SunShot
U.S. Department of Energy

CSP Program Summit 2016

Advanced sCO_2 cycles

Apollo award: DE-EE0001720

UW-Madison, CSM, NREL, SNLs, CompRex and FlowServe.

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Advanced Supercritical Carbon Dioxide Cycles

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T. Neises/NREL, Z. Jia/Comprex, R. Gradle/FlowServe

Technology Addressed

Advanced Power Cycles for CSP

Innovative Aspect

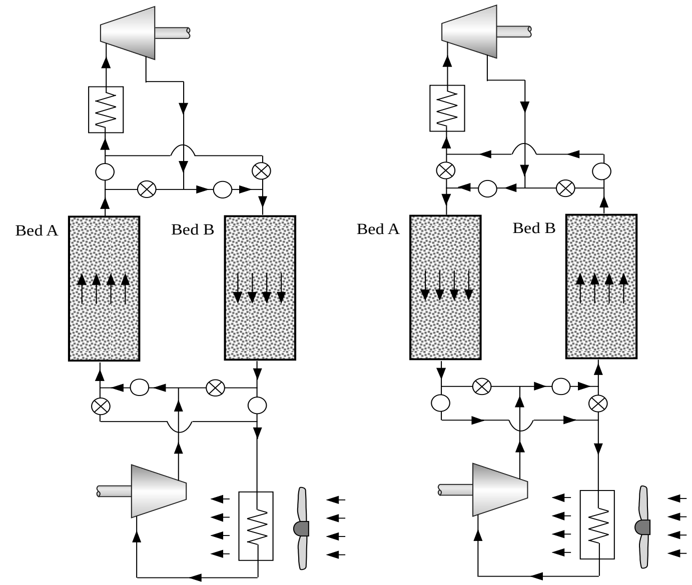
Incorporate switched-bed regenerators in place or in addition of recuperative heat exchangers, into SCO_2 cycles. Decrease cost & increase temp. options.

Impact

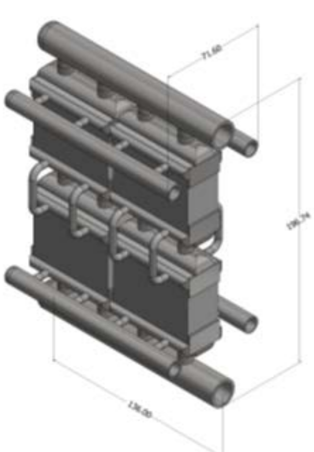
- Reduce cost of component required for regenerative heat transfer
- Increase temperature capability with insulated pressure boundary w/out expensive materials
- Develop cost and performance models

Background and Proposed Work

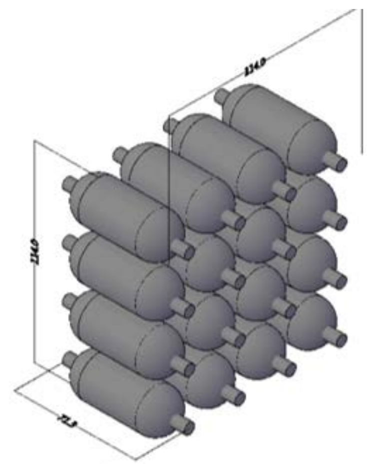
- SCO_2 cycles have been shown theoretically and now experimentally to have several advantages with regard to CSP systems
- This project will focus on addressing the key technical challenges associated with their deployment
- Tasks include the design, fabrication, and demonstration of switched bed regenerators and high temperature valve solutions



switched bed regenerator



High Temperature Recuperator
From Comprex



High Temperature Regenerator

WISCO2
SunShot
U.S. Department of Energy
CSP: APOLLO
WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON
FLOWSERVE
Sandia National Laboratories
COMPREX
COMPREX™ Compact Heat Exchange Reactor
SCHOOL OF MINES 1874 COLORADO
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Project Objectives

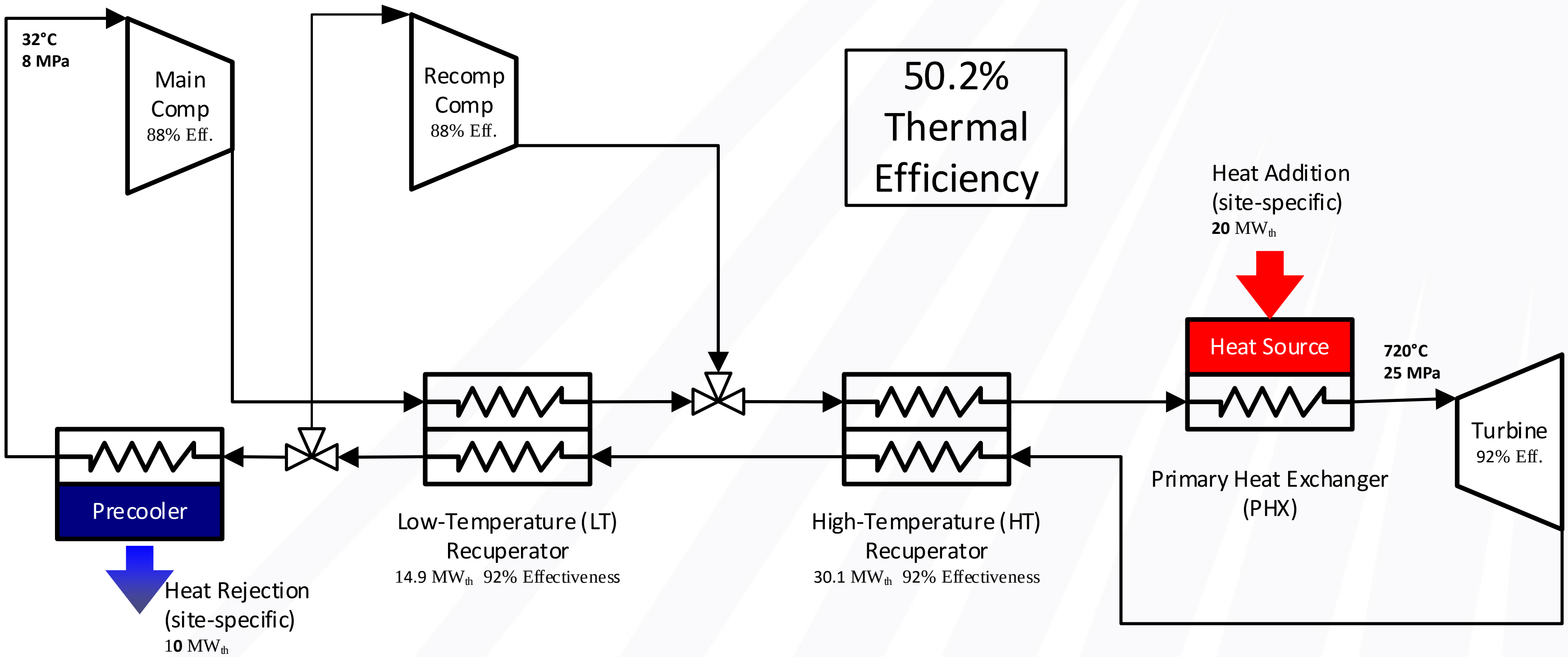
1. Evaluate the possible improvements in the economics and thermodynamic performance of the supercritical carbon dioxide (sCO_2) cycle that can be realized by the replacement of the high cost recuperative heat exchanger (HX) with a potentially lower cost regenerative HX

2. Develop improved thermodynamic and economic models to understand the overall benefit of the sCO2 power block for use in CSP.

This project examines an innovative way to improve the sCO_2 cycle by addressing one of the critical high cost components. It also increases the understanding of the cost associated with a sCO_2 power block and provides real data for performance evaluation of components.

Define detailed STEP cycle configuration

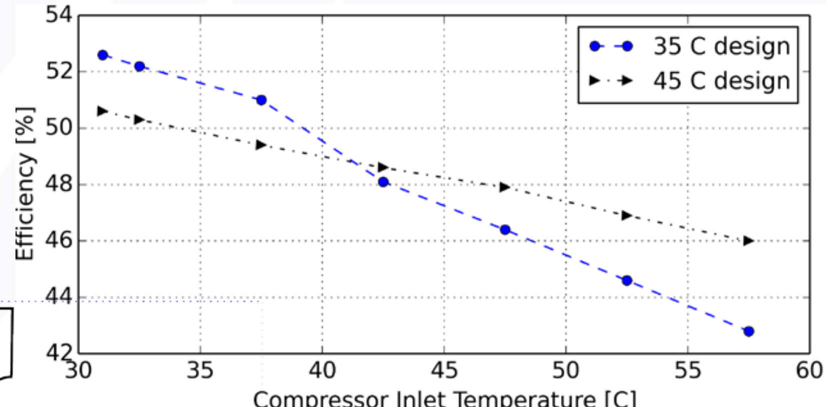
The Supercritical Transformational Electric Power (STEP) facility is a ~10MWe demonstration of the sCO_2 power cycle with a 720°C turbine inlet temperature and dry cooling to a 32°C compressor inlet temperature.

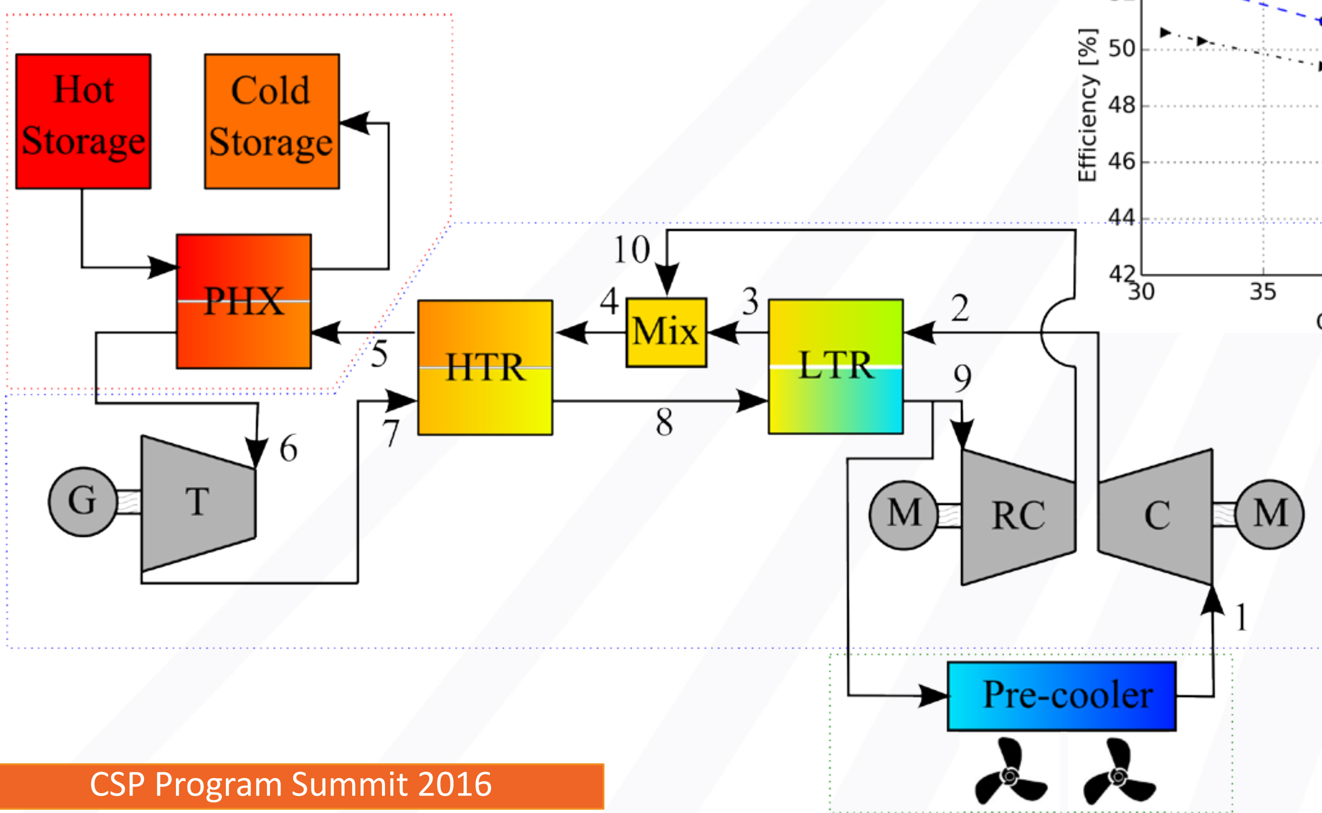


Shown here is a simplified cycle diagram with the major components

Develop cycle performance and cost models

- Developed heat input and heat rejection models to interface with a recompression cycle model
- Currently optimizing system design and control (inventory, compressor speed, recompression fraction) for CSP locations and dispatch schedules
- Next steps are adding cost models to component design models and integrating with SAM's CSP model

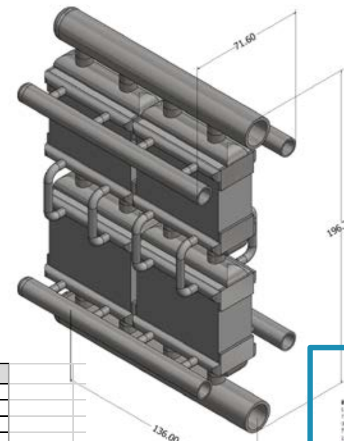


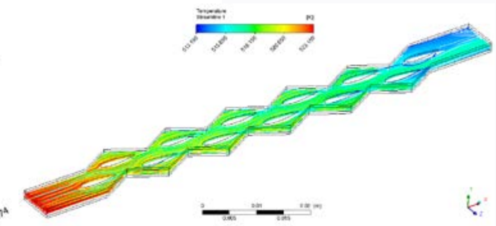


Develop detailed geometry and cost models for recuperative heat exchangers

Use STEP cycle layout as basis for sizing regenerator systems

Develop cost and performance models for recuperators as a function of UA as well as the operating temperature and pressure



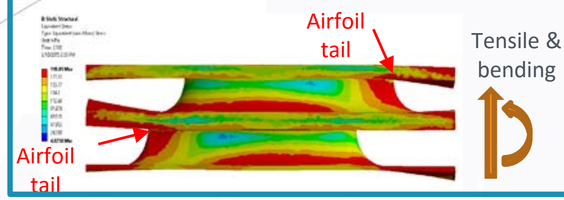


CompRex PLATE-FIN STAINLESS STEEL HEAT EXCHANGER SPECIFICATION

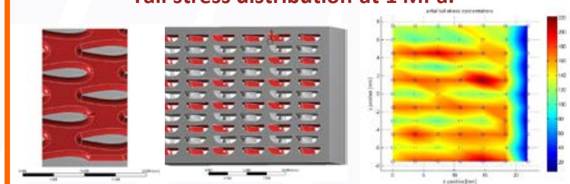
Customer		DOE Apollo	Project	10 MW sCO2 Power plant		Location		
Item number		2027 - 2A	Service	Hot Recuperator 47MW		Date	1/10/2016	Revision
Stream i.d. / fluid name	Unit	A/ Hot CO2		B/ Cold CO2		C/	D/	E/	F/
Flow rate Total	kg/s	104.5		104.5					
Vap./Liq. In	kg/s	/		/		/	/	/	/
Vap./Liq. Out	kg/s	/		/		/	/	/	/
Molecular weight Vap. In/Out	-	44 / 44		44 / 44		/	/	/	/
Liq. In/Out	-	/		/		/	/	/	/
Density Vap. In/Out	kg/m^3	54.76 / 107.59		320.83 / 151.15		/	/	/	/
Liq. In/Out	kg/m^3	/		/		/	/	/	/
Viscosity Vap. In/Out	cP	0.0373 / 0.0243		0.0314 / 0.0376		/	/	/	/
Liq. In/Out	cP	/		/		/	/	/	/
Specific heat Vap. In/Out	J/kg K	1218 / 1158		1479 / 1252		/	/	/	/
Liq. In/Out	J/kg K	/		/		/	/	/	/
Thermal conductivity Vap. In/Out	W/m K	0.0622 / 0.0351		0.0461 / 0.0627		/	/	/	/
Liq. In/Out	W/m K	/		/		/	/	/	/
Temperature In/Out	C	581 / 204		194 / 533		/	/	/	/
Operating pressure In	MPa	8.96		23.99					
Allowable frictional pressure drop	kPa	130		130					
Heat load	MW	-46.6		46.6					
Corrected MTD	C	24.2							
Fouling resistance	m^2 K/W	0							
Design pressure / test pressure	MPa (g)	9.7445 /		26.278 /		/	/	/	/
Design temperatures max / min.	C	608.78 / 0							

Number of cores and assemblies	-	In parallel	2	In series	2	Number of cores/assembly	1	Number of assemblies	1
Core size	mm	Width	609.6	Height	1514.5	Length	1346.2		
Flow pattern	-	Counter		Y	Cross-counter		Cross		Parallel
Approx. weights	kg	Core empty		24515.5	Core operating	24783	Assembly empty		Assembly operating
Number of layers	-								
Fin code: Heat transfer fin	-								
Distributor fin	-								
Heat transfer surface/core	m^2								
Core opening size In/Out	mm	304.8 / 304.8		2x101.6 / 2x101.6		/	/	/	/
Nozzle number × size In/Out	mm	1x203.2 / 1x203.2		2 x 76.2 / 2 x 76.2		/	/	/	/
Manifold pipe size In/Out	mm	/		/		/	/	/	/
Calculated frictional pressure drop	kPa	146.9		142.7					
Code and/or regulation:									
Notes	Tin/Tout: 581/204.11; 194/537.49C. dP: 146.9/142.7kPa								
	User supplied data					Data sheet (rev.1 05/2014)			
	Manufacturer supplied data								

Local Tail Stress from Pressure across channels



Tail stress distribution at 1 MPa.



These models will be incorporated into the developed cycle design and cost assessment tools used to help optimize the cycle layout for CSP plants

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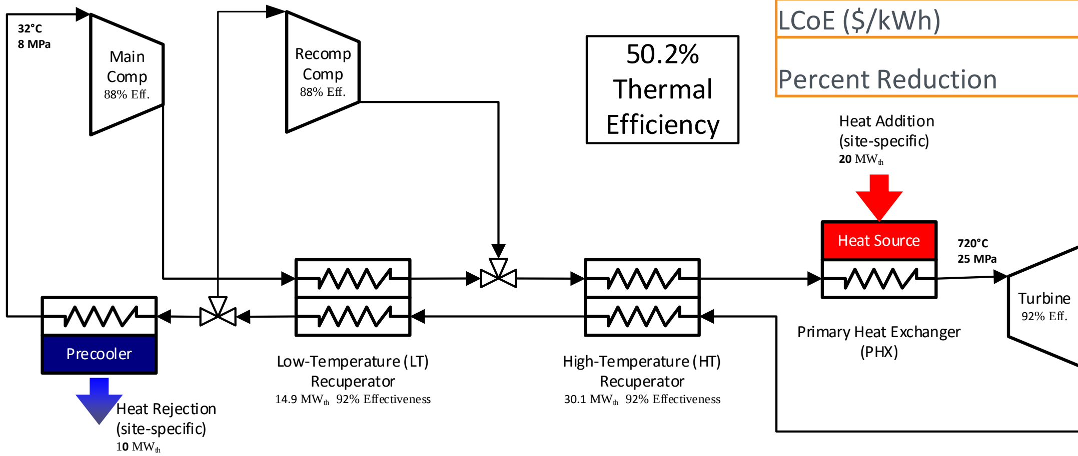
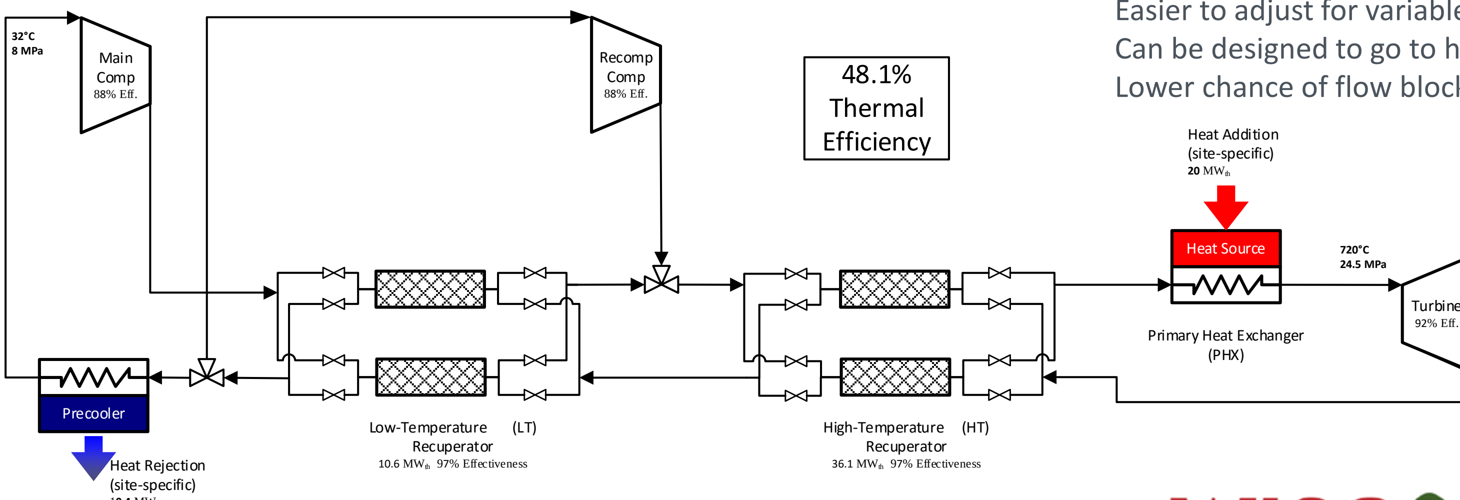
Evaluation of regenerators as a possible replacement for printed circuit recuperators in sCO2 power cycles

	Recuperators	Regenerators
Thermal Efficiency	50.2	48.1
Recup/Regen Costs (k$)	3368	468
Valve Costs (k$)	0	222
LCoE ($/kWh)	0.01870	0.01447
Percent Reduction		22.6%

Recompression Brayton Cycle with recuperators

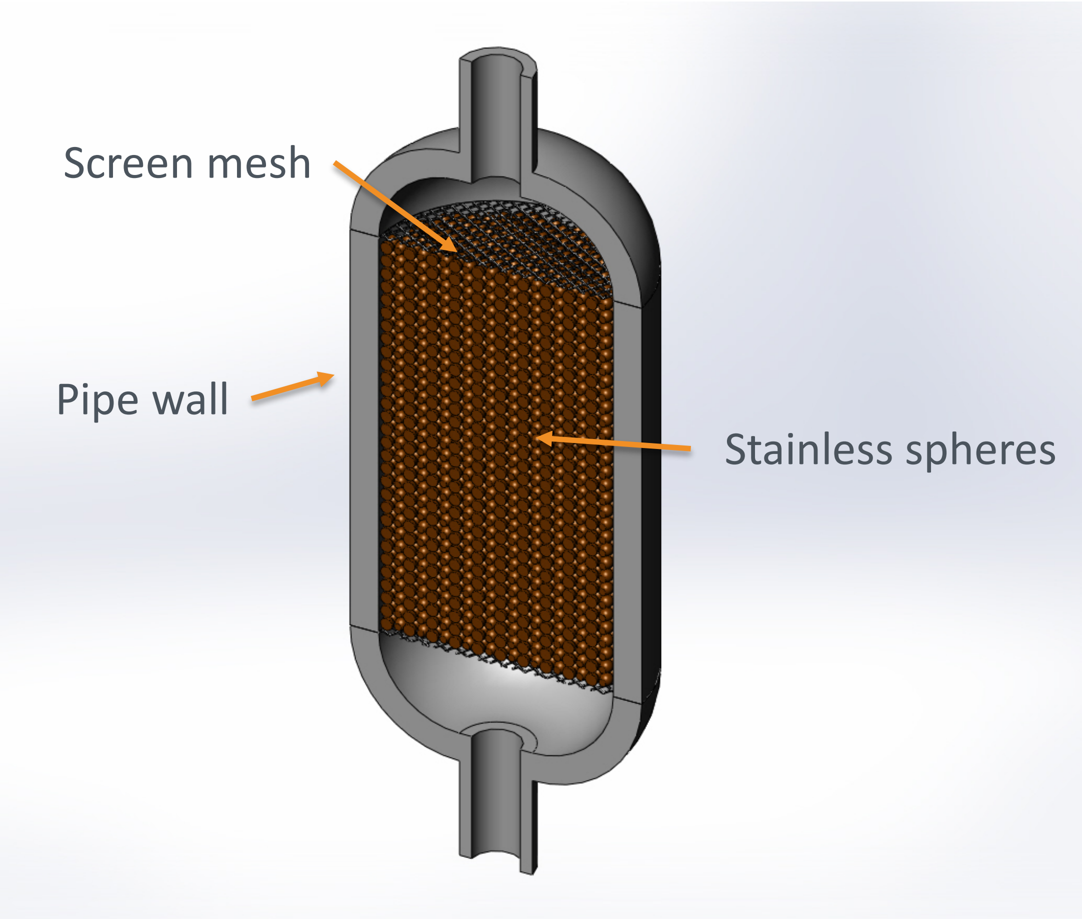


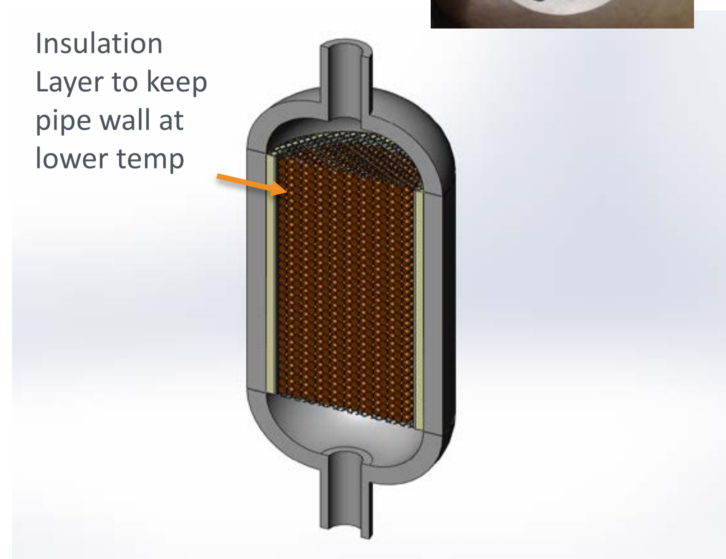
Recompression Brayton Cycle with regenerators



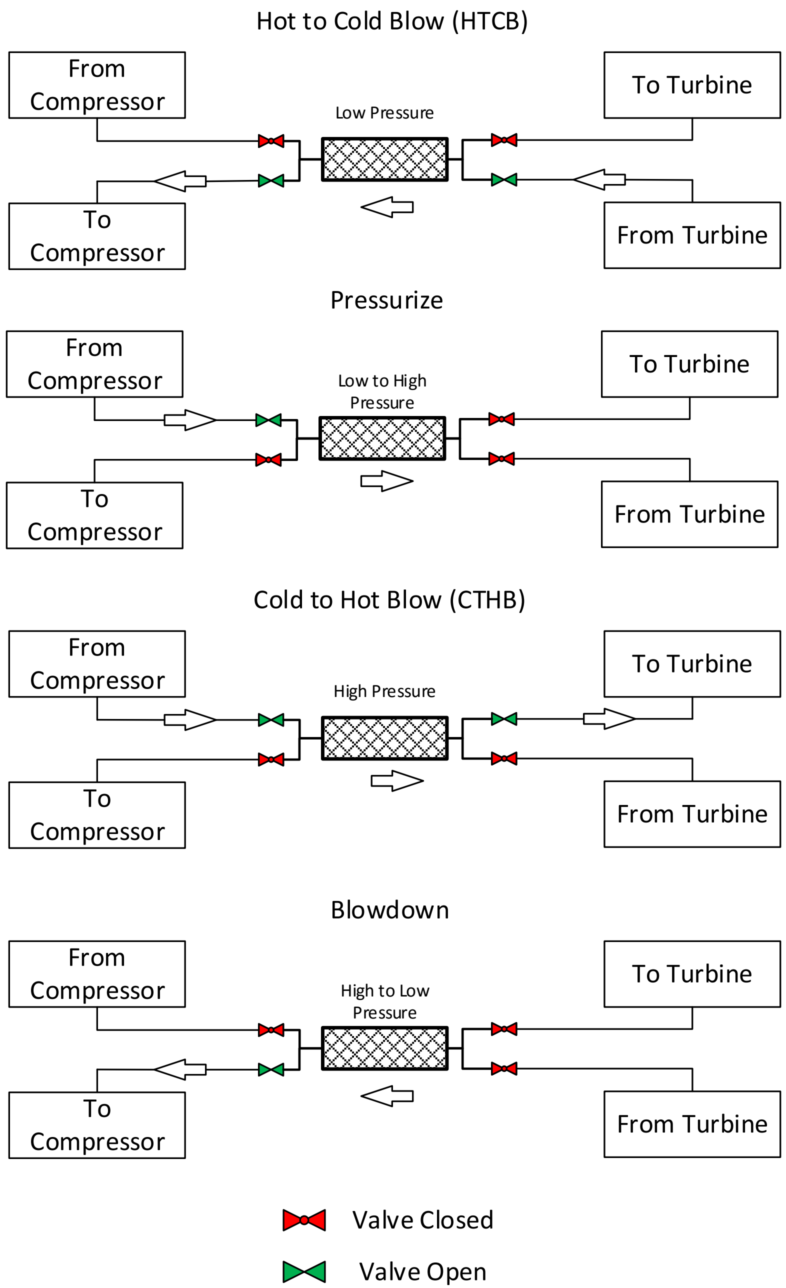
- Lower cost systems
- No need for miles of hermetic seals
- Easier maintenance
- Easier to adjust for variable loads
- Can be designed to go to higher temps
- Lower chance of flow blockage

Conceptual design of regenerator





Operation of regenerative sCO2 system



1) HTCB: Hot fluid exiting turbine flows through the regenerator depositing thermal energy into the packed bed

2) Pressurization: the valve between the compressor and regenerator is opened and high pressure sCO_2 enters the regenerator, increasing the pressure.

3) CTHB: cold fluid is forced by the compressor into the regenerator where it removes heat from the packed bed before entering the primary heater and turbine

4) Blowdown: the pressure in the regenerator is reduced by allowing the high pressure sCO_2 in the regenerator to return to the suction line of the compressor.

operation repeats on ~ 0.03 Hz cycle (i.e., every 30 s) continuously

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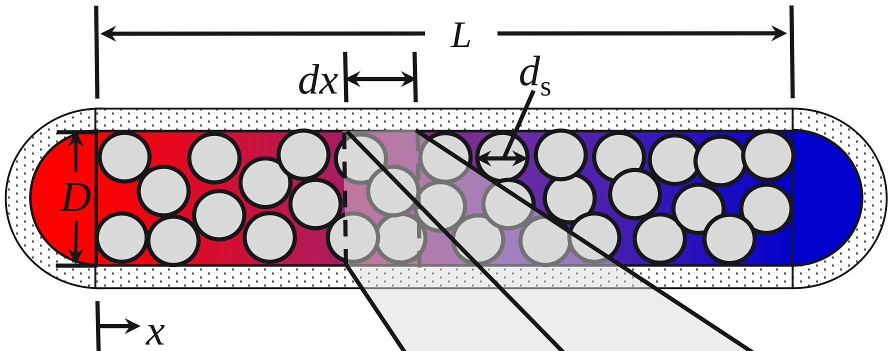
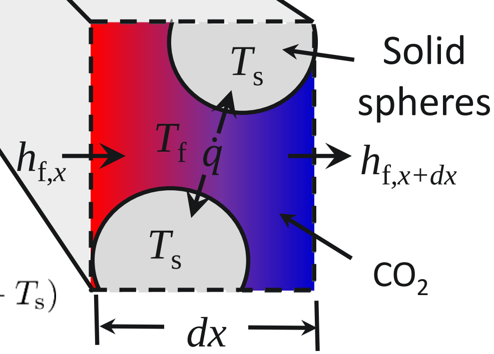
Detailed regenerator modeling to predict performance

- Fully transient simulation
- Allows analysis of additional phenomena:
  - Local property calculations, influence of valves and switching
  - Axial conduction in the solid, entrained fluid heat capacity



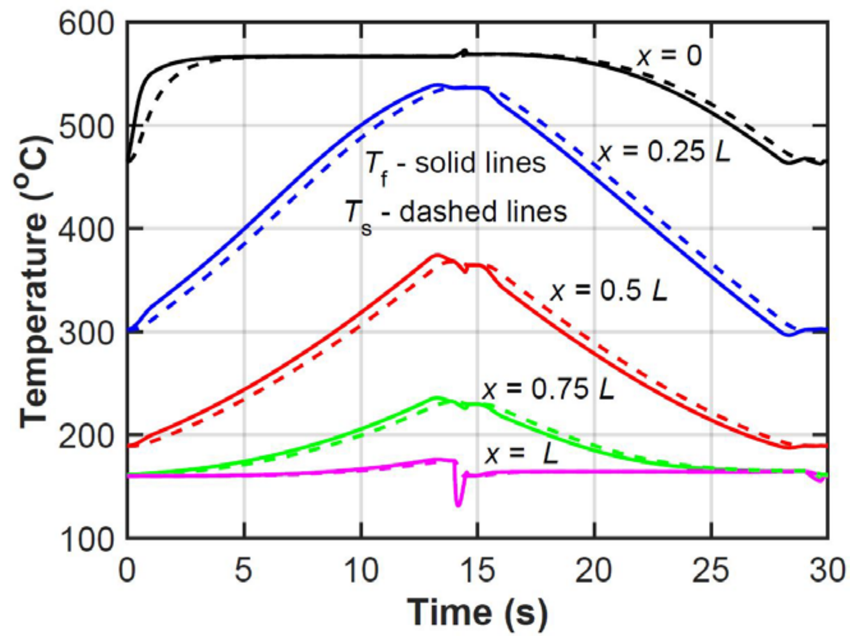


Conservation Equations:

$$\frac{\partial(\rho\phi)}{\partial t} = -\nabla \cdot \mathbf{J}$$

$$\frac{d(\rho_f \phi u_f)}{dt} = -\frac{\partial(Jh)}{\partial x} - \overline{h}_x \alpha (T_f - T_s)$$

$$\frac{d(\rho_s \psi u_s)}{dt} = \psi \frac{\partial}{\partial x}\left(k_s \frac{\partial T_s}{\partial x}\right) + \overline{h}_x \alpha (T_f - T_s)$$

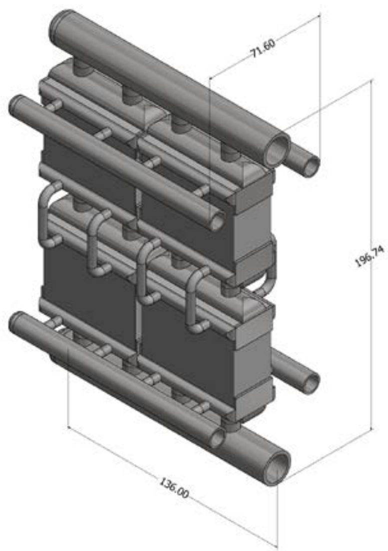


Temperature versus time for different axial locations.

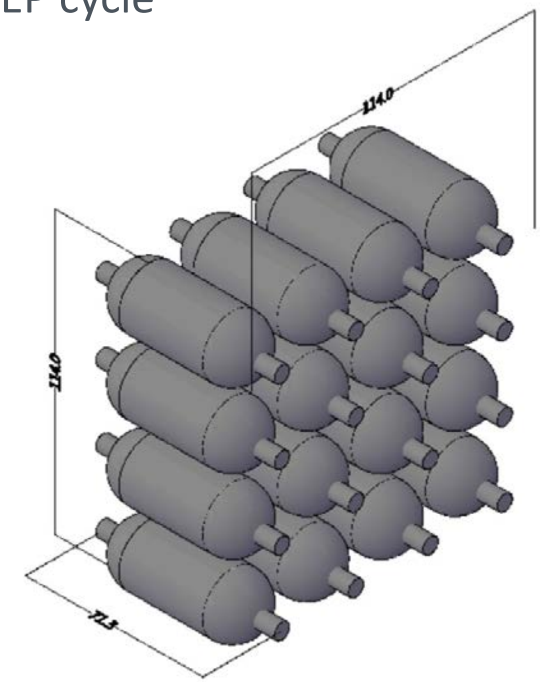
- Initial results agree fairly well with NTU-eff-Cm design model for high temp. regenerator
- Results deviate more significantly for long switching times and for low temp. regenerator

Regenerator sizing and operation compared to recuperator

Sizing and cost based on the 10MWe STEP cycle



High Temperature Recuperator
(from Comprex)

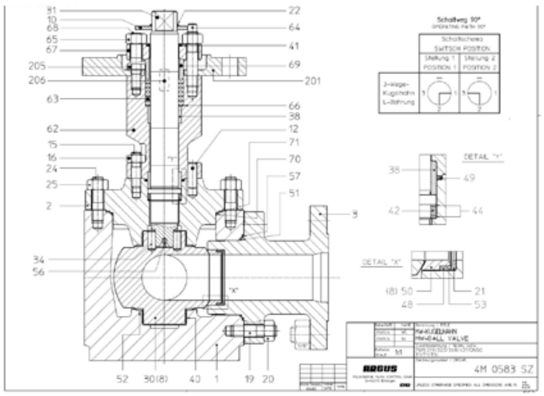


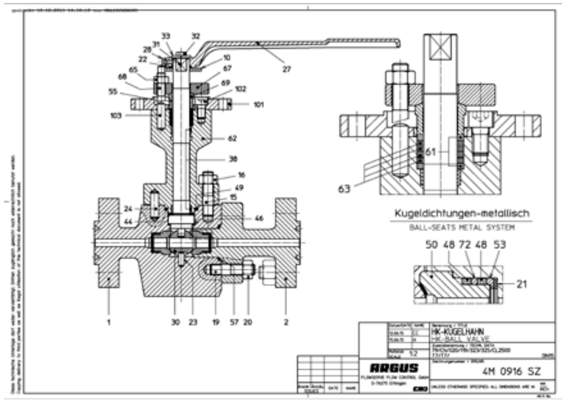
High Temperature Regenerator

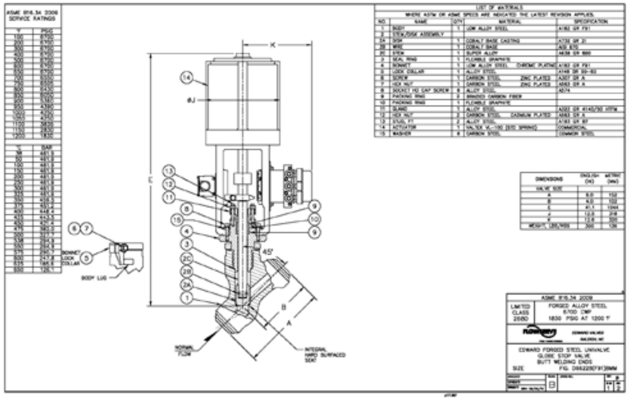
Size of systems are comparable initial estimates indicate that a ~80% reduction in capital cost of unit is possible which leads to a 24% reduction in the LCoE. There may be other advantages with respect to higher temperature operation and off-the-shelf components.

Valve study: Need to ensure valves will survive under high temperature cyclic conditions

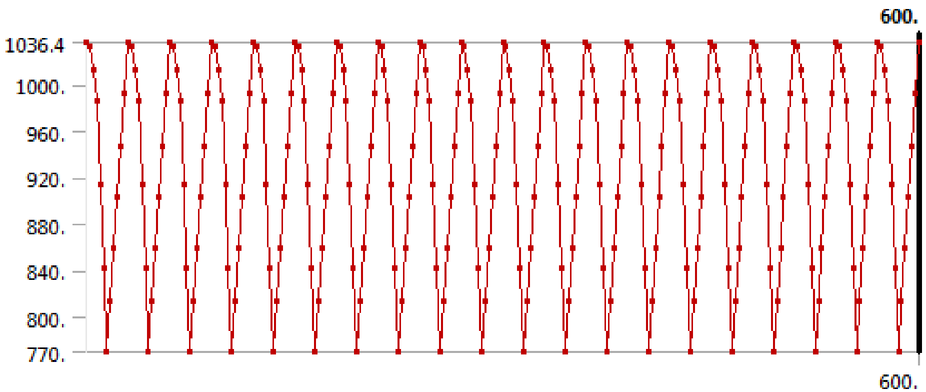
- Regenerator systems require valves that need to be sourced and their performance and cost must be evaluated

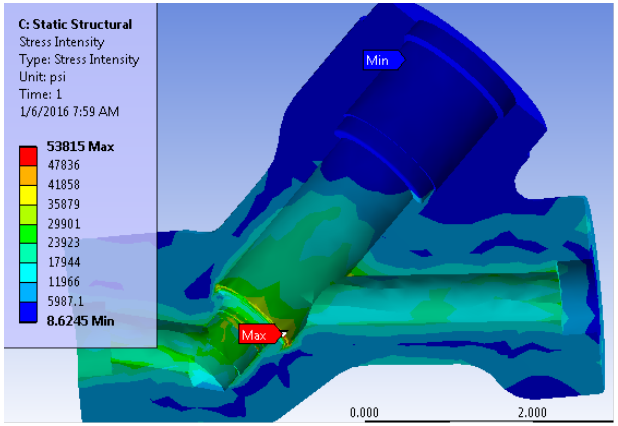






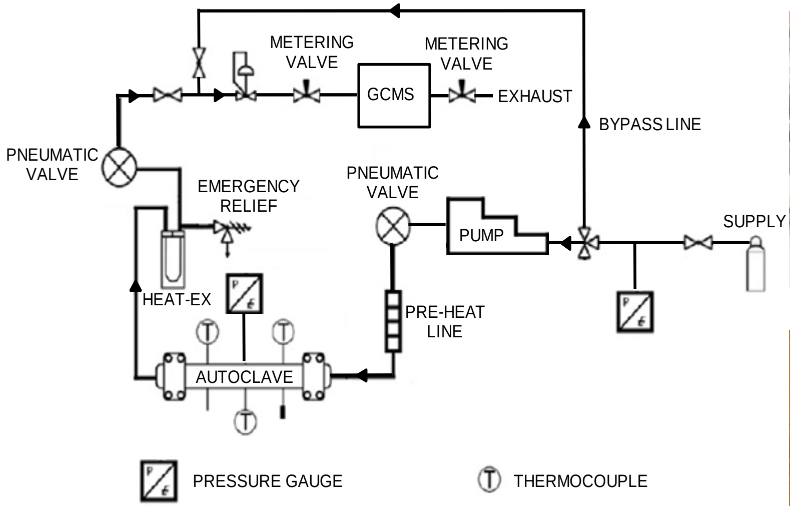
Valve cyclic temperature modeling



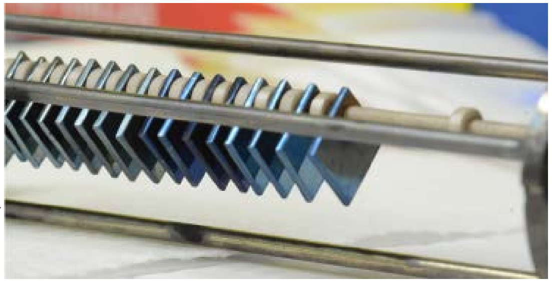


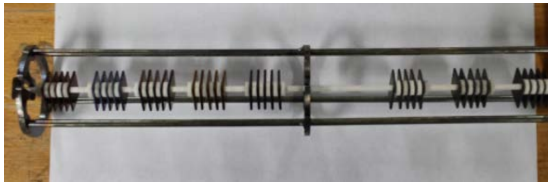
Materials Testing in sCO2: Need to ensure materials hold up for life of plant

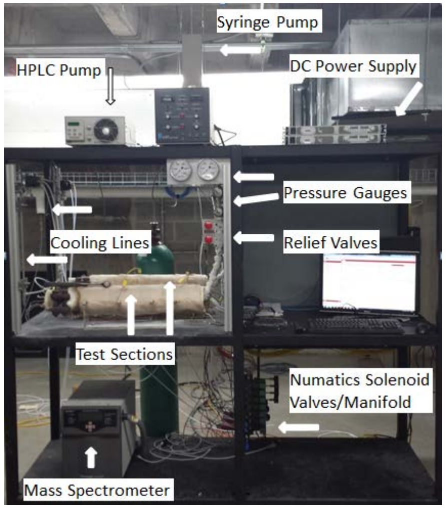
sCO_2 Static autoclave testing



High temperature power plant alloy materials.
IN740, IN 282, 316, P91 are exposed to sCO2 at 750C and 20 MPa

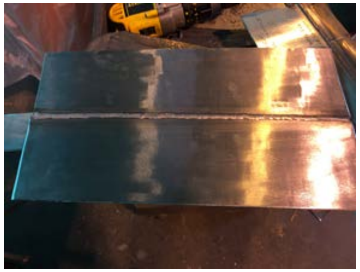




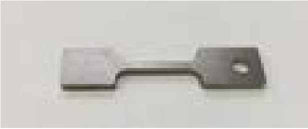


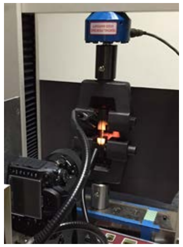
Welded samples

High temperature power plant alloy materials.
IN740, IN 282, 316, P91 are welded to each other and tested

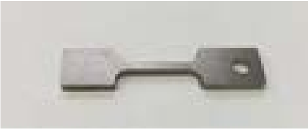


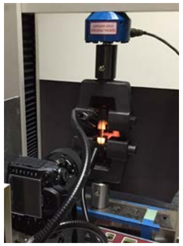
Tensile testing





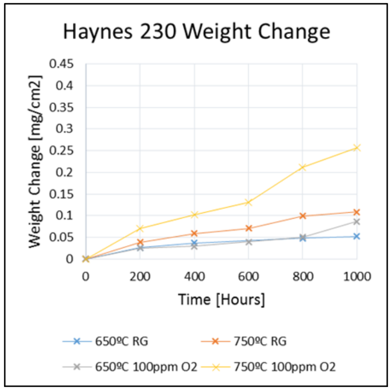
Exposure

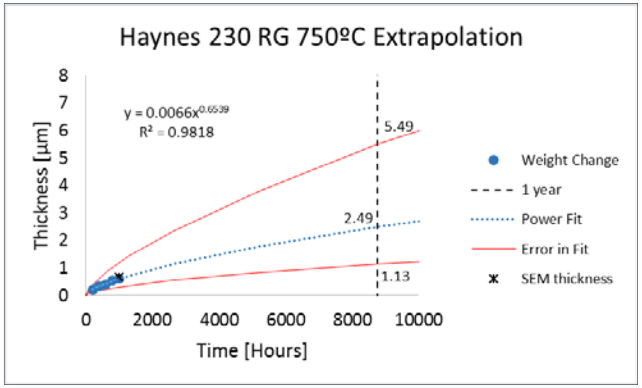




Special thanks to Haynes and Special Metals for material and welded samples

Detailed evaluation of materials and weld joints

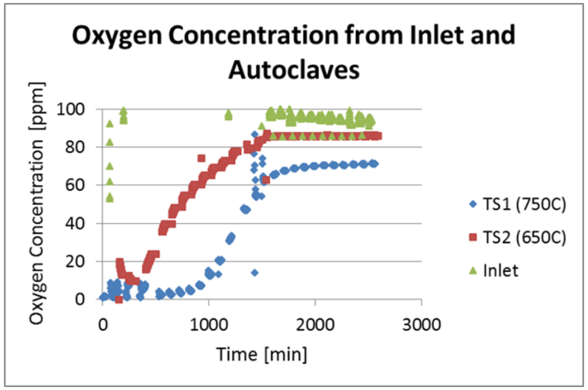




- Based on power fit equation:

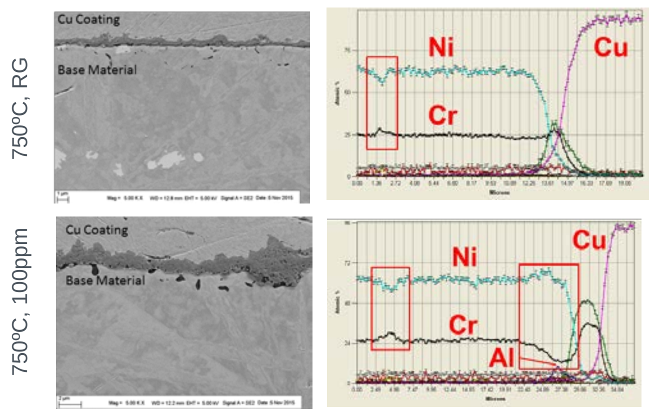
$$W = \alpha t^b$$

- Used time-dependent data out to 1,000 hours
- Used ratio of thickness to weight change from SEM to determine approximate thickness of oxide after 1 year



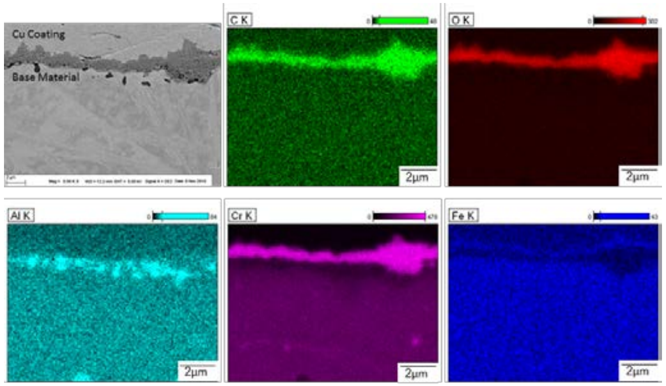
Oxygen levels were recorded in CO_2 gas before entering the testing autoclave (inlet), as well as at the exit of the autoclave for 650ºC and 750ºC tests. (Plotted for 100ppm test above)

H230 Cross Sections after 1000 hours of Exposure



- Sample exposed to RG CO_2 showed no observable chromium depletion zone.
- Chromium depletion zone for oxygen doped exposure in red box on right.
- Chromium carbides found in both samples (indicated by red boxes on left side of both line scans).

H230 Cross Sections after 1000 hours of Exposure in O_2 Doped CO_2



- Increase in chromium along grain boundary suggests presence of chromium carbide.
- Void formation and chromium depletion zone observed in EDS scan.
- Formation of Iron oxide and increase Al concentration observed in EDS mapping.
- No detected large carburization region in high Ni/Cr alloys

Summary

- Qualified team assembled to investigate the sCO_2 cycle
  - Development of cost and performance models
  - Evaluation of regenerative heat exchangers to reduce cost and increase operating temperature
- Detailed assessment of valves for the sCO_2 regenerative cycle
- Detailed assessment of material issues and welds for sCO_2 cycle development
- Evaluation of scaled components at two different scales to add confidence in models.