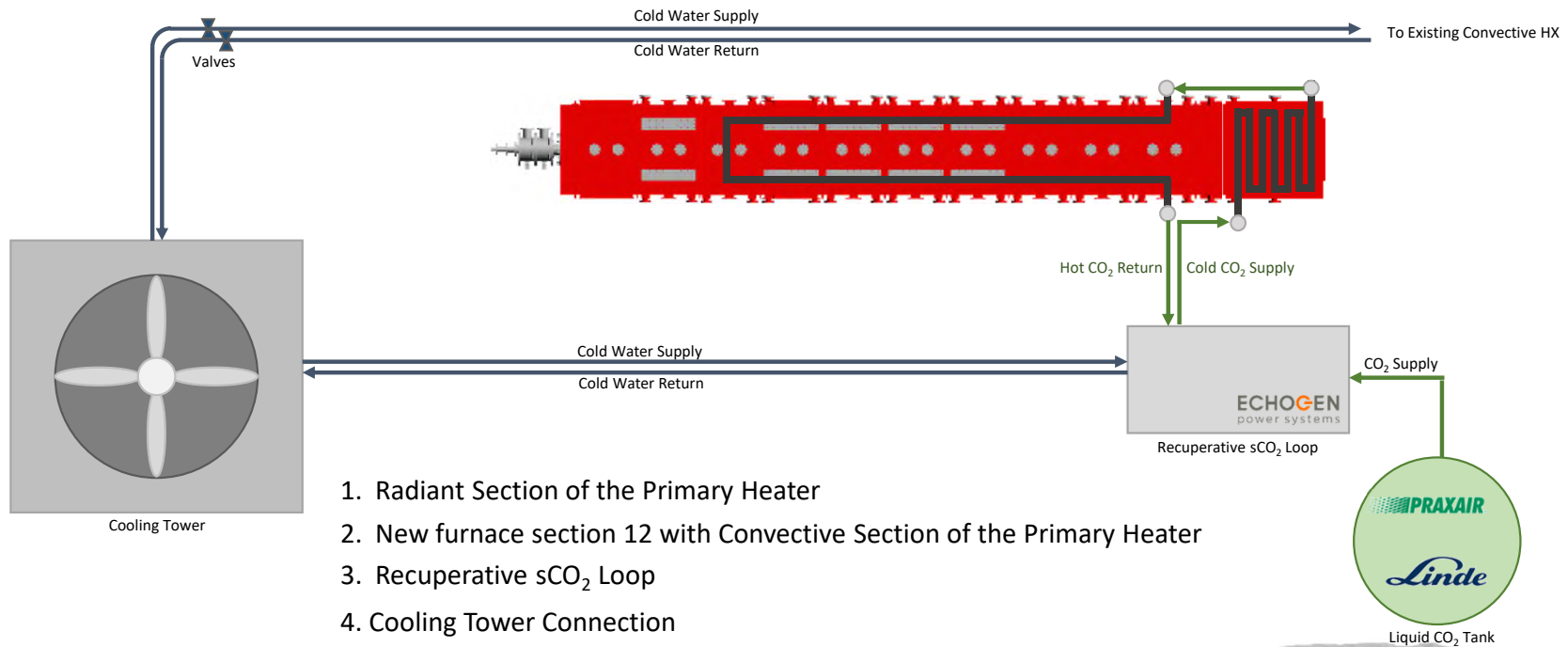
# Adding an sCO<sub>2</sub> Closed-Loop Brayton Cycle to the L1500

## Installation Steps



# Adding an sCO<sub>2</sub> Closed-Loop Brayton Cycle to the L1500

## Installation Steps



1. Radiant Section of the Primary Heater
2. New furnace section 12 with Convective Section of the Primary Heater
3. Recuperative sCO<sub>2</sub> Loop
4. Cooling Tower Connection
5. CO<sub>2</sub> Supply System

# Design, Const. & Install of Solid Fuel Primary Heater



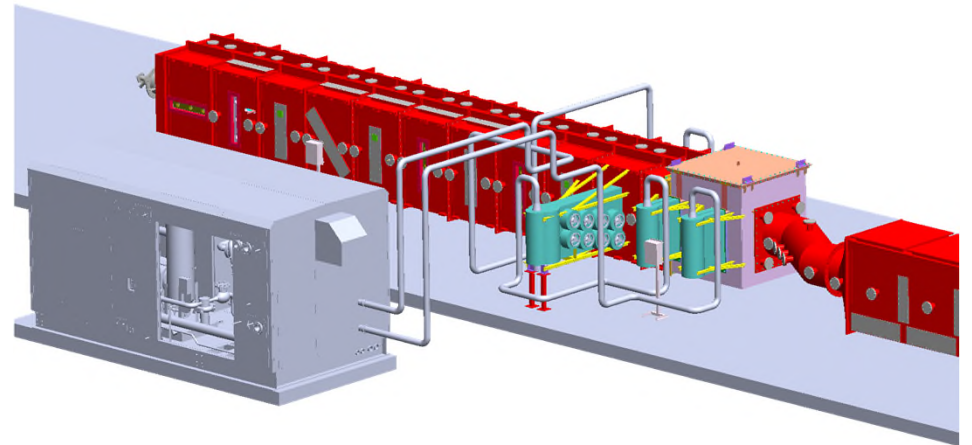
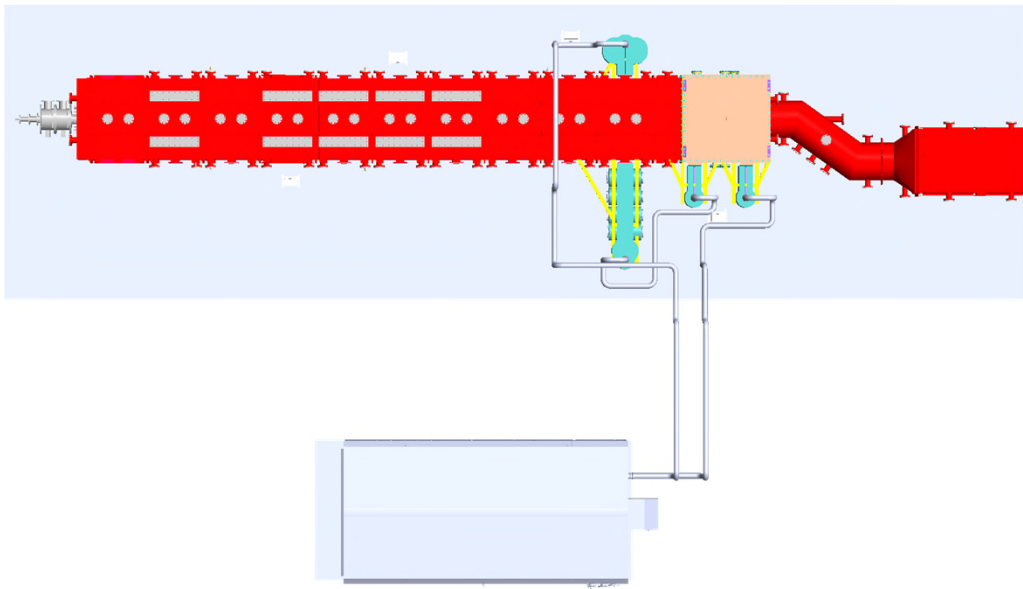
# Design, Const. & Install of Solid Fuel Primary Heater

## Installation of the PHX



# Task 4: Design, Const. & Install of Pilot-scale Primary Heater

Integrated System (SolidWorks)



# Design, Const. & Install of Pilot-scale Primary Heater

## Integrated System

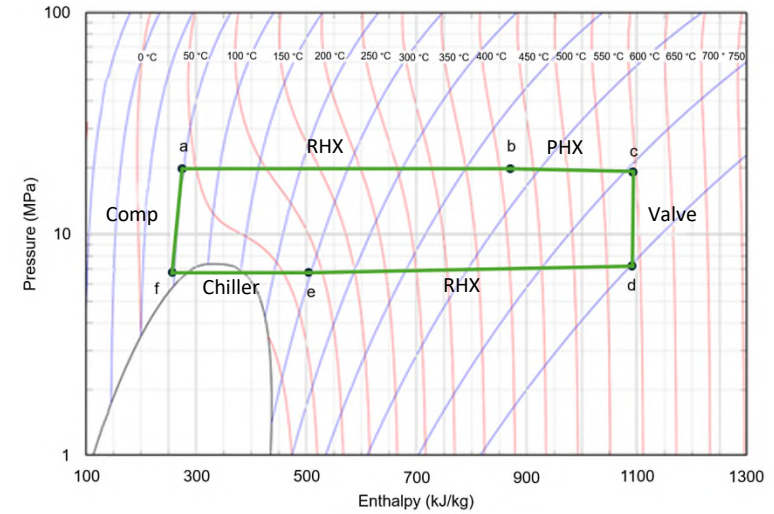
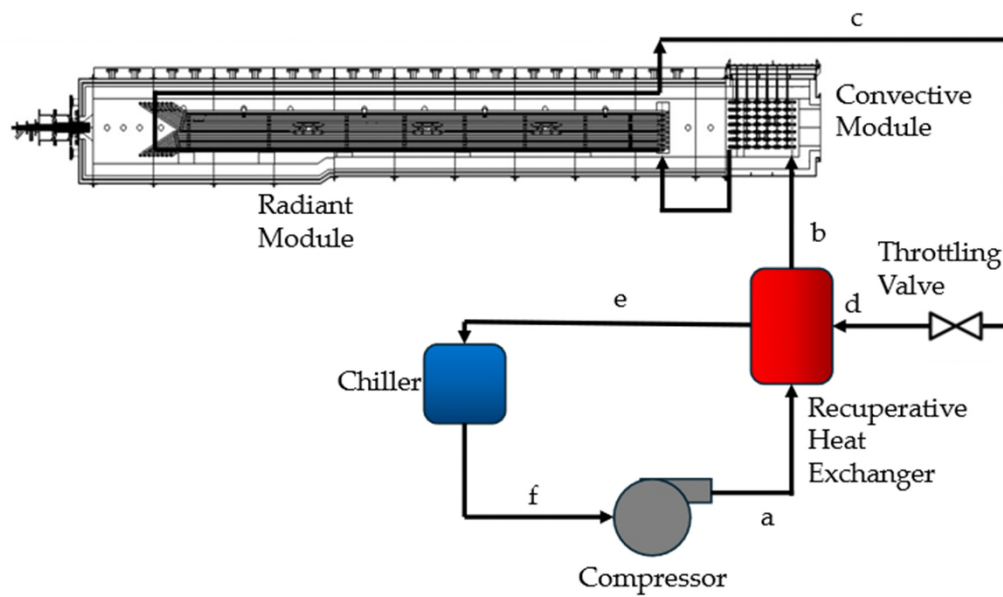


# Design, Const. & Install of Pilot-scale Primary Heater

## Integrated System



# CO<sub>2</sub> Cycle Operating Conditions



State	P (MPa)	T (°C)	h (kJ/kg)	Flow (kg/s)
a	20.7	39	273	5.5
b	20.3	415	869	5.5
c	19.9	600	1098	5.5
d	7.2	593	1098	5.5
e	6.9	80	502	5.5
f	6.8	21	253	5.5

# Task 5: sCO<sub>2</sub> Primary Heater Pilot-scale Testing

## Testing Overview

- We completed 407 hours of operation with 248 hours unattended
- Furnace has been fired on Natural Gas, Western Bituminous Coal, Woody Biomass and Bagasse
- Testing has been performed to, determine hardware capabilities and show the impact of load and fuel changes

	Target	Reached
Firing Rate (MW <sub>th</sub> )	1.7	1.6
PHX Heat Adsorption (MW <sub>th</sub> )	1.2	1.2
CO <sub>2</sub> Temperature (°C)	600	607
CO <sub>2</sub> Pressure (MPa)	20.5	20.3



# Solid Fuels Used

## Fuel Compositions for Experiments

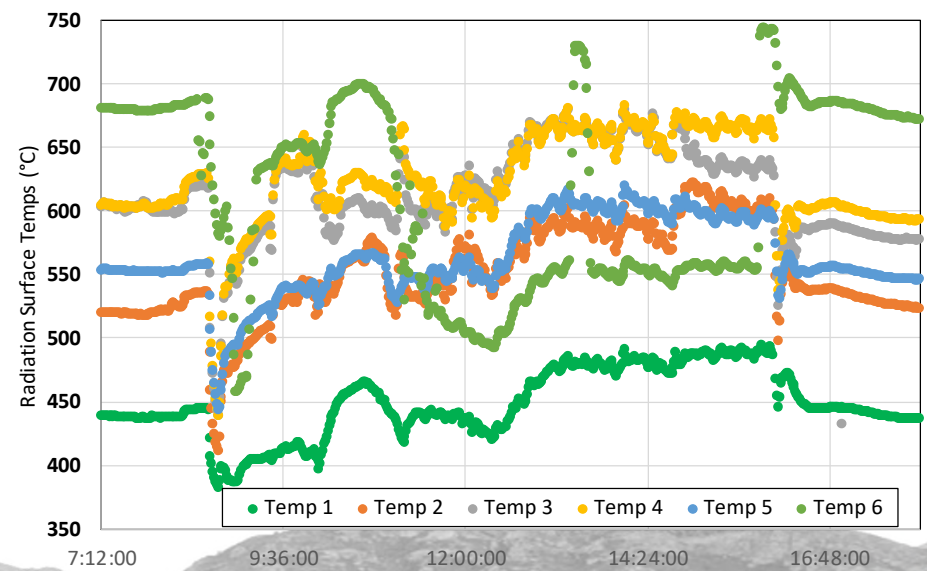
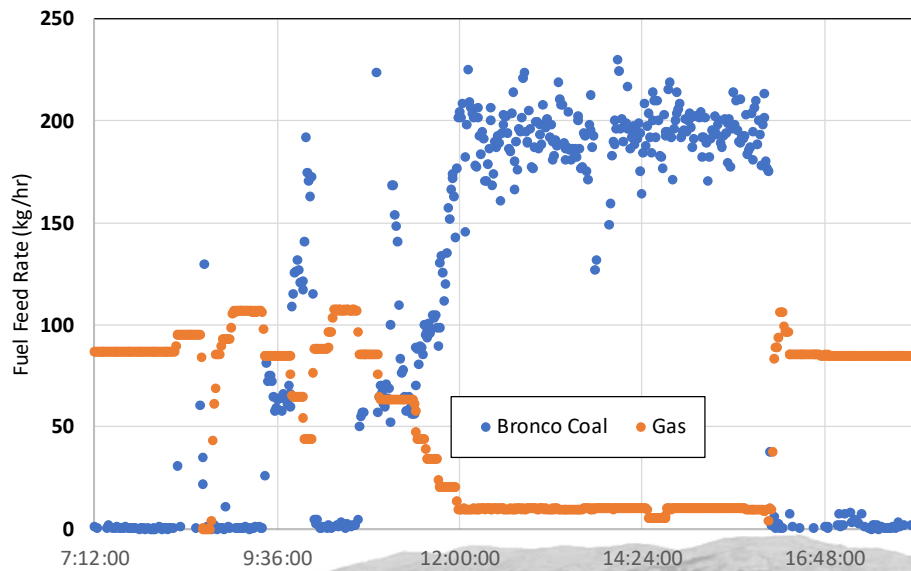
	Bronco Coal	Sufco Coal	Woody Biomass	Bagasse
<b>C</b>	63.14	60.68	49.34	46.02
<b>H</b>	4.36	4.50	5.98	5.81
<b>N</b>	1.13	1.06	0.11	0.22
<b>S</b>	0.45	0.48	0.01	0.03
<b>O</b>	11.63	14.19	40.16	40.52
<b>Ash</b>	12.76	14.19	1.00	3.30
<b>H<sub>2</sub>O</b>	6.53	4.90	3.40	4.10
<b>HHV (Btu/lb)</b>	11168	10616	18275	18310

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	CaO	Fe <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O	MgO	Na <sub>2</sub> O	SO <sub>3</sub>	P <sub>2</sub> O <sub>5</sub>	BaO	MnO <sub>2</sub>	SrO	Undetermined
<b>Bronco Coal</b>	46.23	25.24	1.05	9.52	3.79	0.28	2.78	2.17	5.60	0.27	0.17	0.03	0.24	2.63
<b>Sufco Coal</b>	64.41	15.16	0.74	4.90	4.59	0.75	0.99	2.27	5.17	0.71	0.06	0.01	0.13	0.11
<b>Woody Biomass</b>	37.9	7.3	0.4	17.1	3.8	7.4	4.2	1.9	0.9	1.3	--	1.4	--	--
<b>Bagasse</b>	62.6	7.8	0.4	6.1	4.1	5.8	2.0	0.7	4.0	1.1	--	0.2	--	--



# sCO<sub>2</sub> Primary Heater Pilot-scale Testing

Temperature and Heat Flux Sensing Locations



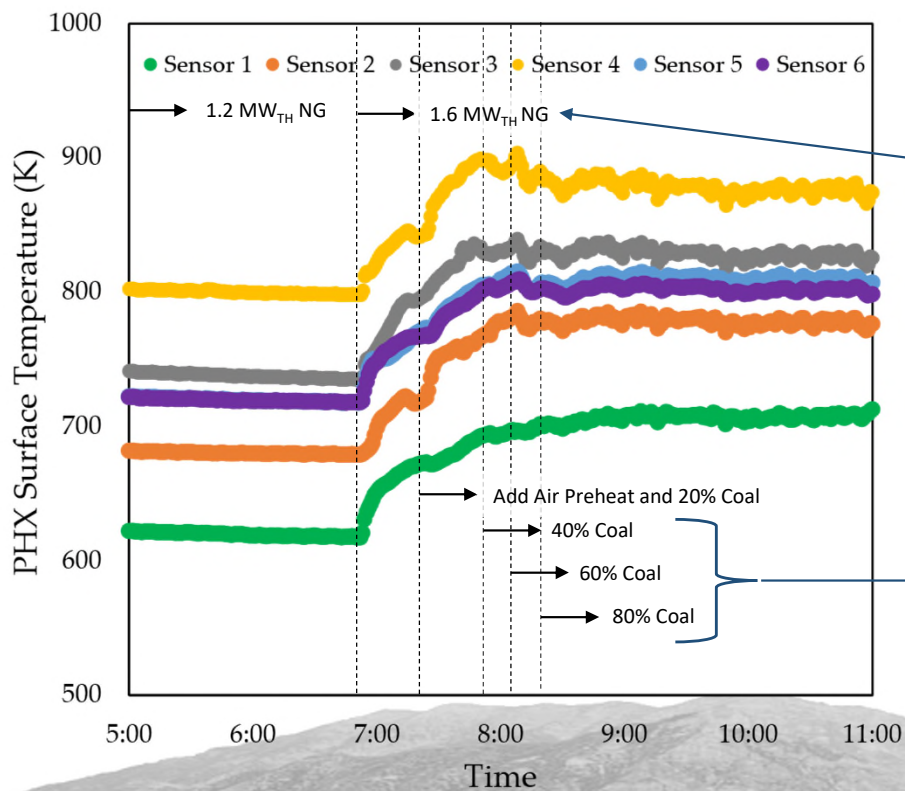
Natural gas and coal feed rate for a 10 hour operating period exhibiting changes in firing rate and fuel blend.

Tube metal temperatures in the radiant section across a 10 hour operating period exhibiting changes in firing rate and fuel blend.



# sCO<sub>2</sub> Primary Heater Pilot-scale Testing

## Increasing Firing Rate



Temperature and Heat Flux Sensing Locations

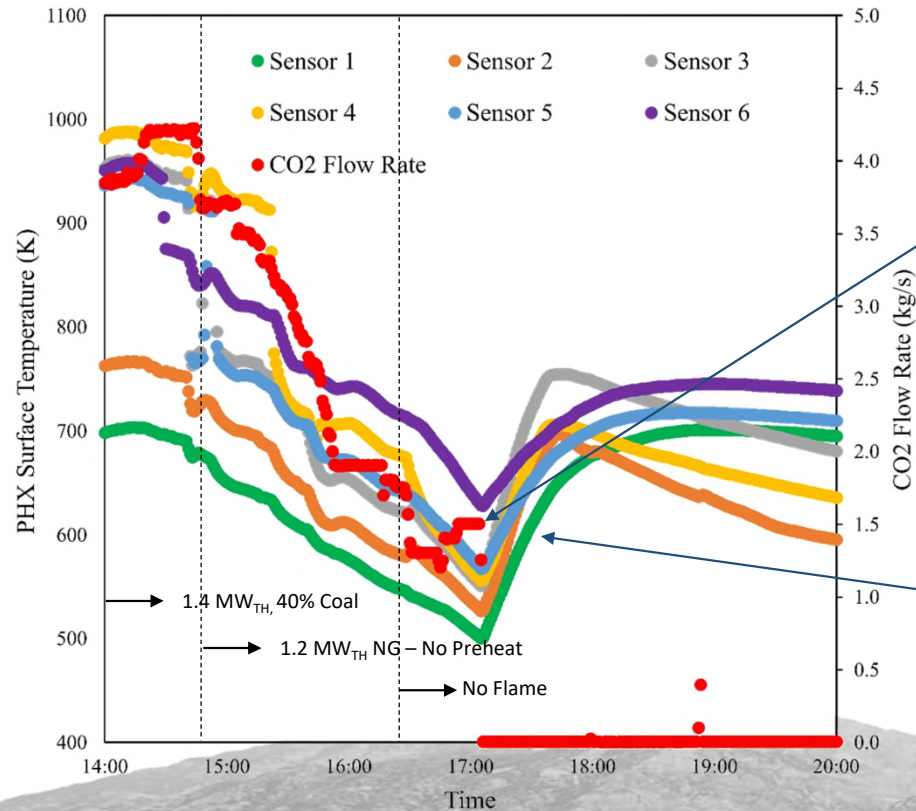


Changing the firing rate has a strong impact on tube metal temperatures

Changing from a gaseous to a solid fuel does not appear to play a significant role in tube metal behavior

# sCO<sub>2</sub> Primary Heater Pilot-scale Testing

## Preparing for Shutdown



Temperature and Heat Flux Sensing Locations

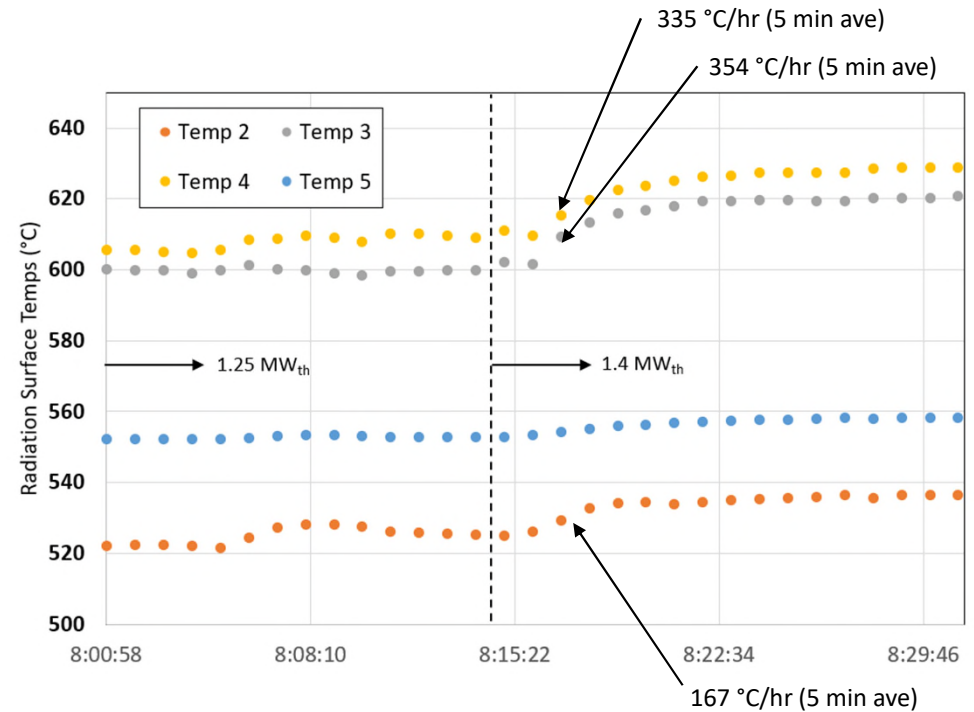
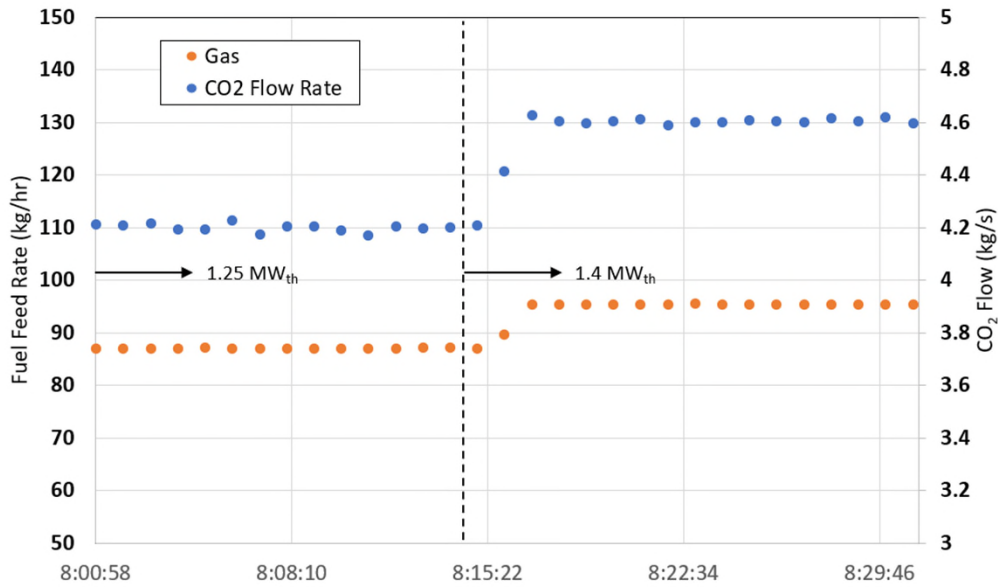


Changing CO<sub>2</sub> flow rate has a strong impact on tube metal temperature

The refractory walls continue to radiate to the PHX after the flame is eliminated

# sCO<sub>2</sub> Primary Heater Pilot-scale Testing

## Analysis with Controlled Variables



# sCO<sub>2</sub> Primary Heater Pilot-scale Testing

## Comparison to Literature Values

	<b>Our Data</b>	<b>Yan</b>	<b>Wang</b>
<b>Temperature Response to Load Change (°C / % Load Change)</b>	107.6	104.9	
<b>Temperature Ramp Rate (°C / hr)</b>	281.8		288
<b>Transient Duration (sec)</b>	450 (90% steady)		201

L. Yan, J. Pu, X. Li, C. Lv, X. Wu, L. Li and X. Lu, "Experimental Study on Temperatures of Water Walls in a 1000 MW Ultra-Supercritical Boiler under the Condition of Flexible Peak Regulation," *Energies*, vol. 17, no. 4375, 2024.

R. Wang, H. Tian, X. Wang, R. Tian and Z. Wu, "Analysis of wall temperature change rate limiting supercritical CO<sub>2</sub> power system flexibility," *Energy*, no. 316, 2025.



# Conclusions

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- Tube metal temperatures were shown to be extremely sensitive to operating conditions.
- The tube metal temperature change as a function of load change was determined to be  $107.6\text{ }^{\circ}\text{C} / \%$  load change, which matches the behavior of tube metal temperatures in full-scale ultra-supercritical coal-fired utility boilers.
- The rate of change was determined to be  $281.8\text{ }^{\circ}\text{C/hr}$  when making load variations of 11%, which matches predicted rate cooling/heating rates in the literature for sCO<sub>2</sub> systems
- The duration of the transient for the L1500 system is longer than predicted in the literature, likely due to the large refractory thermal mass in the L1500



# Acknowledgements

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"This material is based upon work supported by the Department of Energy under Award Number DE-FE0031928." Program Manager Matt Adams.

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**Questions ?**

