Technology Needs for Fossil Fuel Supercritical CO_2 Power Systems

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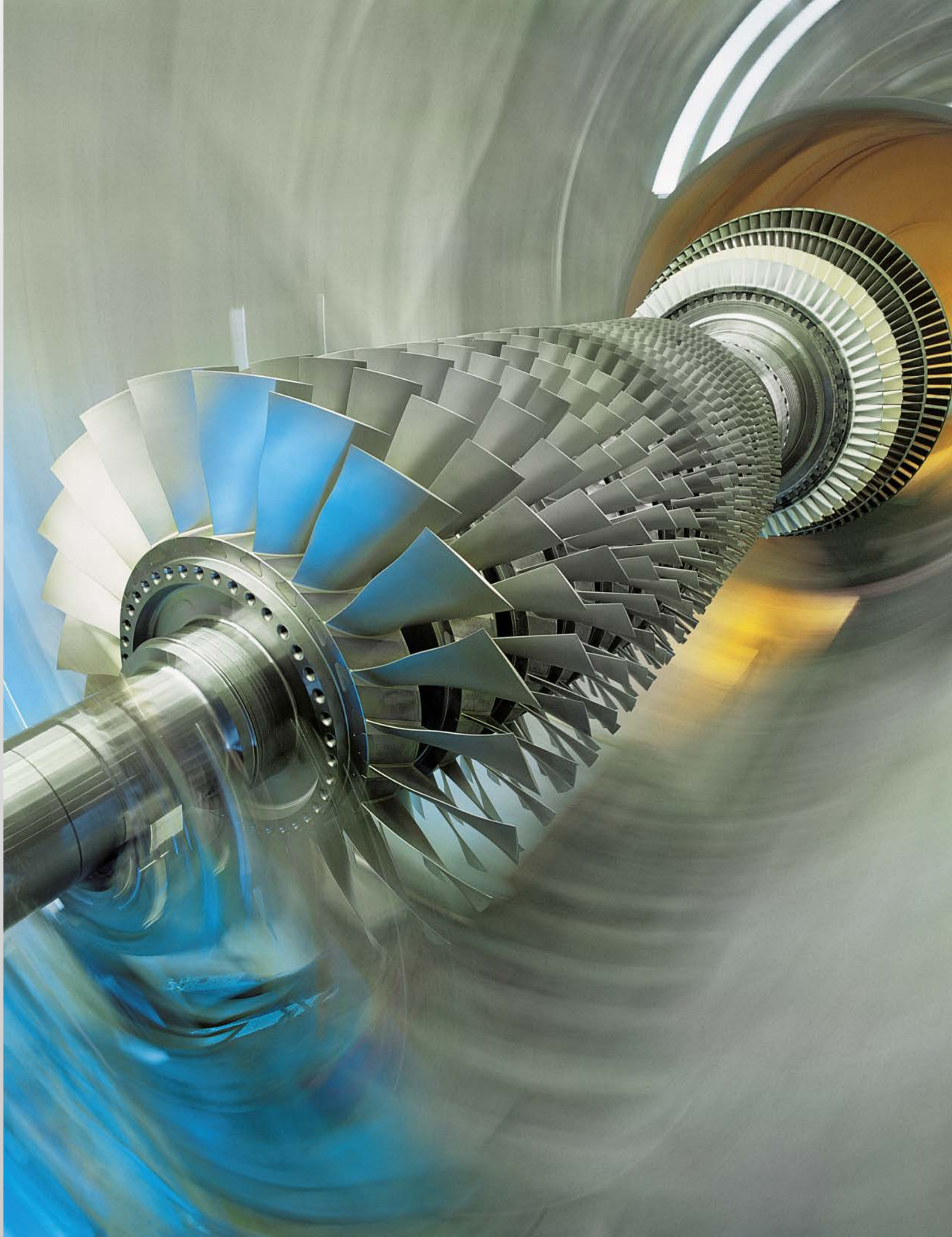
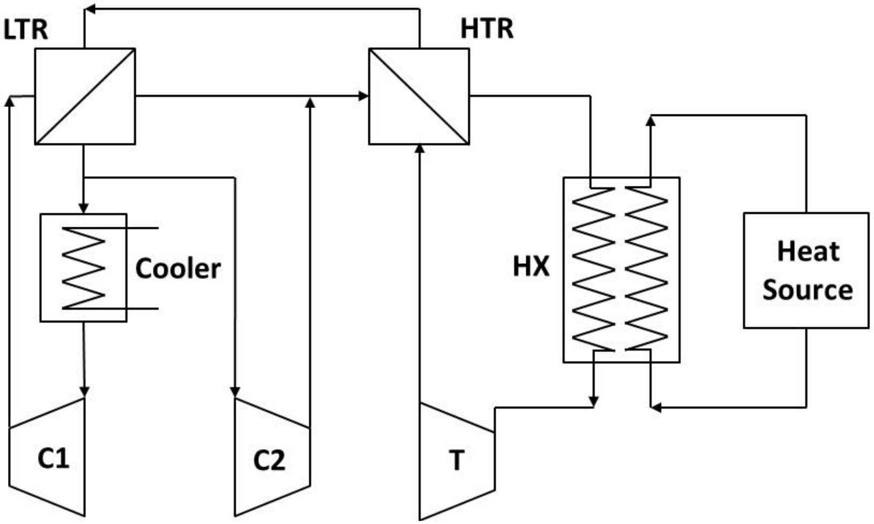
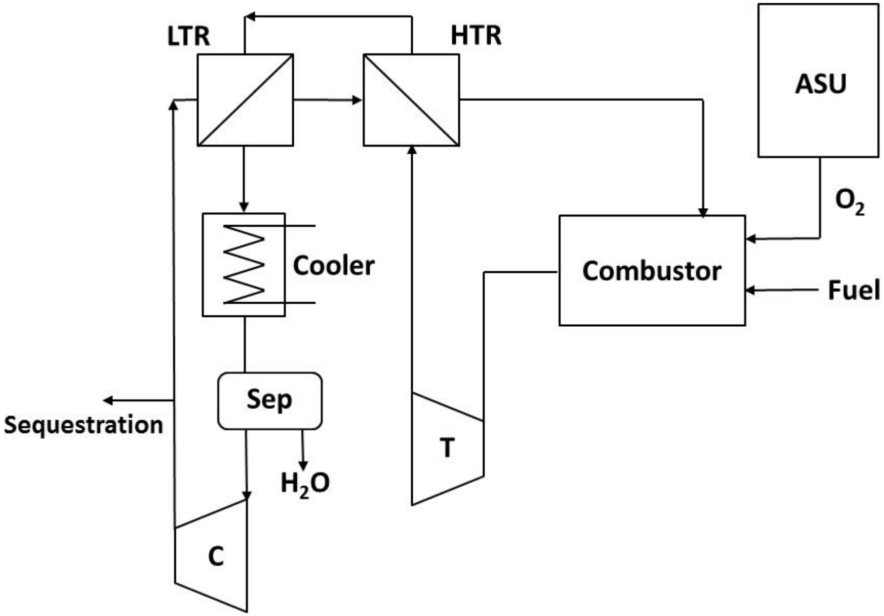


sCO$_2$ Cycles for Fossil Energy

Indirect or “Closed” Recompression Cycle



Direct or “Open” Simple Cycle

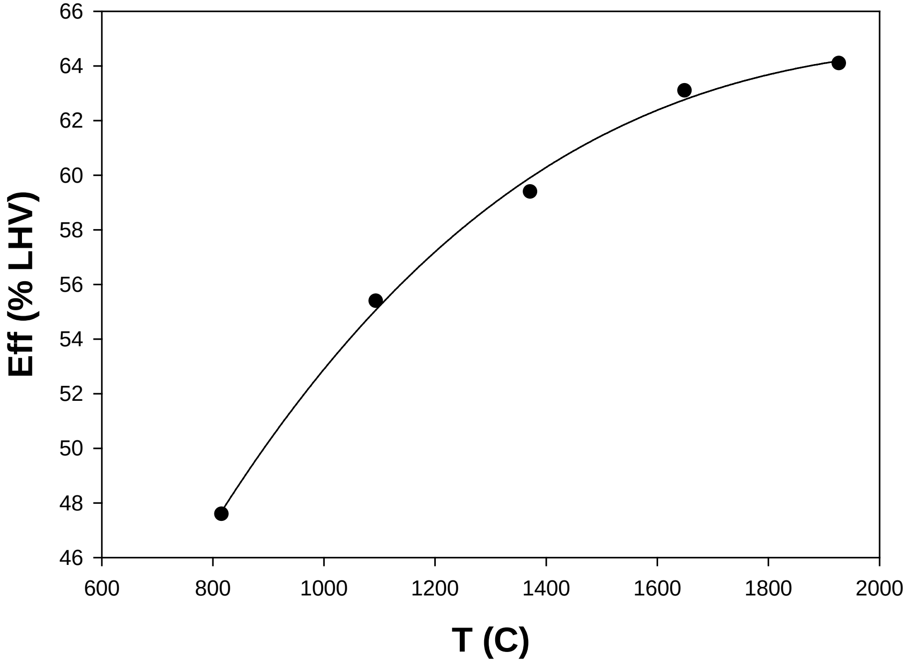


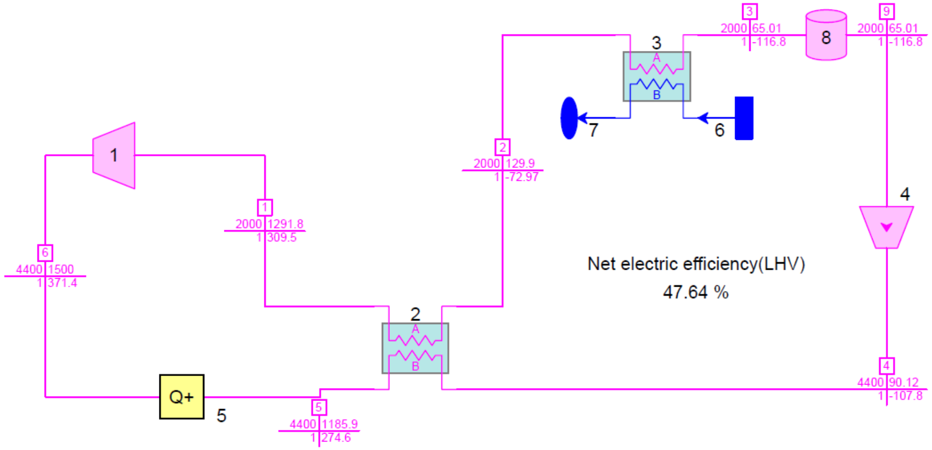
- Both Closed and Open cycles being investigated.
  - Open cycles attractive due to potential for higher TiT (>700°C).
  - Open cycle is also well suited for carbon capture and sequestration.

Effect of Turbine Inlet Temperature on Cycle Efficiency

Closed, Recuperated
Tb=18 °C
Pmax=4400 psi
Pr=2.2

Simple Recuperated sCO2 Cycle
Pr=2.2, Pmax=4400 psi

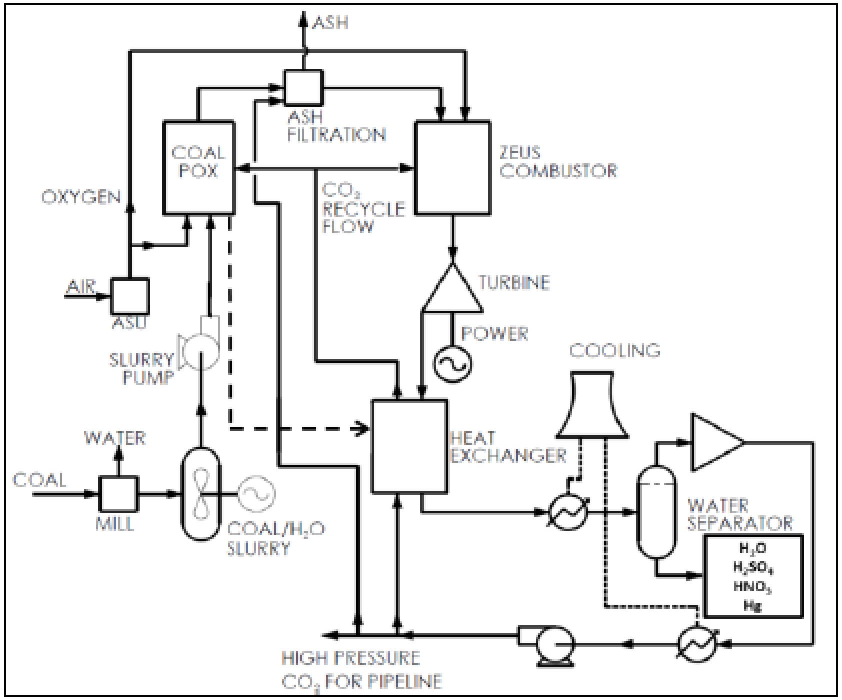




- Significant efficiency gains observed up to 2000°C

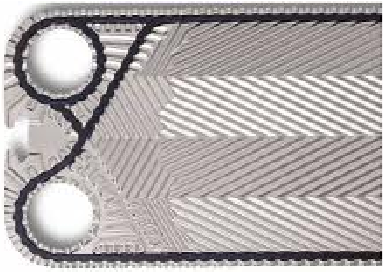
Recuperators

- Compact heat exchangers are the favored technology.
- At 2000°C turbine inlet temperature the recuperator inlet temperature would be around 1500°C!
- For coal syngas applications the recuperator would see H_2SO_4 and HNO_3 along with H_2O.



Netpower Coal Cycle (Energy Procedia, 37, 2013, pp. 1135-1149)



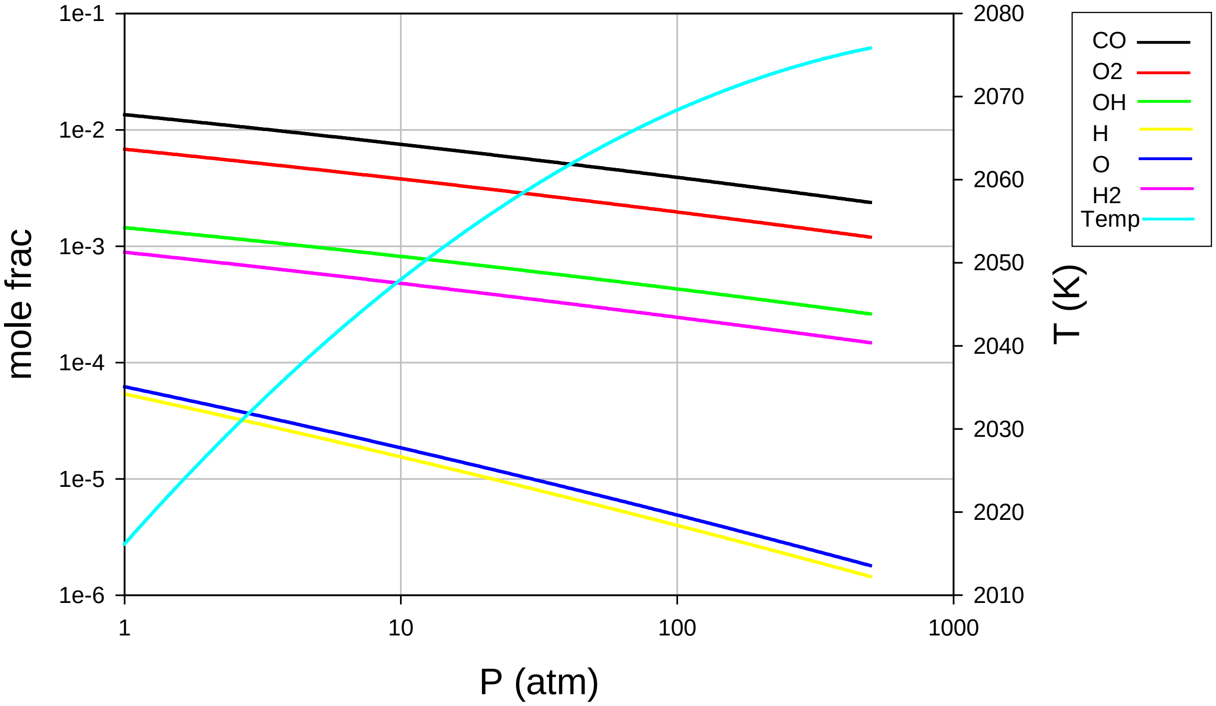


several micro channel heat exchanger designs…

Combustion Dynamics

- High energy release density of sCO_2 oxy-fuel combustor more like a rocket engine than a gas turbine.
- Rocket engines have a long history of dynamics problems.
- Resonant frequency inversely proportional to combustor size.
  - Small combustor = high resonant frequency and large dampening.
  - Rocket engine most damaging frequencies in the 1-10 kHz range due to transverse modes.
- Saturn F-1 instability required 750 full scale tests to solve at $1M/test.

Combustion Kinetics

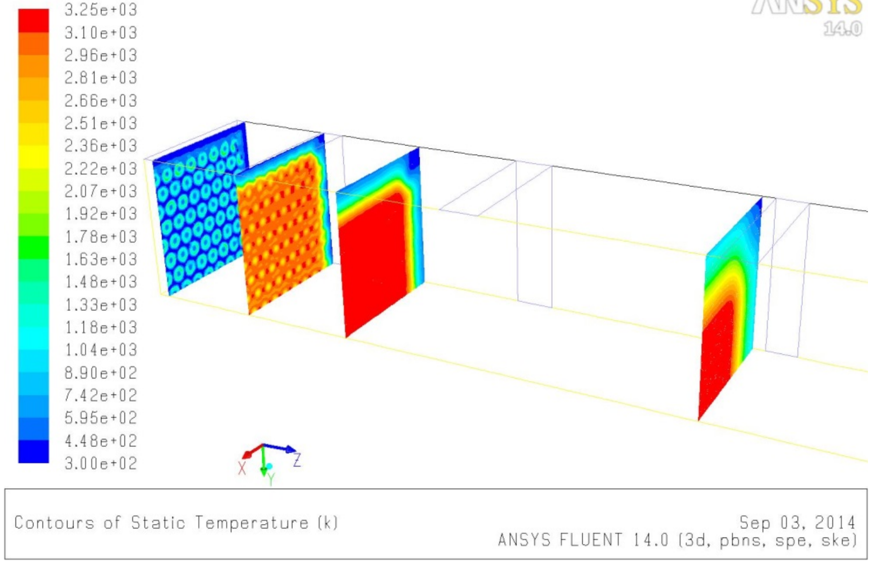


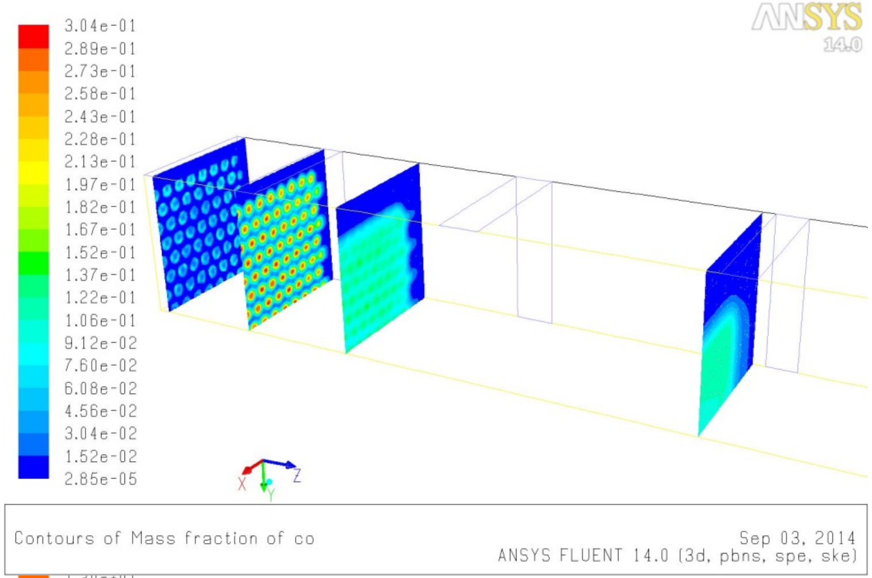
Equilibrium calculation for stoichiometric $CH_4/O_2/CO_2$ mixture

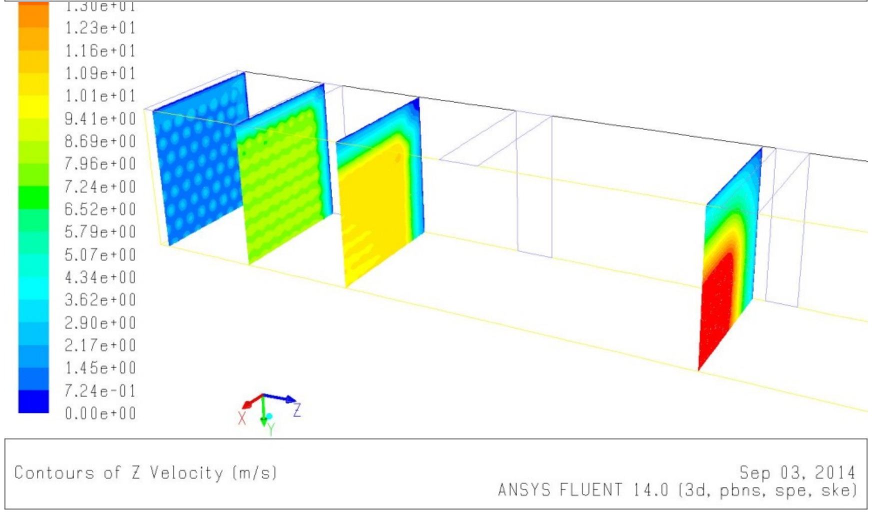
- Increasing pressure shifts equilibrium to product side through 3-body recombination reactions.
- Most methane oxidation models based on GRI Mech, which is only validated below 10 atm.
- Direct fired system combustor pressure as high as 300 bar!
  - Uncertainty in heat release rates, CO concentration …

Combustion CFD Modeling

300 bar, 1MW
$CH_4/O_2/CO_2$
Coax array injector
Detailed chemistry
Slot injection wall Cooling



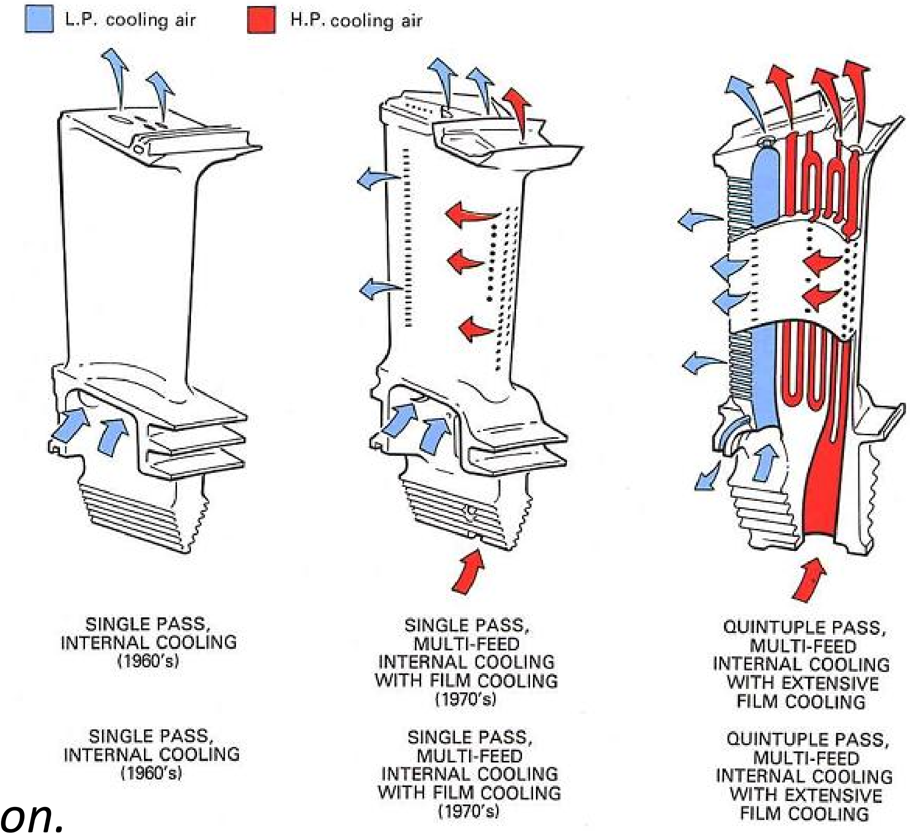




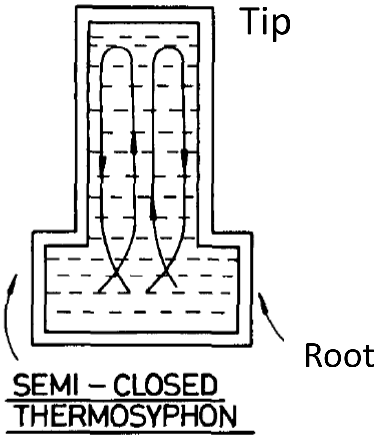
CFD used to assess pressure effects on injector mixing, chemistry and wall cooling.

Turbine Blade Cooling

- Turbine inlet temperatures much above 700 C require cooling strategies.
  - Internal or regen cooling with CO_2 attractive for sCO_2 cycles.
- Thermosyphon might be an option for rotating blades.



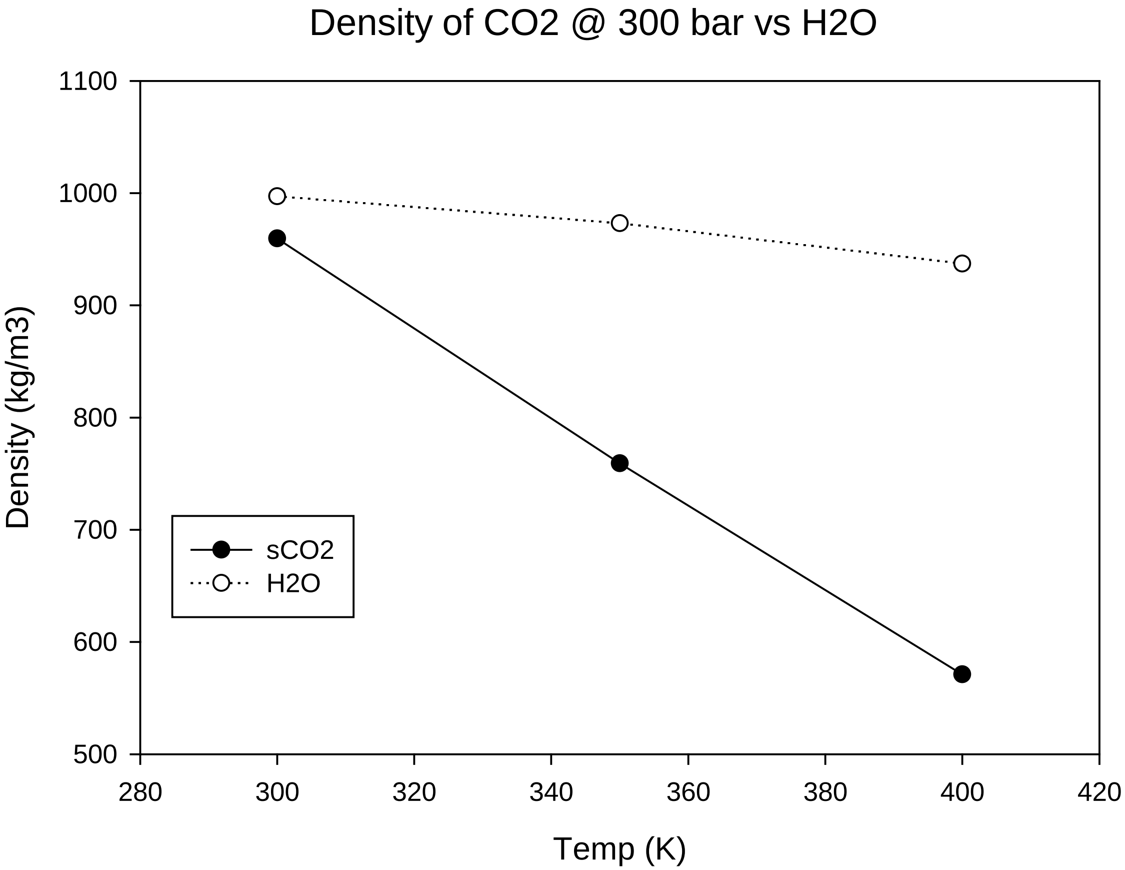
SINGLE PASS, INTERNAL COOLING (1960's)
SINGLE PASS, MULTI-FEED INTERNAL COOLING WITH FILM COOLING (1970's)
QUINTUPLE PASS, MULTI-FEED INTERNAL COOLING WITH EXTENSIVE FILM COOLING



Potential Issues

- *Fouling and corrosion.*
- *Heat and efficiency loss to coolant.*
- *Manufacturing (blind holes, welding, etc.).*
- *Blade failure (cracking, leaking).*
- *Manifolding and sealing on rotating parts.*

sCO_2 Properties vs. H_2O (l)

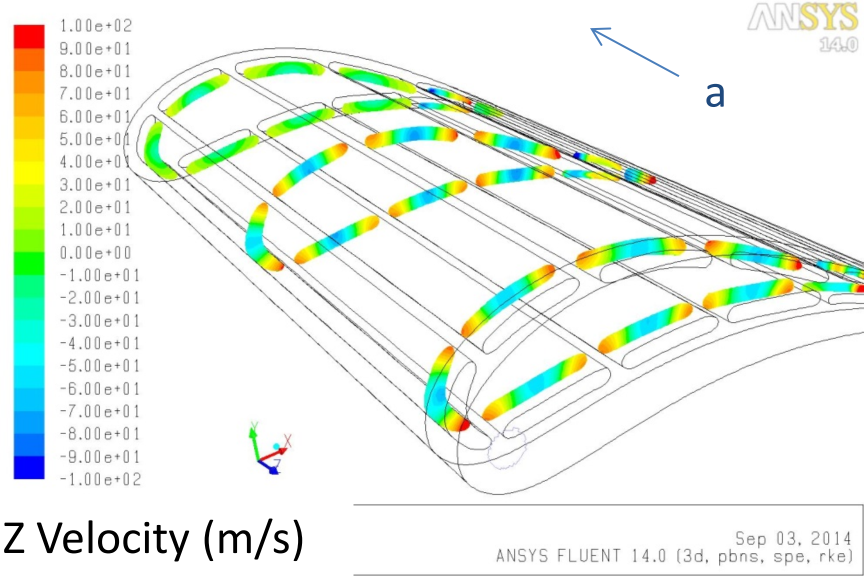


T=300K	sCO_2 @300 bar	H_2O (l)
Cp (J/Kg°K)	1919	4179
k (w/m°K)	120 e-3	613 e-3
μ (m^2/s)	109 e-6	855 e-6
Pr # (ν/α)	1.75	5.83

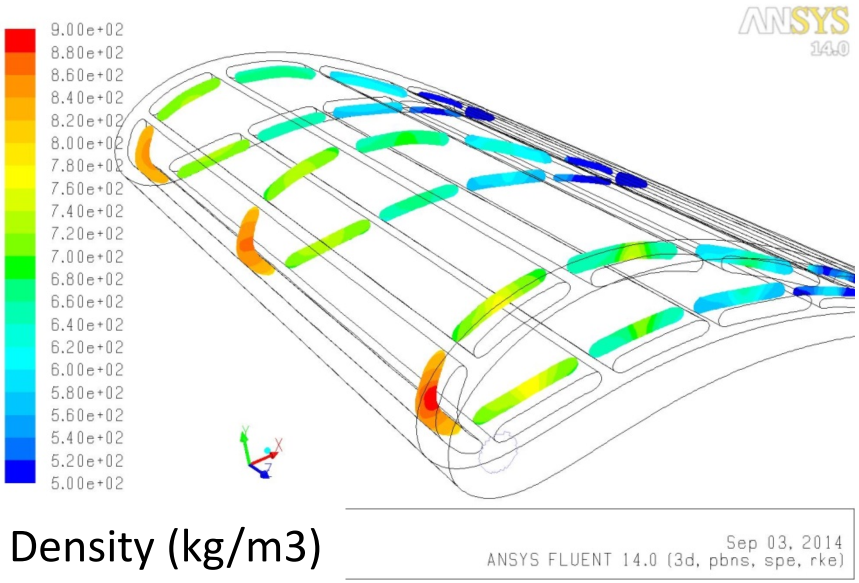
- Much higher temperature dependence for sCO2 means larger thermosyphon effect. Centripetal acceleration: $a_c=(2\pi\omega)^2r$, $dp=\rho(r)(2\pi\omega)^2rdr$ (ω=rev/s). @40,000 rpm & r=10 cm a_c=180,000 g's

CFD Modeling of Blade Cooling

1” long airfoil
1.5 M Cells
Hot Gas: 300 bar, 1400K, 150 m/s
Coolant: sCO2 @ 300 bar, 300K
Acceleration: 1e6 g’s



Z Velocity (m/s)



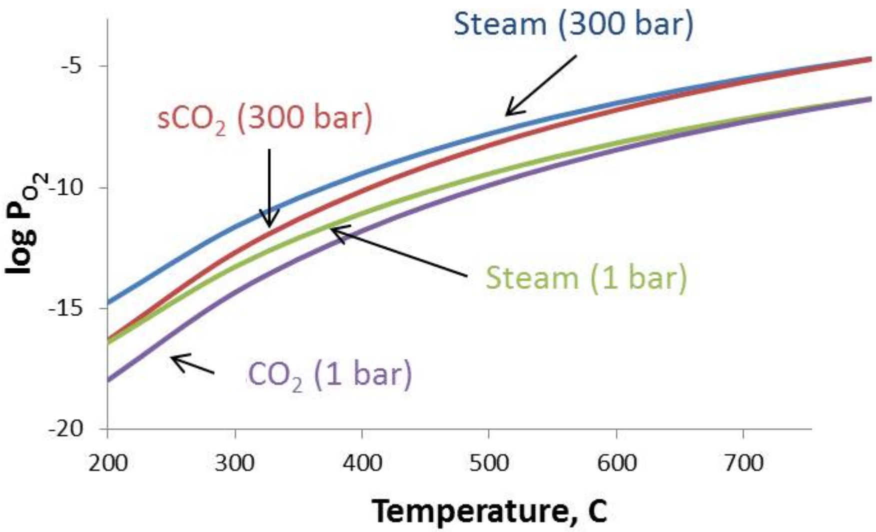
Density (kg/m3)

Thermosyphon effect observed to be very strong for sCO_2: excellent heat transfer.

Materials Issues in sCO_2 Service

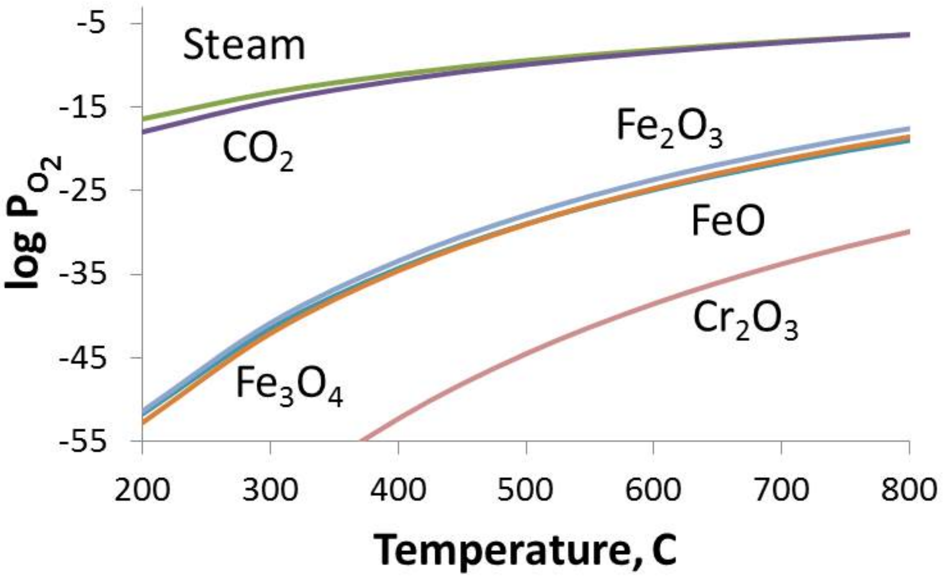
- High-temperature oxidation
- Carburization
- Low cycle fatigue and creep-fatigue (effect of oxidation on the crack surface mechanical behavior)

Oxidizing Potentials Steam vs. CO_2



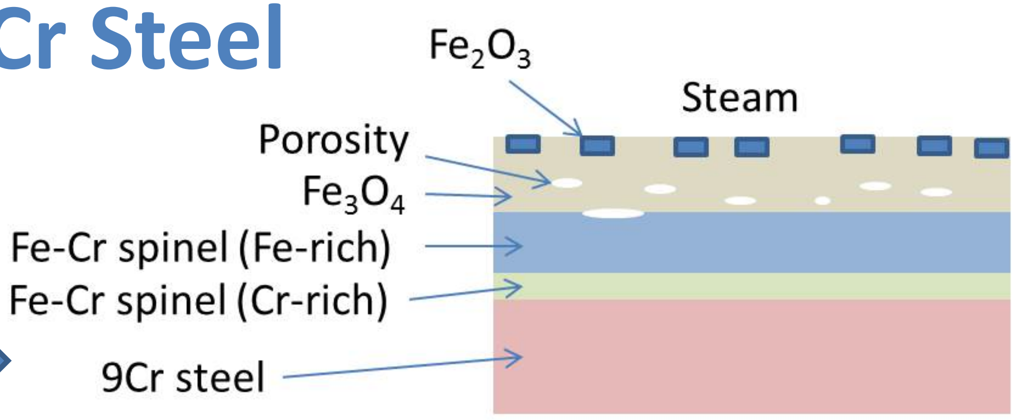
$H_2O = H_2 + \frac{1}{2}O_2$	**ΔG° (J/mol) = 239,500 - 8.14TlnT + 9.25T**
$CO_2 = CO + \frac{1}{2}O_2$	ΔG° (J/mol) = 282,400 - 86.81T

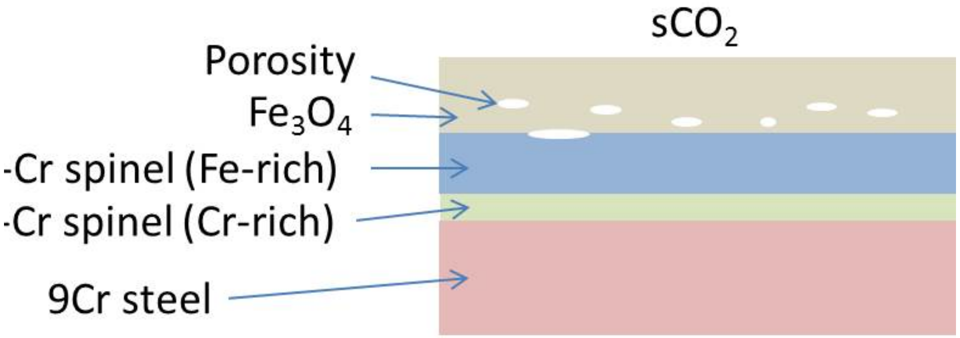
- Oxidizing potentials of steam and CO_2 are similar.
- pO_2 in both steam and CO_2 is much higher than required for relevant oxidation mechanisms.



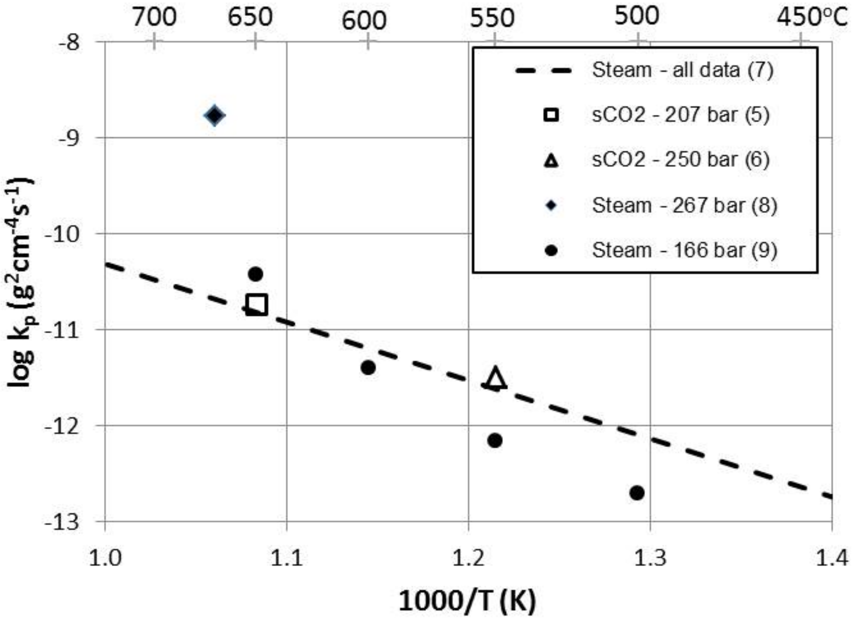
Ferritic/Martensitic 9Cr Steel

Oxidation Products on 9Cr Steels in Steam and CO_2





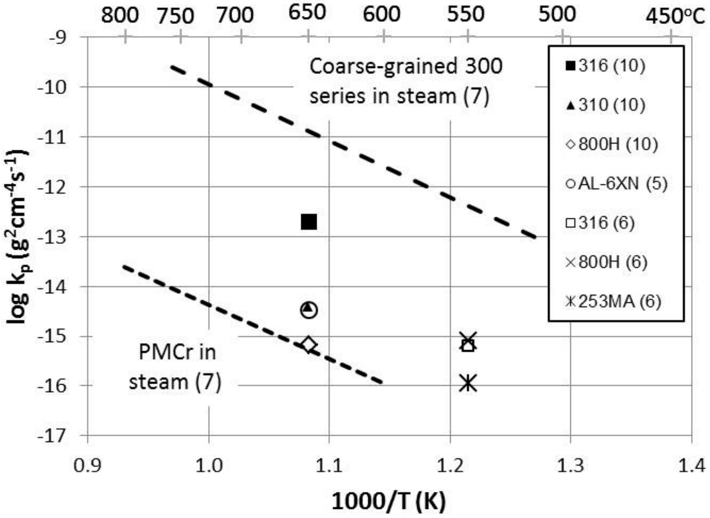
Note – exposure times for CO_2 short (~400 hrs)



Oxidation Kinetics of 9Cr Steels in Steam and CO_2

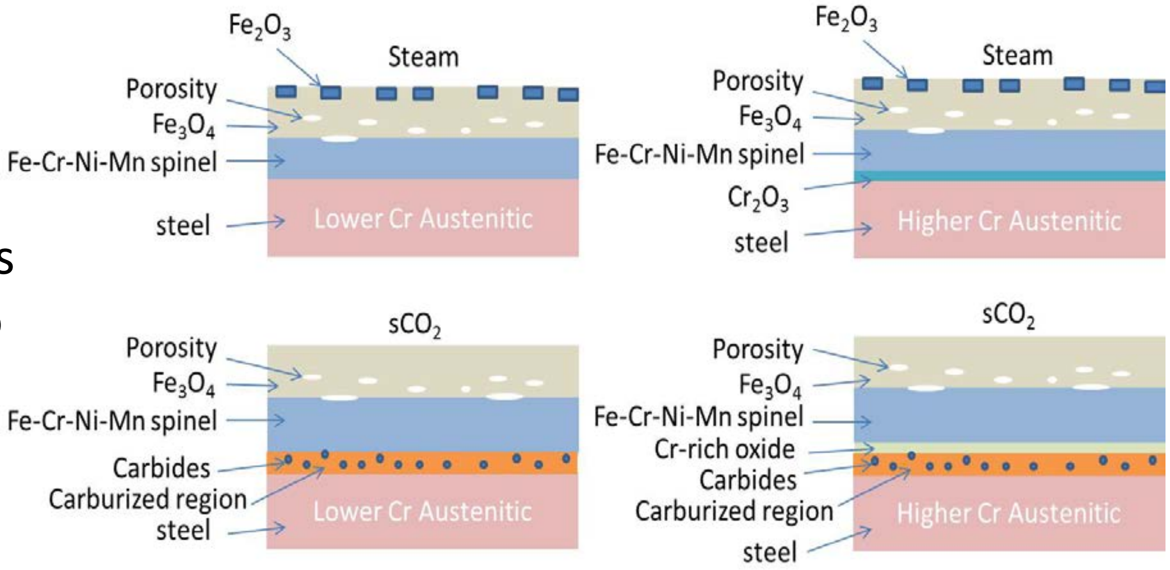
$k_p = \Delta W^2/2t$, where ΔW is mass gain and t is time of exposure

Austenitic Steels



Oxidation Kinetics of Austenitic Steels in Steam and CO_2

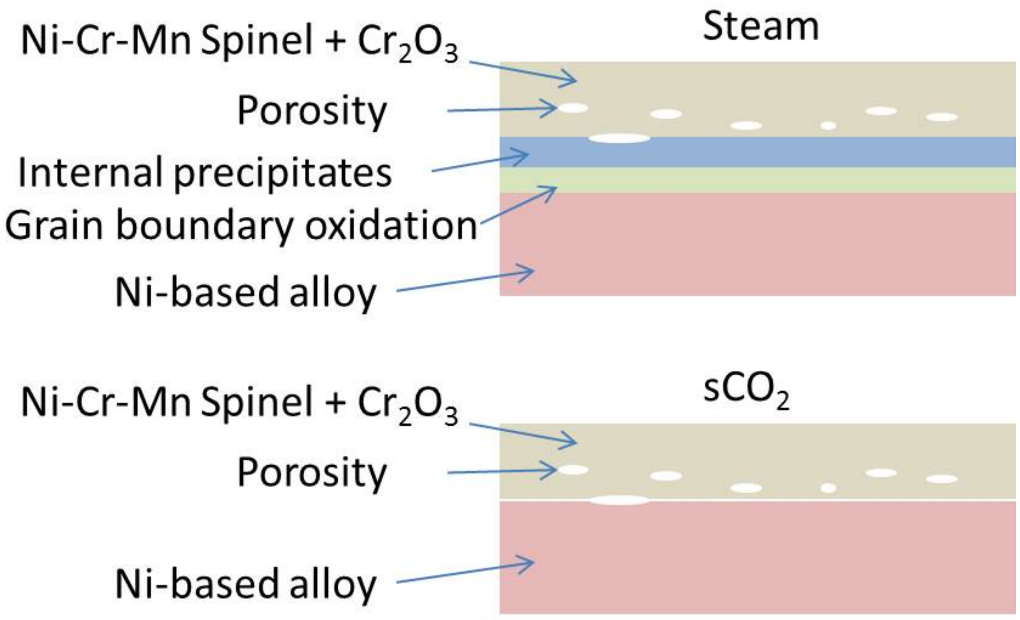
Oxidation Products on Austenitic Steels in Steam and CO_2



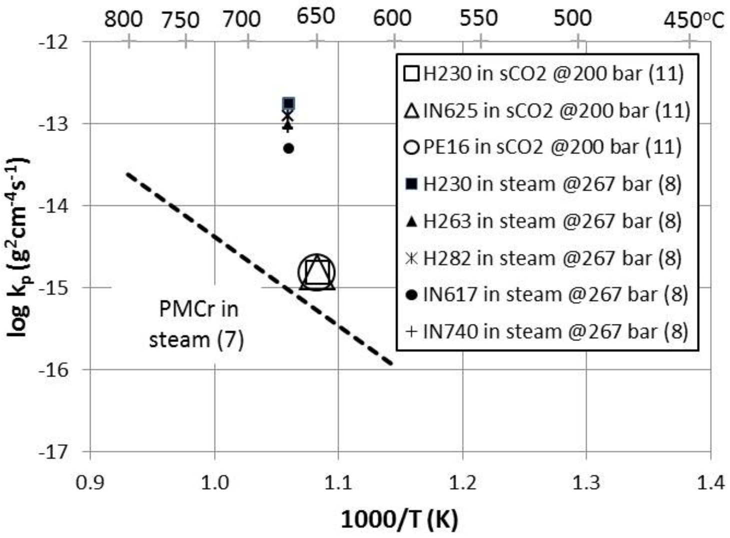
- 316 ss demonstrates fastest oxidation in sCO_2.
- High Cr steels exhibit much less mass gain in sCO_2 compared to 316.
- Carburized layer forms below oxide layers for sCO_2.

Nickel Based Alloys

Oxidation Products on <u>Ni-Based Alloys</u> in Steam and CO_2



Oxidation Kinetics of <u>Ni-Based Alloys</u> in Steam and CO_2

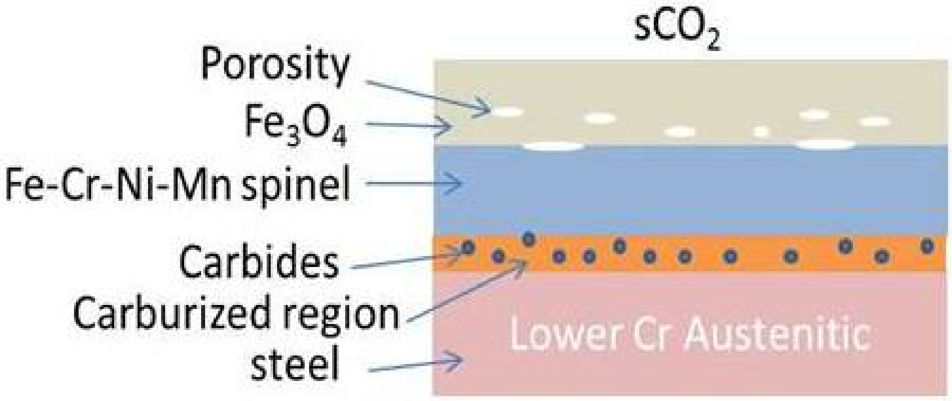


- Ni-based alloys generally show much less mass gain in sCO_2 compared to steam at 650 C.
- No internal oxidation observed for sCO_2 exposure. Could be due to relatively short exposure (~3000 hrs).

Carburization

- The free carbon on the alloy surface can reach the scale-alloy interface via cracks and grain boundaries in the scale and either dissolve or form carbides in alloys.
- Carburization of 9Cr-1Mo steel increases with pressure from 1 bar to 250 bars in CO_2 at 550°C.
- Increasing pressure increases the deposition of carbon in the inner spinel scale.

Need more data with long term exposure!



(Rouillard, F., et al., Oxidation of Metals, 2012. 77(1-2): p. 57-70).

Low Cycle Fatigue and Creep-Fatigue

- Given that sCO_2 is an effective oxidizer, it is expected that exposure of power plant materials to the sCO_2 conditions will influence their LCF and creep-fatigue life. However, there are no reports of investigation of this subject in the open literature.
- Intergranular crack initiation can be facilitated if the grain boundaries near the stress concentration are oxidized.
- The effect of oxidation in the crack propagation stage is also observed. Oxidation-assisted intergranular crack growth occurs if the cyclic oxidation damage is greater than the fatigue damage.

Need more data with long term exposure!

Conclusions

- Some significant technology challenges need to be addressed for FE based sCO_2 power cycles.
  - Recuperators
  - Combustion
  - Turbine cooling
  - Materials
- Good news is that none appear to be show stoppers!