Recent Advances in Power Cycles Using Rotating Detonation Engines with Subcritical and Supercritical CO_2

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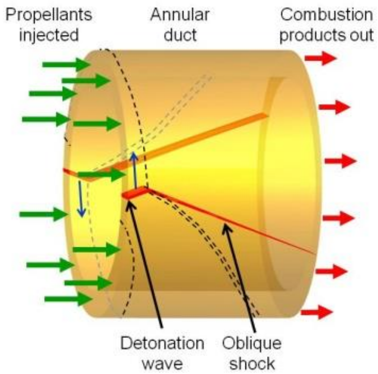
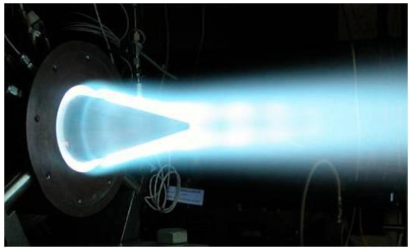
Pressure Gain Combustion/Rotating Detonation Engine Features and Cycle Advantage

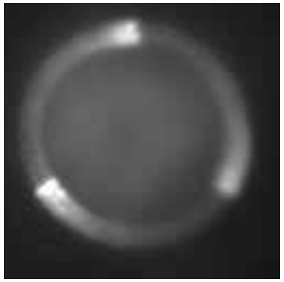
PGC-RDE Features

Rotating Detonation Physics



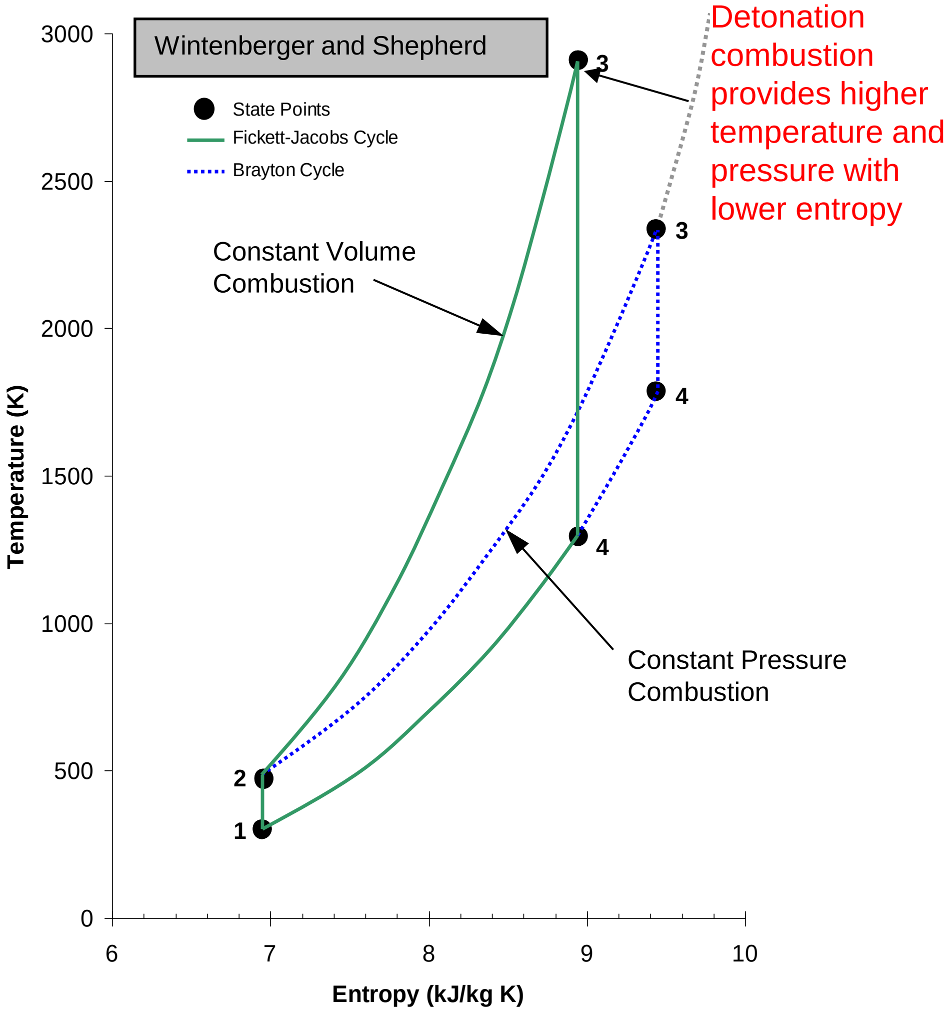
Rotating Detonation Engine Combustor





HS Video Recorded at 180,000 Frames/Second

PGC-RDE Cycle Advantage



Air-Methane (Initial Conditions: 1 bar, 300 K)

Aerojet Rocketdyne RDE Development Progress

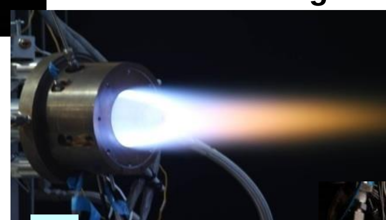
524 Hot Fire Tests to Date

2010 Proof of Concept

2010 Multiple Propellants

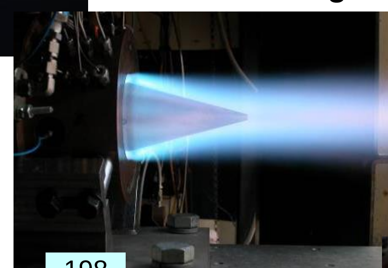
Initiating and maintaining continuous detonation across a range of effective operating conditions

2011 Plasma System Integration

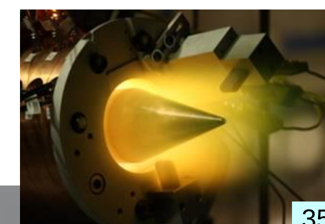


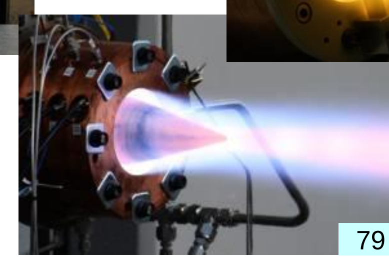
Use of a plasma system to improve efficiency and allow air-breathing operation without supplemental oxygen

DARPA 2012 Code Anchoring Data



DARPA 2013 Vulcan Exhaust Probes

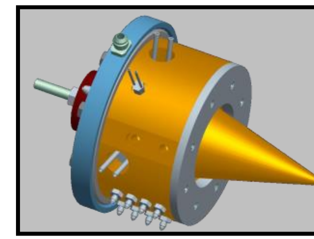




DARPA 2013 Liquid Fuel Demonstration

Efficient energy conversion and scaling

Future Optimization



Detonation Behavior Characterized Across Broad Range of Conditions

Multiple propellants (both gaseous and liquid fuels)

- **Air, enriched air and oxygen**
- **Methane, ethane, hydrogen, JP-8 and JP-10**
- **Equivalence ratio from 0.4 to 1.2**
- **6X throttling range**

Dozens of hardware configurations up to 21 cm in diameter

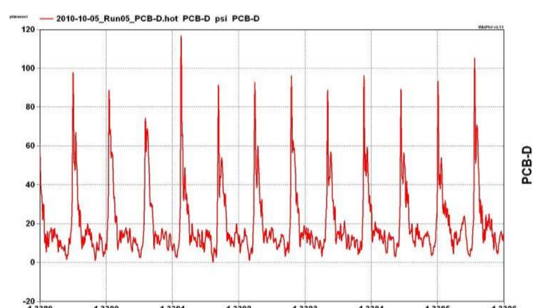
With and without transient plasma augmentation

- **Incorporating a plasma augmentation system in the RDE increased wave velocity and minimized the need for air enrichment to sustain detonation**

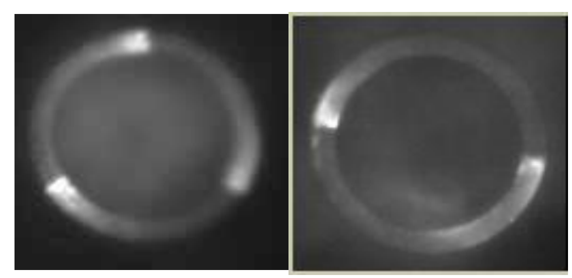
Testing indicates wide variety of behavior at identical flow conditions

- **Highly dependent on engine configuration**

GOX-Methane

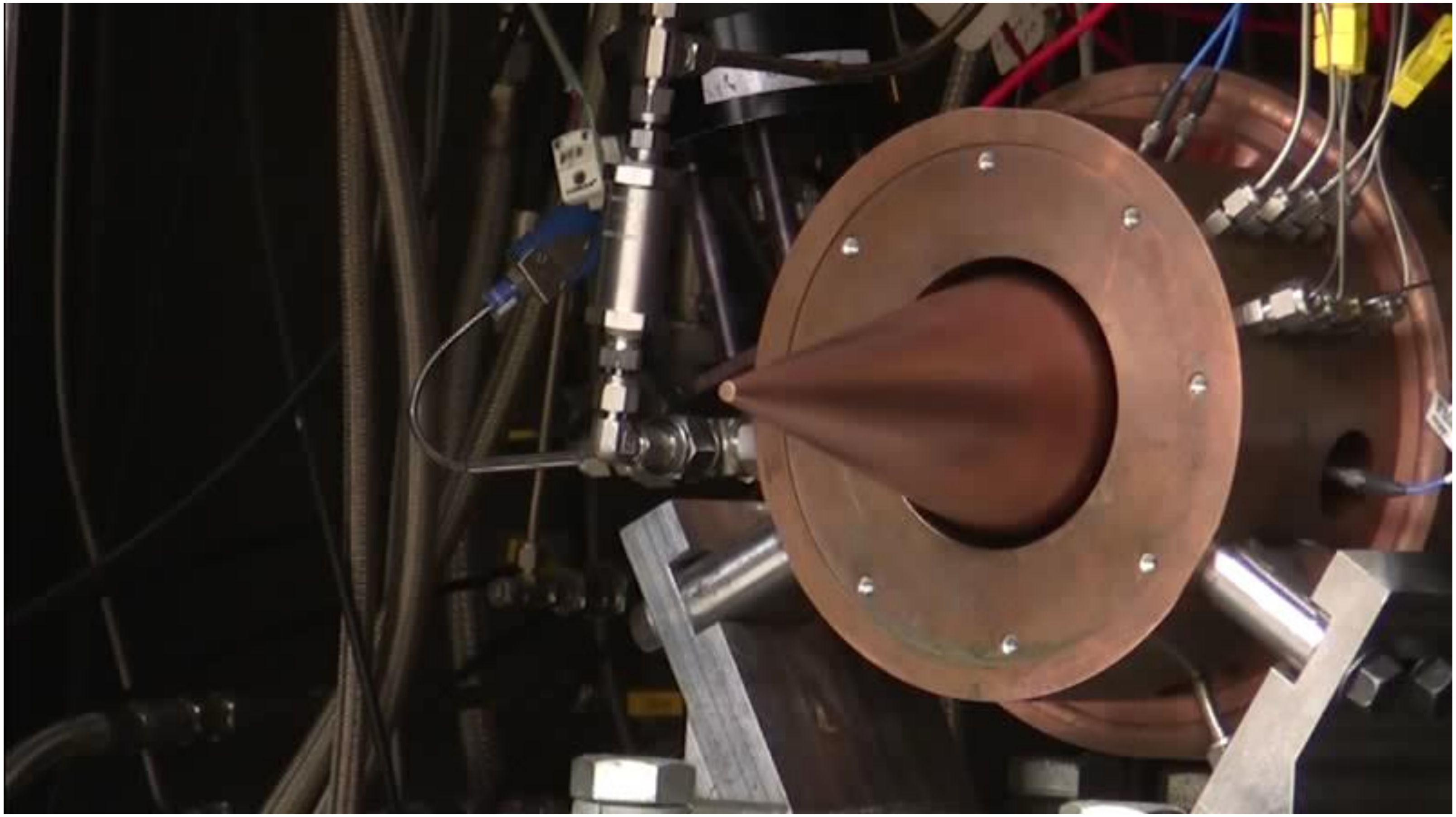


5 MHz High Speed Data



High Speed Video

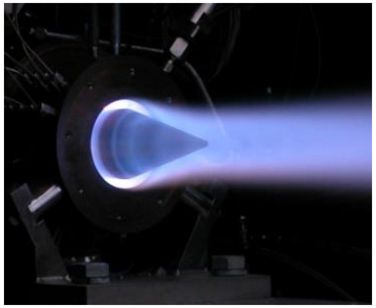
RDE Natural Gas Testing (2012) Video

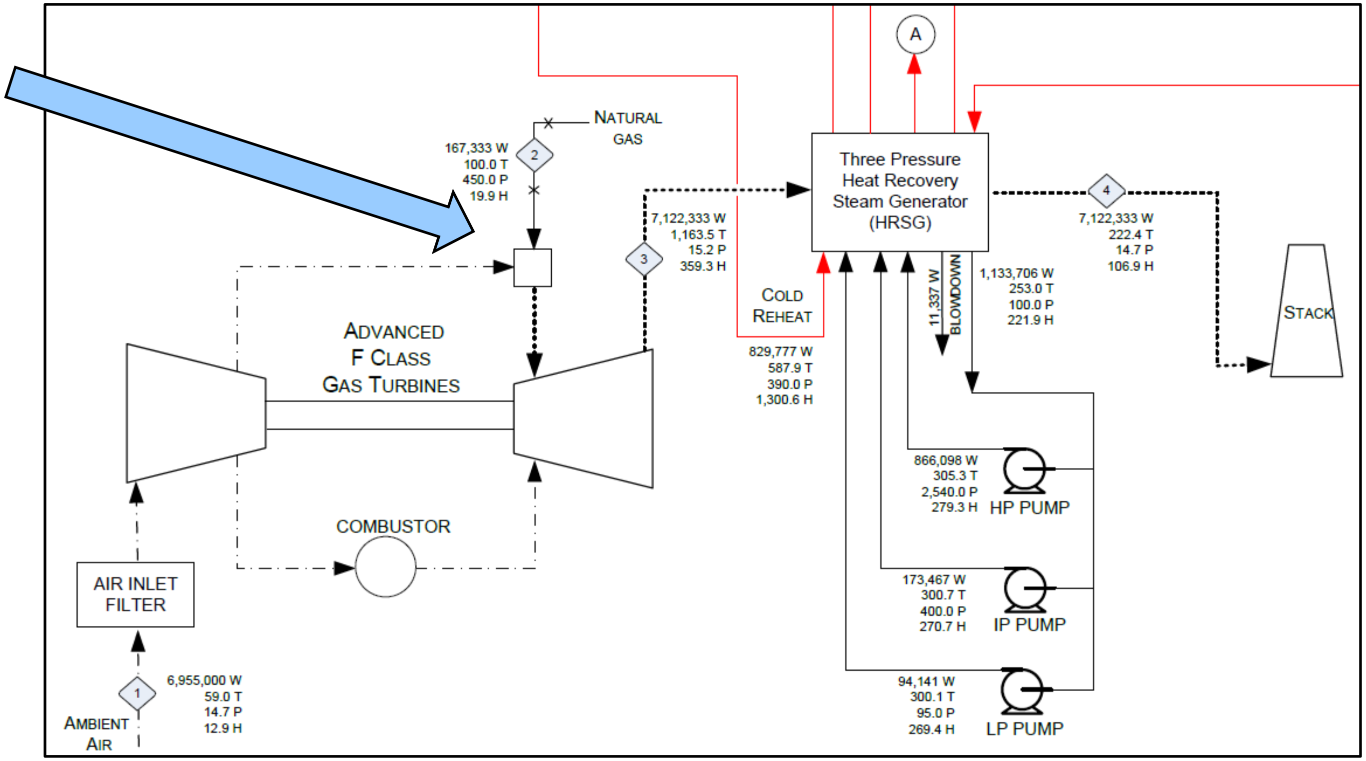


Initial Look at PGC/RDE Benefits and Impact

•By replacing conventional gas turbine burners with rotating detonation combustors, equivalent thermal output can be generated with 14% less fuel consumption.

•For Natural Gas Combined Cycle baseline plant conditions (DOE/NETL Case #13), plant efficiency (LHV) is estimated to improve from 55.7% to approximately 61%.





Pressure Gain Combustion/Rotating Detonation Engine: ARPA-E Project Overview

Goal: Achieve 15% reduction in Natural Gas Power Plants Specific Fuel Consumption (SFC) while simultaneously reducing NOX emissions.

Concept/Innovation: Replace conventional burners with rotating/continuous detonation combustors

Impacts: Decrease SFC by 10-20% for ground base power generation. 15% reduction in SFC equates to:

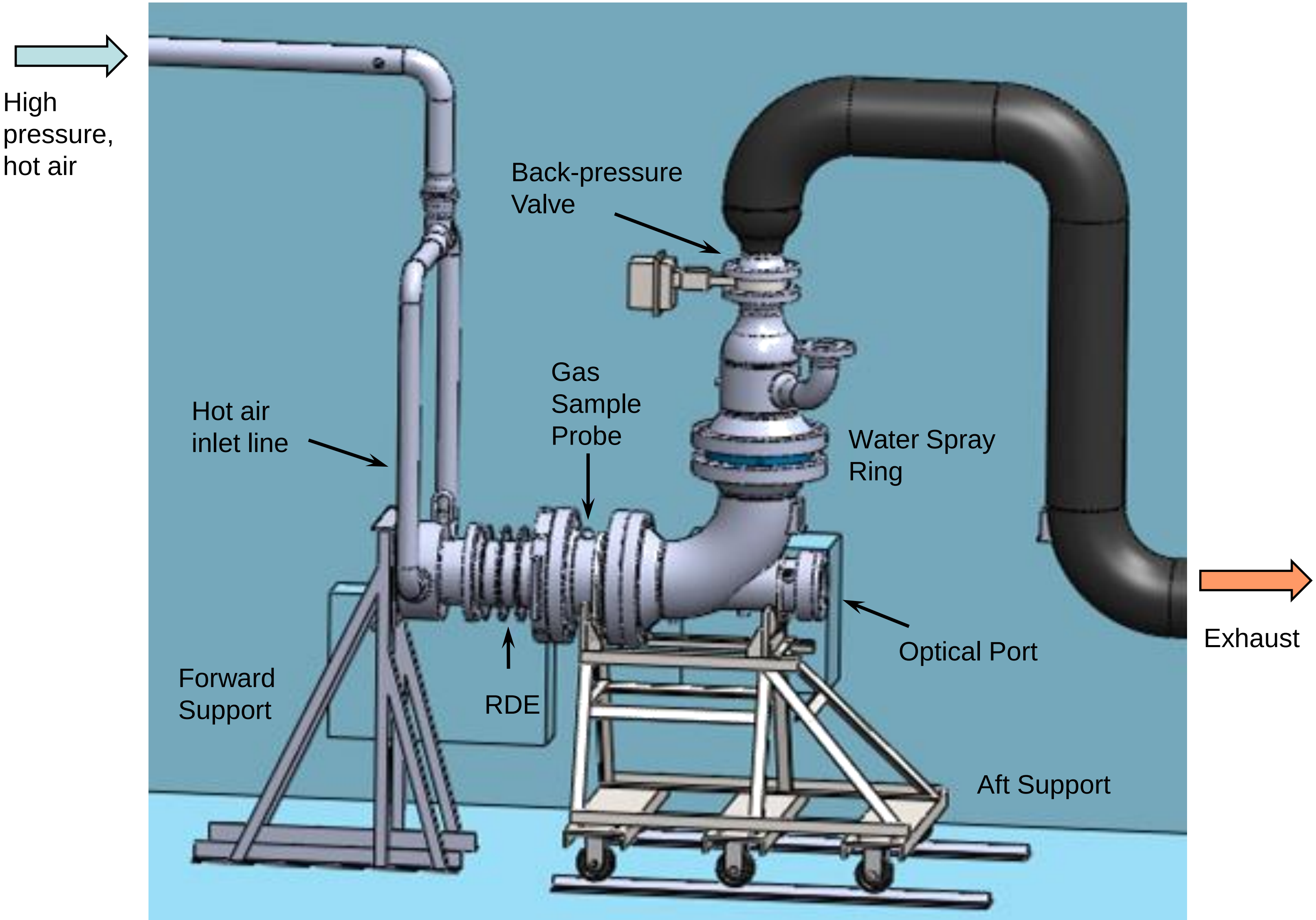
- 1.2×10^{12} scf/yr reduction in natural gas use in U.S. (3% of power grid)
- 6.0×10^{7} metric tons of CO_2 emissions reduction per year
- 5 million dollars per year savings in reduced fuel cost per large scale turbine in service (Frame 7FA)

Key Risks and Mitigation: Efficient detonation without supplemental oxygen; to be obtained through hot-fire tests.

TRL: From 2 to 3

Forward Plans: Implement "Technology to Market Plan" by securing government and commercial partnering to enable testing in a gas turbine engine

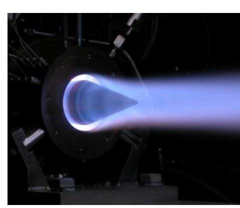
UTRC Jet Burner Test Rig is Being Used to Simulate Gas Turbine Conditions

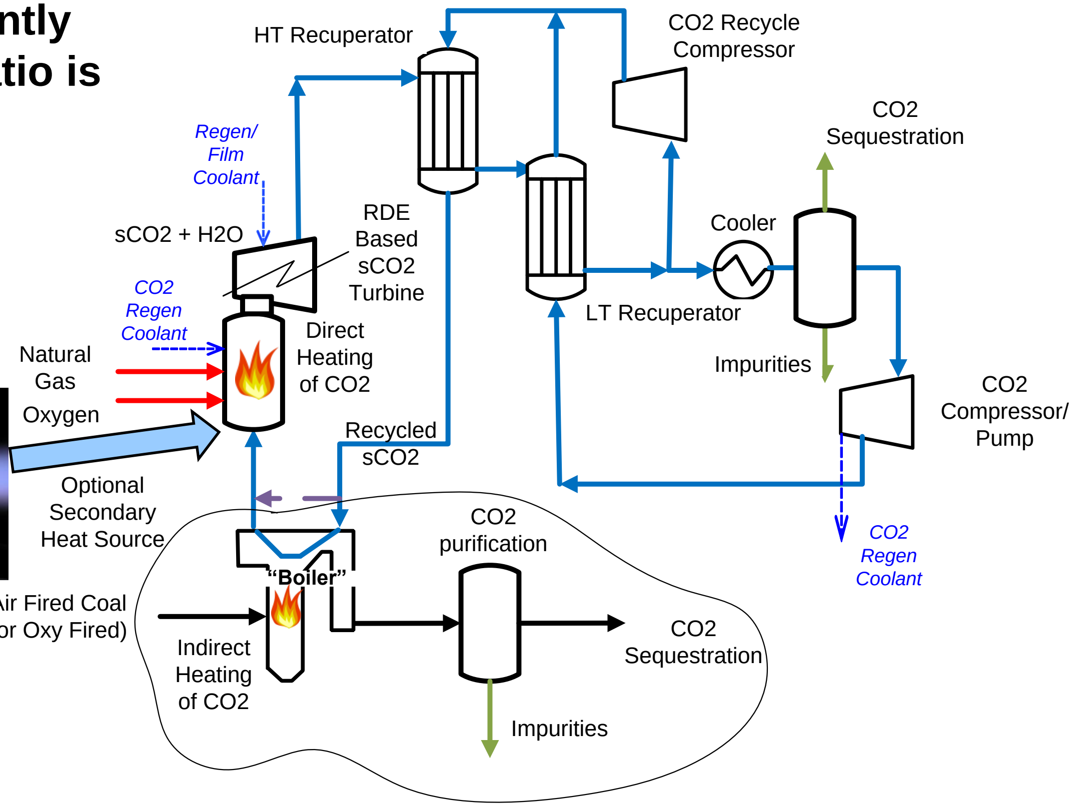


Initial Look at Applying an RDE to sCO_2 Cycles

- **A recompression Brayton cycle with CO_2 as the working fluid was modeled with and without rotating detonation.**
  - **Natural gas and oxygen are combusted in an RDE and the exhaust is directly mixed with recycled CO_2**
  - **Introduction of natural gas and oxygen into the sCO_2 loop requires water/impurity separation and CO_2 removal from the loop**

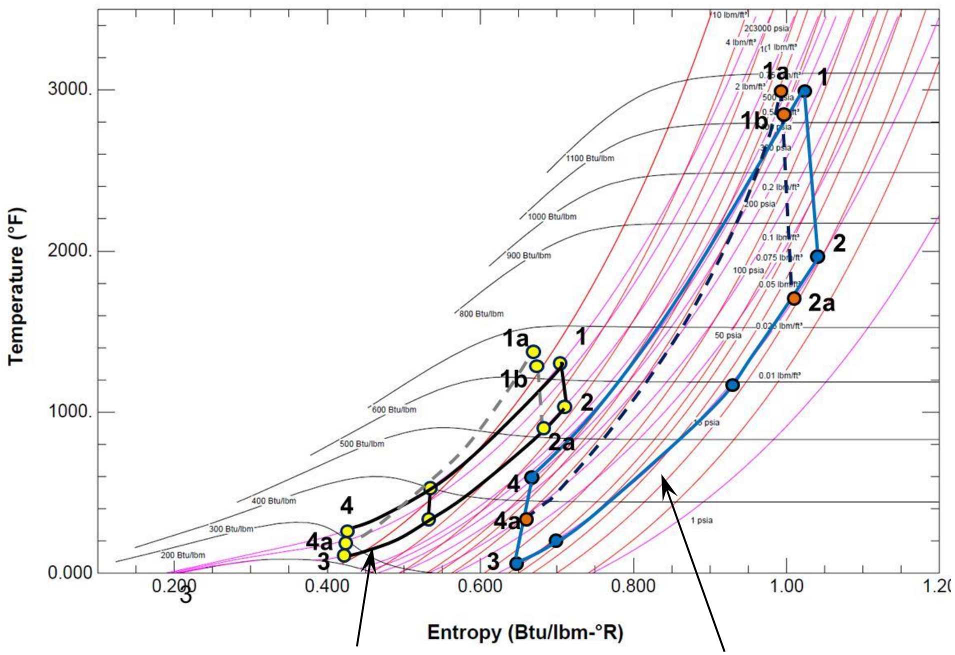
- **Because of pressure gain combustion in the RDE, CO_2 compression is significantly reduced and/or turbine pressure ratio is increased**





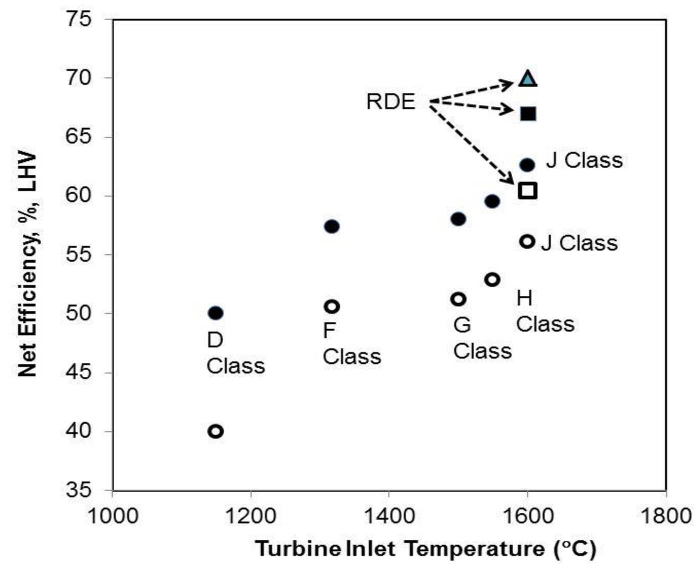
Super- and Sub-critical Recompression Brayton Cycle Analysis

- Cycle analysis has been conducted using AspenPlus with REFPROP v9.1
  - Methodology suggested by NETL/DOE Quality Guidelines for Energy Systems Studies (QGESS) documents was used
  - Efficiency values for F, H and J class turbines were taken from DOE/NETL-341/061013
- Without carbon capture, RDE-based J class turbine offers 67% LHV efficiency as compared to 62.6% offered by conventional combustion
- The RDE-based sCO_2 cycle has a net plant LHV efficiency of 70%



Supercritical CO_2 cycle

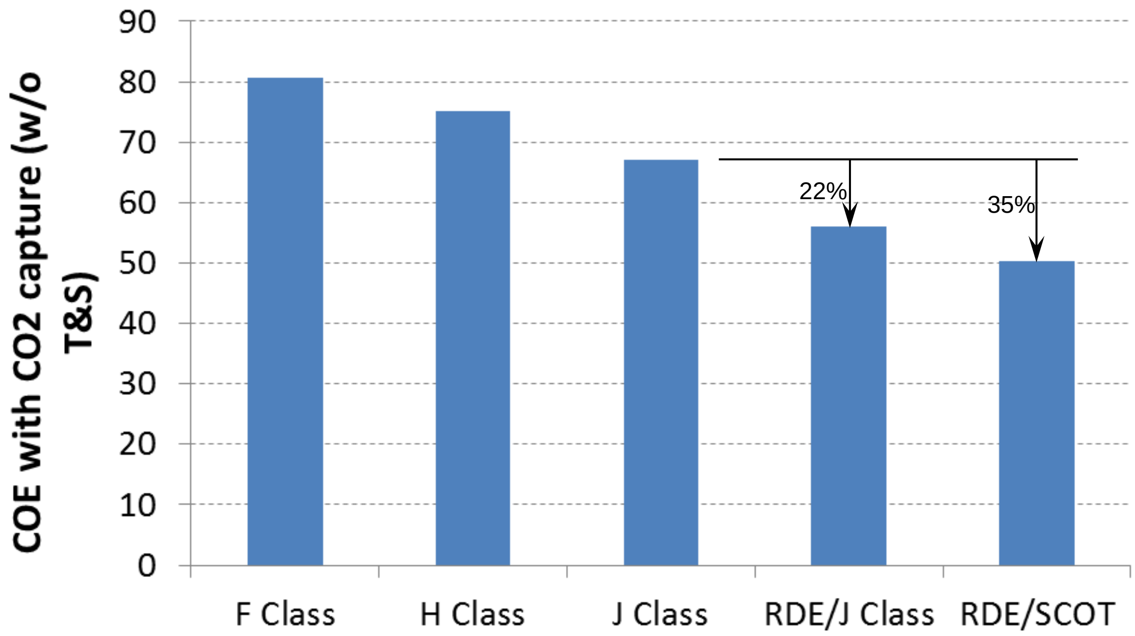
Subcritical CO_2 cycle



Solid symbols = no carbon capture
Open symbols = carbon capture
Triangle = RDE in sCO_2 cycle

LCOE Modeling has been completed

- Levelized cost of electricity (LCOE) has been modeled using Power Systems Financial Model (PSFM v6.6)
  - Material and equipment cost for RDE based J Class turbine was assumed to be 10% higher than conventional adiabatic combustors
  - Labor cost was scaled proportionally to capital costs
- RDE-based power plants promise lower LCOE than conventional natural gas power plants
  - For the same power, reduced fuel consumption is the primary driver for reduced costs.



Summary

Since 2010, Aerojet Rocketdyne has conducted over 520 tests of multiple configurations of a rotating detonation engine

AspenPlus cycle analysis of RDE-based power plants has been completed.

- **By replacing conventional gas turbine burners with rotating detonation combustors, equivalent thermal output can be generated with 14% less fuel consumption**
- **For Natural Gas Combined Cycle baseline plant conditions, plant efficiency (LHV) is estimated to improve from 55.7% to 61% with carbon capture and from 62.6% to 67% without carbon capture**
- **The RDE-based sCO_2 cycle has a net plant LHV efficiency of 70%**

Power Systems Financial Model has been used to determine LCOE for various cycles

- **RDE-based sCO_2 cycle has 35% lower LCOE than a conventional NGCC plant**

Advancements in technology to interface the RDE with compressors and turbines are needed prior to implementation