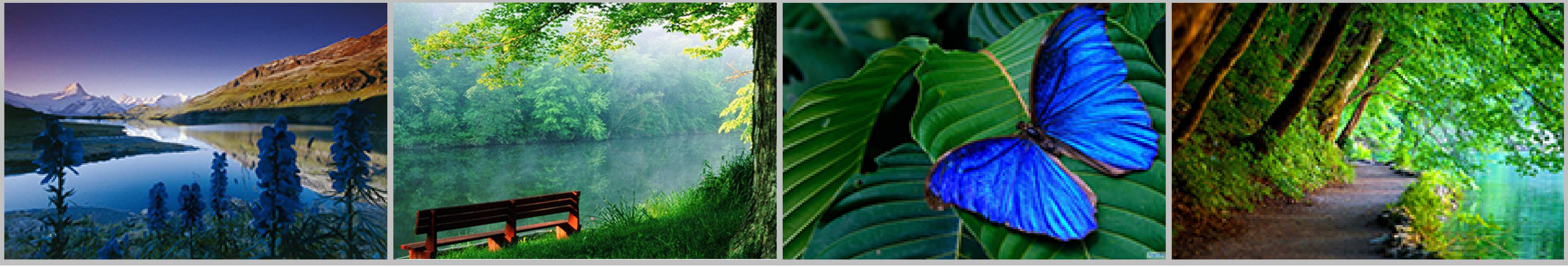


DOE Initiative on SCO2 Power Cycles (STEP)

- Heat Exchangers: A Performance and Cost Challenge -

EPRI-NETL Workshop on Heat Exchangers for SCO2 Power Cycles

San Diego, CA; October 15, 2015

Rich Dennis,
Technology Manager

Presentation Outline

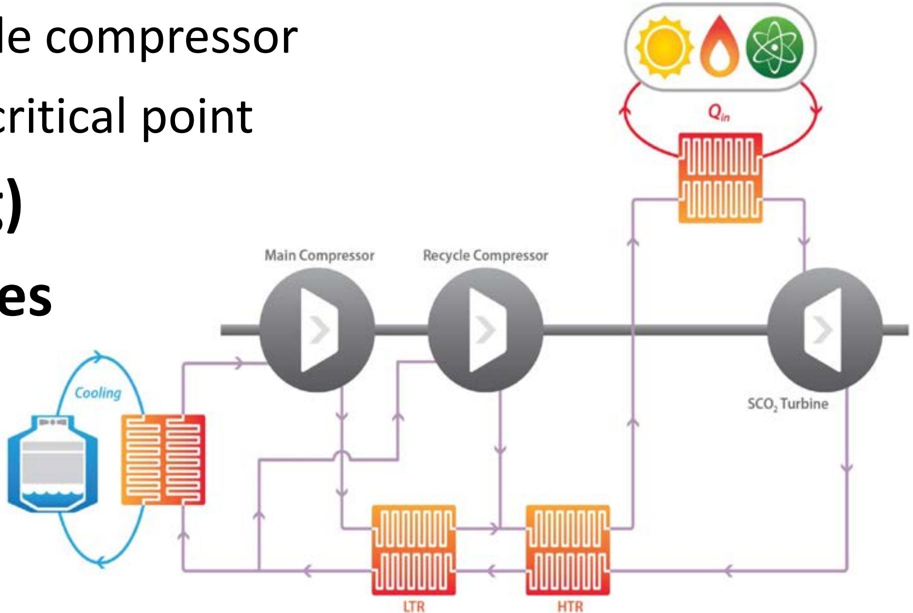
DOE Initiative on SCO2 Power Cycles (STEP)

- Heat Exchangers: A Performance and Cost Challenge -

- **Why SCO2 Power Cycles**
- **FE Applications of SCO2 Power Cycles**
- **Recuperators for SCO2 Power Cycles**
- **Overview of the DOE SCO2 Crosscut Initiative**
- **Summary**

Why Use Supercritical CO_2 (SCO2) for Power Cycles?

- **Applicable to multiple heat sources for indirect heating**
- **Potential for higher efficiency relative to traditional power cycles**
  - Double recuperated with recycle compressor
  - Beneficial properties near the critical point
- **Closed cycle (noncondensing)**
- **Reduced turbomachinery sizes**
- **CO_2 is generally stable, abundant, inexpensive, non-flammable, and less corrosive than H_2O**



Source: NETL

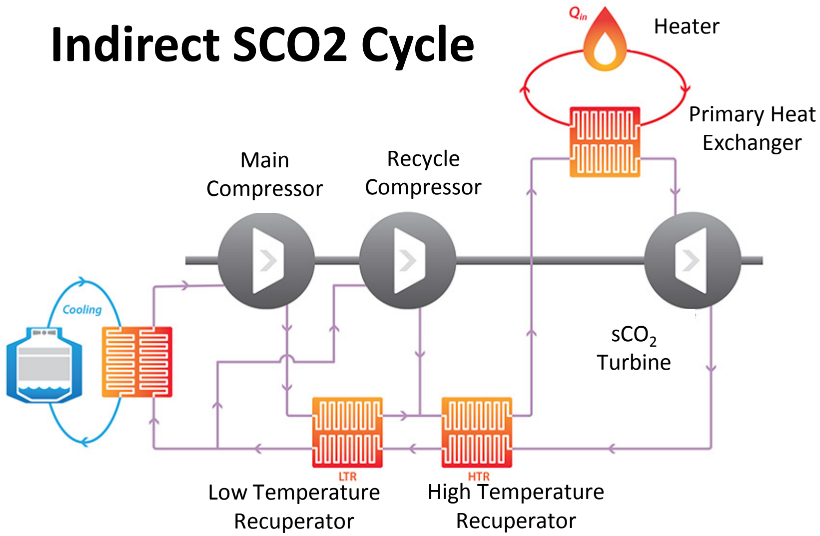
Common FE, NE, EERE Application Space

Application	Size [MWe]	Temperature [°C]	Pressure [MPa]
Nuclear (NE)	10 – 300	350 – 700	20 – 35
Fossil Fuel (FE) (Indirect heating)	300 – 600	550 – 900	15 – 35
Fossil Fuel (FE) (Direct heating)	300 – 600	1100 – 1500	35
Concentrating Solar Power (EERE)	10 – 100	500 – 1000	35
Shipboard Propulsion	<10 – 10	200 – 300	15 – 25
Waste Heat Recovery (FE)	1 – 10	< 230 – 650	15 – 35
Geothermal (EERE)	1 – 50	100 – 300	15

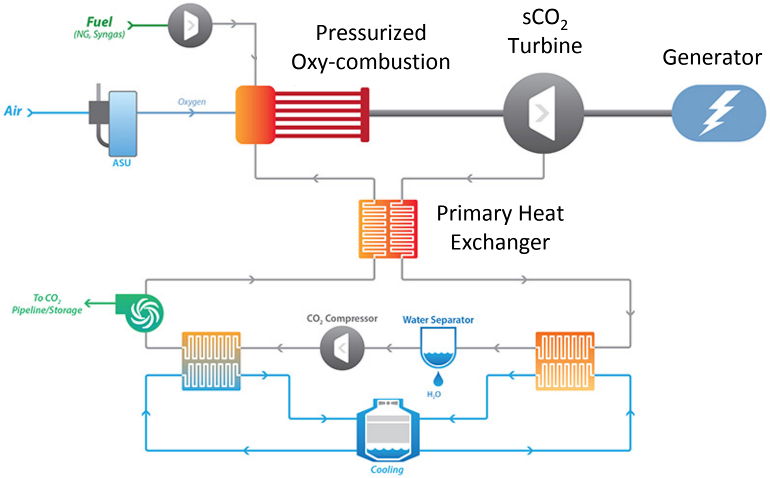
(Ref. sCO$_2$ Power Cycle Technology Roadmapping Workshop, February 2013, SwRI San Antonio, TX)

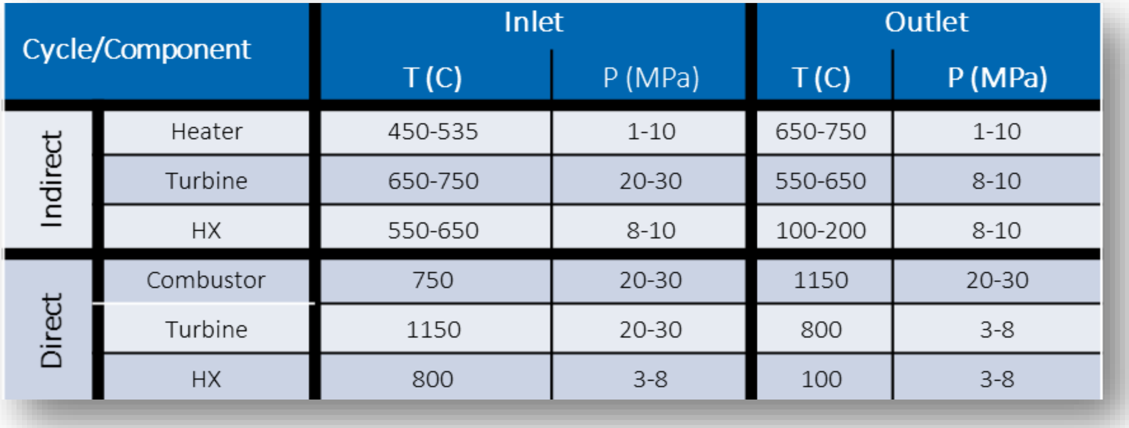
FE Applications of the Indirect and Direct Supercritical CO_2 Power Cycle

Indirect SCO2 Cycle



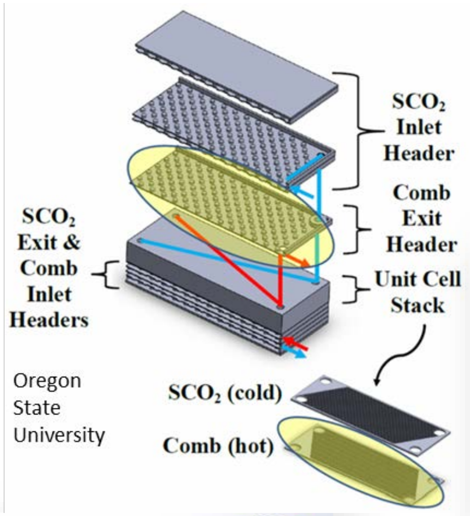
Direct SCO2 Cycle



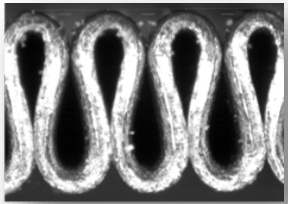


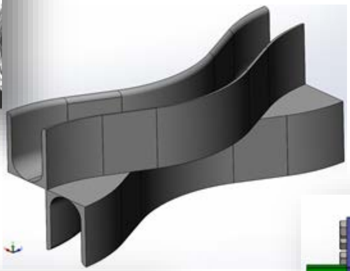
Cycle/Component		Inlet		Outlet	
		T (C)	P (MPa)	T (C)	P (MPa)
Indirect	Heater	450-535	1-10	650-750	1-10
	Turbine	650-750	20-30	550-650	8-10
	HX	550-650	8-10	100-200	8-10
Direct	Combustor	750	20-30	1150	20-30
	Turbine	1150	20-30	800	3-8
	HX	800	3-8	100	3-8

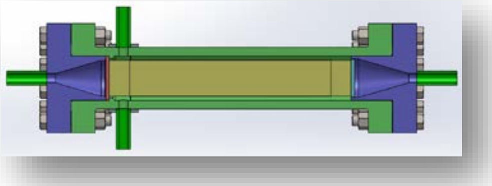
Recuperator Discussion

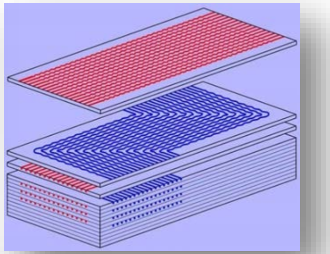


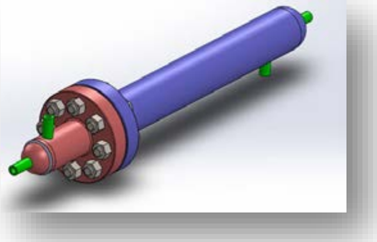
Oregon State University

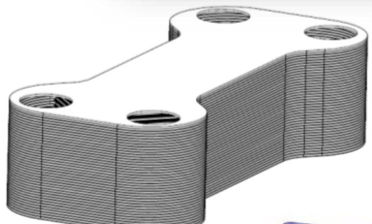


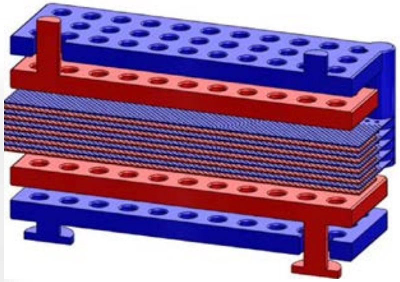


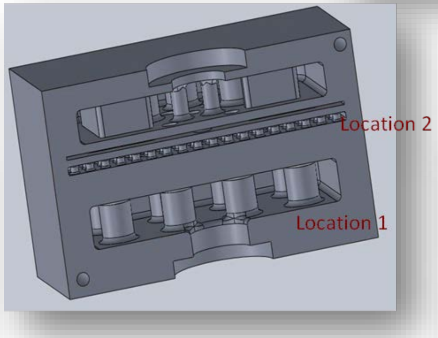


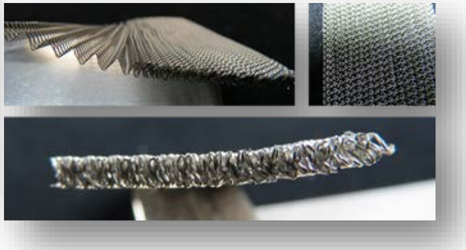


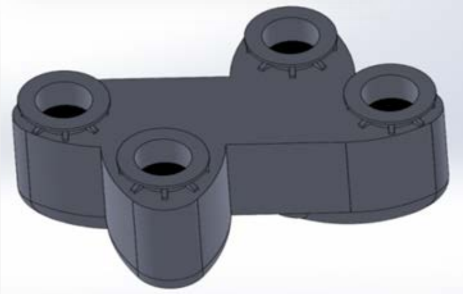






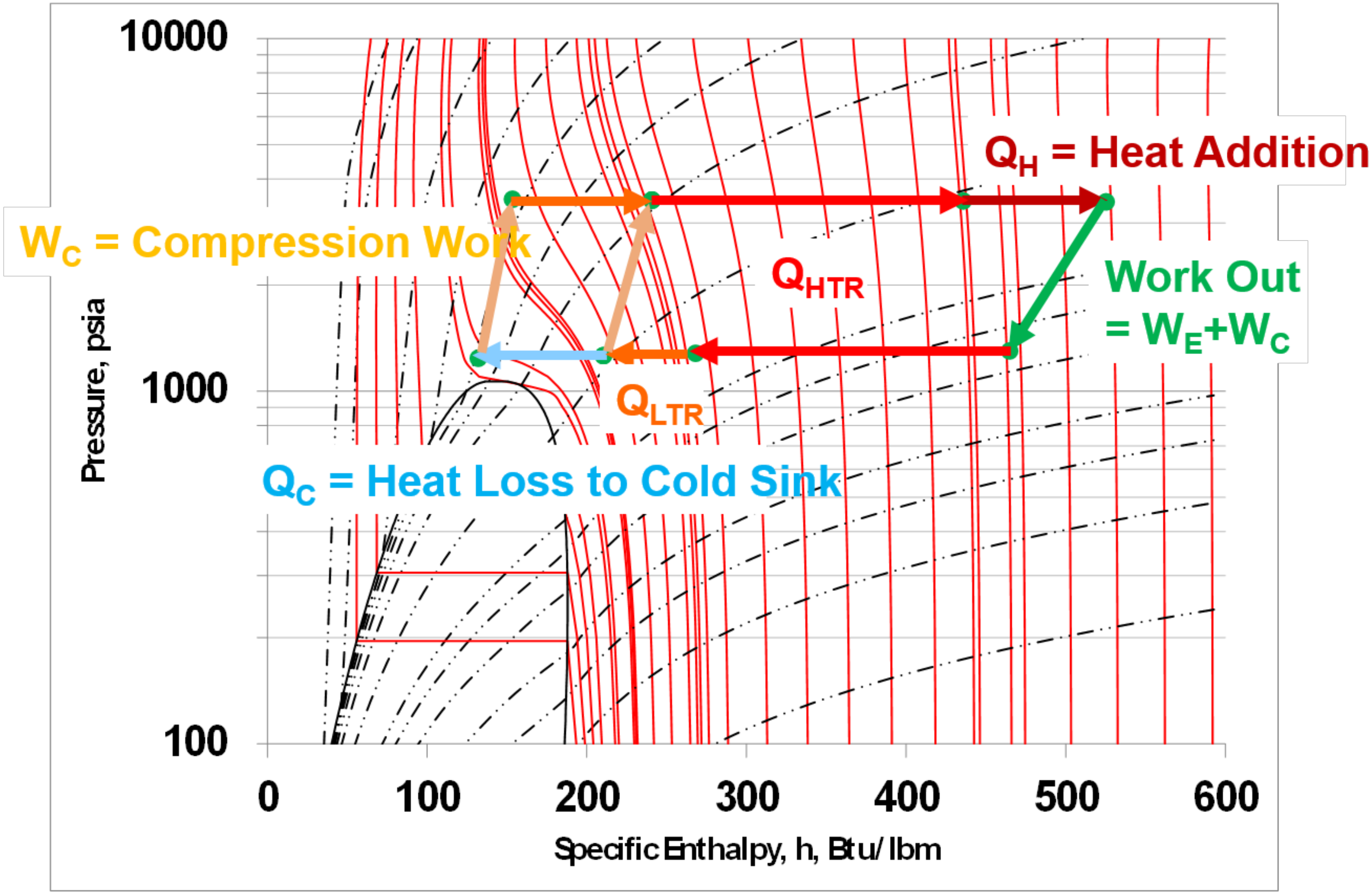






Recompression Closed Brayton Cycle

~ 2/3 of the heat in the cycle is recuperated



Pressure vs. Specific Enthalpy Diagram

Recuperators – Basic Heat Transfer

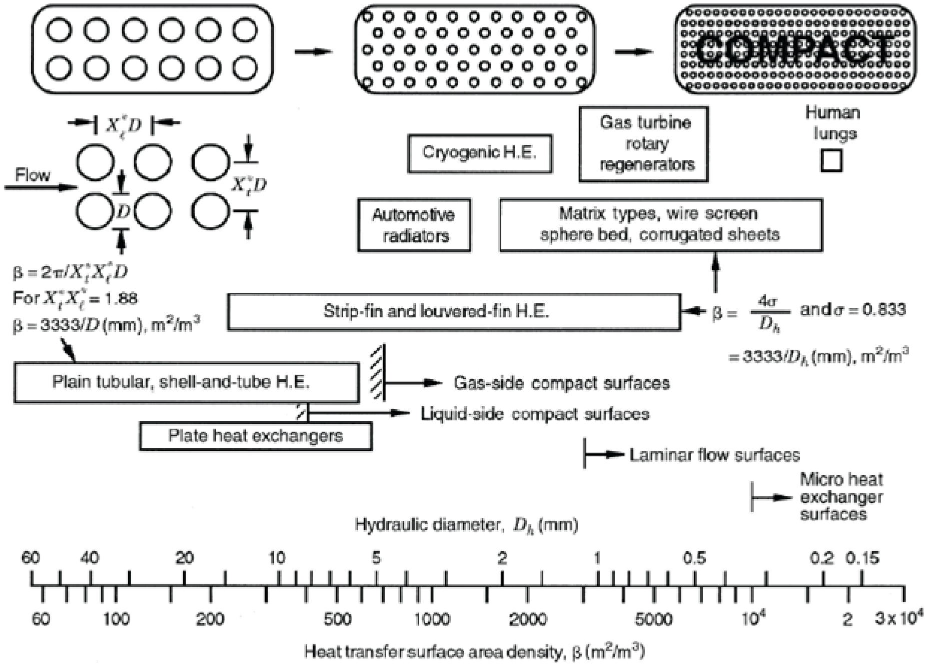
Heat Transfer = Overall HX Coef. * Area * Temperature Difference

$$Q = U*A*\Delta T$$

As ΔT decreases, effectiveness increases, but the area must increase to make up for the decrease in ΔT

- **Increasing the contact area generally results in an increase in volume of material required**
- **Heat exchangers are often characterized by the ratio of contact area to volume:**

$$\beta = A/V$$



(Shah 2003)

Recuperators – Basic Heat Transfer

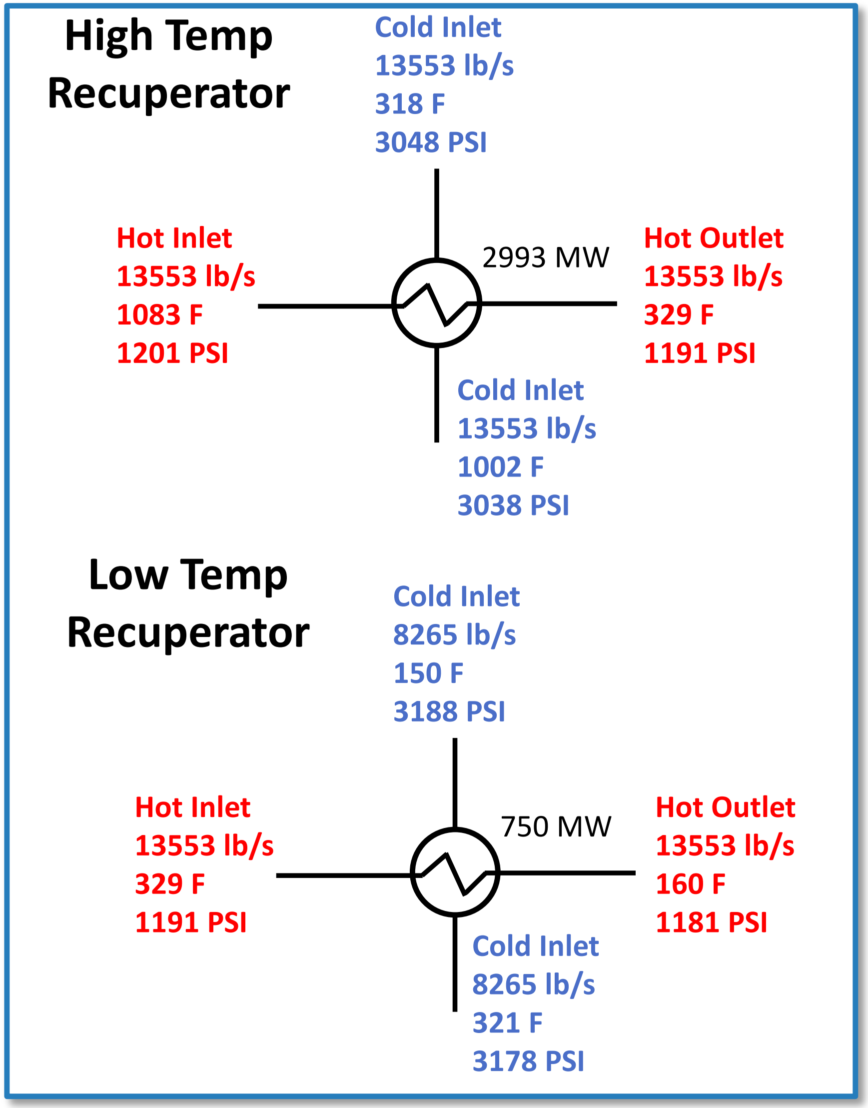
What about pressure drop?

- **Heat transfer coefficient increases with an increase in turbulence, but so does pressure drop**
- **Increasing heat transfer coefficient, U, allows less contact area, A, and a smaller heat exchanger**
  - Q = U*A*ΔT
- **However for a given heat exchanger design, increasing U comes with the penalty of increased pressure drop**

Vendor Inquiries for Recuperators

Recuperators for a 550 MWe power plant

- **OF PFBC w/ SCO2 power cycle**
    - 550 MWe; 1280 MWth,
    - 50.5 cycle efficiency
    - 2993 MWth HTR / 750 MWth LTR
- **Recuperator development plans**
    - Development plan
    - Qualifications
    - +/- 30 % cost estimate
    - Compactness criteria 700 m^2/m^3
- **Vendors requested to provide**
    - conceptual design, development plan, commercial cost estimate
- **Limited vendor response**



High Temp Recuperator

Cold Inlet
13553 lb/s
318 F
3048 PSI

Hot Inlet
13553 lb/s
1083 F
1201 PSI

2993 MW

Hot Outlet
13553 lb/s
329 F
1191 PSI

Cold Inlet
13553 lb/s
1002 F
3038 PSI

Low Temp Recuperator

Cold Inlet
8265 lb/s
150 F
3188 PSI

Hot Inlet
13553 lb/s
329 F
1191 PSI

750 MW

Hot Outlet
13553 lb/s
160 F
1181 PSI

Cold Inlet
8265 lb/s
321 F
3178 PSI

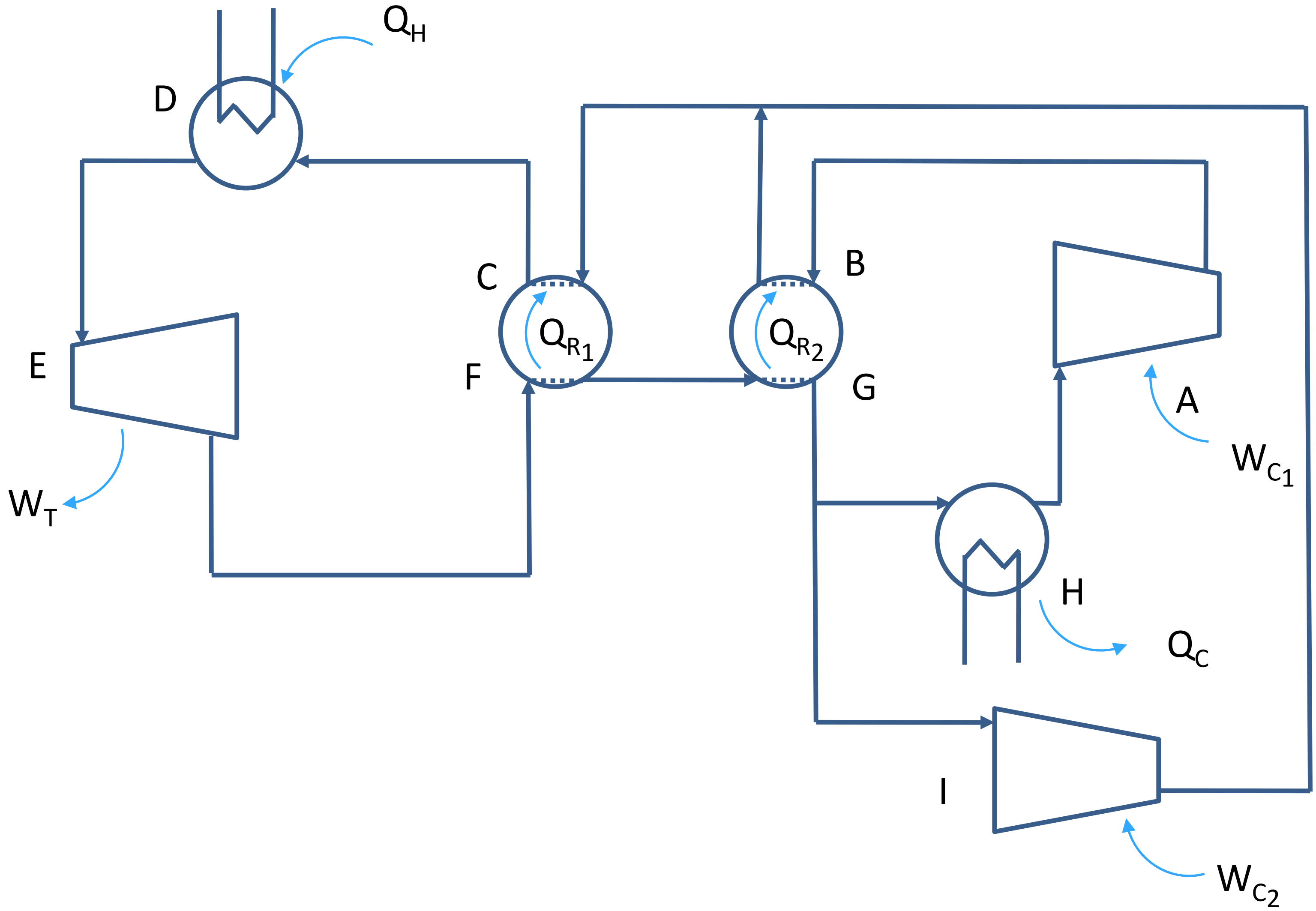
Turbine Technology Program Phase III – Task 1(a) & (b): Supercritical CO2 Turbomachinery (SCOT) System Studies Incorporating Multiple Fossil Fuel Heat Sources and Recuperator Development; DE-FE0004002, 6/1/2013, Aerojet Rocketdyne, Canoga Park, California

Vendor Inquiries for Recuperators

Recuperators for a 550 MWe power plant

- **Suggested materials: Inconel (HTR), 316H (LTR)**
- **Allow delta P to double -> 10 to 20 psi**
  - Allows over all mass to be reduced by 2x
  - Core matrix volume can be reduced by 25 % cuts price in half
- **Cost range for mature commercial product**
  - (~$120M - ~ $280M)
  - Savings ~ $160 M yields 7.2 % reduction in COE (0.88 Cents/kwh)
- **Challenges**
  - Balancing cost, performance and cycle optimization
  - Optimizing design for the application
  - Facilities for the fabrication of commercial systems

Recompression Brayton Cycle



An Assessment of Supercritical CO_2 Power Cycles Integrated with Generic Heat Sources, 9/10/2014 DOE/NETL-4001/09/091014,
Presented at the 4th Symposium on SCO2 Power Cycles

Recompression Brayton Cycle

Baseline Cycle Operating Parameters

Parameter	Value
Working fluid	CO_2
Compressor pressure	Varied
Compressor efficiency	0.85
Turbine inlet temperature	1300 °F
Turbine exit pressure	1320 psia
Turbine efficiency	0.927
Cooler pressure drop	20 psia
Cooler temperature	95 °F
Heater pressure drop	20 psia
Heater duty	100 MMBtu/hr
Minimum temperature approach	10 °F
High temp recuperator cold side pressure drop	20 psia
High temp recuperator hot side pressure drop	20 psia
Low temp recuperator cold side pressure drop	20 psia
Low temp recuperator hot side pressure drop	20 psia
Cooler bypass fraction	0.2853

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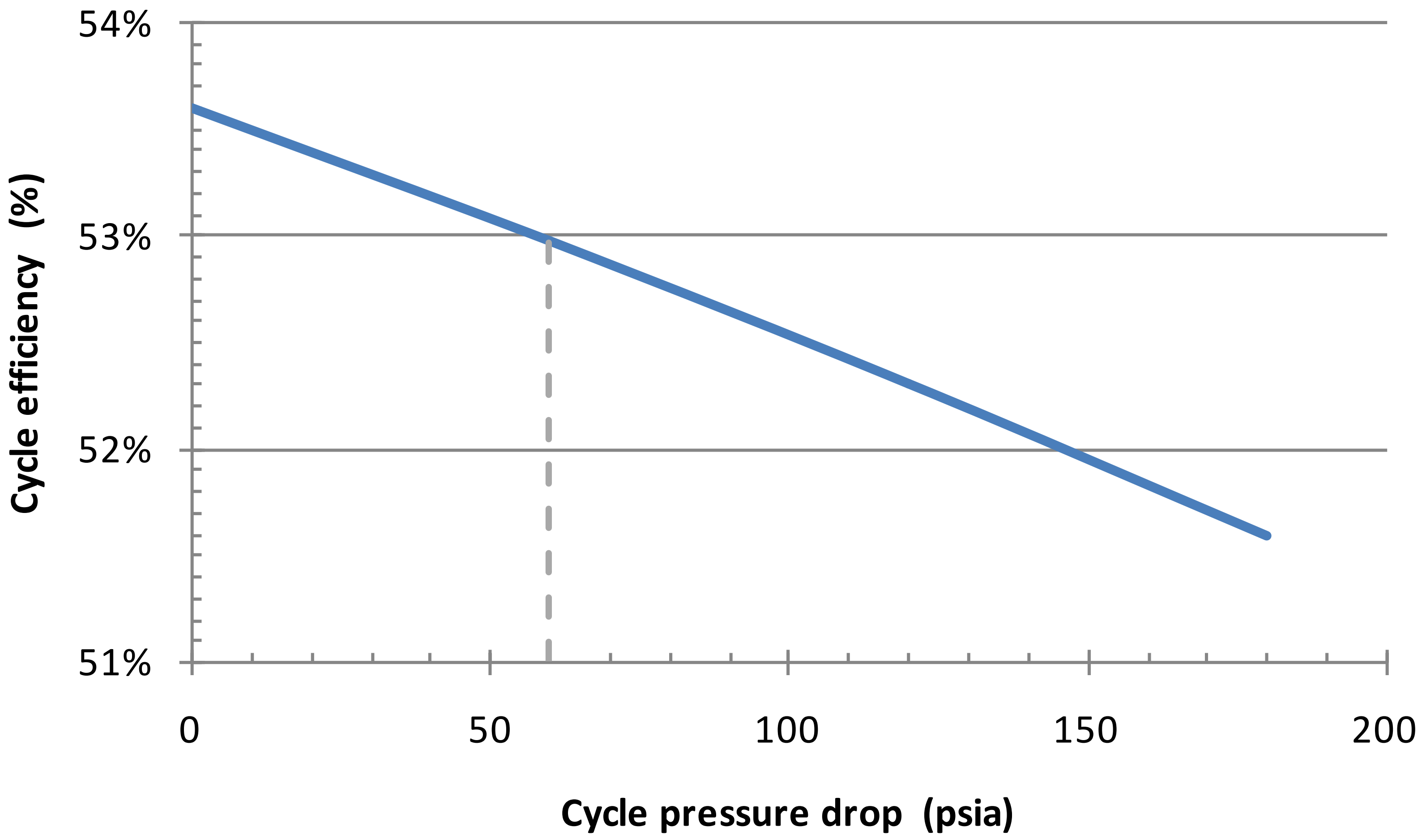
Recompression Brayton Cycle

Sensitivity to Pressure Drop



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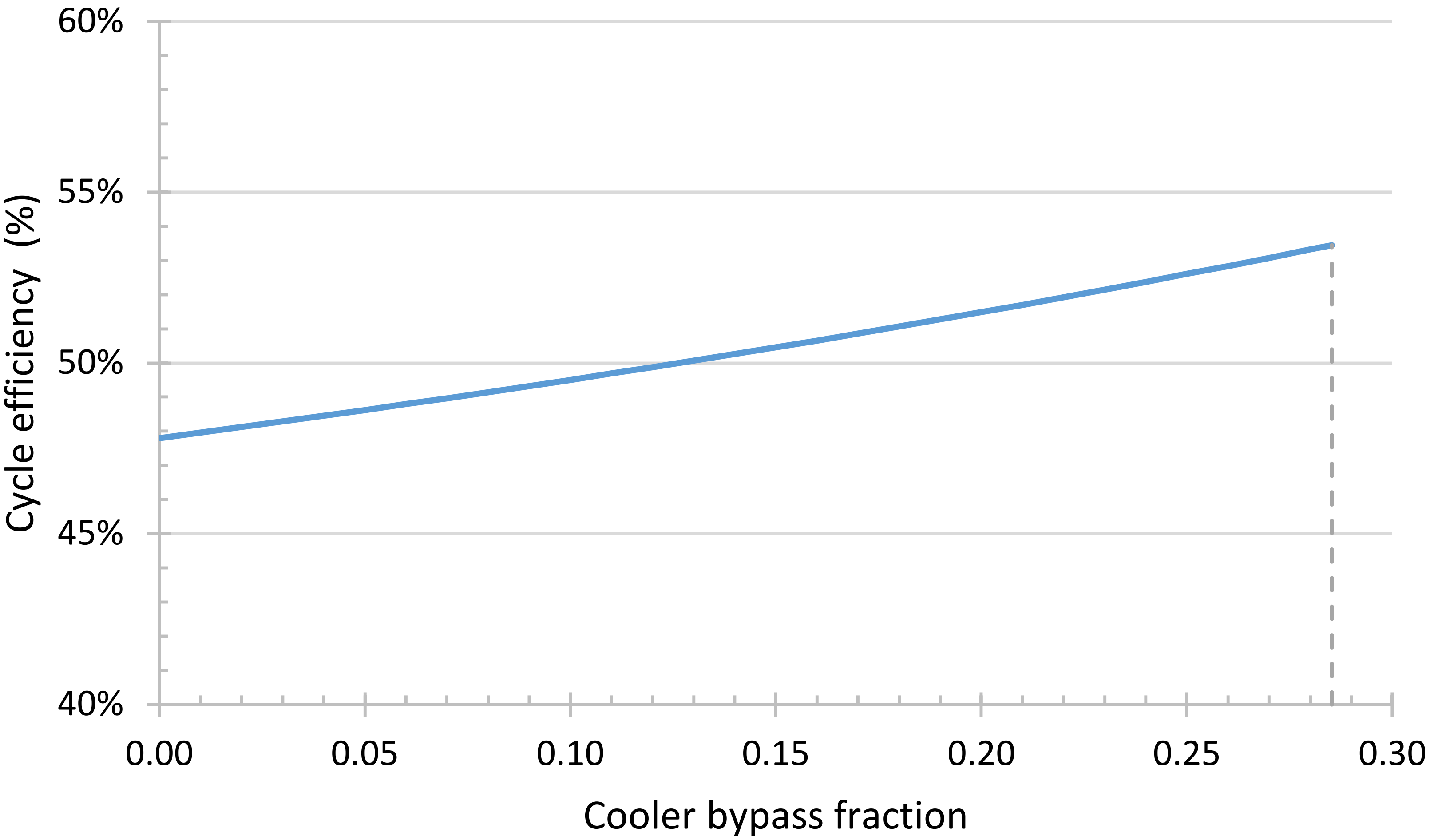
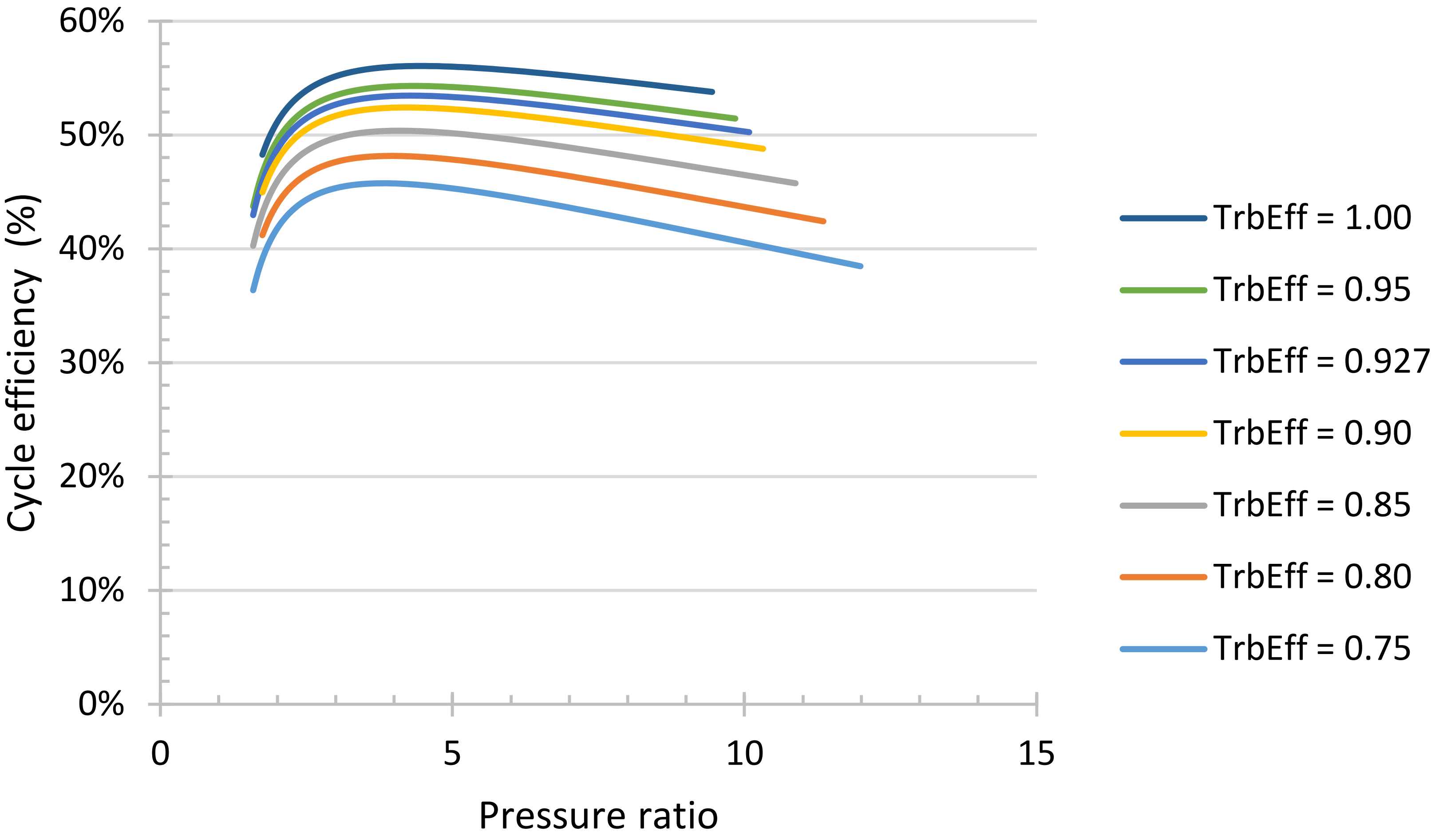
Recompression Brayton Cycle

Sensitivity Analysis to Cooler Bypass Fraction



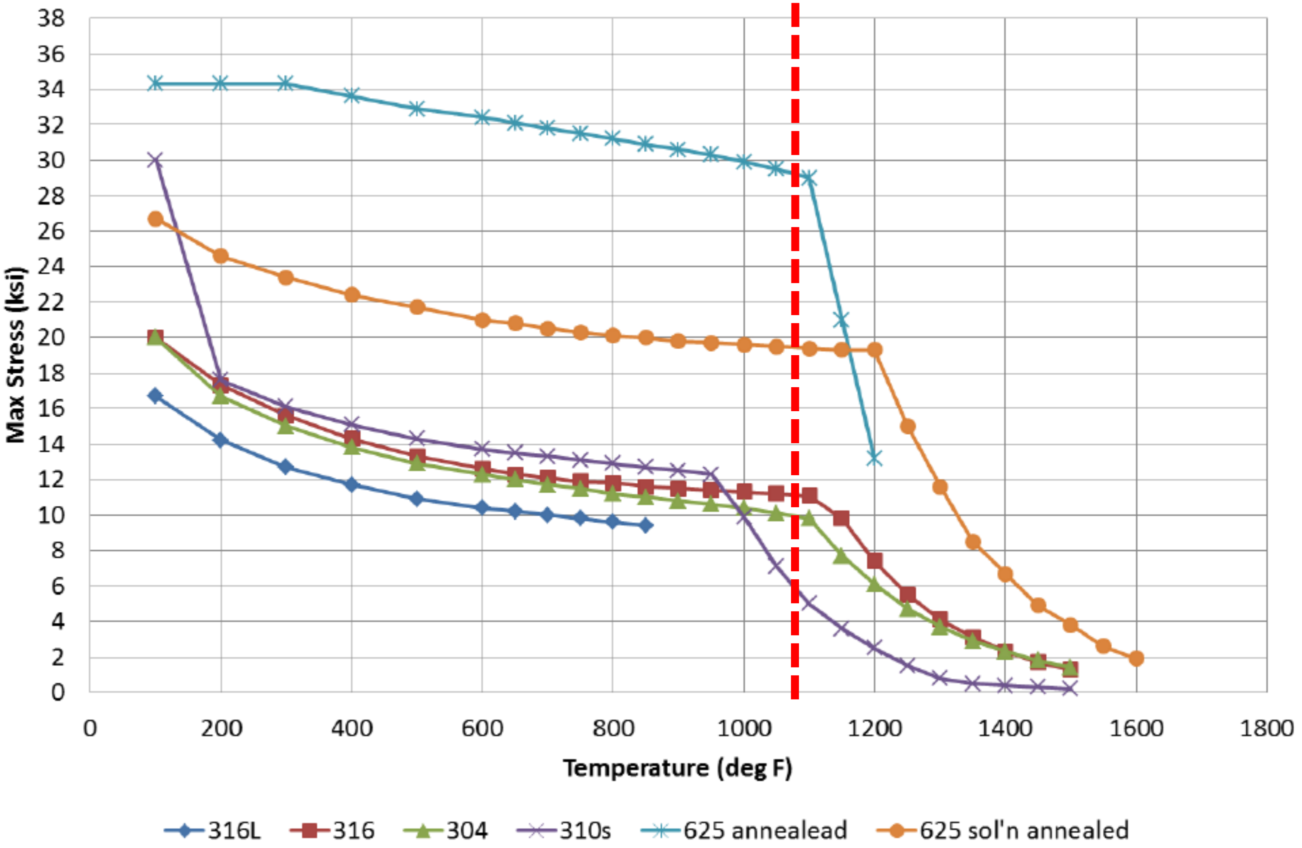
Recompression Brayton Cycle

Sensitivity Analysis to Turbine Efficiency



Materials Considerations for Recuperators

Maximum Allowable Stress per ASME Section II, Part D
Max value shown is max allowable for a Section VIII Pressure Vessel



- **TIT = 700C -> recuperator inlet temp. would be ~ 580C (1080F) – red line**
- **Stress levels < ~10 ksi for SS and higher for more expensive nickel-alloys**

FE Project Activities in SCO2 Based Power Cycles

- **Turbo Machinery for Indirect and Direct SCO2 Power Cycles**
  - Low-Leakage Shaft End Seals for Utility-Scale SCO2 Turbo (GE)
  - Adv. Turbomachinery Comp. for SCO2 Cycles (Aerojet Rocketdyne)
- **Oxy-fuel Combustors for SCO2 Power Cycles**
  - Coal Syngas Comb. for HP Oxy-Fuel SCO2 Cycle (8 Rivers Capital)
  - HT Combustor for Direct Fired Supercritical Oxy-Combustion (SwRI)
  - Oxy Fuel Combustion (NETL)
  - Autoignition and Combustion Stability of High Pressure SCO2 Oxy-Combustion (GA Tech)
  - Chemical Kinetic Modeling and Experiments for Direct Fired sCO2 Combustor (UCF)
- **Recuperators / Heat Exchangers for SCO2 Power Cycles**
  - Low-Cost Recuperative HX for SCO2 Systems (Altex Tech. Corp)
  - Mfg. Process for Low-Cost HX Applications (Brayton Energy)
  - Design, Fab, and Char. Microchannel HX for FE SCO2 cycles (Oregon State U)
  - HT HX for Systems with Large Pressure Differentials (Thar Energy)
  - Thin Film Primary Surface HX for Advanced Power Cycles (SwRI)
  - HX for SCO2 Waste Heat Recovery (Echogen / PNNL, SBIR)
- **Materials, Fundamentals and Systems (AT)**
  - R&D materials & systems (NETL)
  - Materials Issues for Supercritical carbon Dioxide (ORNL)
  - Thermodynamic and Transport Properties of SCO2 (NIST)

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Thar Energy Recuperator Development Projects

High Temperature Heat Exchanger Design and Fabrication for Systems with Large Pressure Differentials

Thar Energy

- Prime contractor
- Technical gap assessment
- Prototype recuperator
  - Design
  - Fabrication
- Test stand design and assembly
- Recuperator testing and evaluation

SwRI

- FEA modeling

Bechtel Propulsion

- Technical Support
  - Materials science
  - Prototype testing

Technology Development of Modular, Low-Cost, High-Temperature Recuperators for sC0₂ Power Cycles

Thar Energy

- Prime contractor
- Technical gap assessment
- Design for manufacturing
  - Focus manufacturability & cost
  - Multiple design analysis
- Design for operability, prototyping, & fabrication
  - Down select
- Final Design for manufacturability
- Recuperator fabrication

SwRI

- Combined system engineering design
- Thermodynamic analysis
- FEA modeling

ORNL

- Materials science
  - Long-term corrosion resistance
  - Creep resistance
  - New alloy and/or coating formulation

Georgia Institute of Technology

- CFD simulation & analysis of heat exchanger concepts

In Summary Recuperator Challenges for SCO2 Power Cycles

- **Objectives**
  - Maximize heat transfer efficiency
  - Minimize pressure drop
  - Ensure even flow distribution
  - Minimize Cost
- **Challenges**
  - Seals and pressure containment
  - Materials strength and stability
  - Oxidation resistance
  - Fouling effects

DOE SCO2 Crosscut Initiative

- **One of a handful of recognized intra-office DOE crosscut teams**
- **Nuclear Energy (NE), Fossil Energy (FE) and Energy Efficiency & Renewable Energy (EERE) collaborate on SCO2 power cycles**
- **Based on advantages of SCO2 power cycles**
  - Heat source neutral
  - Applicability to wide range of stakeholders
  - Potential higher efficiency and lower COE
- **Mission**
  - Realize a lower COE with SCO2 power cycles compared to SOTA steam cycles
  - Reduce technical barriers and risks to commercialization

SCO2 Crosscut Initiative

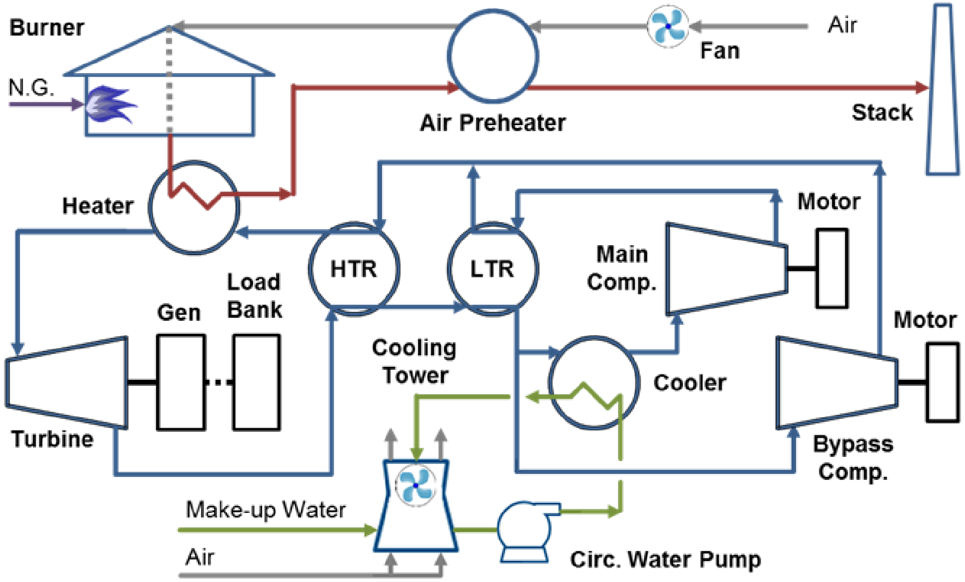
Status / Accomplishments

- **Request for Information**
  - RFI 1 & RFI 2
- **Workshops**
  - SwRI/NETL/SNL/NREL; June 2014; September 2014
- **Symposium and Conferences**
  - ASME IGTI Turbo Expo & Int. Symp. on SCO2 PC
- **Collecting information for an effective solicitation**
  - Technical approach and cost for a 10 MWe facility
- **On going SCO2 base programs with FE, EERE and NE**
  - Focusing on respective technology application issues

SCO2 Crosscut Initiative

Next Steps / Path Forward

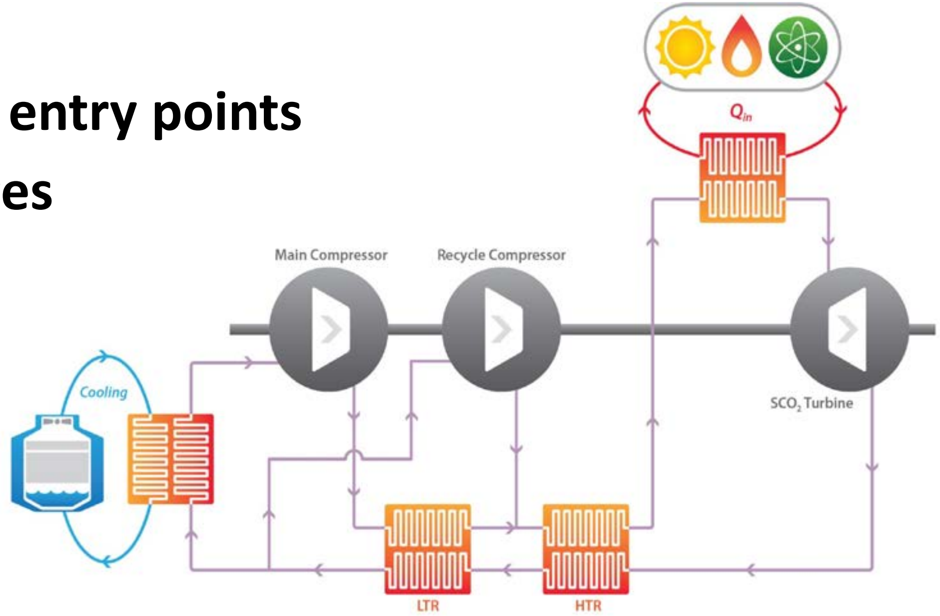
- **DOE Offices of NE, FE & EERE collaborating on this initiative**
- **"…gather information and engage industry to develop an effective solicitation for a public-private cost-shared supercritical carbon dioxide demonstration program…." (1)**
- **"..10-megawatt supercritical CO2 technology electric power (STEP) demonstration project.." (2)**



(1) http://docs.house.gov/billsthisweek/20141208/113-HR83sa-ES-D.pdf;
(2) http://energy.gov/news-blog/articles/secretary-monizs-written-testimony-house-committee-appropriations-subcommittee

Summary

- **SCO2 power cycles provide an attractive alternative to the incumbent H_2O based Rankine cycles**
  - Efficiency
  - Broad application to heat sources
  - Characteristic benefits
- **Unique and ubiquitous market entry points**
- **Near term technology challenges**
  - Recuperators
  - Turbomachinery
  - Materials
  - Controls
  - COE



- **DOE sCO_2 Crosscut Initiative**
  - Plan for an effective cost shared solicitation

Upcoming Events

EPRI INTERNATIONAL CONFERENCE ON CORROSION IN POWER PLANTS

October 13 – 15, 2015 • Hilton Mission Bay • San Diego, California USA

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

NETL

NETL-EPRI WORKSHOP ON HEAT EXCHANGERS FOR SUPERCRITICAL CO_2 POWER CYCLES

October 15, 2015 • *Co-located with EPRI International Conference on Corrosion in Power Plants*

2015 UNIVERSITY TURBINE SYSTEMS RESEARCH WORKSHOP

November 3-5, 2015

Georgian Terrace Hotel , Atlanta, Georgia

UTSR University Turbine Systems Research

U.S. Department of Energy | Office of Fossil Energy | National Energy Technology Laboratory | Georgia Institute of Technology

U.S. DEPARTMENT OF ENERGY | NETL

Georgia Institute of Technology

2016 ASME POWER & ENERGY

JUNE 26-30, 2016

CHARLOTTE CONVENTION CENTER | CHARLOTTE, NC USA | GO.ASME.ORG/POWERENERGY

ASME IGTI GAS TURBINE FORUM 2016

ASME SETTING THE STANDARD

TURBO EXPO

Turbomachinery Technical Conference & Exposition

Presented by the ASME International Gas Turbine Institute

CONFERENCE June 13 - 17, 2016 EXHIBITION June 14 - 16, 2016

COEX Convention & Exhibition Center, Seoul, South Korea

The 5th International

Supercritical CO_2 Power Cycles Symposium

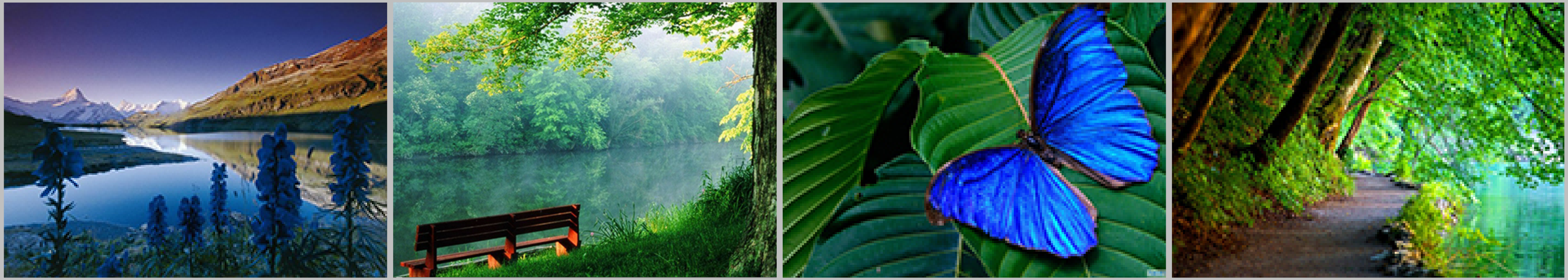
will be held

March 29 to 31, 2016

in

San Antonio, Texas

It’s All About a Clean, Affordable Energy Future



For More Information, Contact NETL

the ENERGY lab

Delivering Yesterday and Preparing for Tomorrow