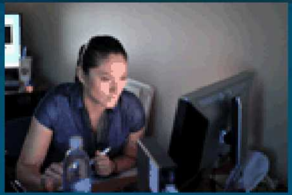
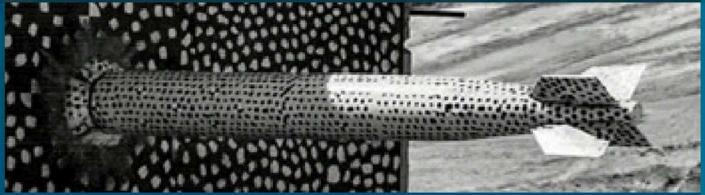
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2018-14299C

Supercritical CO_2 Energy Conversion and Heat Exchanger Research





PRESENTED BY

Blake Lance, Ph.D.

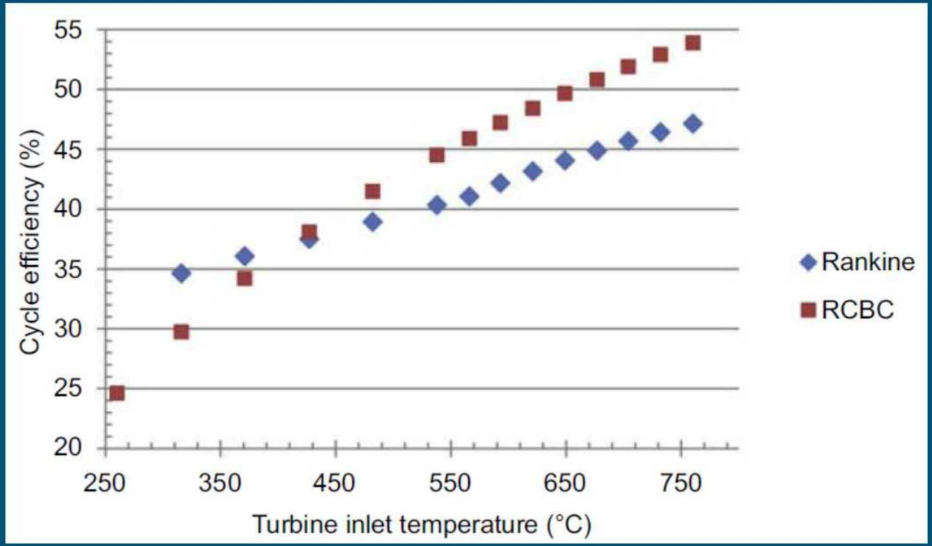
AIAA SciTech Forum, 2019-01-07

Systems, Components and Technology Development for Supercritical Carbon Dioxide Power Systems

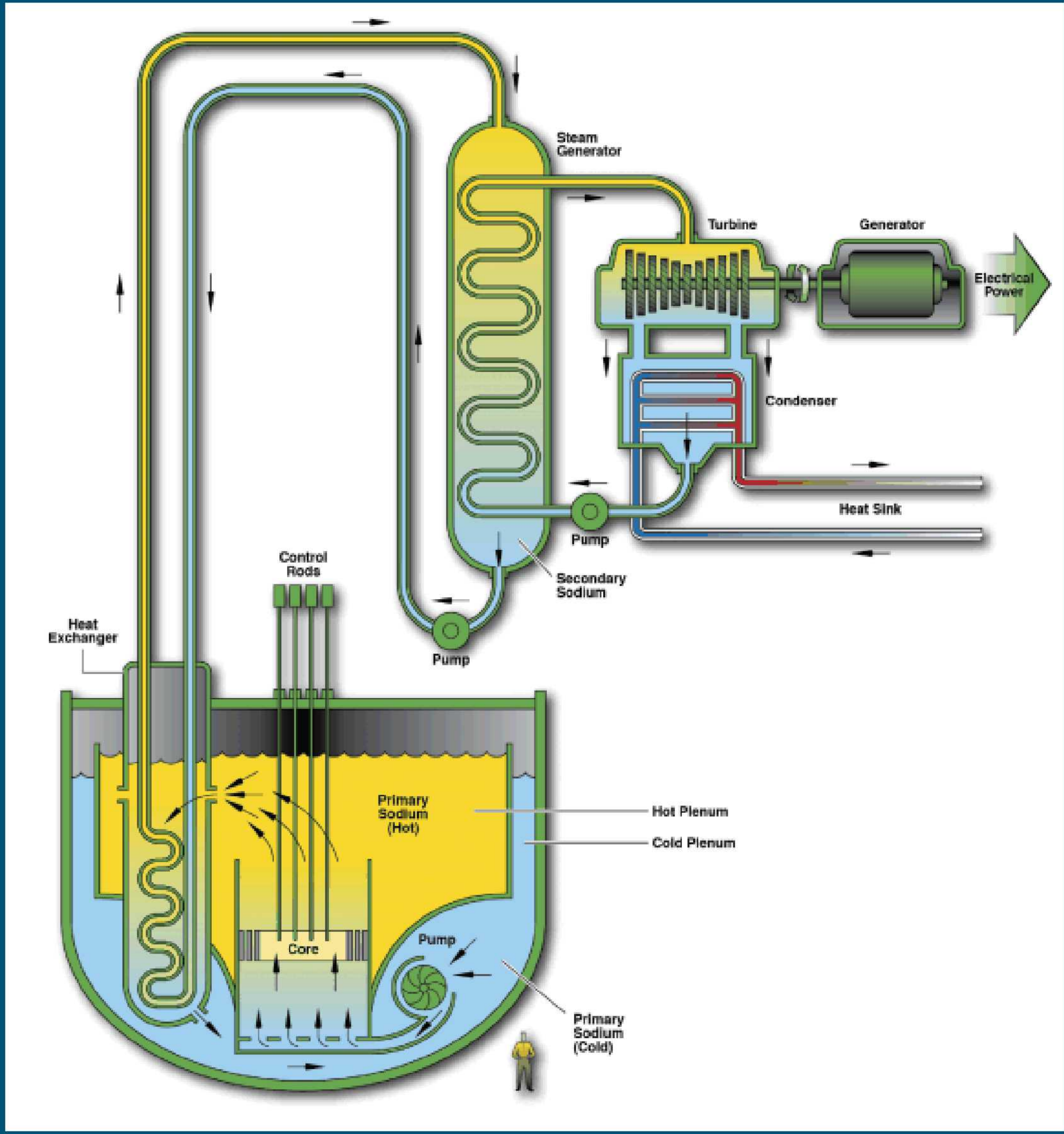
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Supercritical CO_2 power cycles have application in advanced nuclear

- sCO_2 power cycles are being investigated for advanced nuclear (sodium fast reactor initially), fossil (natural gas and coal), renewable (concentrated solar power), and waste heat recovery heat sources
- For the Sodium Fast Reactor (SFR), the use of sCO_2 as a substitute for steam eliminates the potential for water-sodium reaction, increases cycle efficiency, and can reduce capital cost and LCOE
- For the SFR, the high temperature is 500-550°C in a closed heat source, so a recompression closed Brayton cycle (RCBC) is a favorable configuration for efficiency

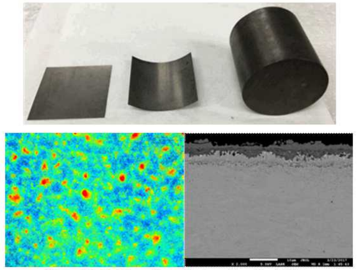


White, C., "Analysis of Brayton Cycles Utilizing Supercritical Carbon Dioxide - Revision 1", DOE/NETL-4001/070114.



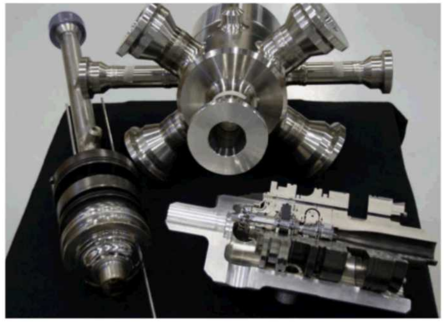
https://www.energy.gov/ne/articles/3-advanced-reactor-systems-watch-2030

Sandia National Labs' sCO_2 research covers many areas



Gas Foil Bearing Behavior in CO_2

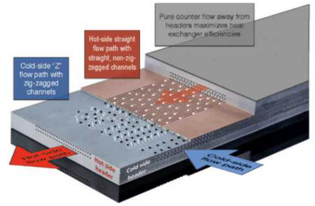
Turbine Degradation RCA

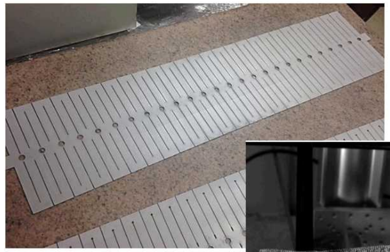


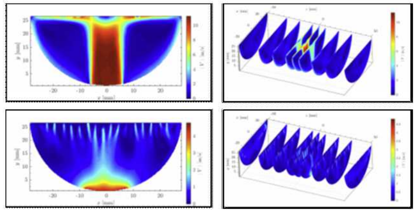
Peregrine Turbine Technologies Turbo-compressor[1]

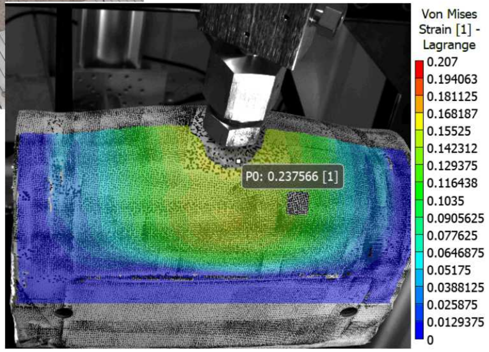
FlowServe Seal Test Platform for dry gas lift-off seals[2]

Turbomachinery







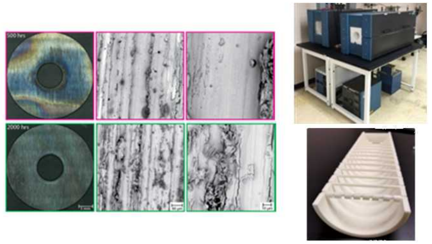


Semi-circular header burst test with optical strain measurement

Heat Exchangers

Materials

In Situ Corrosion/Erosion Monitoring



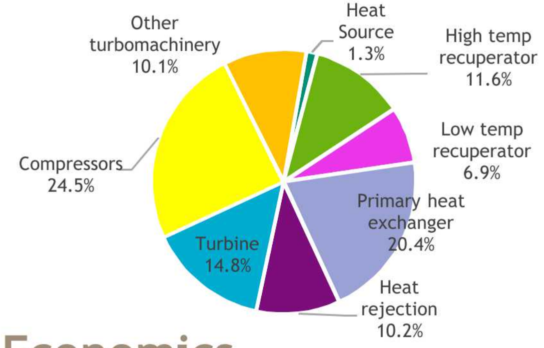
Alloy Corrosion Experiments

Sandia National Laboratories

The University of Wisconsin Madison

Oak Ridge National Laboratory

EC Structural Materials Consortium



Economics

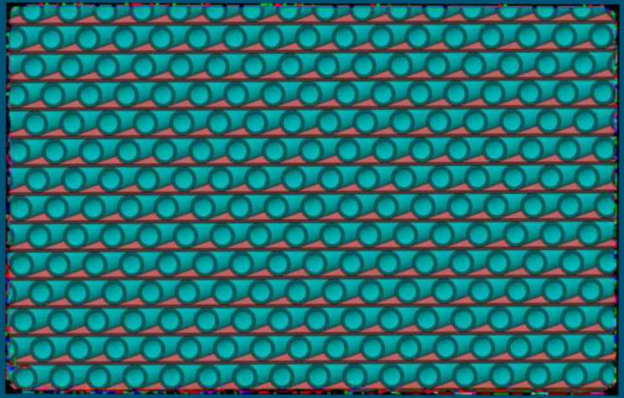
[1]Stapp, David, "sCO2 Symposium WHR Panel", 6th International sCO2 Power Cycles Symposium, March 27-29, 2018, Pittsburgh, PA.
[2]Fleming, Darryn, "Seal Development Platform", sCO2 Power Cycles Summit, November 14-16, 2017, Albuquerque, NM.

Heat exchangers for sCO_2 cycles must handle high pressure

- sCO_2 power cycles typically have pressures of 300 bar and temperatures 550-750°C
- There are only a handful of heat exchanger designs that can handle the pressure

Shell & Tube

SPX, 2016-08-03, *Shell & Tube Heat Exchangers*, http://spxheattransfer.com/products/detail/shell-tube-heat-exchangers



Micro Shell and Tube

Chordia, Lalit and Portnoff, Marc, "Development of Modular, Low-Cost, High-Temperature Recuperators for the sCO2 Power Cycles – Project Update", 2017 University Turbine Systems Research Project Review Meeting, November 2, 2017, Pittsburgh, PA.

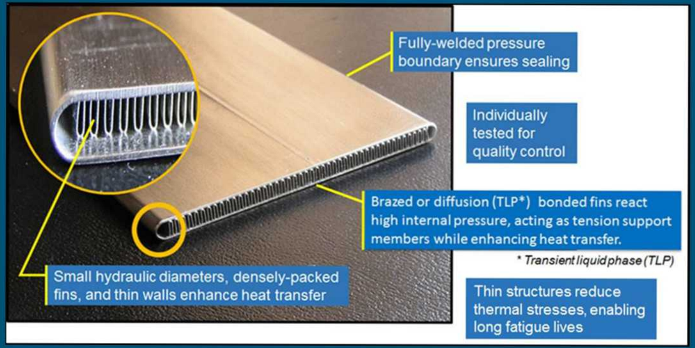
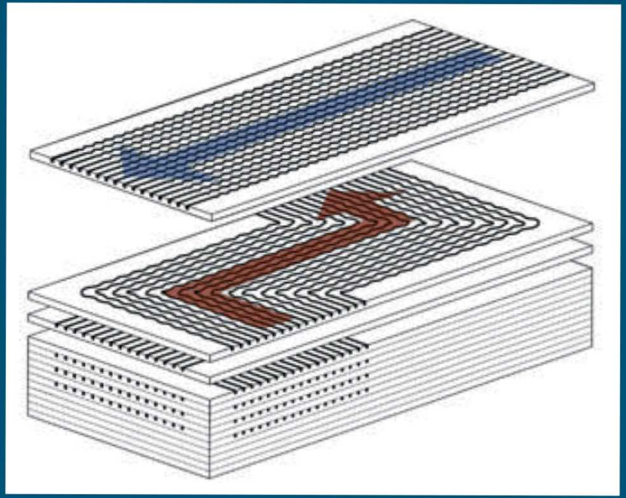
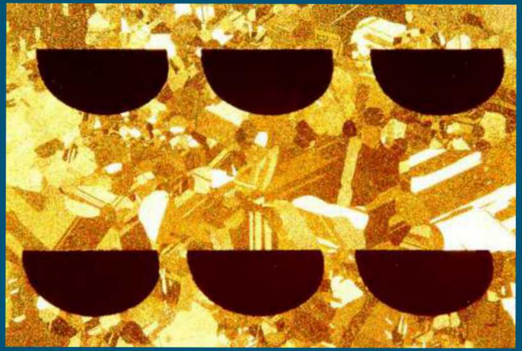


Plate-fin

EERE. (2016, 2016/08/01). EERE Success Story—Solar Receiver Redesign Enables CSP to Beam Ahead. Available: http://energy.gov/eere/success-stories/articles/eere-success-story-solar-receiver-redesign-enables-csp-beam-ahead



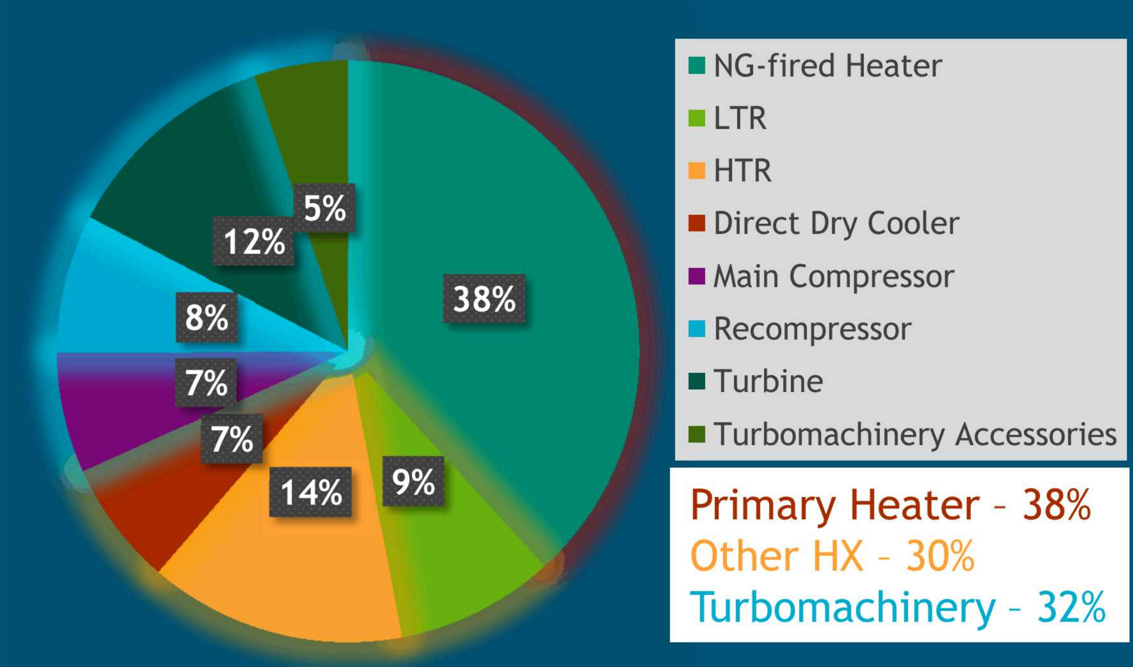
Printed Circuit Heat Exchanger (PCHE)



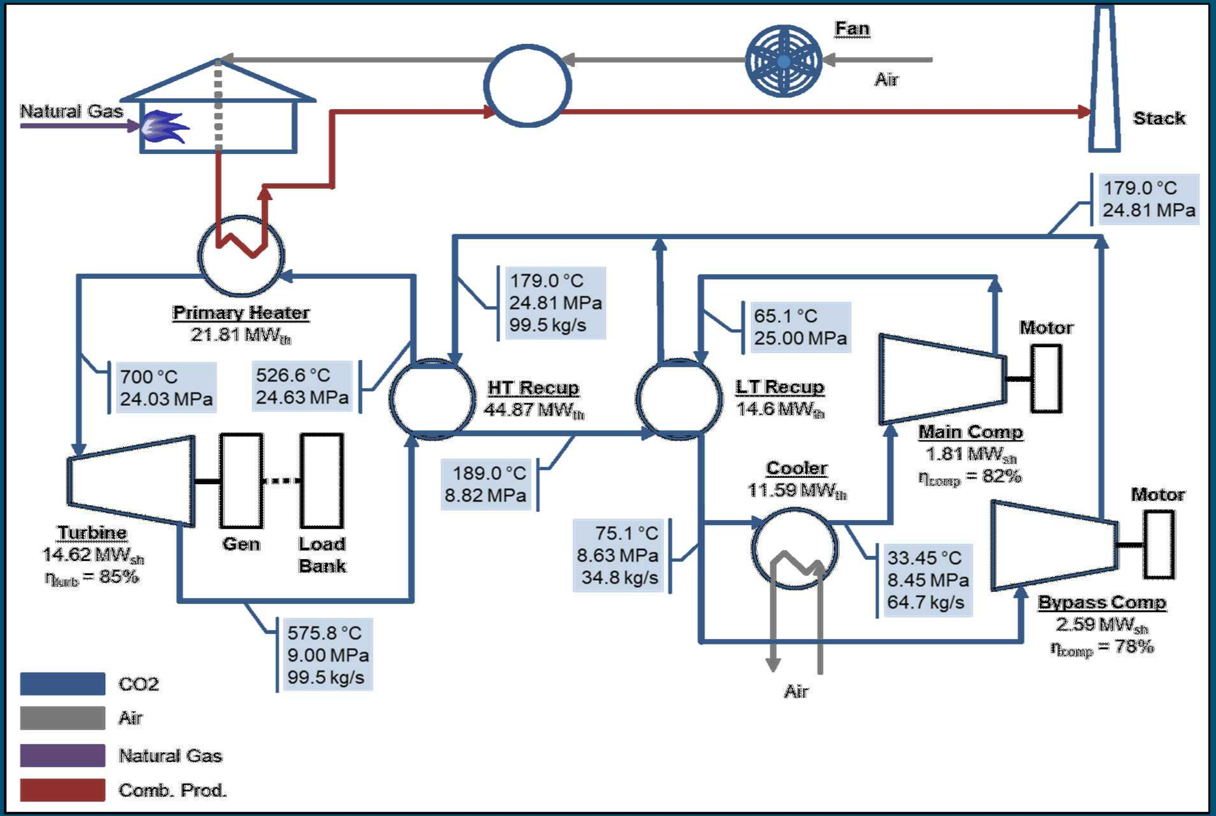
- The traditional shell and tube design is 3-5x more expensive at high pressure

Heat exchangers in sCO_2 power cycles are a sizeable portion of component costs

- The heat duties of the recuperators is larger than the net power output
  - 10.2 MWe net power
  - 21.8 MWth Primary Heater
  - 44.9 MWth High Temperature Recuperator
  - 14.6 MWth Low Temperature Recuperator
  - 11.6 MWth Cooler



Primary Heater – 38%
Other HX – 30%
Turbomachinery – 32%



10 MWe STEP Project Conditions, NETL

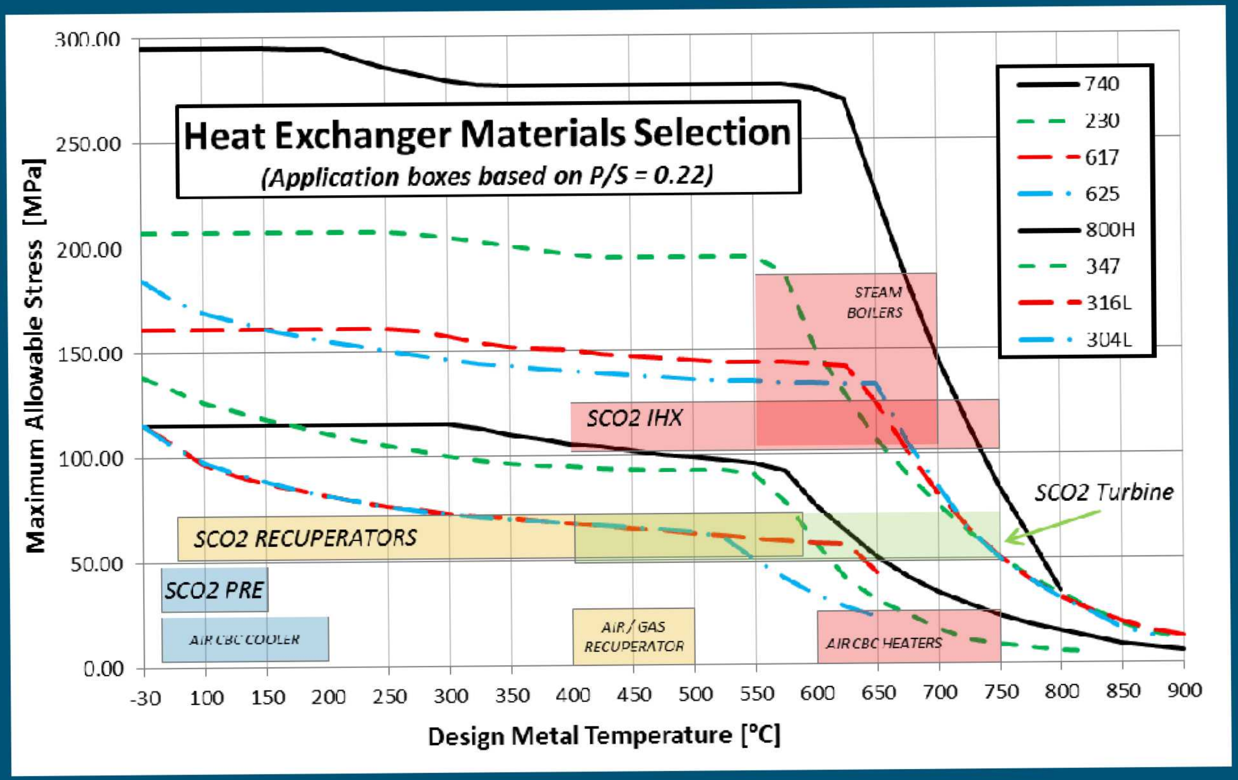
Weiland, Nathan T., Lance, Blake W., and Pidaparti, Sandeep R., "sCO2 Power Cycle Component Cost Correlations from DOE Data Spanning Multiple Scales and Applications", 2019 ASME Turbo Expo, June 17-21, 2019, Phoenix, AZ.

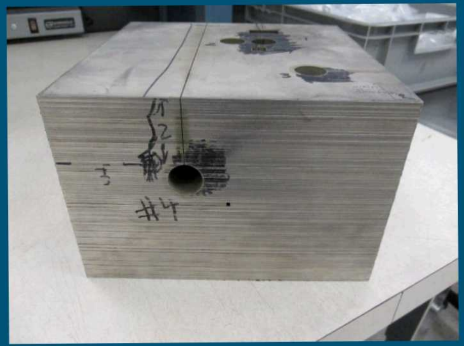
Our group has discussed heat exchanger R&D needs by application

Technology Readiness Levels		from Direct Gas Combustion	from Exhaust Gas	from 3 MPa Helium	from Steam	from floride molten salts	from nitrate molten salts	from liquid sodium	from liquid lead-bismuth	from Heat Transfer Oil	from Combusting Particles	from Inert Solid Particles	from Geothermal Resources	from sunlight	Yet To Be Identified Materials	Advanced Nickel Alloys	Conventional Nickel Alloys	Austenitic Stainless Steels	to Water	to Humidified Air	to Dry Air	TIT / °C
Molten Salt Reactor	**NE**					3											4-5	6-8	6-8	2	2-4	*700 to 850*
Sodium Fast Reactor (SFR)	**NE**							3										6-8	6-8	2	2-4	*550*
Lead Fast Reactor (LFR)	**NE**								3								4-5	6-8	6-8	2	2-4	*550 to 800*
Helium Gas Reactor (GFR, VHTR)	**NE**			4-5											2	3	4-5	6-8	6-8	2	2-4	*700 to 1000*
Nuclear Shipboard Propulsion	**NE**																	6-8	6-8			*200 to 300*
Direct CSP Tower	**EE**													4			4-5	6-8	6-8	2	2-4	*500 to 1000*
CSP Tower with Thermal Storage	**EE**						8	2		2		4		4			4-5	6-8	6-8	2	2-4	*500 to 1000*
CSP Trough with Thermal Storage	**EE**						8			2								6-8	6-8	2	2-4	*300 to 600*
CSP Dish Generator	**EE**							2		2				4-5			4-5	6-8			2-4	*500 to 1000*
Direct Geothermal Plant	**GT**												2					6-8	6-8	2	2-4	*100 to 300*
Indirect Geothermal Plant	**GT**				4-5													6-8	6-8	2	2-4	*100 to 300*
Direct Natural Gas Combustion	**FE**	3-5	4												2	3	4-5	6-8	6-8	2	2-4	*1100 to 1500*
Integrated Gasification Coal	**FE**	3-5													2	3	4-5	6-8	6-8	2	2-4	*1100 to 1500*
Pulverized Coal Fluidized Bed	**FE**										4					3	4-5	6-8	6-8	2	2-4	*550 to 900*
Waste Heat Recovery	**FE**		4-5															6-8	6-8	2	2-4	*230 to 650*
Gas Turbine Bottoming	**FE**		4-5															6-8	6-8	2	2-4	*230 to 650*
Municipal waste to energy	**FE**		4-5															6-8	6-8	2	2-4	*230 to 650*
10 MWe Pilot	**FE**		4-5														4-5	6-8	6-8	2	2-4	*550 to 700*
50 MWe Demonstration	**FE**		4-5														4-5	6-8	6-8	2	2-4	*550 to 700*
		N/A	**Gas**			**Liquid**					**Solid**				**>750**	**750**	**650**	**550**	**sCO2 Cooling**			
		sCO2 Heating from Various Sources													**Recuperation MDMT / °C**							

High temperature heat exchangers still need development

- Heat exchangers made from 300 series stainless steels typically work up to 550-600°C
  - Limit primarily due to corrosion and secondarily allowable stress
- Nickel-based alloys can handle higher temperatures, but diffusion bonding still needs to be developed for PCHEs
- Ongoing research:
  - NEUP IRP: ASME BPV code materials for nuclear service (800H, 316H SS)
  - SuNLaMP: Development of Inconel 625 bonds



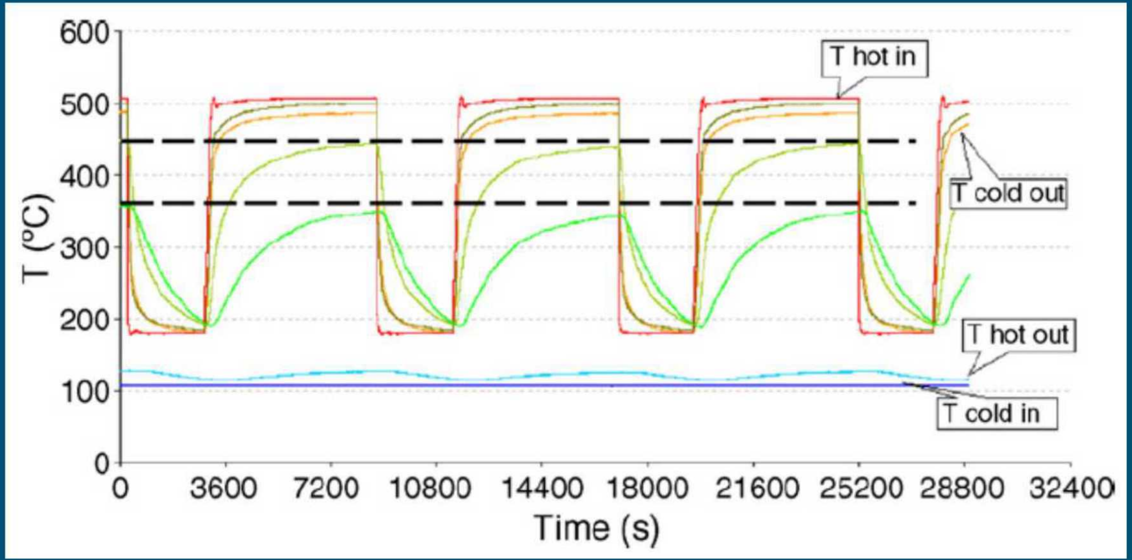


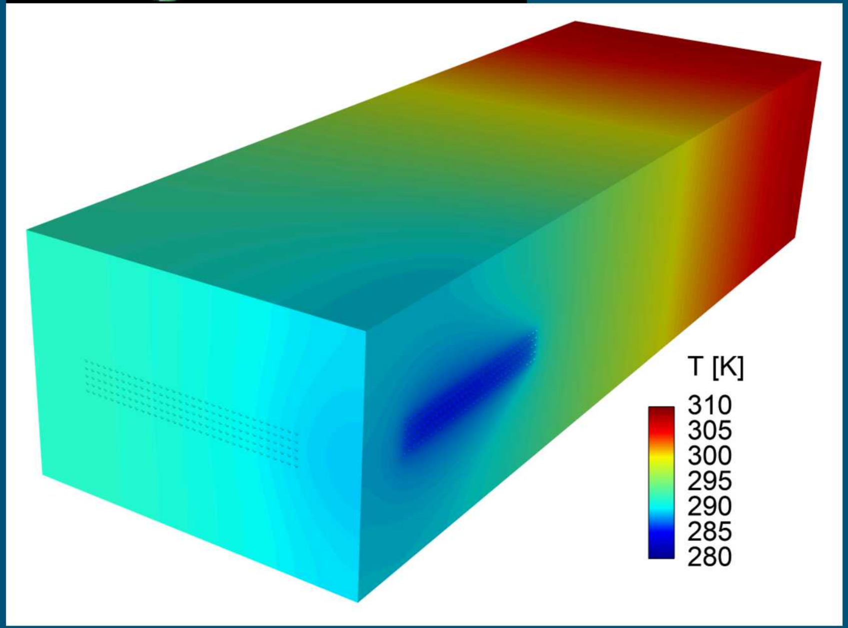
Vacuum Process Engineering Bonding Process Certification

Thermal transient and fatigue limits are unknown in PCHEs

- Heat exchanger vendors typically certify steady-state use without cycling
- In the modern grid with increasing renewable penetration, sCO_2 power cycles will need to be flexible
- We are simulating thermal transients for an understanding of limits
- We are seeking funding for complementary experiments

HPC4 MATERIALS for Severe Environments





F. Pra, P. Tochon, C. Mauget, J. Fokkens, and S. Willemsen, “Promising designs of compact heat exchangers for modular HTRs using the Brayton cycle,” *Nuclear Engineering and Design*, vol. 238, no. 11, pp. 3160–3173, Nov. 2008.