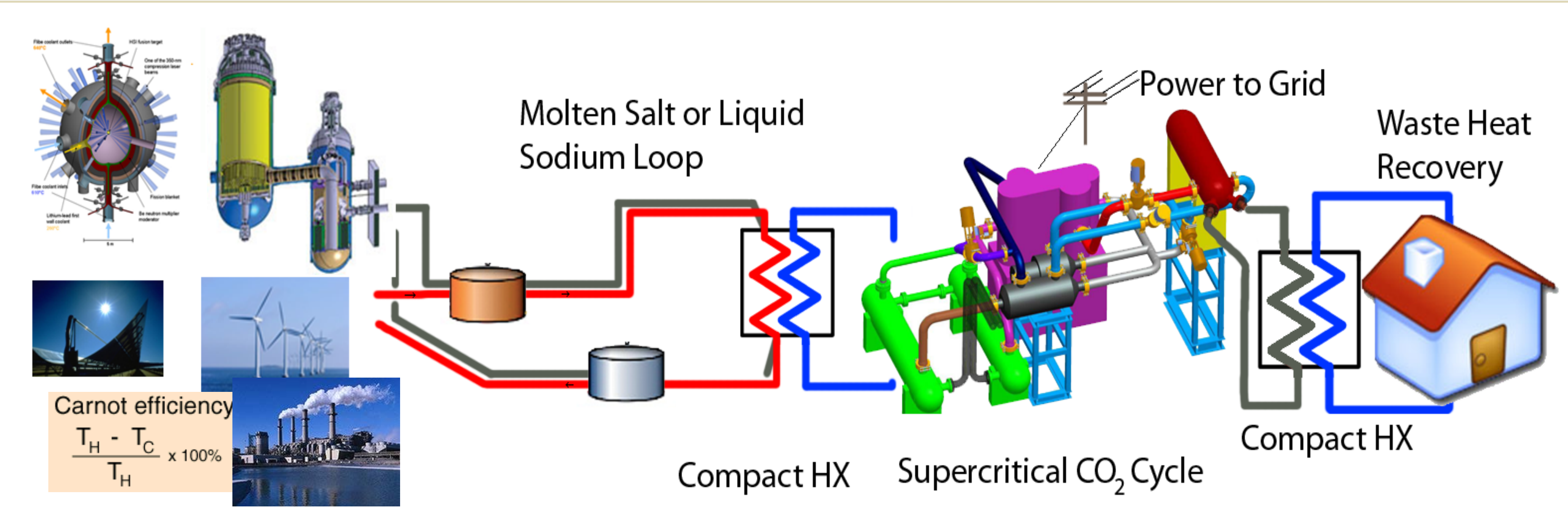
UW-Madison sCO2 Advanced Power Cycle Development

High Temperature Energy Generation and Waste Heat Recovery



Study advance energy sources to increase efficiency and power output

- Fission-VHTR,FHR,SFR
- Fusion
- Concentrated solar
- Biomass
- Clean coal

Use or store energy to make use in different applications

- Electrical power generation
- Chemical processes
- Advanced oil recovery
- Grid power stabilization and utilization

Develop and integrate with new power conversion cycles

- Improved efficiency
- Lower cost
- Smaller components
- Higher temperatures
- Lower water usage

Reduce waste heat and promote Energy Utilization

- Use low quality waste heat
- Recycle heat from chemical process
- Backup power conversion

Power Systems Research at UW

WISCO2

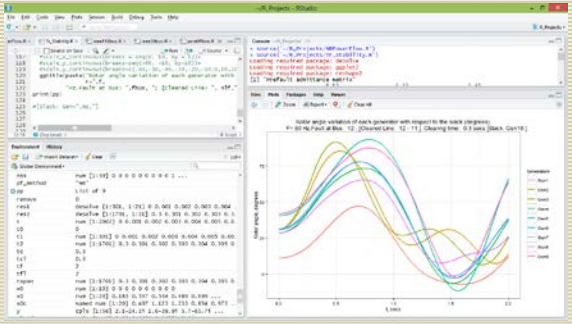
PSERC

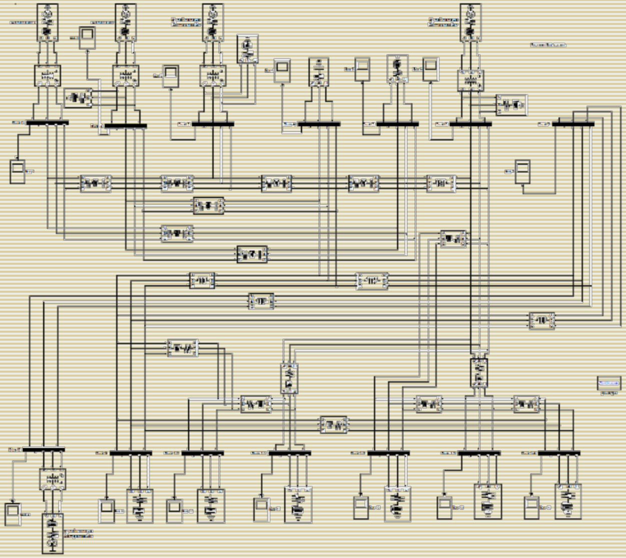
Power Systems Engineering Research Center

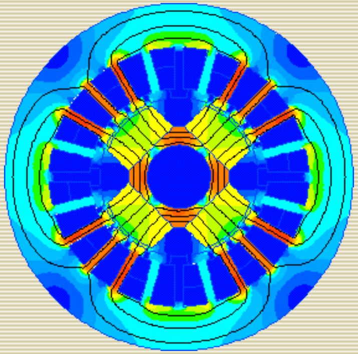
- Eight Internationally Recognized Faculty
- 65 Current Graduate Students
- 450 MS & PhD s
- 90 Corporate Sponsors

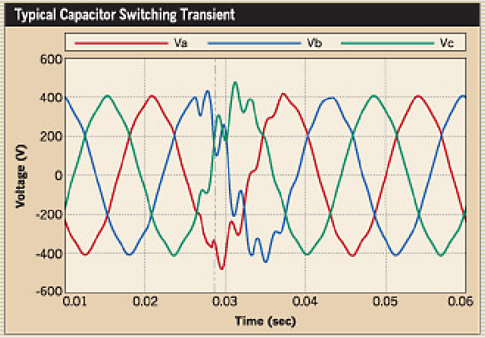
WEMPEC

Wisconsin Electric Machines and Power Electronic Consortium

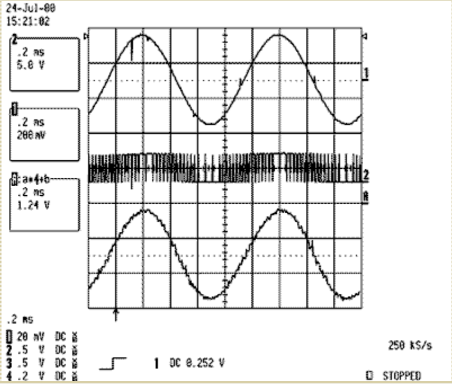




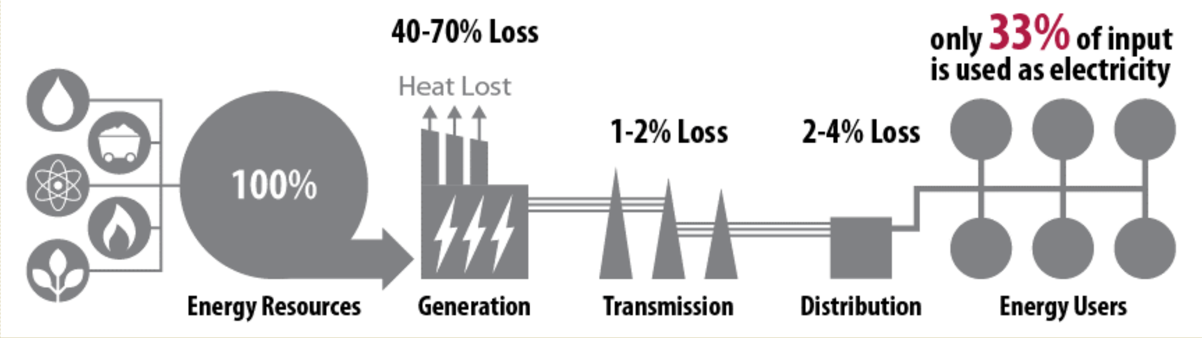


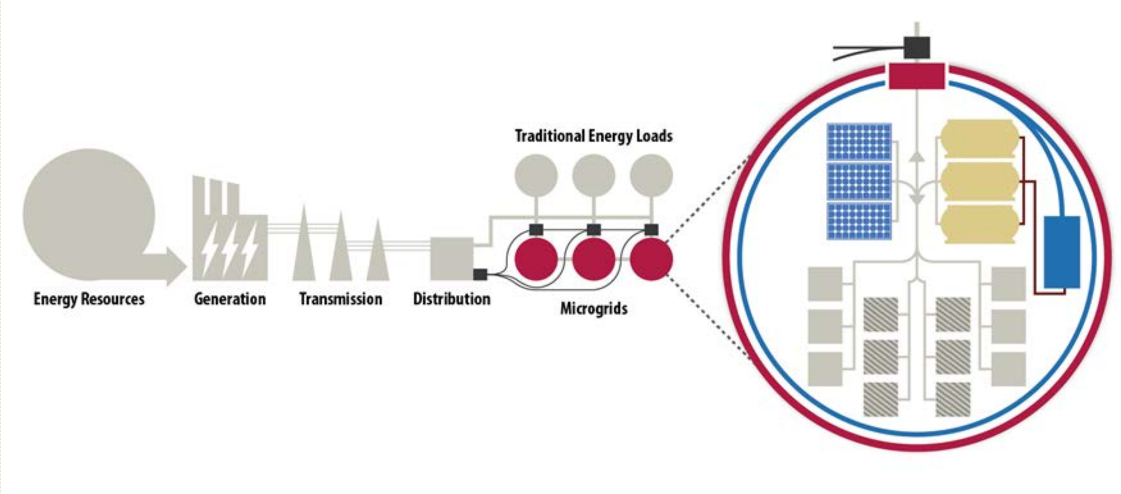


- 130 Sponsored Projects
- 4 Labs
- Power Systems Dynamics
- Electric Machines
- Power Electronics



Microgrids, Advanced Distribution Networks and Energy Storage Solutions





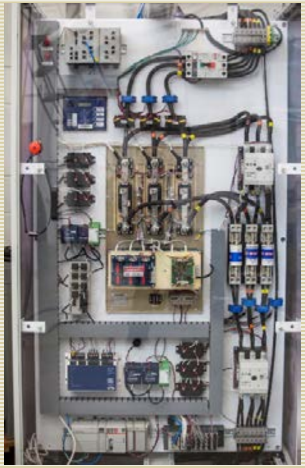
- Enables greater efficiency and resiliency.
- Helps address $100B in business losses due to power disruptions.
- Deployed at hospitals, military bases, factories, more
- Offers new products and supply chains for Wisconsin's electrical equipment manufacturers.

Working with several industrial partners including Johnson Controls

UW Power Systems Lab at the Wisconsin Energy Institute

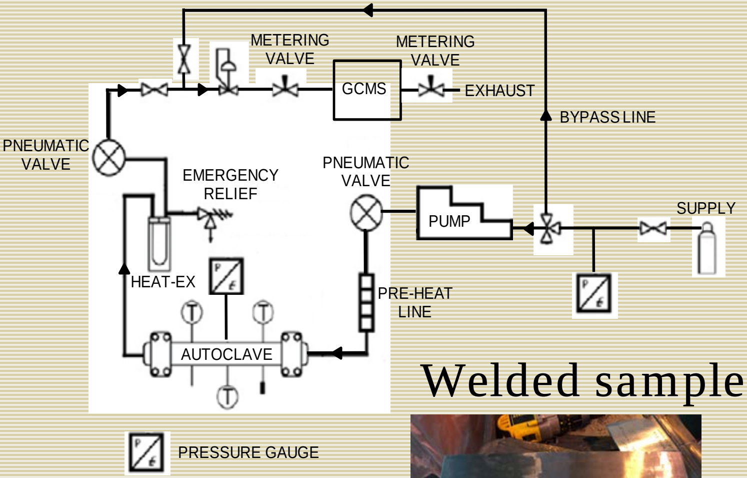
Small Scale Models of a Larger Grid

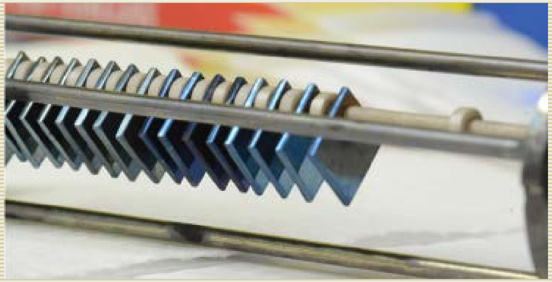
Johnson Controls Energy Storage System Test Lab

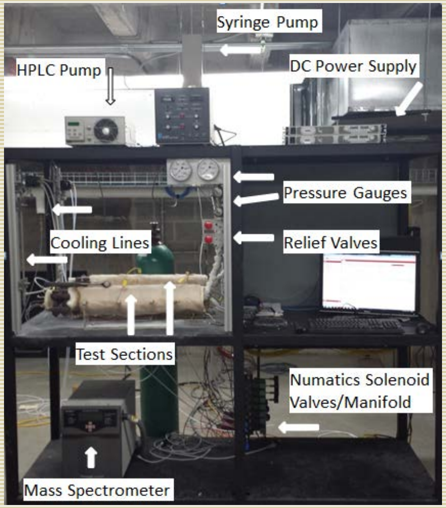


Materials Testing in sCO2

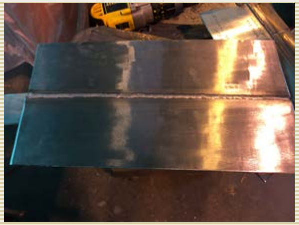
S-CO_2 Static autoclave testing





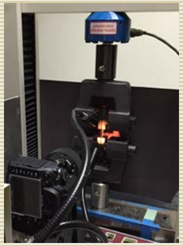


Welded samples



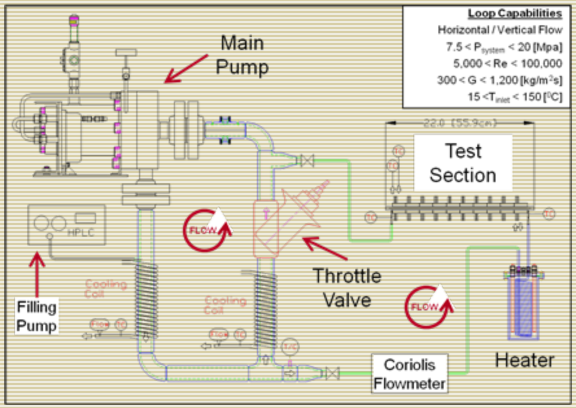
Flow

Tensile testing



Component testing

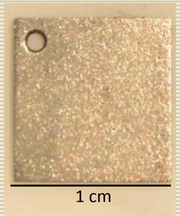
S-CO_2 Flow testing (corrosion/erosion)



Dissimilar metal welds

Advanced materials:

SiC, ZrC-W



ZrC/W Sample

Effects of Impurities

CO, O2, H2O, etc

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

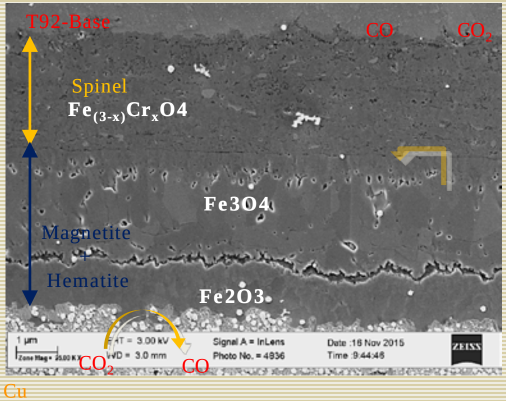
Wide Range of Materials Tested

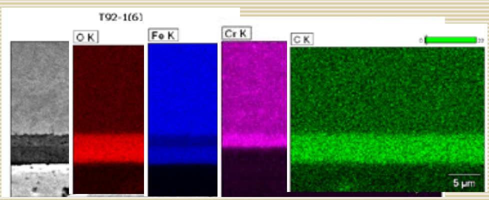
WISCO2

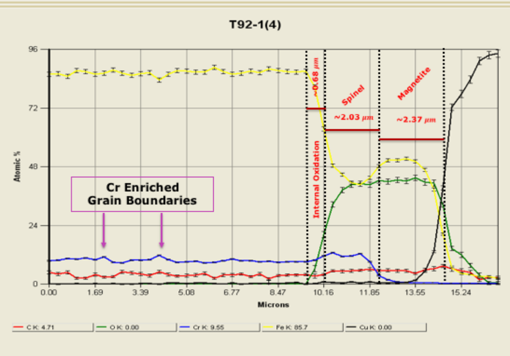
Alloys	Oxide	Number Density	overall corrosion rate	Comments
IN740	Elongated Nb-Ti rich oxide cluster (50um)	Low	~1um-2um/year	Excellent corrosion resistnace/ good strength at temp
	Cr rich oxide (<1um)	High		
Haynes 282*	No Current SEM data		Not enough data to make a reasonable guess	Excellent corrosion resistance up to 550C. More testing needed for higher temperatures
Haynes 625*	Cr rich oxide present Similar oxide layer to Hanes 230 alloy, more testing needed		450C - <1um/year 550C - <1um/year 650C –1-4um/year	Good corrosion resistance. Needs to be looked at for higher temps.
Haynes230	Elongated W rich oxide cluster (30um)	Medium	450C - <1um/year 550C - <1um/year 650C - 2-5um/year	Good corrosion resistance. Needs to be looked at for higher temps.
	Cr rich oxide (<1um)	High		
IN 617*	No Current SEM data		Initial weight gain data indicates similar corrosion rate to Haynes 625	Good corrosion resistance up to 550C. More testing needed for higher temperatures
IN 718*	No Current SEM data		Initial weight gain data indicates similar corrosion rate to IN800H	Good corrosion resistance up to 550C. More testing needed for higher temperatures
IN800H	Ti oxide cluster (20um)	Low	450C - 1-2um/year	Performed similar to 347 but cost is considerable higher
	Cr-Mn rich oxide (<1um)	High	550C- 5 um/year	
	Octahedral Fe oxide cluster (30um)	Medium	650C - 30 um/year	
347SS	Nb oxide (<1um)	Medium	450C - 5um/year 550C- 5um/year 650C - 35um/year	Alloy performed pretty well at most temps - started to fall off at 650 not suitable for higher temps
	Needle Cr-Mn rich oxide scale	Some spallation		
	Octahedral Fe oxide cluster (20um)	High		
316L	Octahedral Fe oxide scale	70% of surface	450 C - 10um/year 550 C - 30-50um/year 650 C- 100um/year	Ok for lower temperatures 347 performed
	Octahedral Cr-Mn rich oxide scale	30% of surface		
AFA-OC6	Nb oxide (<10um)	High	450C - 1-2um/year 550C- 5-10um/year 650C - 200um/year	Ok for low temperatures/ alloy somewhat unstable
	Cr-Mn rich oxide (<1um)	Very high		
	Fe oxide (<10um)	Low		
P91/T122	Magnetite and spinel layers	100% coverage high corrosion	>1000mu/year	not suitable for 450C+

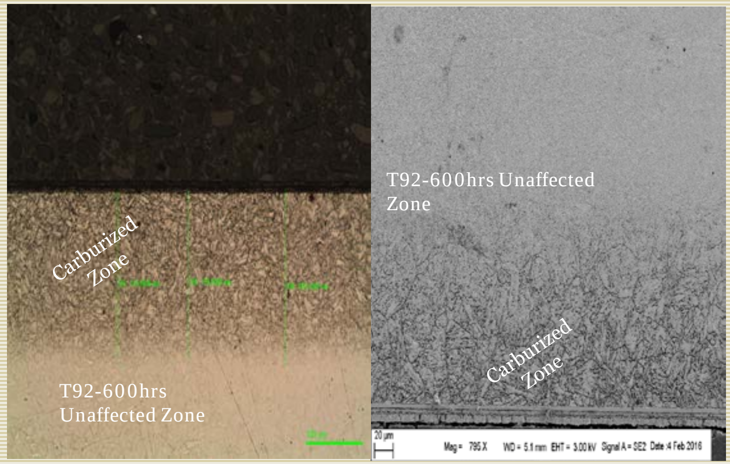
*Currently being tested at UW-Madison. Assumptions based on data from ongoing testing

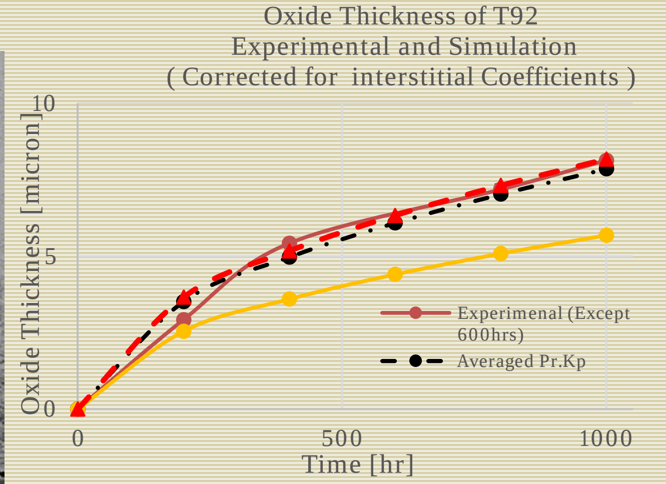
Low Temperature Alloys < 450° C
Carburization and Oxidation of T92 in sCO_2

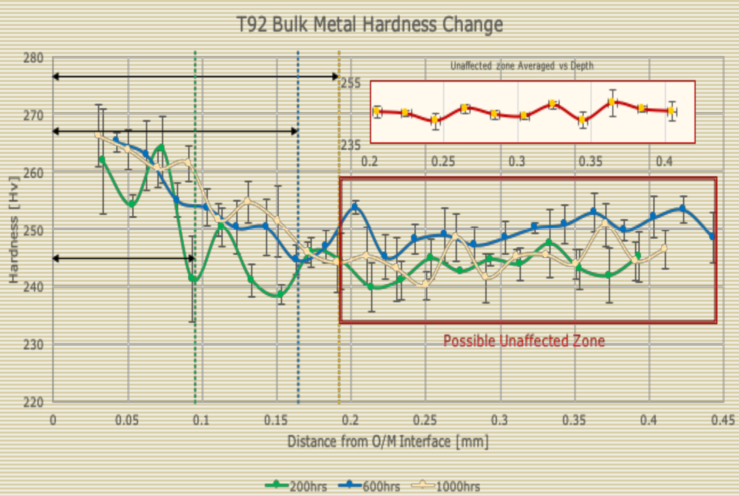


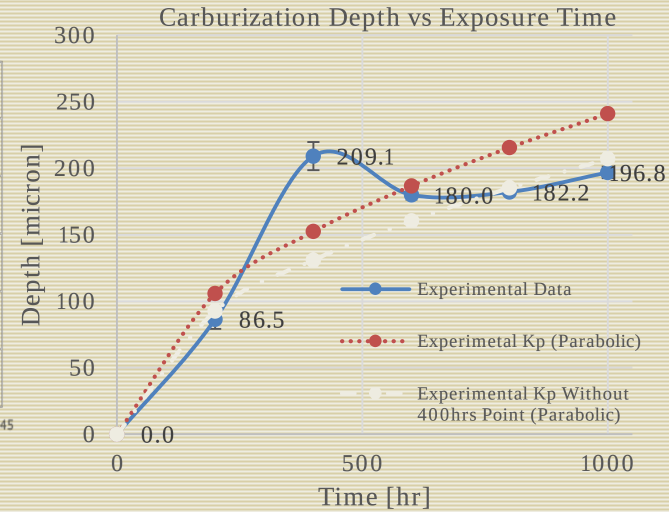




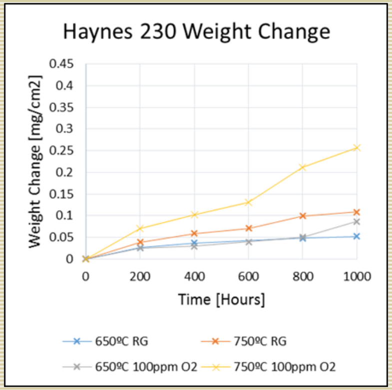


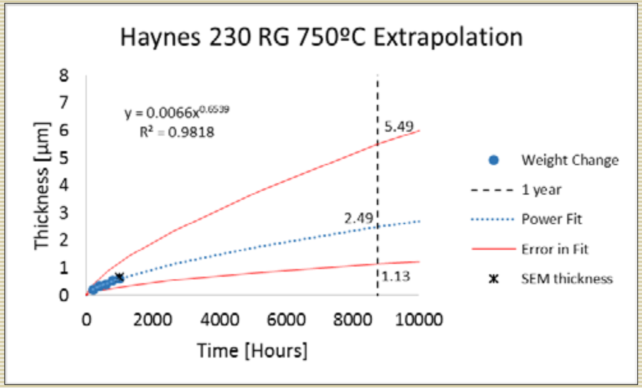


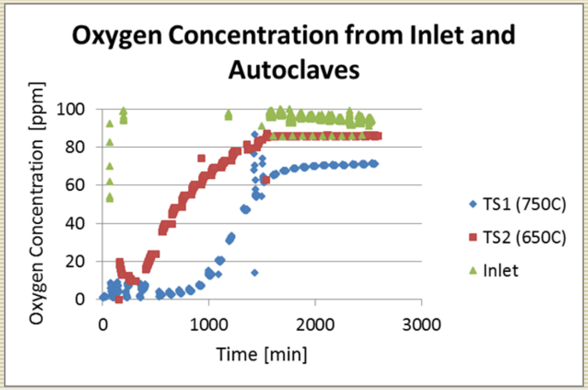




High Temperature Alloy Corrosion







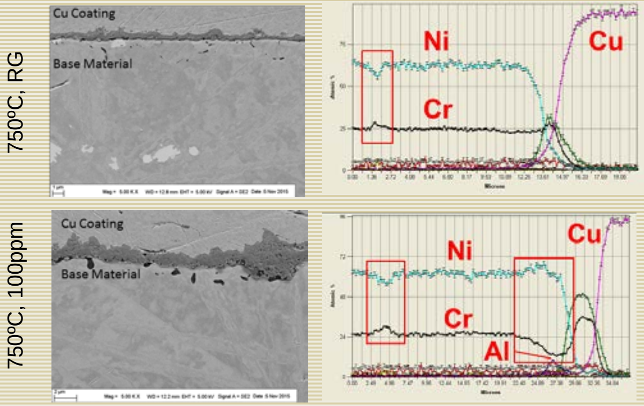
- Based on power fit equation:

$$W = \alpha t^b$$

- Used time dependent data out to 1000 hours
- Used ratio of thickness to weight change from SEM to determine approximate thickness of oxide after 1 year

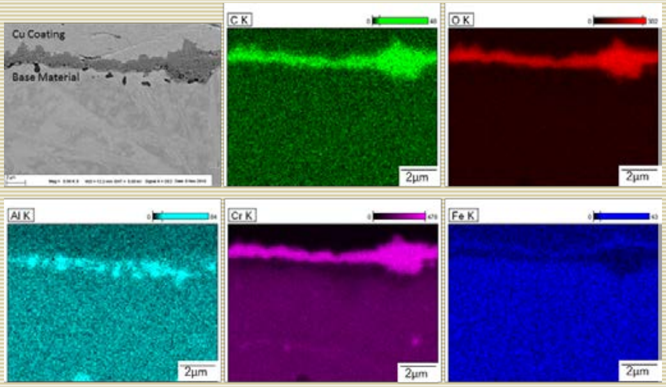
Oxygen levels were recorded in CO_2 gas before entering the testing autoclave (inlet), as well as at the exit of the autoclave for 650 and 750ºC tests. (Plotted for 100ppm test above)

H230 Cross Sections after 1000hours 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 1000hours 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

Round Robin Materials Testing
Collaboration with Different Institutions on a Global Scale

Working together to understand the materials issues

- Oregon State University: Julie Tucker
- University of Wisconsin-Madison: Mark Anderson
- Oak Ridge National Laboratory: Bruce Pint
- National Energy Technology Laboratory: Omer Dogan
- Carleton University: Henry Saari
- Korea Advanced Institute of Science and Technology: Changheui Jang
- CSIRO Energy Center: Rene Olivares

- **Corrosion Coupon Support**
- Electric Power Research Institute: Steven Kung & John Shingledecker

Testing 5 alloys at two different temperatures at each institution.

740H (700°C only)
625
316L
HR120
Grade 91 (550°C only)

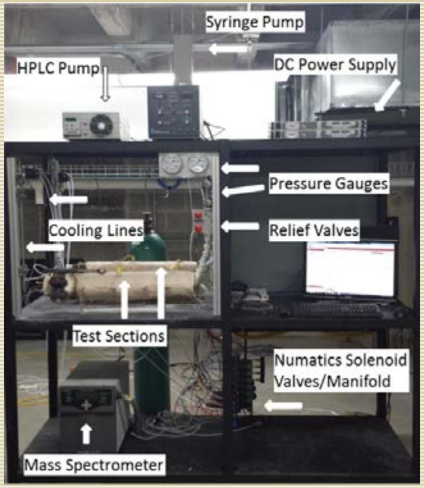
Separate effects tests and CFD analysis

Heat exchangers, valves, seals, pumping, components, properties

Valve, seal, high speed flow test facility

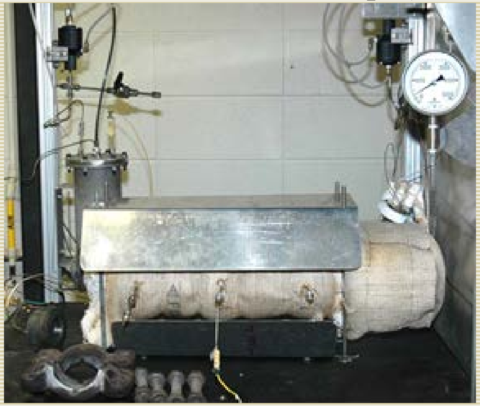
600 ºC / 1112 ºF– 3600PSI In625 sCO2 Loop - 160GPM

Heat Transfer test facility



Current setup of test facility

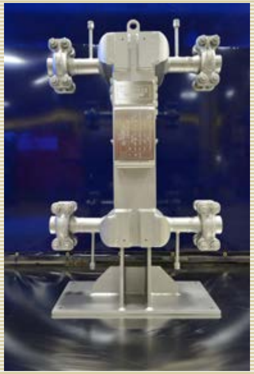
5 separate
sCO2 materials corrosion autoclaves
(800 ºC /1472 ºF, 4000psi)



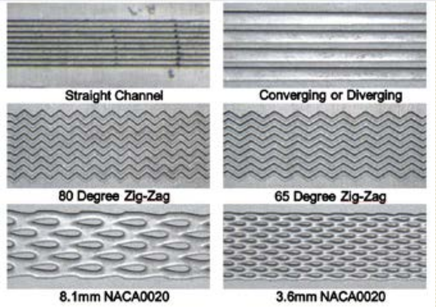
Separate Effects Tests and CFD Analysis

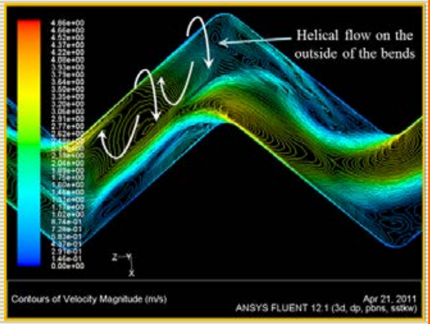
sCO_2 Heat exchanger testing

WISCO2

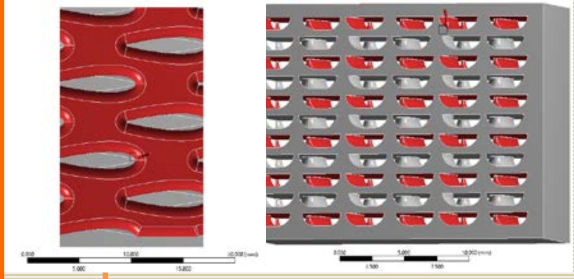


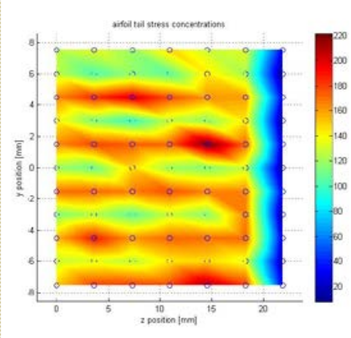
COMPREX
CompRex™ Compact Heat Exchange Reactor



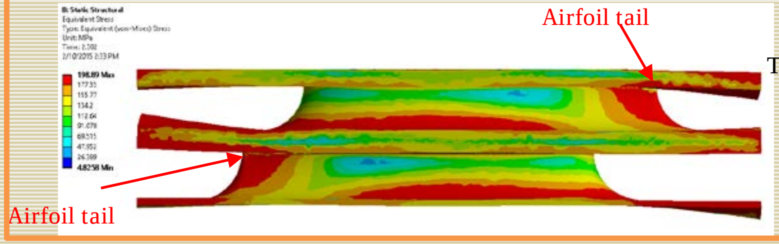


Tail stress distribution at 1 MPa pressurization.

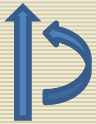


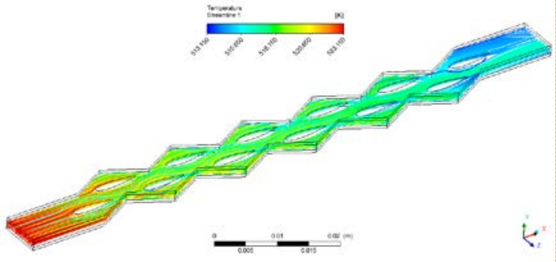


Local Tail Stress from Pressure across channels



Tensile & bending





Advanced Supercritical Carbon Dioxide Cycles

M. Anderson/UW, M. Carlson/Sandia, R. Braun/CSM
T. Neises/NREL, Z. Jia/Comprex, R. Gradle/FlowServe

WISCO2 SunShot U.S. Department of Energy

CSP: APOLLO

Technology Addressed

Advanced Power Cycles for CSP

Innovative Aspect

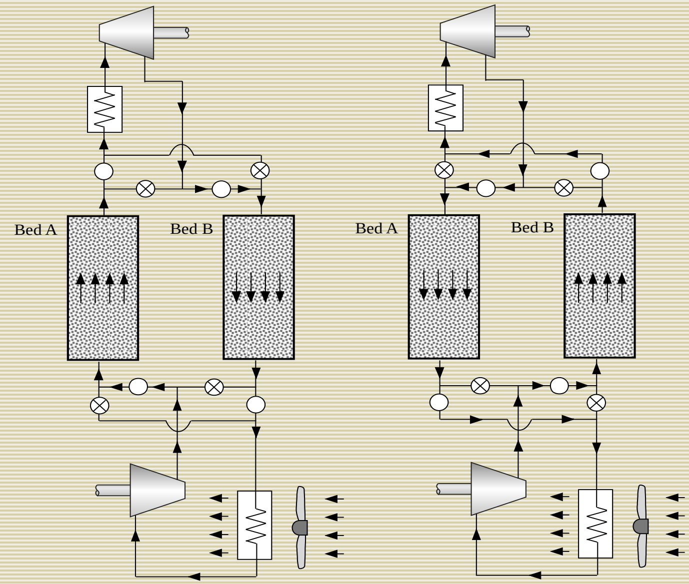
Incorporate switched-bed regenerators in place or in addition of recuperative heat exchangers, into SCO_2 cycles. Decrease cost increase temperature options

Impact

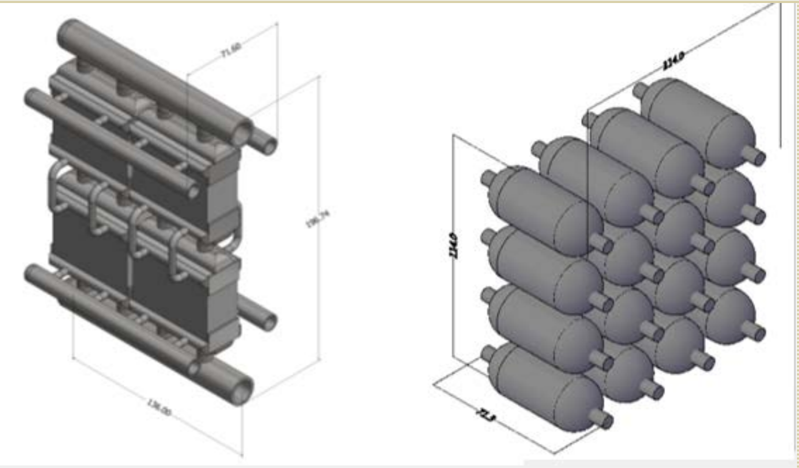
- Reduce cost of component required for regenerative heat transfer
- Increase temperature with insulated pressure boundry
- Develop cost and performance models

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

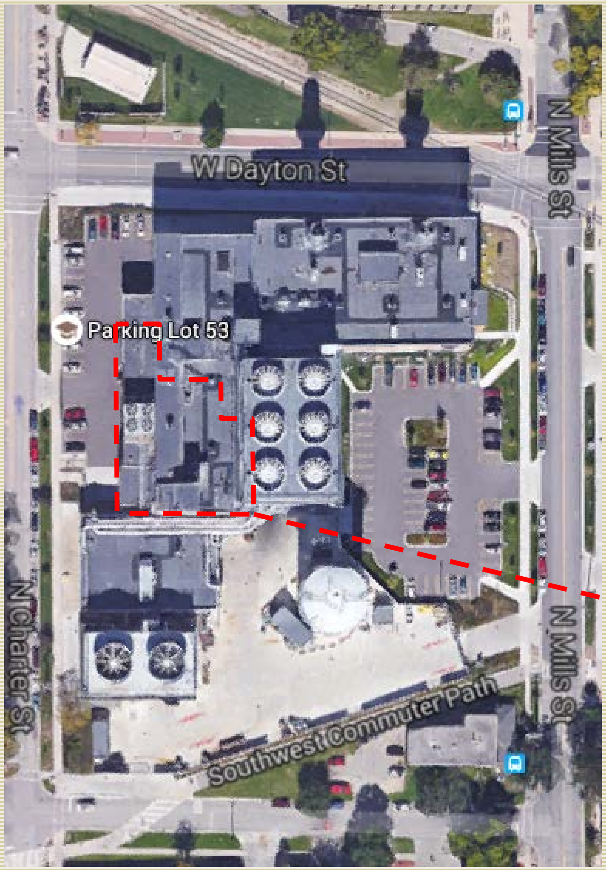
High Temperature Regenerator

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

Larger Scale Testing and Outreach to Utilities, Industry and Public with regard to the benefits of sCO2 cycle.

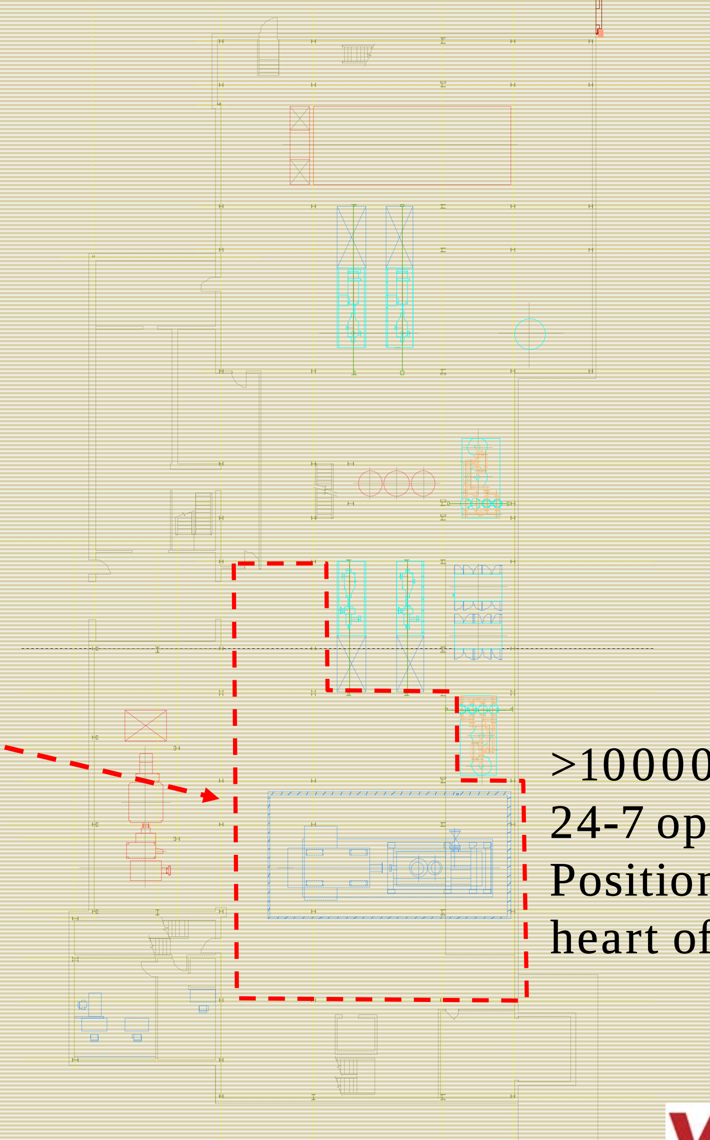
https://energy.wisc.edu/wisco2/

Charter Street Plant



Size, location, and Infrastructure for 10-20MWe sCO2 system tied to the local grid.

Facility Area of Interest



>10000 sq.ft.
24-7 operation
Positioned in the heart of Wisconsin

WISCO2