Supercritical CO_2
Power Cycles
Symposium

Combustor for Direct-Fired Supercritical CO_2 Cycle

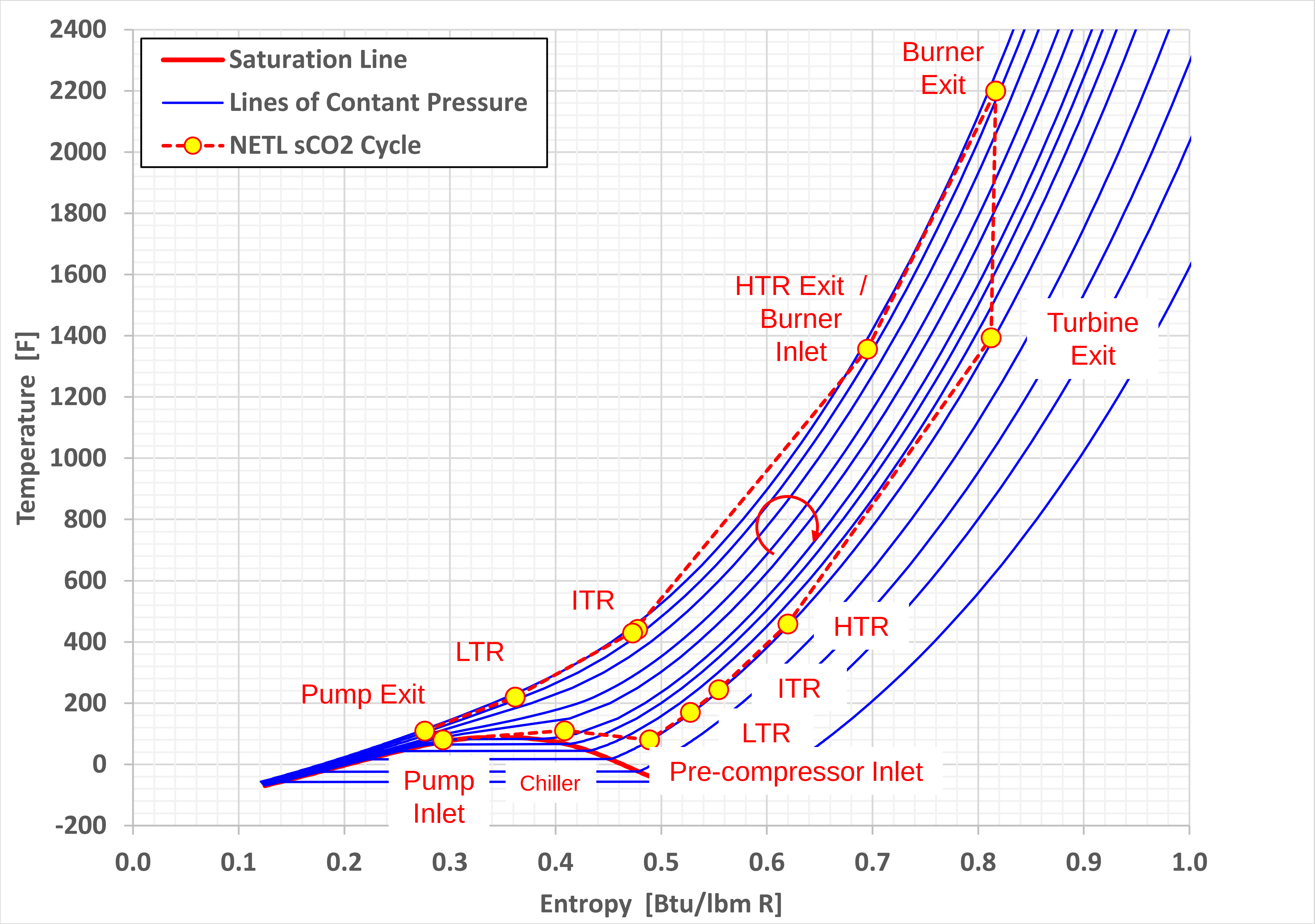
Mark Winquist (gti)
Institute Engineer
Energy Supply and Conversion

Agenda

- sCO_2 cycle summary
- Comparison to rockets
- Flame temperature impacts (non-CO_2 species)
- Pressure drop impacts (cycle efficiency)
- Design window
- Conflicting requirements
  - Combustion efficiency vs. species composition
  - Stability vs. ΔP
  - Combustion efficiency vs. ΔP
  - Mixing (temperature uniformity) vs. wall cooling
- Conclusion

sCO$_2$ Cycle on CO$_2$ T-S Diagram

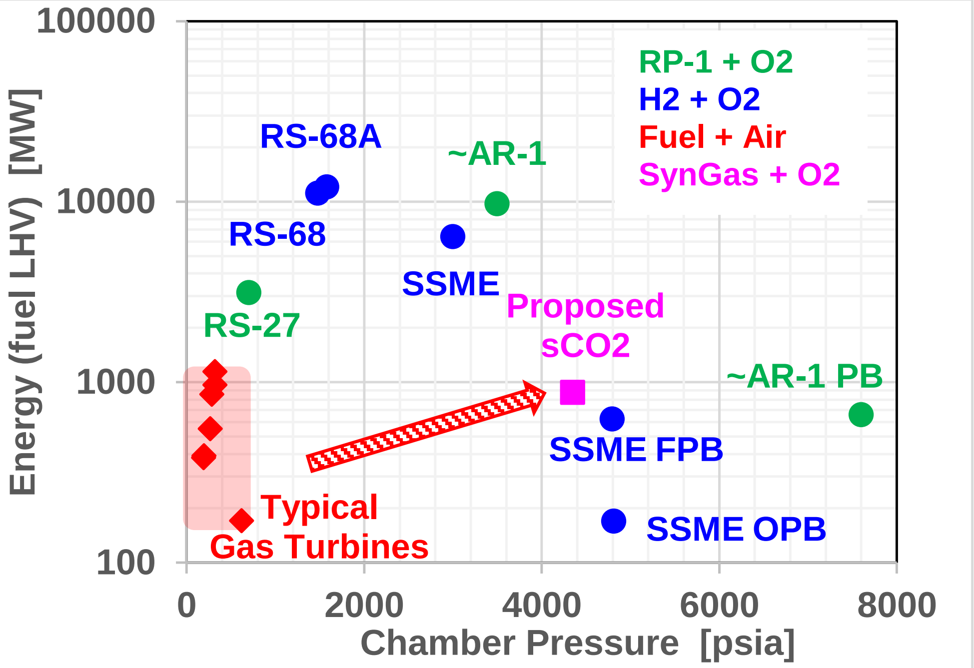
- sCO$_2$ cycle*
  - High density compression to ~300 bar (4400 psia)
  - Temperature increase through series of recuperators
  - Heat input from oxy burner
  - Expansion through turbine
  - Cooling through recuperators
  - Pre-compression and chiller to pumps
    - Just above critical point
    - High density yields lower compression loads



* Weiland, N.T. and White, C.W. (2019). Performance and Cost Assessment of a Natural Gas-Fueled Direct sCO2 Power Plant. NETL-PUB-22274

Direct-Fired sCO_2 Burner Operating Conditions Compared to Rocket Engine

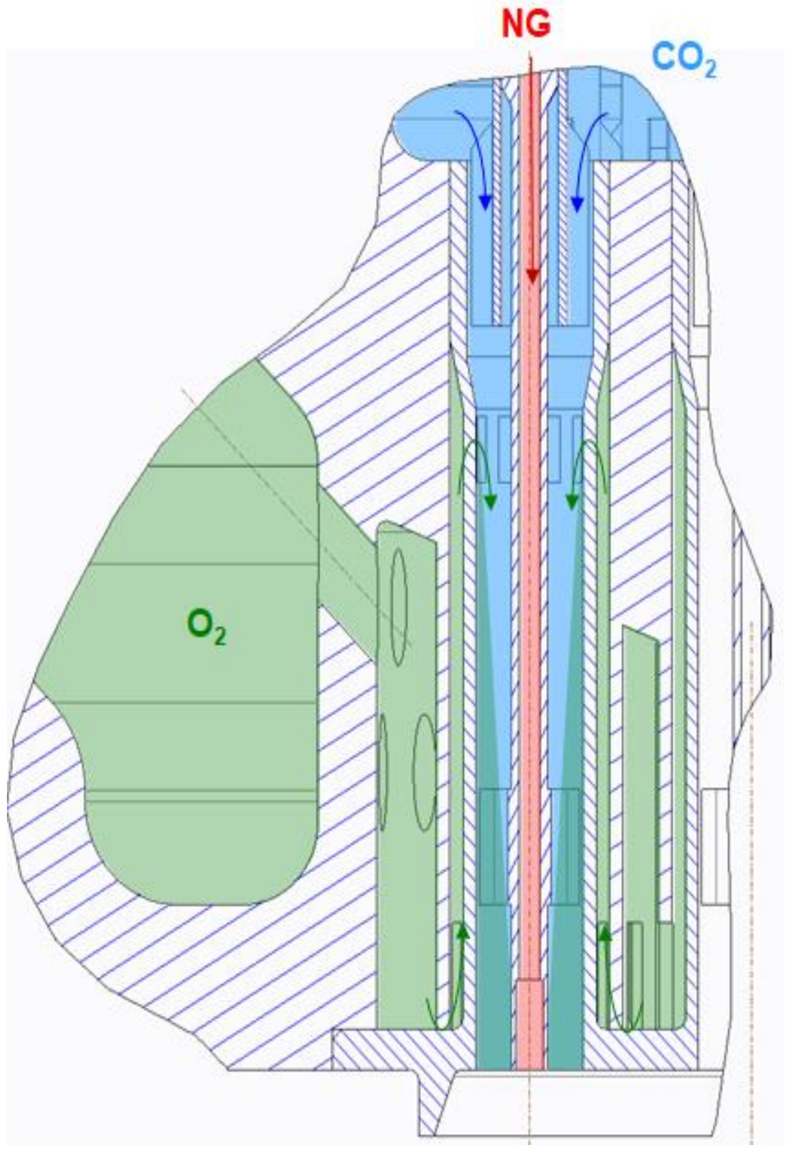
- "*The RS-25 evolved from Aerojet Rocketdyne's Space Shuttle Main Engine (SSME) that successfully powered 135 flights of the Space Shuttle. ... Between the shuttle program and the SLS program, the RS-25 and SSME engines have collectively experienced more than 1.1 million seconds of use*."*
- 1.1 millions sec < 13 days
- Power plant sCO_2 combustor operating conditions are similar to rocket engine pressures and heat fluxes, but must operate for much longer durations



*https://rocket.com/space/liquid-engines/rs-25-engine

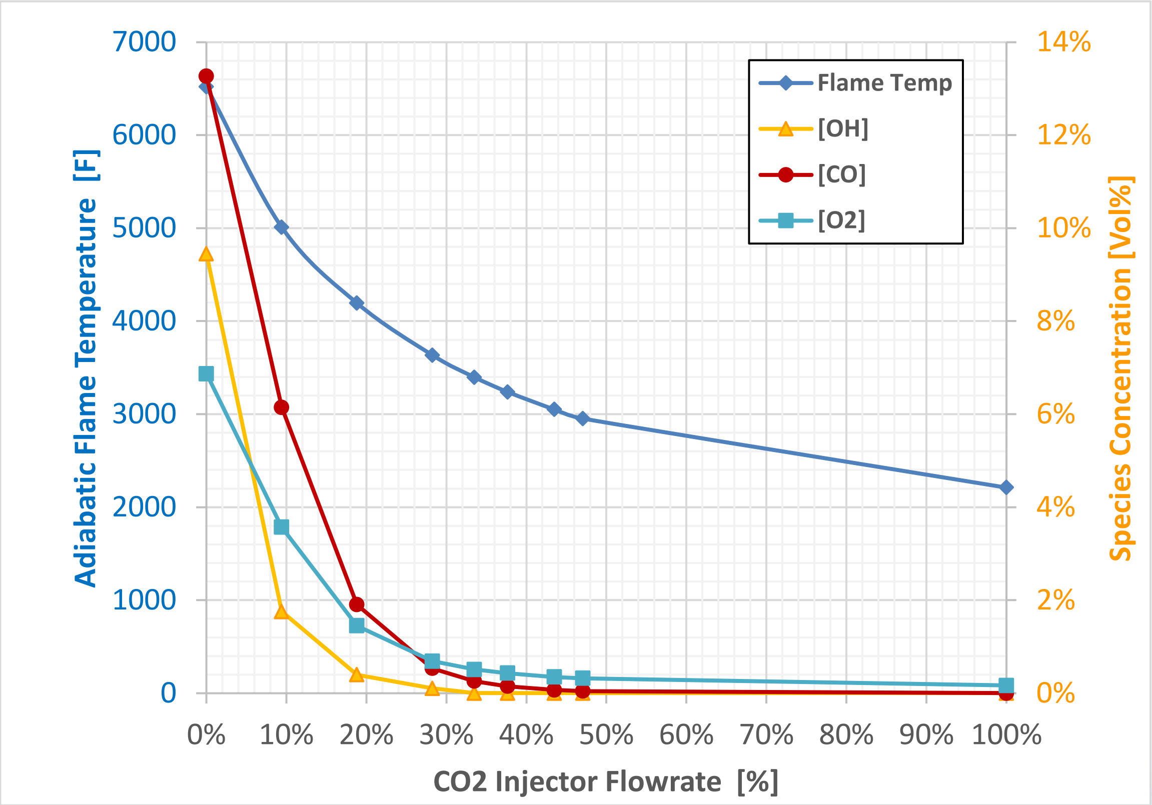
Critical Coax Injector Element Design Parameters

- Pressure drop (manifold – burner)
- Injection velocity and momentum ratios
  - Fuel to oxidizer
- Flame temperature
- Combustion stability
  - Flame, acoustic, reactant supply
- Burner wall compatibility
- Turbine inlet flow uniformity (mixing)



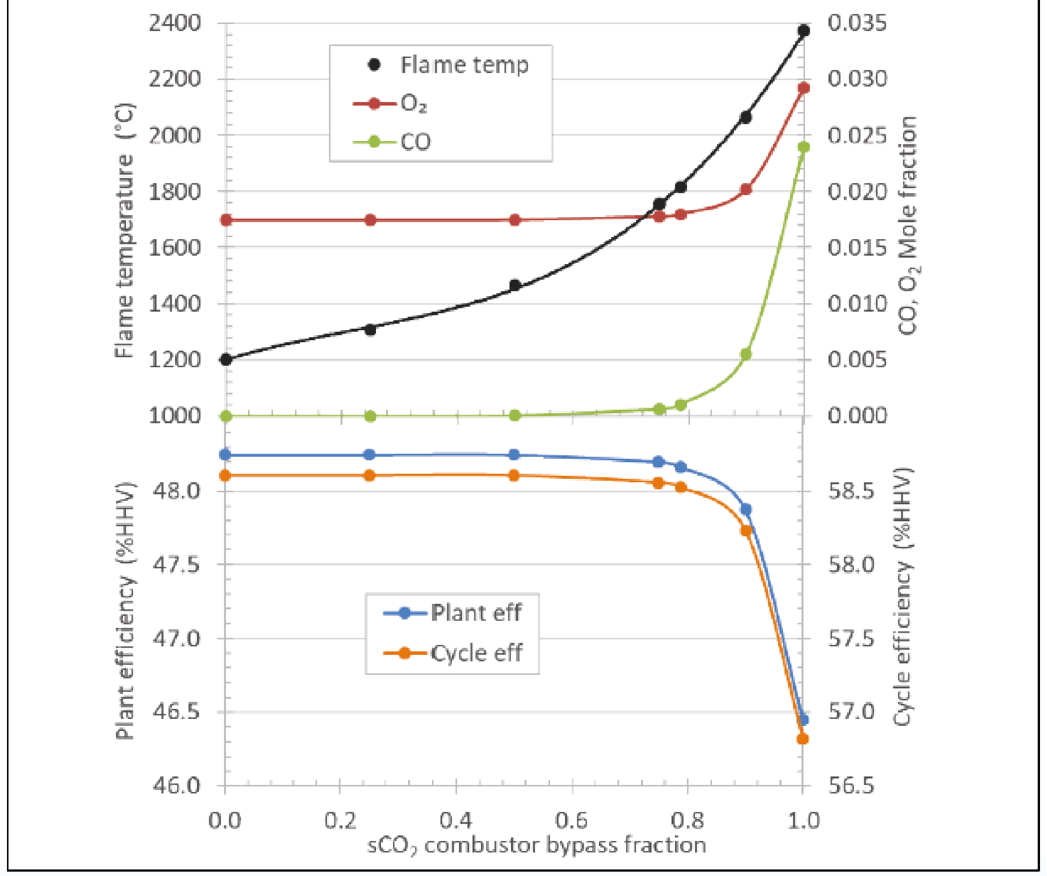
Non-CO_2 Species Reduce Cycle Efficiency

- To control flame temperatures, pre-mix CO_2 with O_2
  - Higher CO_2 content lowers flame temp and reduces CO, OH and O_2 concentrations



- Higher flame temperatures results in more non-CO_2 species
  - Higher compression loading

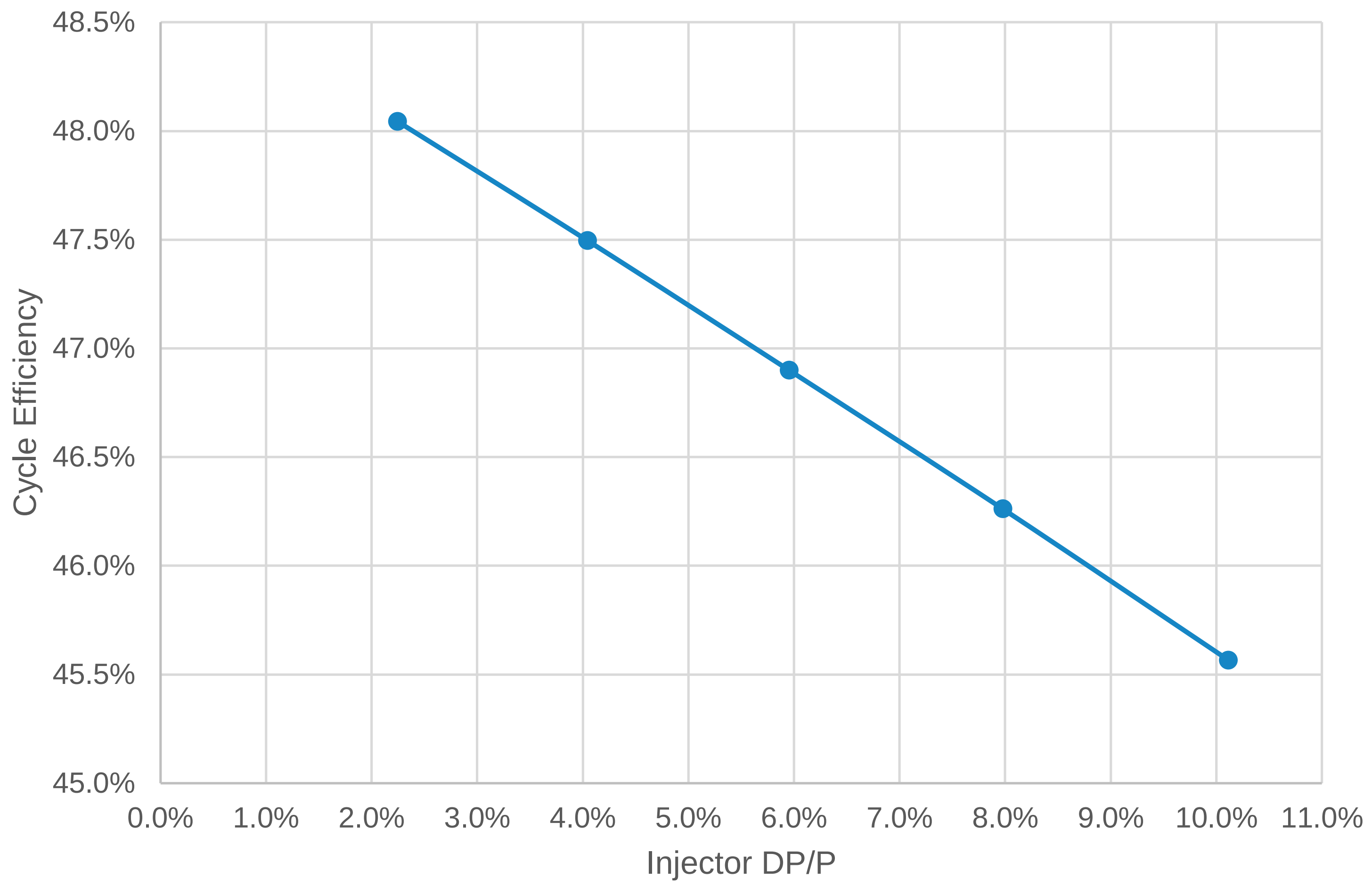
Exhibit 6-10. Effects of combustor bypass fraction on flame temperature, CO and O_2 exit mole fractions, plant efficiency, and cycle efficiency



Weiland, N.T. and White, C.W. (2019). Performance and Cost Assessment of a Natural Gas-Fueled Direct sCO2 Power Plant. NETL-PUB-22274

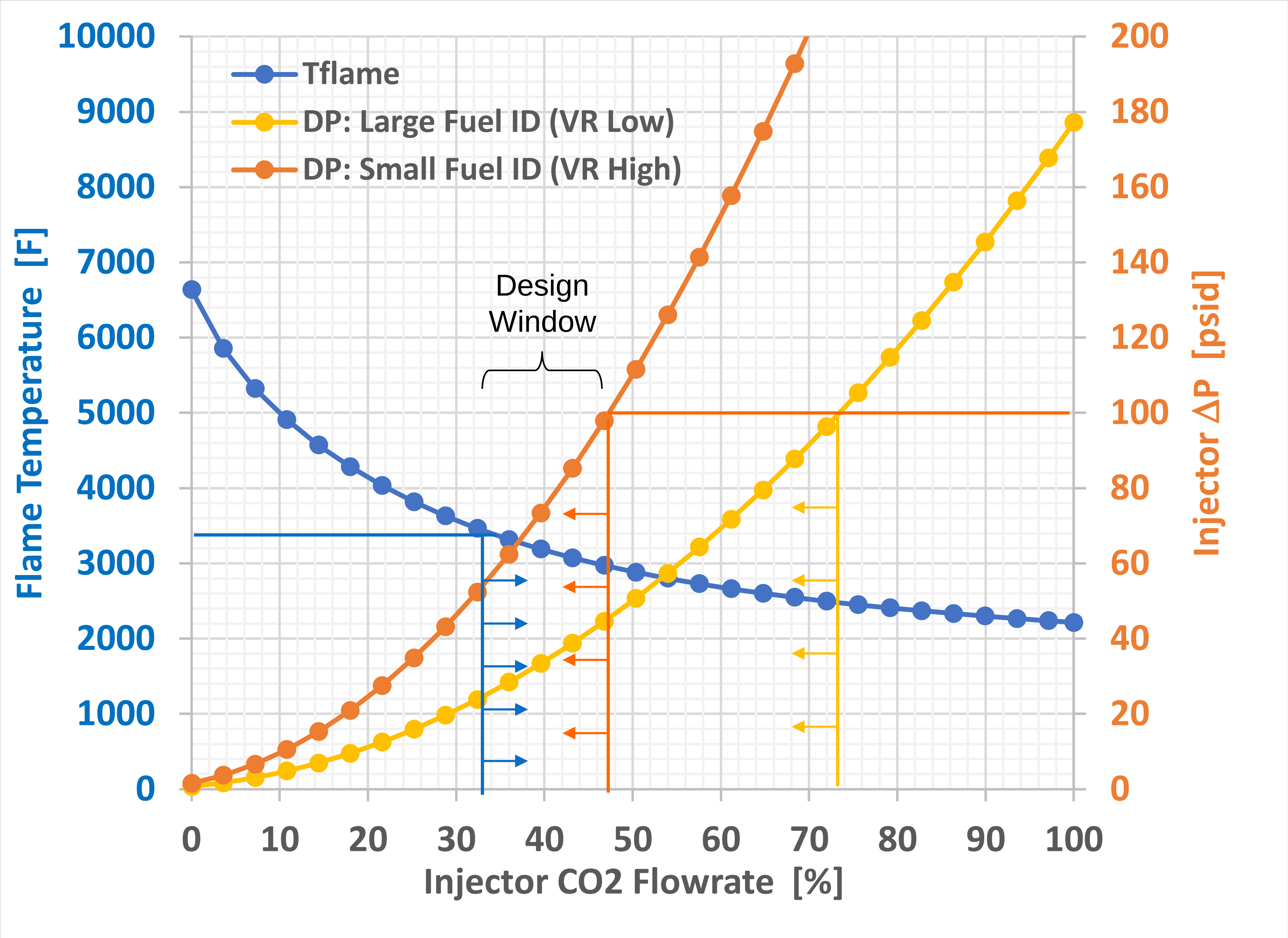
Increased Injector Pressure Drop Reduces Cycle Efficiency

- Injection velocities determined by element geometry and pressure drop
  - Higher fuel-side injection velocities yield shorter mixing lengths
    - Better mixing and performance
  - Higher injector ΔP requires more compression loading
    - Reduced cycle efficiency



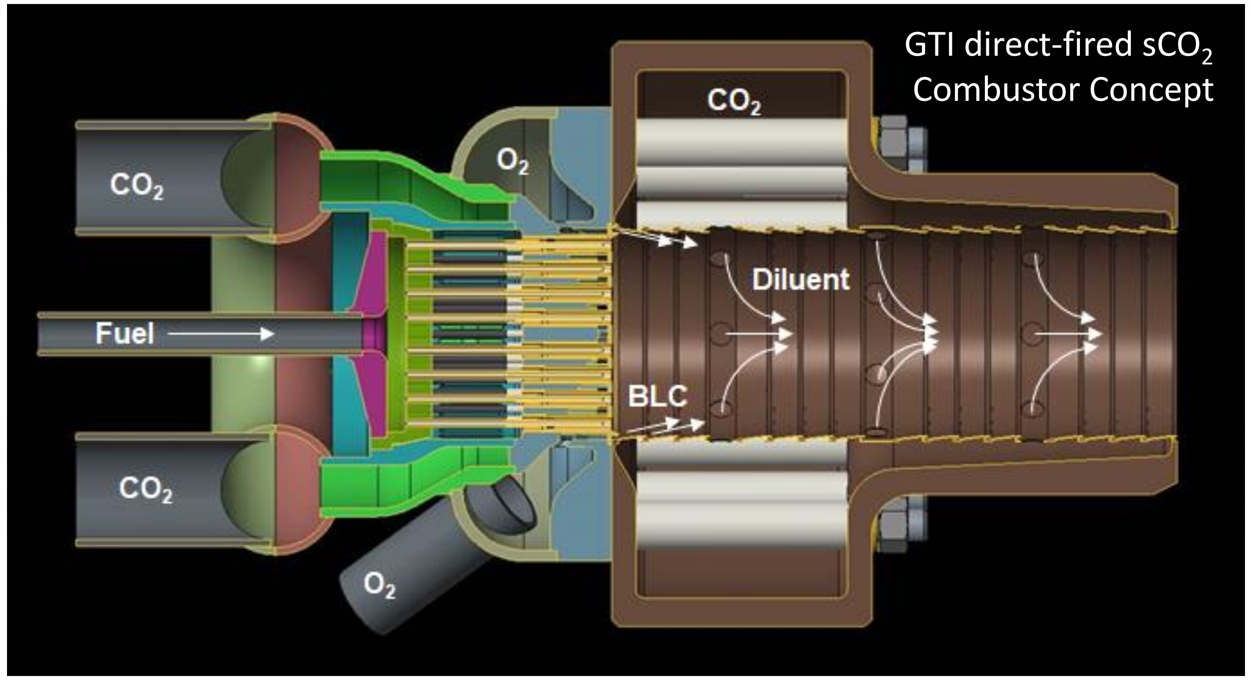
Pressure Drop and Flame Temperature Limits Define Design Window

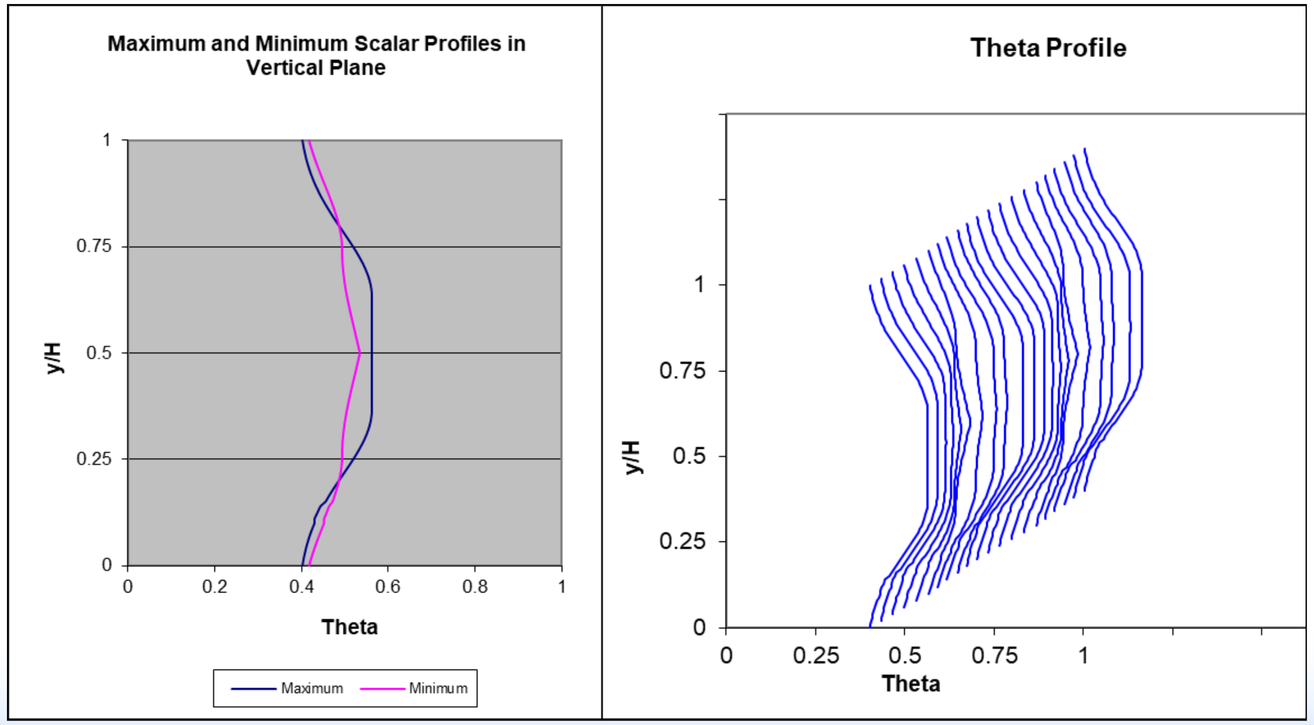
- Example for design limits of <100 psid and <3400 F
  - Need > 33%of injector CO_2 to meet temperature limit
  - Need 73% of injector CO_2 to meet ΔP limit for low velocity ratio (VR) element
    - Longer mixing length, longer burner
  - Need 47% lbm/sec of injector CO_2 to meet ΔP limit for higher velocity ratio (VR) element
    - Shorter mixing length



Burner with CO_2 Coolant and Diluent

- CO_2 not routed to injector is used as boundary layer coolant (BLC) and diluent
  - BLC designed to cool wall so mixes poorly
  - Diluent injection designed to maximize mixing but provides minimal wall protection
    - NASA mixing tool utilized for diluent injection design


GTI direct-fired sCO_2 Combustor Concept



Conflicting Design Requirements

Design Feature	Parameter	If Design Feature Too High	If Design Feature Too Low
Flame Temperature	Species Composition	Excess non-CO_2 species and cycle efficiency loss	High injector CO_2 yields high ΔP and cycle efficiency loss
Velocity Ratio	Stability	Potential flame instability, high ΔP, cycle efficiency loss	Potential low frequency combustion instability, poor mixing
Pressure Drop	Combustion Efficiency	High ΔP and cycle efficiency loss	Low velocity ratio, poor element mixing and longer burner
BLC and Diluent Injection Mixing	Turbine Inlet Gas Uniformity	Poor mixing with combustion gases and non-uniform turbine inlet temps	Overheated wall and short life and/or wall damage

Conclusion

- High pressure direct-fired sCO_2 burners have many design challenges
- Conflicting requirements often result in small design windows
- An injector/ burner combination that navigates those design requirements to meet system cycle performance has been created