SOLAR STRATEGIC GROWTH

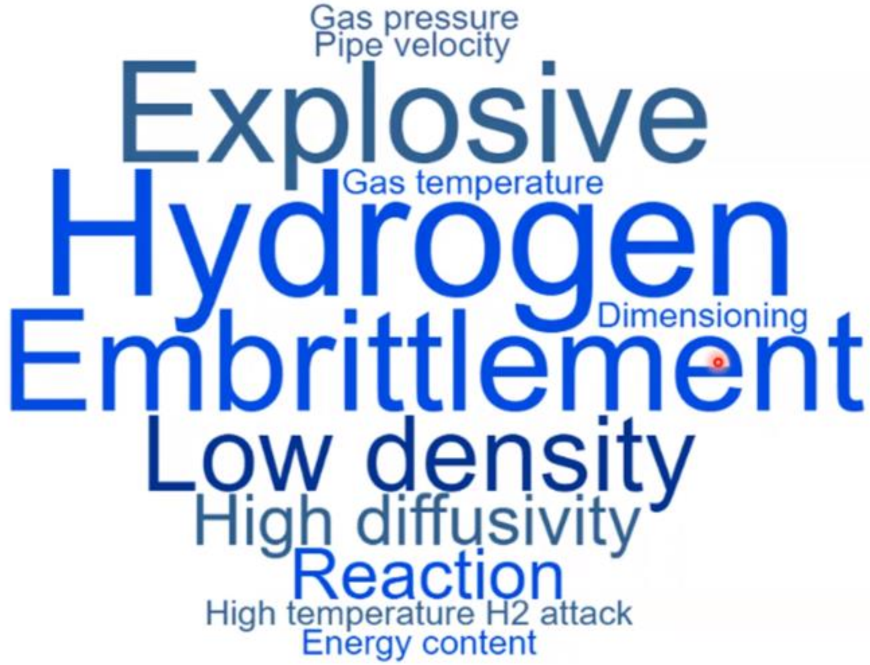
Overview of Expected Impacts on Materials using Hydrogen

Ferenc Pankotai
Manager, Combustion Engineering and Additive Manufacturing

March 18, 2021

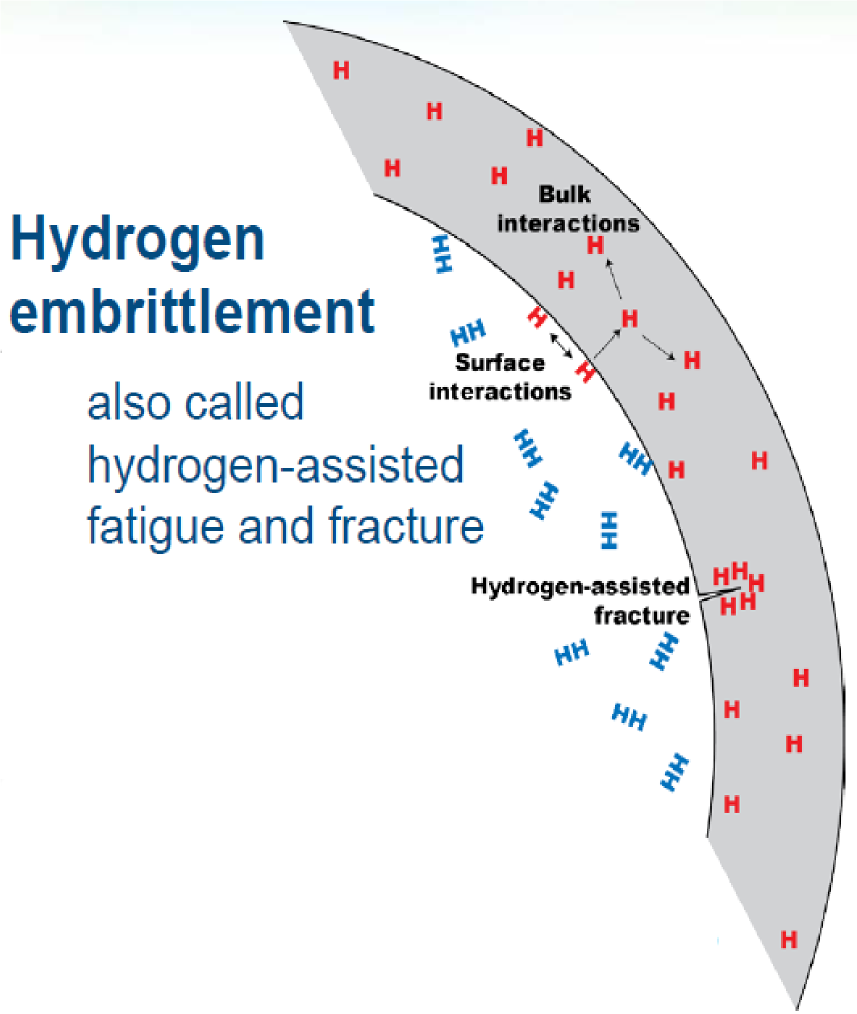
Potential Hydrogen Impact on Engine and Package

- Injector Flashback
- Pollutant Emissions
- Combustion Stability
- Operability
- Engine Component Durability
- Fuel System Embrittlement
- Package Safety
- Start-up
- Flameout
- Flame Detection



Hydrogen Impact on Gas Turbine Materials

- More Diffusive
  - Material Selection Important
  - Using Appropriate Seals
    - Elastomers appropriate for H_2 in valves and gas compressors
    - Metallic seals compatible with H_2
    - Leaks may contain disproportionate H_2 levels
  - Prevent Hydrogen Embrittlement
    - Stainless Fuel System Components
    - Pipes, Valves, Tubing, etc.



Solar's H_2 Technology Experience

1985

- First high-H_2 experience
- 40% H_2 (wet)

1992

SoLoNOx™ introduced

1995

U.S. refinery runs Taurus 60 at 100% H_2

2003

Titan 130 SoLoNOx™ at 9% H_2

2010

First Titan 130 High Hydrogen Generator Set commissioned in China at 60% H_2

2013

Partnered with DOE for High-H_2 rig testing & analysis

2018

46 High Hydrogen Generator Sets reach 2M operating hours

Today

SoLoNOx™ 20% H_2 capable

Solar Product Hydrogen Capabilities*

SoLoNOx™ (DLE)

Up to 20% H2

- Refineries in United States up to 20% H_2
- Chemical Plant Applications in China & Europe up to 14% H_2

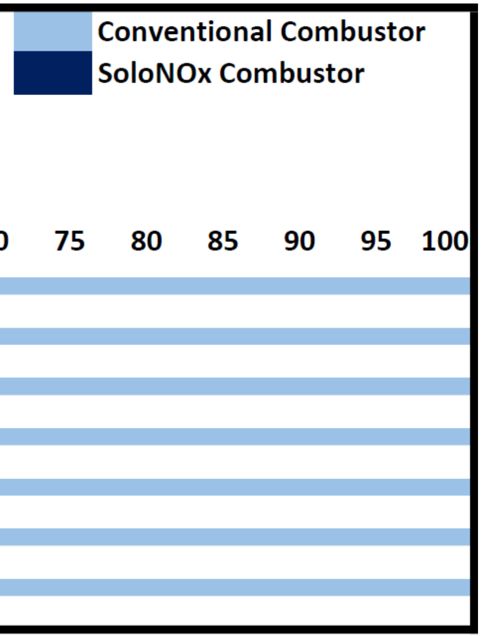
Conventional Combustion

Up to 100% H2

- Steel Industry Applications in China up to 65% H_2
- Propane Dehydrogenation application in Belgium up to 83% H_2
- Refinery Application in the United States up to 37% H_2

H2 Product Capabilities
Solar Turbines - Gas Turbine Engine and Package (New Equipment)

Model	Horsepower hp	Kilowatts kW
Centaur 40	4,700	3,515
Centaur 50	6,130	4,600
Taurus 60	7,700	5,670
Taurus 70	11,110	8,180
Mars 100	15,900	11,350
Titan 130	23,470	16,530
Titan 250	31,900	23,100



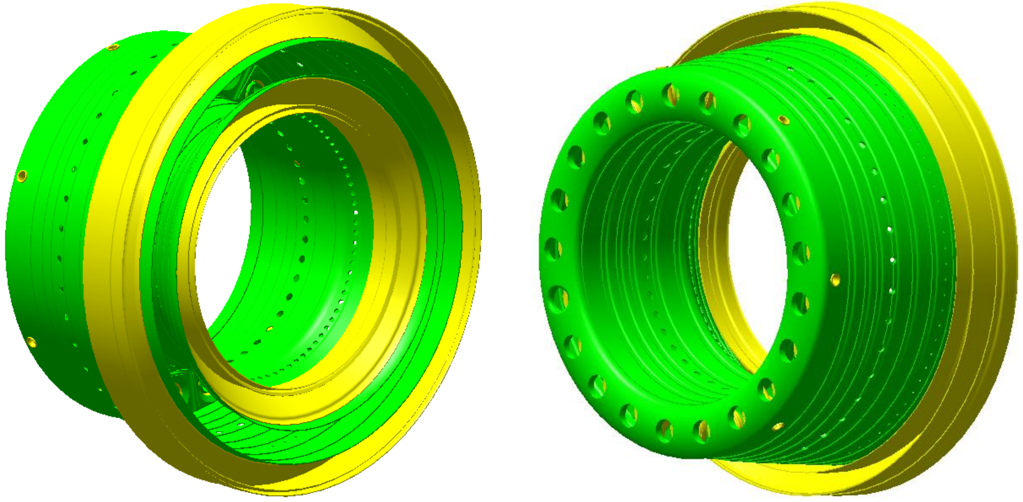
*Hydrogen capabilities shown are for new equipment configurations. Depending on operating conditions and requirements, some restrictions and/or additional engine and package hardware and software modifications may apply. Higher hydrogen requirements can be considered on a case-by-case basis.

Coke Oven Gas (65% H_2) Fleet Durability Experience

- Multiple Generator Set Customers In China
- First T60GS Sold In Year 2005, First T130GS Commissioned In Year 2010
- 17 Customers in China
- 46 Packages Total, 36 Titan 130 and 10 Taurus 60
- Approaching 2 million hours of operation

Conventional Combustion System (Titan 130)

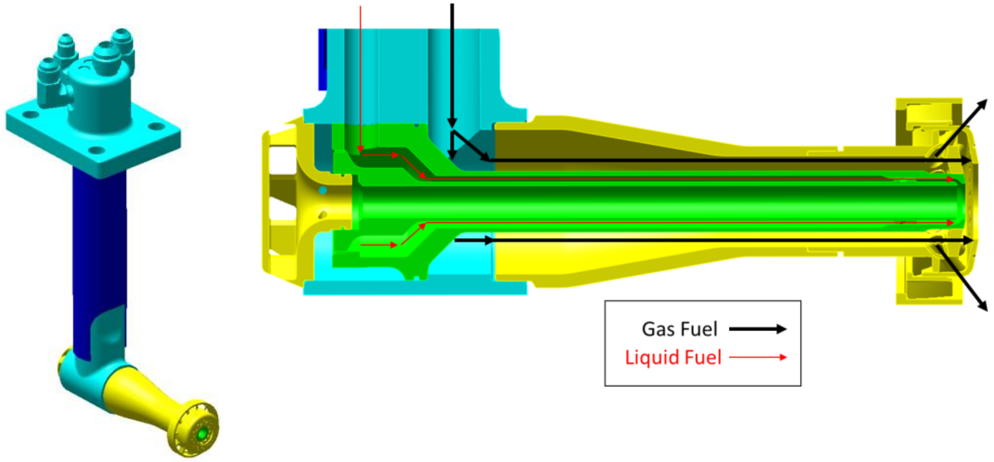
- Liner (standard conventional liner):



Materials

Alloy X | Alloy 230

- Injector(s) (MBTU/LBTU Dual Fuel):
  - Low BTU Dual Fuel Variant (most common)
  - Med BTU Dual Fuel Variant



Materials

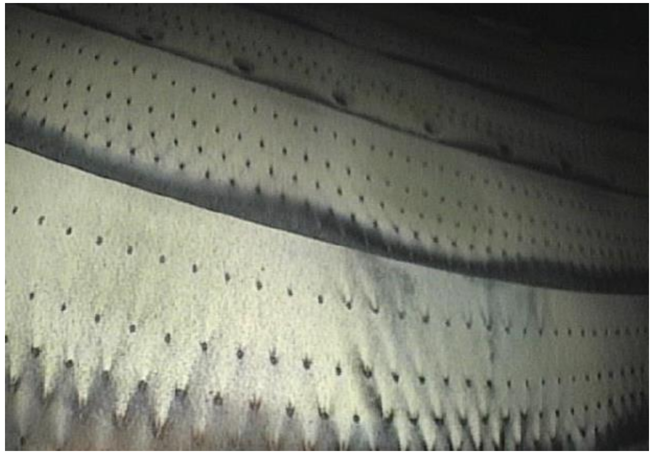
Alloy X | Alloy 230 | SS 316L | SS 316

In-situ Coke Oven Gas Experience

- 36 x Titan 130 units – operating on COG (65% H_2)

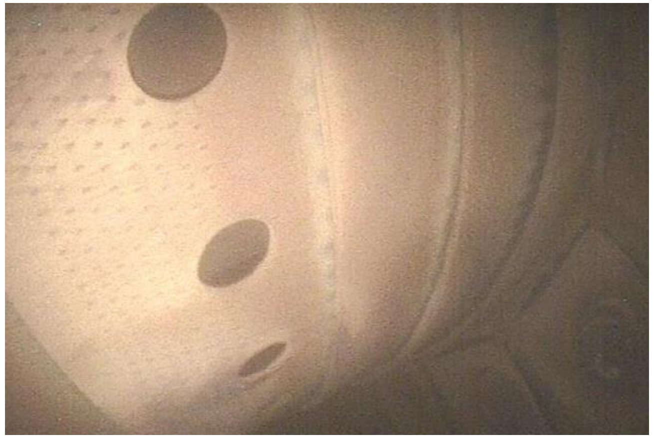
<u>Titan 130</u>
Inspected at site
~22,000 Hours

Good hardware condition



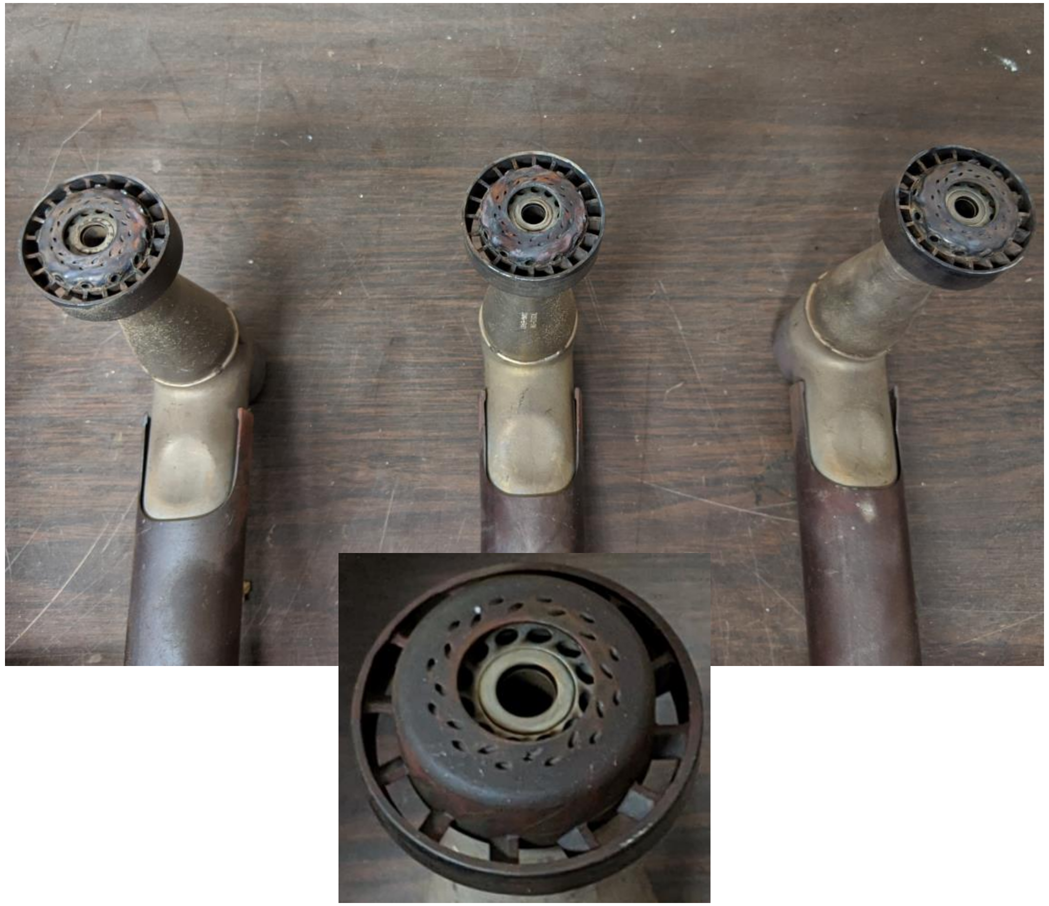
<u>Titan 130</u>
Inspected at site
~23,500 Hours

Liner spider cracking discovered
(low number of units)
(Does not affect engine performance 30,000 hours still obtainable)



Post Engine Exchange Coke Oven Gas Experience

- Titan 130 inspected after engine return ~30,000 hours



Coke Oven Gas Experience Summary

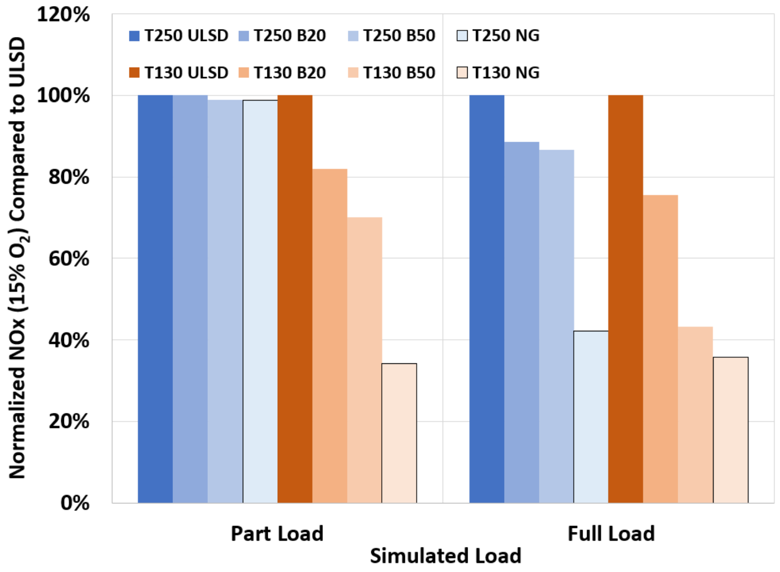
- Combustion system material well performing on COG (H2) and has demonstrated this with a sizeable fleet
- <u>Fuel quality </u>is very important to minimize hardware component life degradation
- Cracks found in combustion liners have not impacted performance or service life on any deployed units
  - Experience is pointing to <u>fuel quality</u>
  - To date, observed liner cracking has not impacted engine operation or reliability
- Injector distress is attributed to <u>poor fuel quality / handling</u>
  - To date, overserved injector distress has not impacted engine operation or reliability
- High time hardware is generally in good condition upon return
- Our currently utilized material ready to support the High Hydrogen DLE technology

Progress in Enabling Biofuels at Solar Turbines

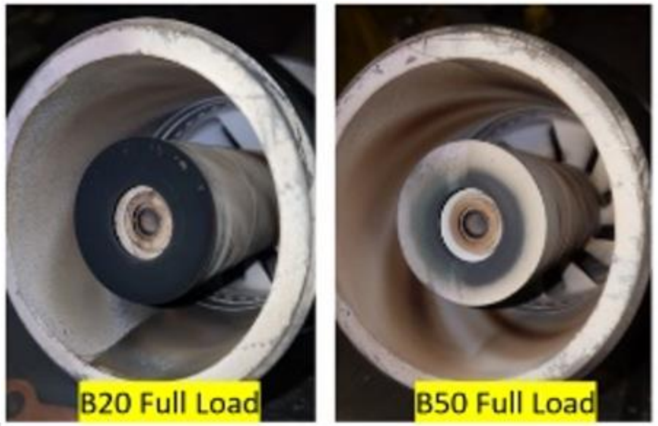
- **Gas Turbine Users Exploring Biodiesel to Replace Diesel Fuel for Carbon Emission Reductions**
  - 80% Reduction in CO_2 Possible on Lifecycle Basis compared to Diesel Fuel Operation
  - Customer Interest in Biodiesel Blended with Diesel Fuel from 20% (B20) to 100% (B100)

- **Developing Capability in Collaboration with National Biodiesel Board (US based)**
- **Conventional Combustion Turbines Proven to B100**
- **SoLoNOx (DLE) Qualification in Progress**
  - Combustion Rig Testing using B20 & B50 on Titan 250, Titan 130 & Taurus 70
  - Emissions (NOx, CO, UHC and smoke) Comparable to Diesel
  - Injector Durability Proven – Primary Concern is Injector Carbon Deposition
  - Summary Paper Accepted for 2021 ETN Gas Turbine Conference in October

Emissions Using ULSD, B20 And B50



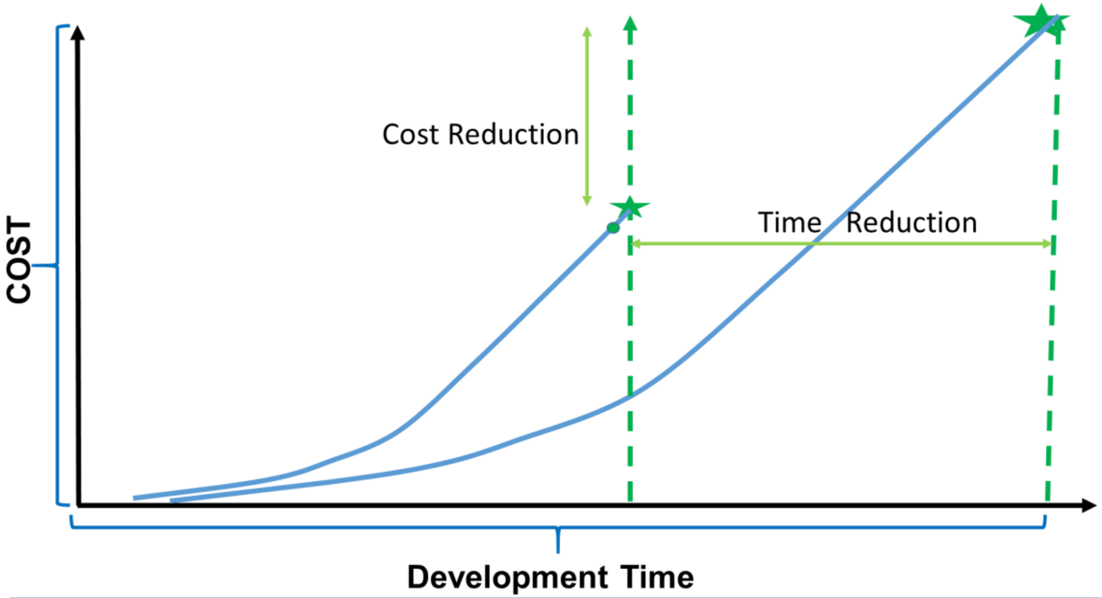
Titan 130 Injectors After The Tests



- **Planning Engine Field Trial in 2022**
  - Verify Rig Data and Demonstrate Startup & Longer Duration Operation

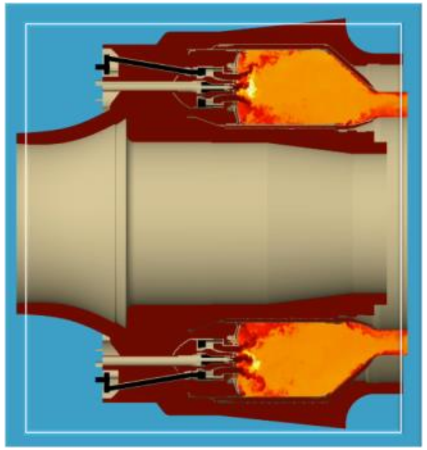
- **Fuel Quality Is Of Utmost Importance For Success**
  - Must Comply With Fuel Specifications. Longer Shelf-life needed for emergency/backup use.
  - Need Biodiesel Producers, Suppliers And Users To Follow Best Practices.

Hydrogen Technology Enablers

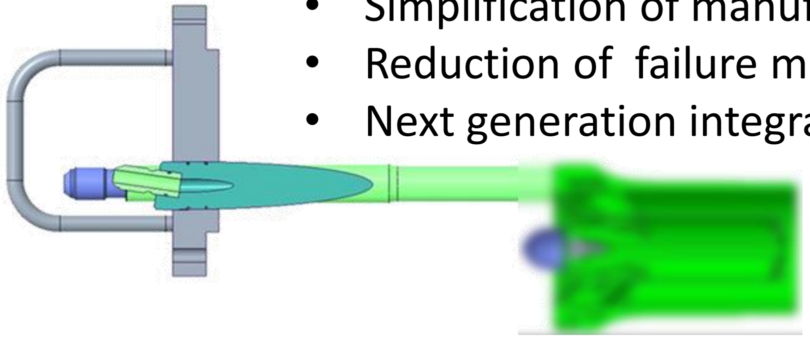


Combustion Digital Platform

- Thermo-Acoustic Frequencies and Mode Shapes
- Aero-Thermal Studies (Flow split/ pressure drops)
- Thermal, Structural & Modal Analysis



Additive Manufacturing



- Optimized designs
- Simplification of manufacturing
- Reduction of failure modes
- Next generation integrated burners

Combustion Test Facility

- Mixing Rig
- High Pressure Single Injector Rig
- Annular Rig atmospheric pressure test

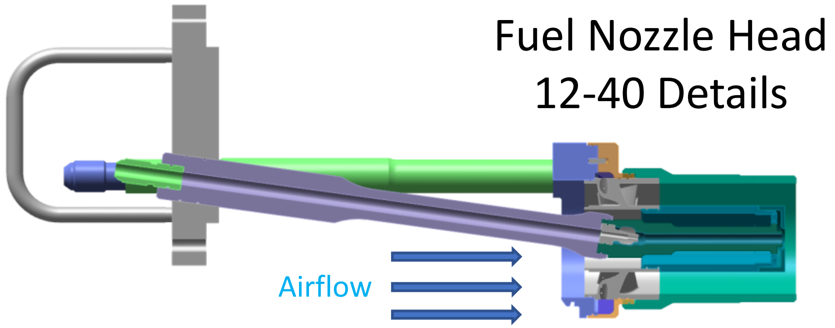
Test Cell & Injector Rig

DfAM SoLoNOx (DLE) Injector

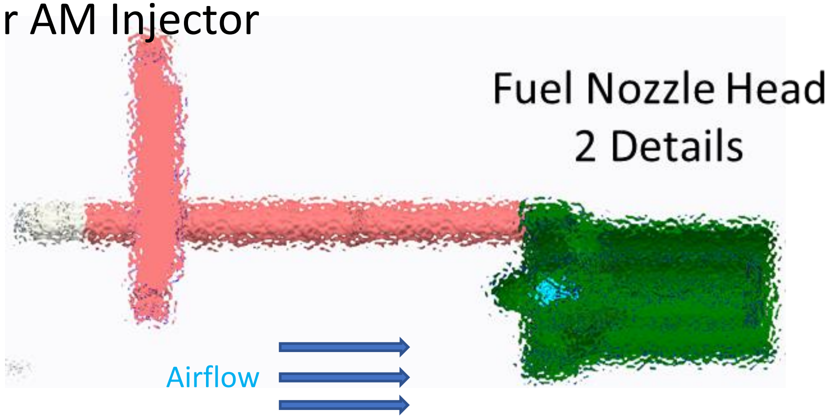
Design for Additive Manufacturing

- Optimize Design
- Utilizing Current Material
- Simplify MFG
- Reduce Failure Modes
- Reduce Development Cost and Cycle Time by 70%

Current Production



Design for AM Injector

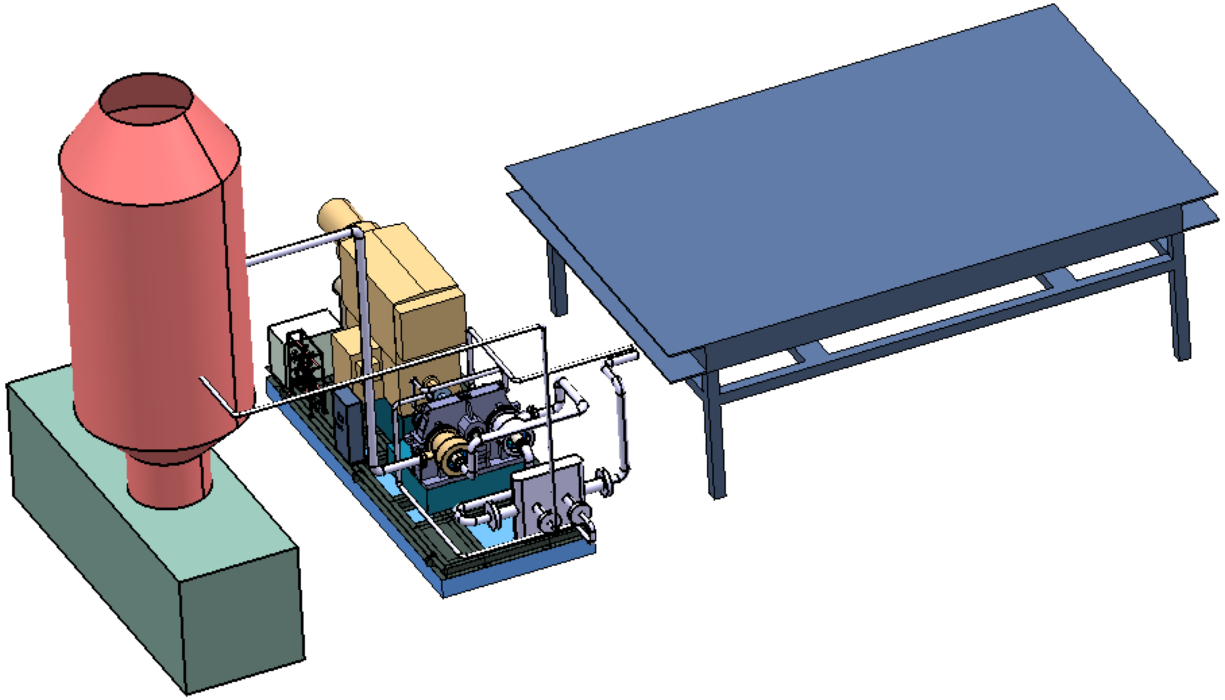


Exhaust Heat Utilization - Supercritical CO_2

Uses “Supercritical CO_2” or sCO_2 as the fluid instead of steam for a bottoming cycle heat recovery

Compared to steam from boiler production:

- Improved thermodynamic efficiency
- Less complex and less maintenance
- Increased station reliability
- Lower risk to operator
- Greater economic benefits
- Zero water use
- Additional power extracted is zero carbon



Material Needs - sCO_2 System Components

- Erosion resistance
- Mechanical properties/material stability and durability in sCO2 environments
- Cost effective fabrication (e.g. welding, additive manufacturing, etc.)

Thank You