sCO_2 Research & Development at NETL

Nathan Weiland, Peter Strakey, Omer Dogan, Jim Black, Eric Liese, and Walter Shelton – NETL, Research and Innovation Center

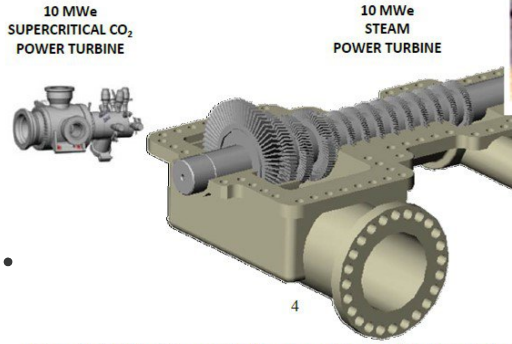
6th International Supercritical CO_2 Power Cycles Symposium, March 27-29, 2018, Pittsburgh, PA

Solutions for Today | Options for Tomorrow

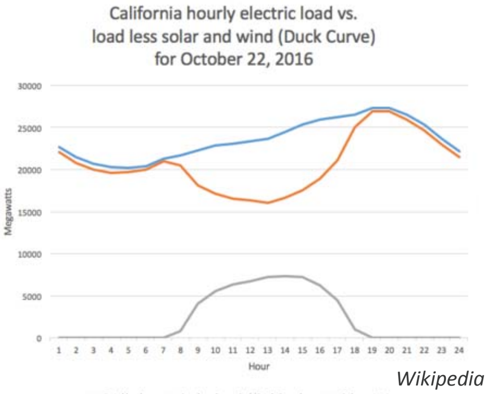
NETL's Vision for sCO_2 Power Generation

- Higher efficiency (up to 4 pts above AUSC steam).
- Reduced footprint.
- Potential for dry cooling.
- Enabling technology for clean coal.
- CO2 sequestration (especially for direct cycle).
- Scalability (5 to 500 MW).
- Flexibility (load following, quick start/shutdown)?

www.breakingenergy.com

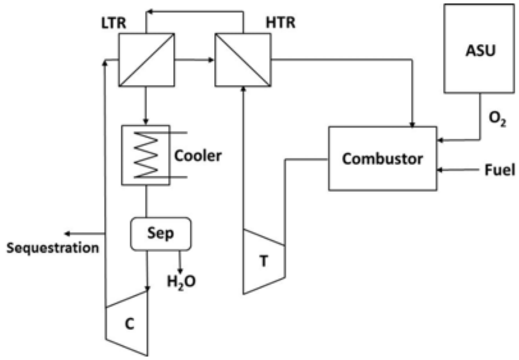


Echogen's 10 MWe sCO_2 power turbine compared to a 10 MWe steam turbine.



Wikipedia

Direct or "Open" Simple Cycle



NETL Research & Innovation Center (RIC)

Role in Supercritical CO_2 Technology Program

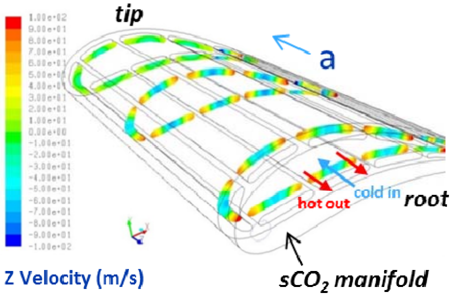
Goal – Develop technology toward achieving the program goal of increased efficiency using sCO_2-based power cycles.

Approach **–** Perform R&D on turbine blade cooling, oxy-combustion, and materials, along with systems studies.

Aerothermal/Heat Transfer

PI: Jim Black

Cool turbine blades to allow higher turbine inlet temperatures.

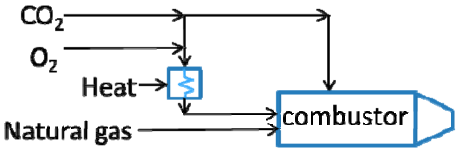


Source: NETL

Oxy-combustion

PI: Peter Strakey

Improve efficiency using higher temperature direct-fired cycle with oxy-combustion.



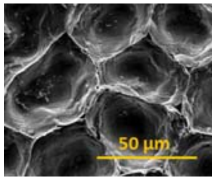
Proposed Oxy-Fuel Combustor

Source: NETL

Materials

PI: Omer Dogan

Evaluate material corrosion, erosion, mechanical property degradation in sCO_2. Identify materials compatible in sCO_2.

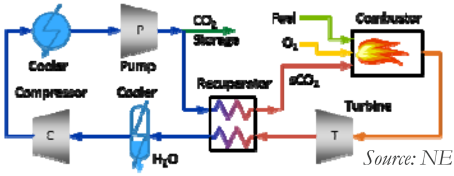


Source: NETL

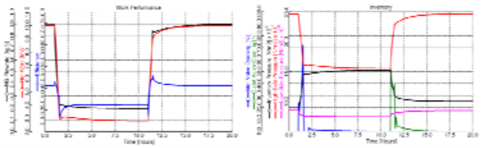
Systems Analyses

PIs: Weiland, Shelton, Liese

Steady-state and dynamic modeling, techno-economic evaluations of various configurations of sCO_2 power cycle plants (direct- and indirect-fired cycles)



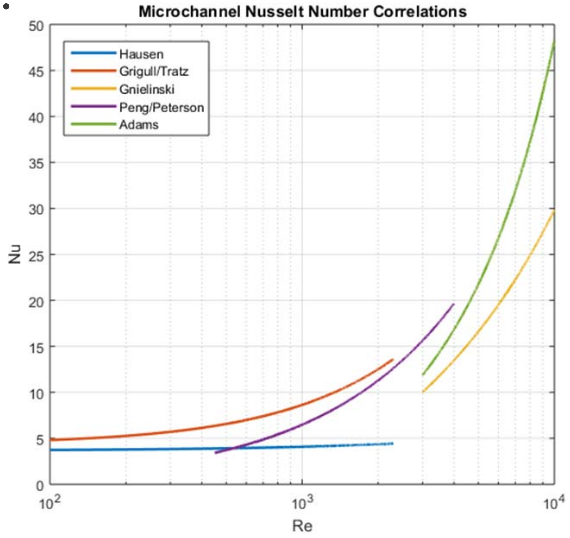
Source: NETL



Aerothermal and Heat Transfer R&D

Convective Heat Transfer Coefficients

- Wide Re range of interest for sCO_2 power cycle components – $1{,}000 < Re < 500{,}000$
- Thermophysical properties change rapidly near the critical point making accuracy of calculation in this region difficult.
- Many correlations proposed in the literature. Difficult to compare unless they are graphed.

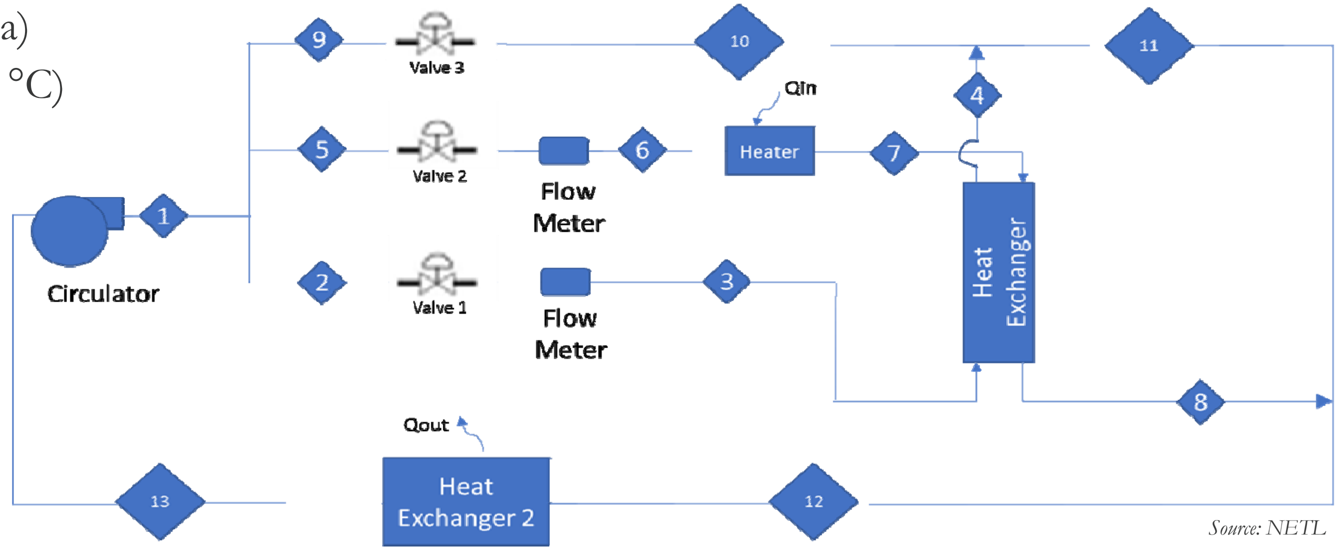


Author	Nu Correlation	Range Valid
Hausen (1959)	$Nu = 3.66 + \frac{0.19(RePr\ D/L_h)^{0.8}}{1 + 0.117(RePr\ D/L_h)^{0.467}}$	$Re < 2300$
Grigull and Tratz (1965)	$Nu = 4.36 + \frac{0.00668\left(\frac{d_h}{x}\right)RePr}{1 + 0.04\left[\left(\frac{d_h}{x}\right)RePr\right]^{\frac{2}{3}}}$	laminar
Gnielinski (1976)	$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1.07 + 12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}\left(Pr^{\frac{2}{3}} - 1\right)}$ $f = (1.82 \cdot \log(Re) - 1.64)^{-2}$	$3{,}000 < Re < 5 \times 10^6$ $0.5 \le Pr \le 2000$
Adams et al (1997)	$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1.07 + 12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}\left(Pr^{\frac{2}{3}} - 1\right)}(1 + 7.6 \times 10^{-5}\ Re(1 - (d_h/d_o)^2)$ $d_o = 1.164\text{mm}$	turbulent
Peng and Peterson (1995)	$Nu = 0.072\left(\frac{D_h}{W_c}\right)^{1.15}[1 - 2.421(Z - 0.5)^2]Re^{0.8}Pr^{1/3}$ where $Z = \frac{\min(H,W)}{\max(H,W)}$ H- height, W- width	$450 < Re < 4000$

Aerothermal and Heat Transfer R&D

Heat Exchange & Experimental Testing (HEET) Rig

- **Objective: Validate or develop new correlations for calculating convective HT coefficients**
- **Utilize Wilson Plot measurement technique**
- **Capabilities:**
  - Max Pressure – 3,500 psig (24 MPa)
  - Max Temperature – 1,000 °F (538 °C)
  - Max Flow Rate – 3 lb/s (1.5 kg/s)
  - Max Reynolds Number – 500,000
  - Pure CO_2 or mixture with up to 10% N_2



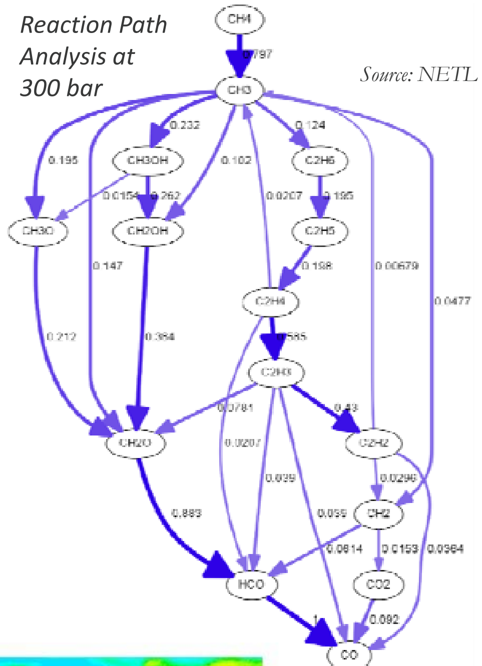
Source: NETL

Oxy-Combustion R&D

Analysis of Combustion Fundamentals

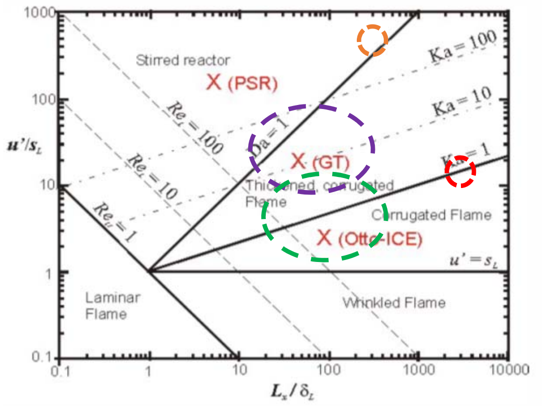
- **Natural Gas or Syngas with Oxygen and CO_2 dilution (P ~300 bar, TIT ~1500 K).**
- **Issues**
  - Operating Conditions - Virtually no validation data, no kinetic models, no experience at 300 bar!
  - Heat Release - More likely to resemble a rocket engine than a gas turbine combustor: Combustion dynamics may be an issue.
  - Kinetics - Most methane oxidation models based on GRI Mech, which is only validated below 10 atm.
- **Approach: Utilize CFD as well as simple 0D and 1D models to assess the issues.**

Reaction Path Analysis at 300 bar



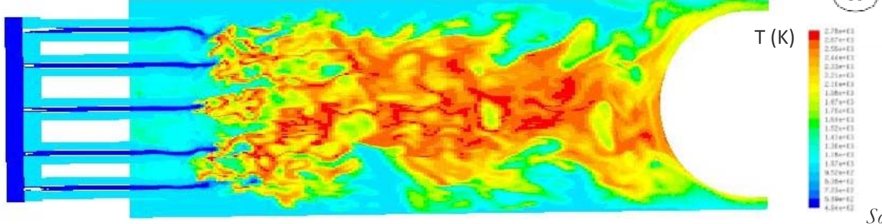
Source: NETL

Gas Turbines
IC Engines
300 bar sCO2 (.31O2+.69CO2)
S_L = 0.58 m/s (T_F=2690K)
δ_L = 0.67 µm
Ka=0.7
T_{ign}=9.2e-4 s
300 bar sCO2 (.09O2+.91CO2)
S_L = 0.05 m/s (T_F=1610K)
δ_L = 6.60 µm
Ka=361
T_{ign}=2.5e-3 s



Borghi Phase Diagram

CFD of Oxy-Combustor

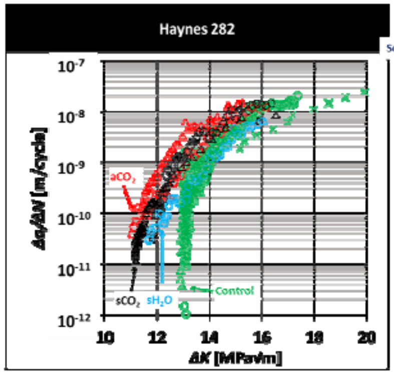


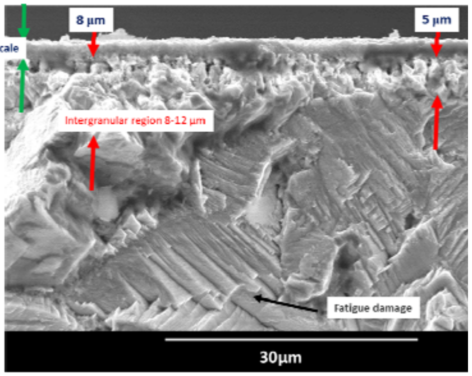
Source: NETL

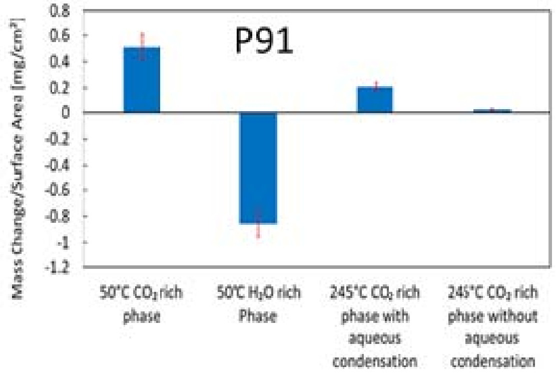
sCO_2 Materials R&D

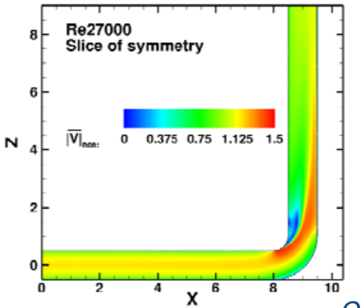
Materials Compatibility

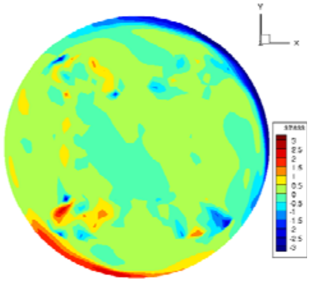
- **Effect of sCO_2 cycle environments on mechanical properties**
  - Measurement of fatigue crack growth rates after sCO_2 exposures
- **Low-temperature corrosion in direct sCO_2 cycles**
  - Inexpensive alloys (e.g. P22, P91), corrode with carbonic acid
- **High-temperature oxidation in direct sCO_2 power cycles**
  - 750 °C exposure testing with H_2O, O_2, and SO_2 impurities
- **Erosion of components in sCO_2 cycles**
  - CFD of pipe bends shows high-shear oscillations that may cause erosion of oxide scale



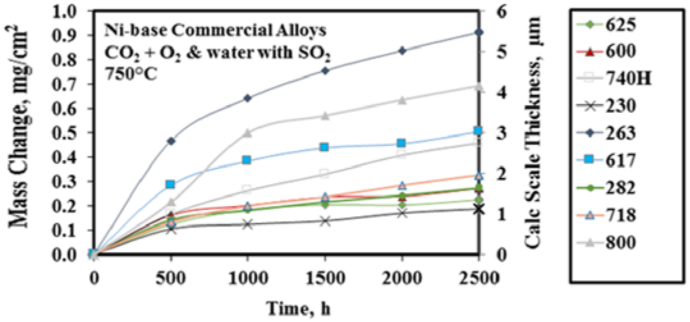








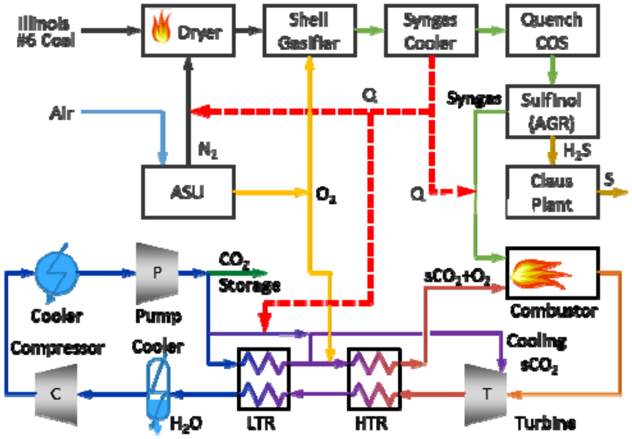
Oregon State



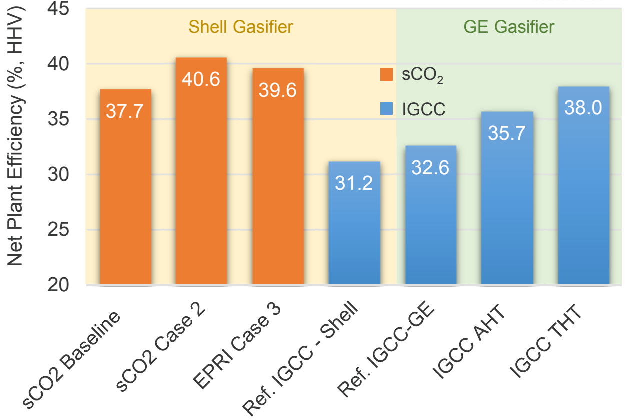
Techno-Economic Analysis R&D

Direct sCO_2 power plants

- **Modeled two thermally-integrated Shell gasifier/ direct sCO_2 plants with carbon capture**
  - Thermal efficiency of 40.6% (HHV) with 99% carbon capture
  - 20% Cost of Electricity improvement over IGCC systems with carbon capture
- **Ongoing and future direct sCO_2 analyses:**
  - Change gasifier types and/or syngas cleanup strategies to improve plant efficiency
  - Analysis of natural gas-fired direct sCO_2 system, with detailed turbine cooling model and effect of incomplete combustion
  - Development of component models and control strategies to facilitate off-design and part load studies
  - Improve sCO_2 component cost accuracy



Source: NETL



NETL Research and Innovation Center

sCO_2 Research Team Contacts

Most of this work is being presented at the 6th International Supercritical CO_2 Power Cycles Symposium in Pittsburgh, March 2018.

Aerothermal & Heat Transfer:
James.Black@netl.doe.gov
412-386-5458

Oxy-Combustion:
Peter.Strakey@netl.doe.gov
304-285-4476

Materials:
Omer.Dogan@netl.doe.gov
541-967-5858

System Dynamics:
Eric.Liese@netl.doe.gov
304-285-4610

Techno-Economic Analyses:
Nathan.Weiland@netl.doe.gov
412-386-4649

Walter.Shelton@netl.doe.gov
304-285-4209