UTSR2018

Daytona Beach, FL

Oct 30 – Nov 1, 2018

Pressure Gain Combustion for Land Based Power Generation

Providing Clean Energy Technology Through Innovative Ideas

NETL – Research & Innovation Center (R&IC) and Advanced Energy Systems Program (AES)

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U.S. DEPARTMENT OF ENERGY

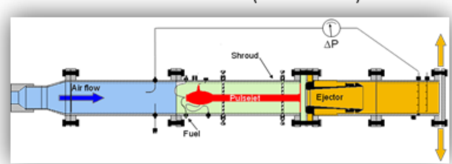
Outline

- **Background**
  - DOE Pressure Gain Combustion
  - RDE focused objectives
- **NETL in-house research**
  - Experimental facilities
  - A few results
- **Looking Forward**

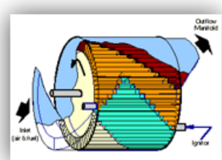
Current Technology Trends in PGC

	Pulse Combustion	Wave Rotor Engine	Pulse Detonation Engine	Rotating Detonation Engine
System Analysis	- Lower pressure gain potential - Eliminates complexities of detonation waves	Large tube numbers reduce provide nearly steady flow	- Detonation offers greatest PG potential - 10% improvement in thermal efficiency	Benefits of PDE with near steady flow and hot gas ignition.
System Integration	-Few/no moving parts -Impact of ejector on unsteady flow?	- Availability as a topping cycle - Complex flow path - Start-up issues	-Cycle timing dictates hardware. -Turbine interactions need quantified -Cooling air challenges	- Small package with big impact - Start-up and wave travel issues
Components / Materials	Heat transfer/cooling concerns	- Sealing issues - Bearings	-Injectors - Thermal management -Turbomachinery	-Thermal Management -Turbomachinery
Basic Physics and Chemistry	Basic physics are understood although difficult to predict amplitudes of pulses	Basic physics of detonation or fast deflagration	- DDT challenges - Ionized flow behind shock	- Similar to physics of PDE - Complex flow field

Resonant Pulse Combustor (NASA-Glenn)

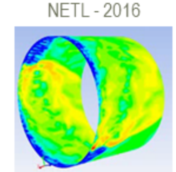


Wave Rotor Engine (IUPUI)



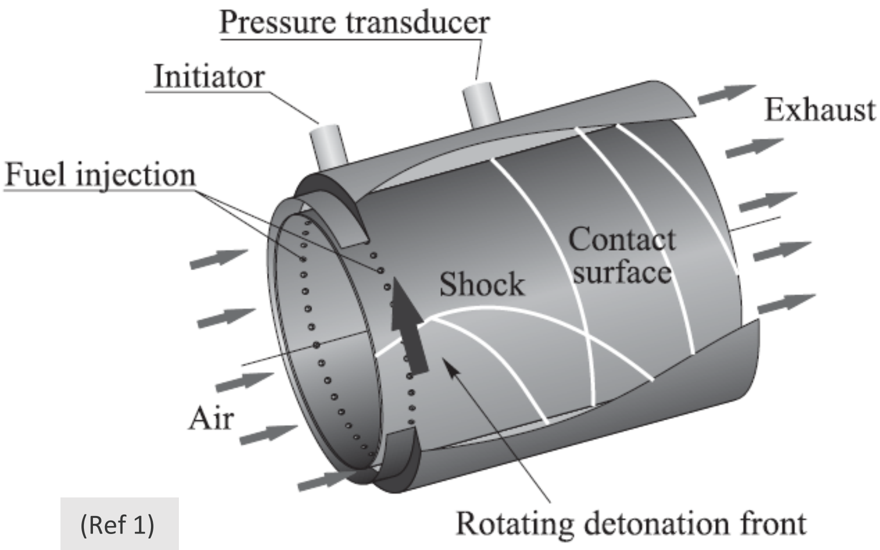
Multi-Tube PDE
G.E. Global Research Center 2005

RDE Simulation
NETL - 2016

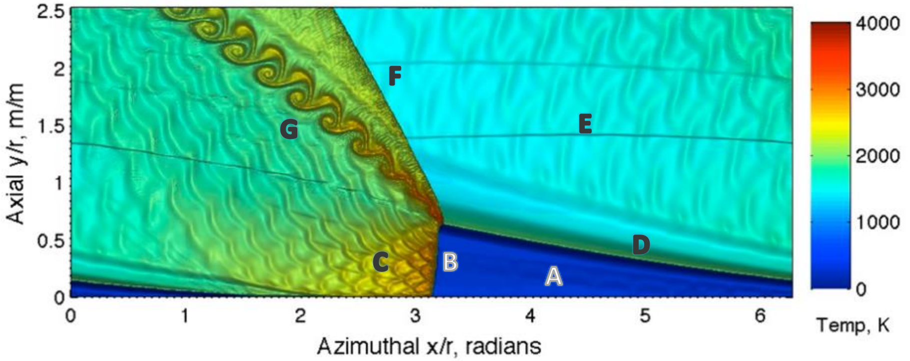


Rotating Detonation Engines

Application and Advantages



(Ref 1)



A. Fresh Reactants
B. Detonation wave
C. Post-Detonation / Transverse Waves
D. Contact Surface (Def)
E. Product Expansion (Det, Det+Def)
F. Oblique Shock Wave
G. Shear Layer

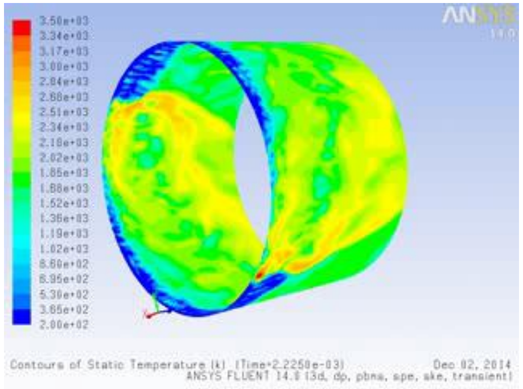
(Ref 2)

- **Fuel and air has a bulk axial flow with detonation wave traveling circumferentially, producing a *"continuous wave"***
- **No moving parts – No complex valving required at the inlet compared to PDE's**
- **Detonation wave, once initiated, is self-sustained.**
- **Unsteady periodic flow at high frequency may have minimal impact on turbine performance.**
- **Potential for low NOx**

1. *Wolanski, P., Proc. Comb. Institute, 2013*
2. Nordeen et al, 49th AIAA Aerospace Sciences Meeting, Orlando, FL:, 2011.

DOE Pressure Gain Combustion Objectives

- **Improve fundamental understanding of stable continuous wave detonation in a semi-enclosed channel**
  - Wave directionality, bifurcation, translation speed (~CJ)
  - Det wave influence on operational parameters (i.e fuel injection/mixing)



- **Develop scaling laws to better understand the parametric impacts**
  - Flow, pressure temperature, fuel composition (det cell size)
  - Gap width, combustor length, diameter (number of waves)

- **Maximize pressure gain / turbine work availability and reduce emissions**
  - Inlet / exhaust transition configuration (including valves for PDE's)
  - Deflagration, shear layer and downstream shocks
  - CO, NOx exhaust emissions and emissions formation

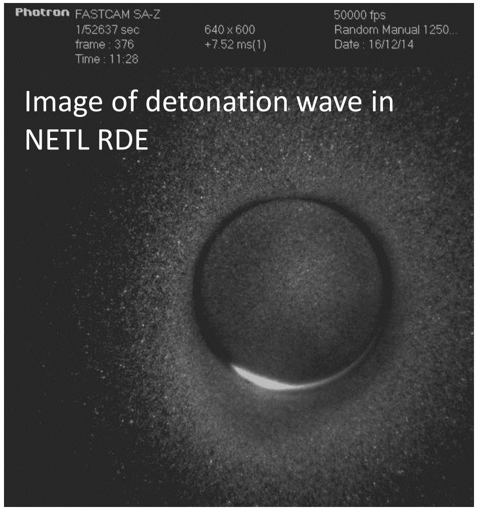
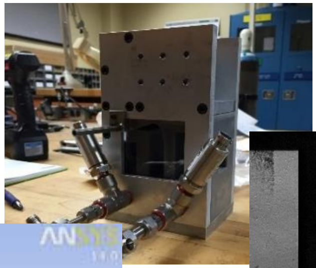


Image of detonation wave in NETL RDE

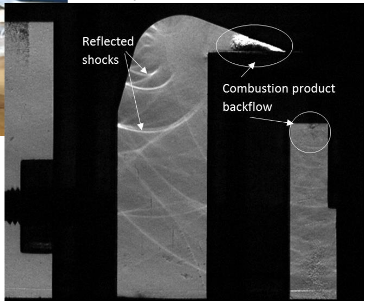
- **Improve modeling capabilities**
  - Simultaneous detonation and deflagration
  - Grid dependences, chemical kinectics
  - Reduced order thermo and chemical models

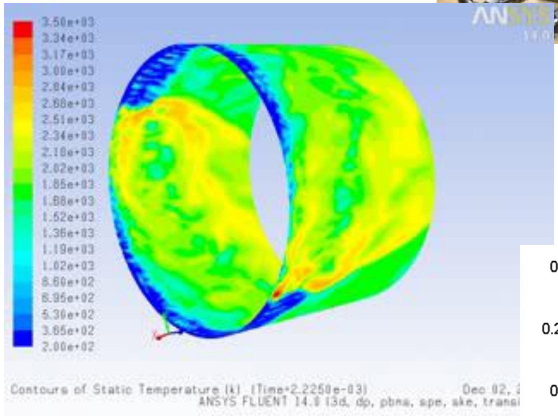
NETL In-House Research Activities

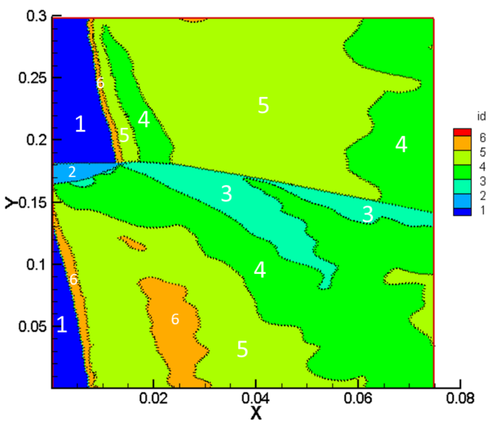
- **RDE Sector / Inlet Lab-Scale Test Rig**
  - Rapid evaluation of inlet concepts with correlation to lab-scale combustor.
- **Computational Studies**
  - Chemical Reactor Network (CRN)
    - Reduced order model with emissions
  - CFD
    - Fundamental aspects of detonation
    - Inlet / geometry physics
    - Turbine integration
- **Lab-Scale Full RDE Experiment**
  - Approximate gas turbine conditions
    - Pressure and temperature
  - Increased percentage of NG (H2/Air)
  - Model validation



300 slpm air, no He flow







Understanding RDE Inlet Dynamics

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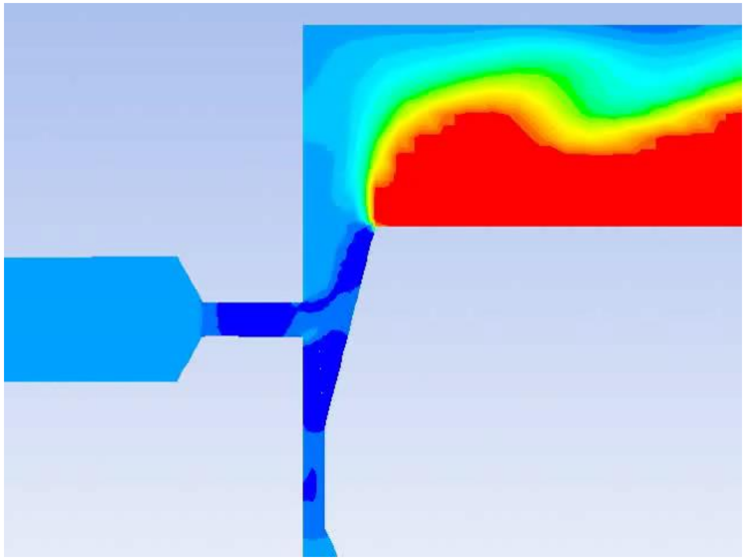
- **Inlet design, reactant mixing critical to realizing PGC potential**
- **Mixing in an RDE is not a static process**
- **Injector/inlet response dictates instantaneous mixture composition**
  - In particular: unequal response between fuel/air, product recirculation can result in significant deflagrative burning, unburnt fuel exiting combustor[9]



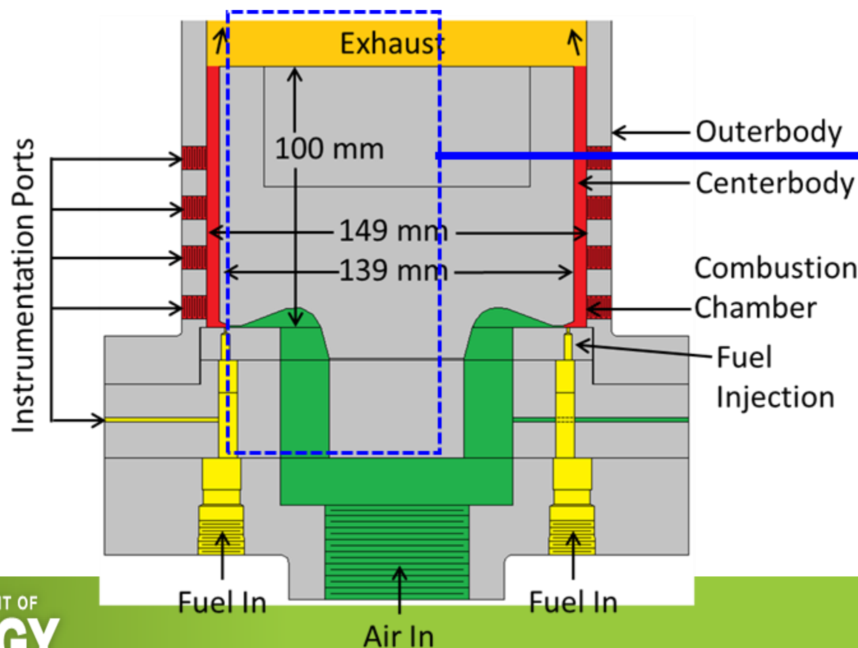
Understanding injector dynamic response is important to developing improved designs, achieving desired reactant mixedness

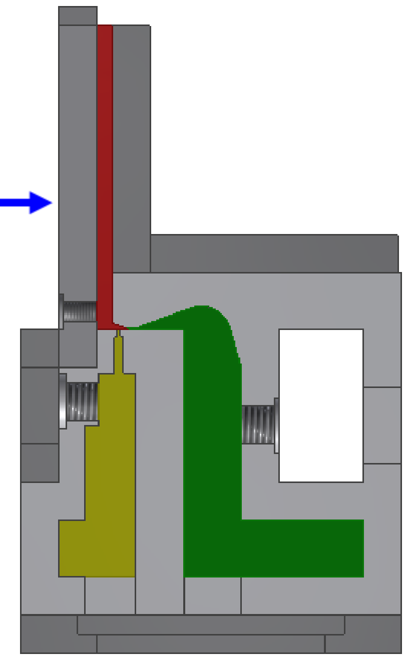
[9] Strakey, P., Ferguson, D., Sisler, A., Nix, A, "Computationally Quantifying Loss Mechanisms in a Rotating Detonation Engine", 54th AIAA Aerospace Sciences Meeting, San Diego, CA, 2016.

NETL Lab-Scale RDE Inlet Sector Rig

- **Small Pilot-scale 6 in diameter RDE presently operated**
  - Combustion annulus width 0.02 in
  - Continuous air slot between fuel plate and centerbody (gap size 0.022 in)
  - 80 discrete fuel injectors (ID 0.035 in)
  - Nominal H_2/air flow rates of 10,000/40,000 scfh

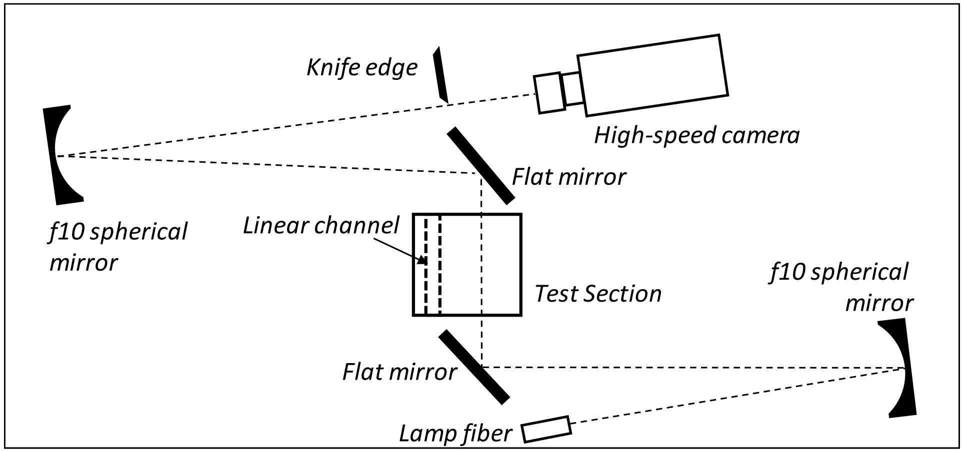
- **Linear extrusion of full-scale RDE cross-section creates a representative geometry for investigating inlet designs, while simplifying diagnostics**



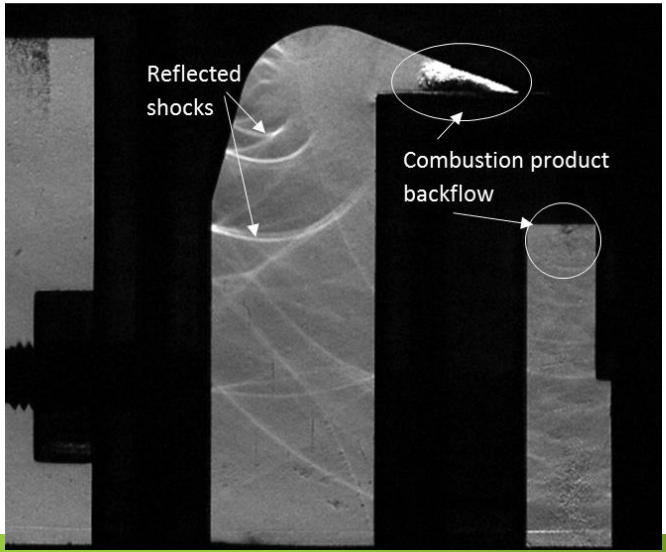


NETL Lab-Scale RDE Inlet Sector Rig

- **RDE "slice" extruded 7.5cm @ 1:1 scale (full RDE with 47cm circumference)**
- **Semi-cold flow approach:**
  - Discrete pressure pulses introduced to linear channel ("combustion annulus") via separate H_2/air pre-detonator tube
  - Inert gases within inlet paths (He/air)
- **Instrumentation:**
  - Optical access provided within inlet plenums on opposing sides for schlieren imaging
  - Dynamic pressure measurements within linear channel and inlet plenums
  - Static He/air supply pressures for inlet ΔP

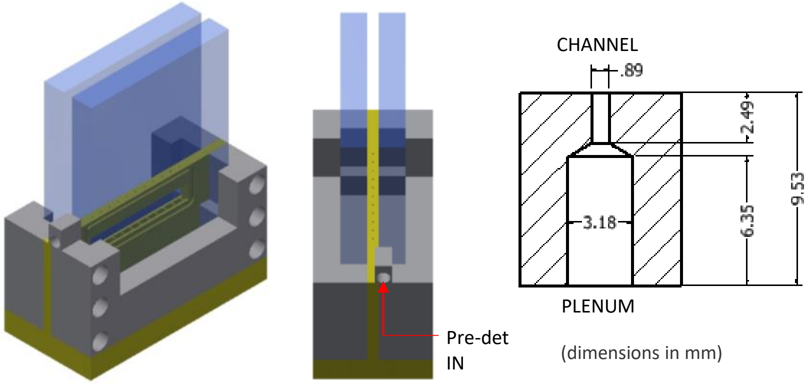


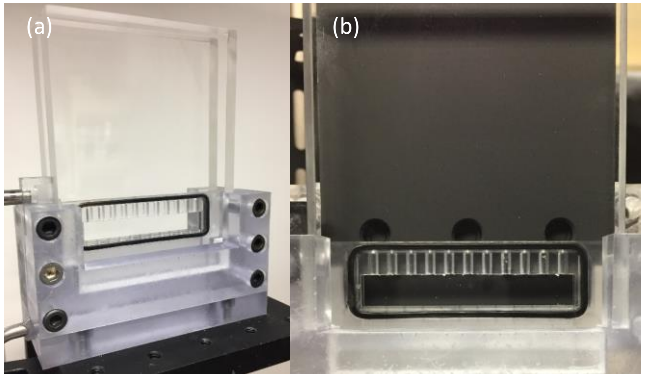
300 slpm air, no He flow



RDE Injector Response using Acetone PLIF

- **Prior work[3] examined inlet response in a reduced-scale linear testing platform**
- **Provided qualitatively similar interruption/backflow to CFD**
- **Modified configuration developed to specifically investigate in-channel fuel injector response, facilitate future mixing experiments**
  - 3D printed linear injector array
  - Geometry equivalent to NETL RDE
  - CDST to force interruption
  - Helium delivered to injectors
  - Amenable to schlieren and laser-based diagnostics, along with dynamic pressure measurements
- **Current work presents results from high-speed acetone-PLIF experiment**

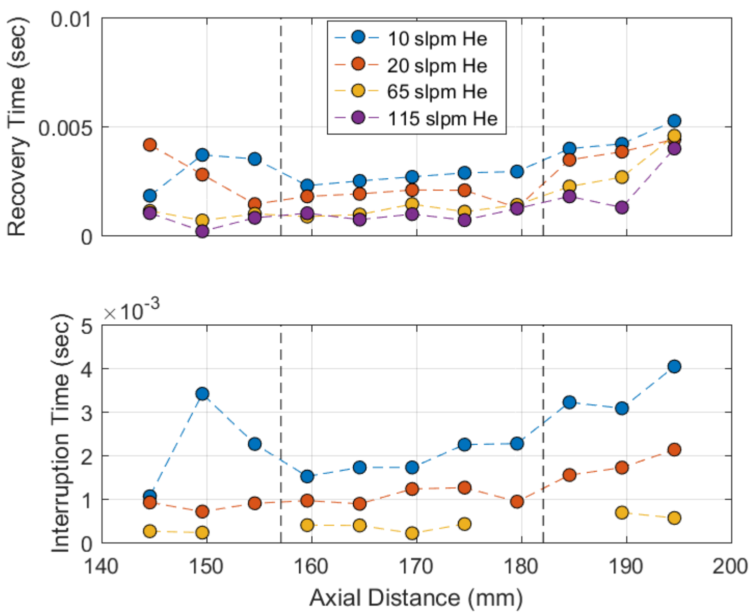


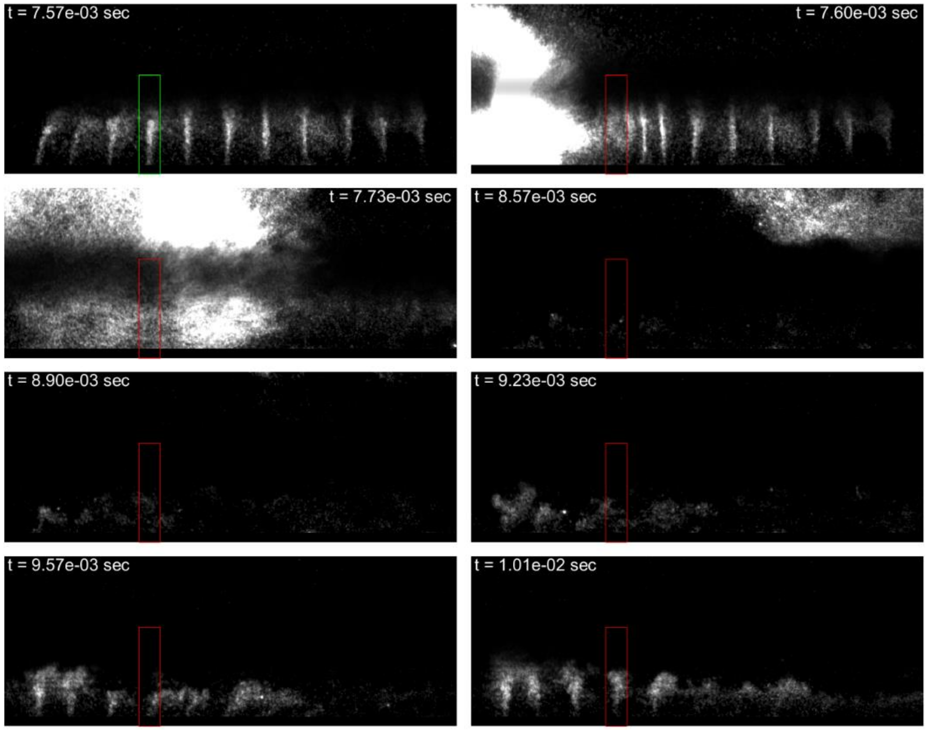


[3] Bedick, C., Sisler, A., Ferguson, D., Strakey, P., Nix, Andrew, Billips, D. “Development of a Lab-Scale Experimental Testing Platform for Rotating Detonation Engine Inlets”, 55th AIAA Aerospace Sciences Meeting, Grapevine, TX, 2017.

Dynamic Jet Analyses

- PLIF image sequence analyzed to extract pertinent information
- Complete interruption easily observed
- Recovery occurs left-to-right
- Individual jet interruption and recovery tracked using sub-regions
- 2D correlation coefficients computed W.R.T. pre-shock reference frame

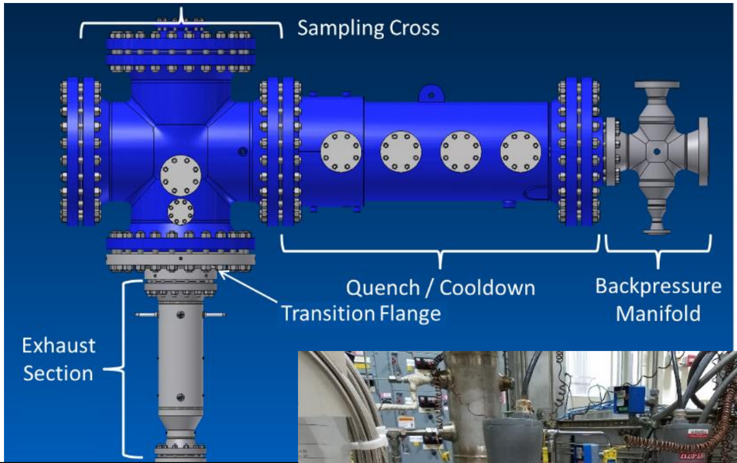


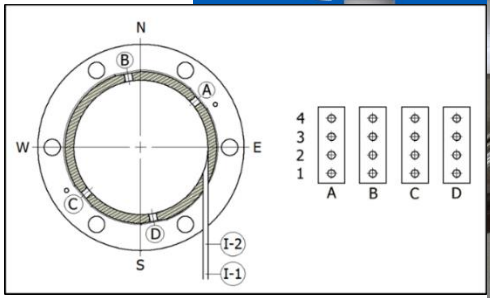


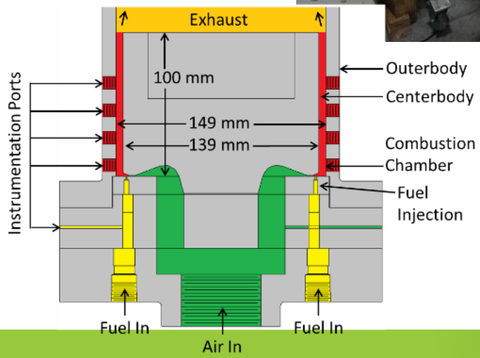
- Run-average interruption and recovery times determined for each jet, at each condition
- Jets near channel ends inconsistent due to entrainment, possible sheet misalignment

NETL Lab Scale RDE

- **Rig design**
  - AFRL 6 inch rig
  - Enclosed flow with back pressure control valve
  - Post combustor burners to control start-up flares
- **Rig capability**
  - Natural gas, hydrogen, propane, ethane (0.1 kg/sec)
  - Air (1.2 kg/sec)
  - 20 atm, 800 K air preheat
- **Experimental focus**
  - Flow rate
  - Equivalence ratio
  - Fuel Composition (H2 / NG)
  - Air Preheat (600 K)
  - Operating Pressure

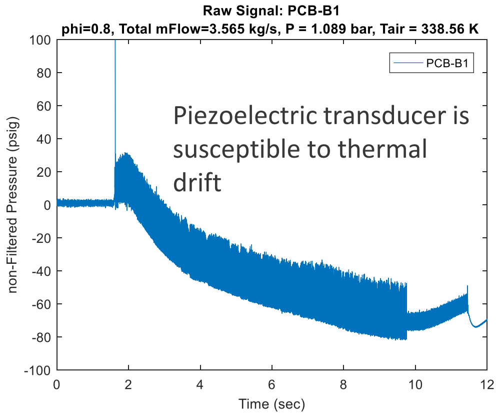




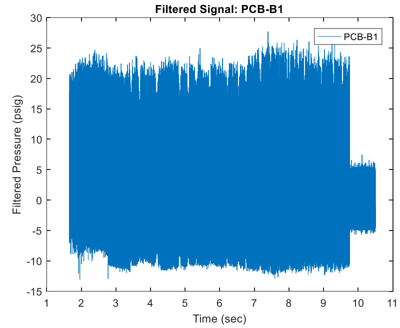


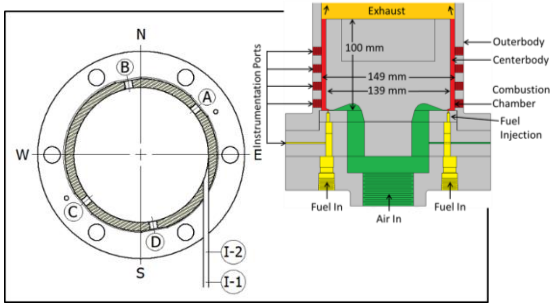
Example Data Analysis - H2 in Air

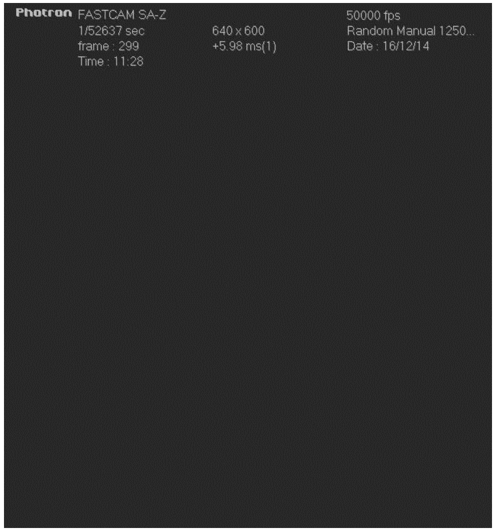
phi=0.8, Total mass flow ~ 0.356kg/sec P = 1.089 bar, Tair = 338 K

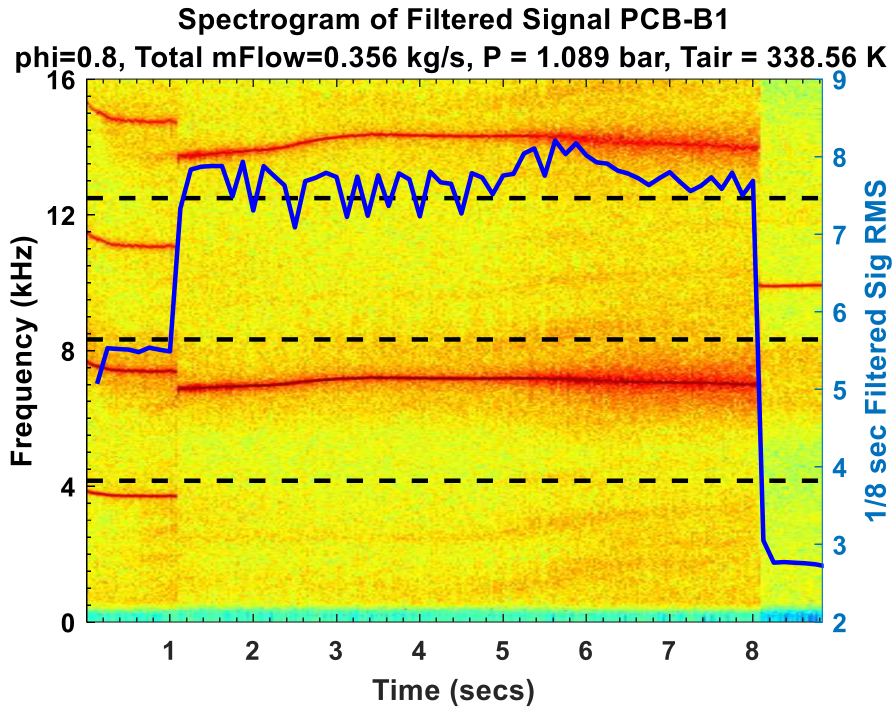


Highpass band butterworth filter to remove thermal drift from dynamic Pressure sensor



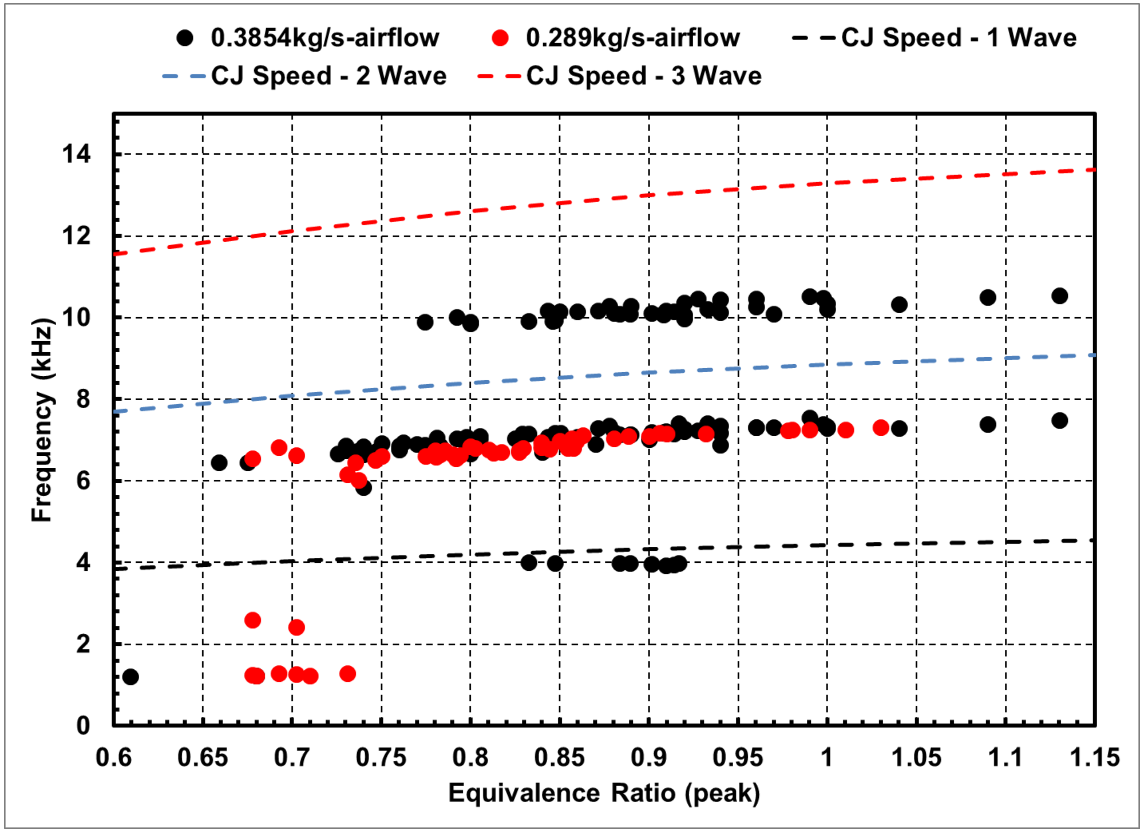






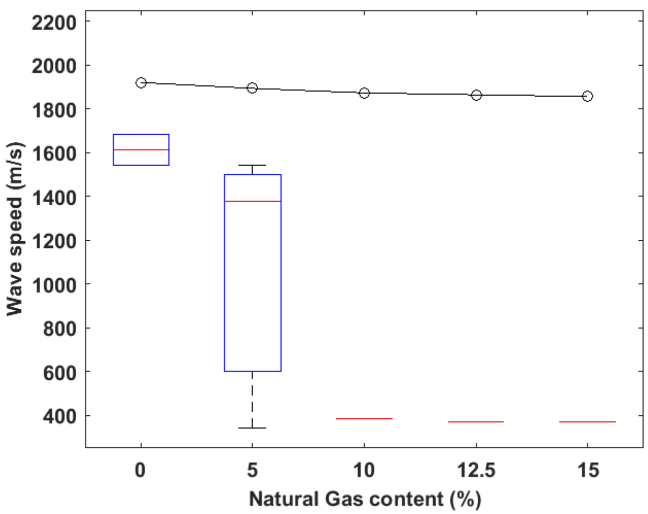
Summary of Test Conditions

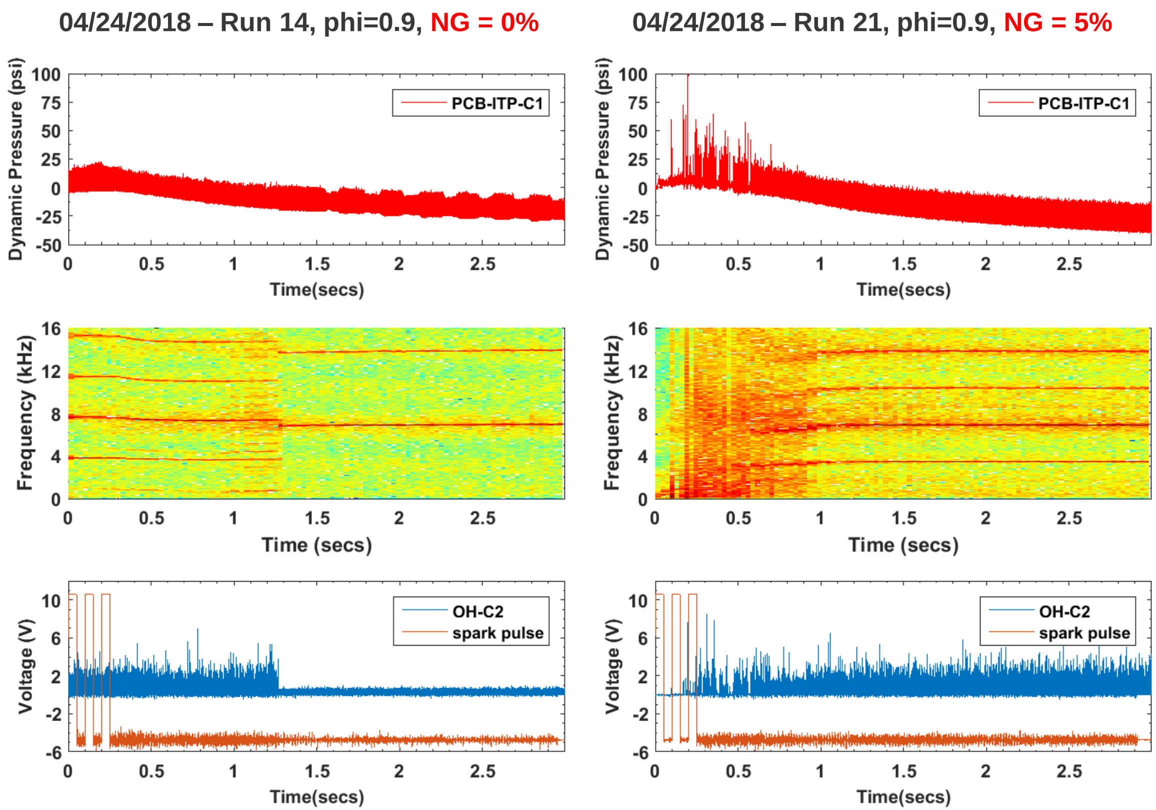
Operating Conditions			
Air Flow Rates (kg/s)	Eq. Ratio	Preheat (°C)	Back Pressure (bar A)
0.289	0.6 – 1.1	65/204	1.06
0.3854	0.6 – 1.1	65/204	1.06 – 3.068



Effect of Natural gas addition – 0.3in annulus

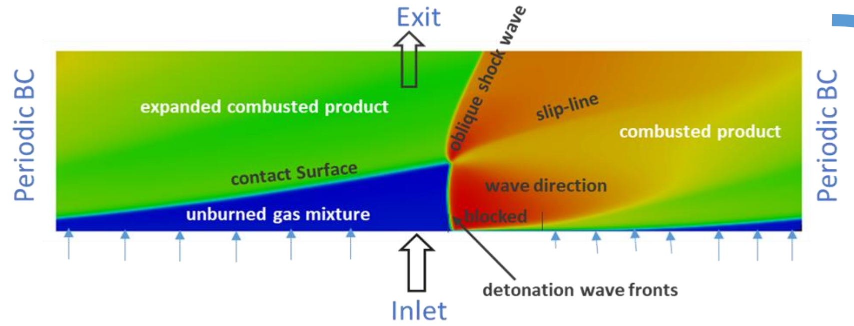
RDE performance at Tair – 150F, P – 1atm, phi = 0.9, total flow rate ~ 60,000scfh

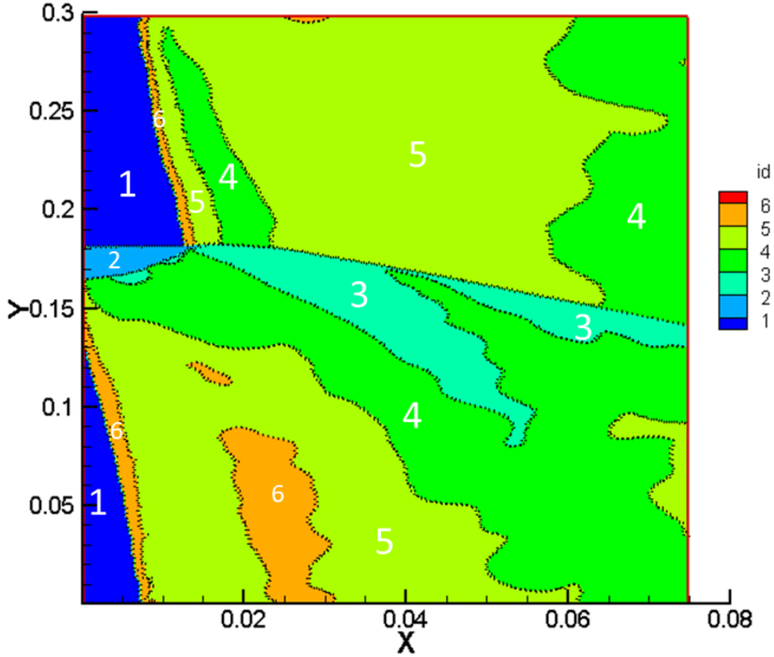




- **Successful detonation achieved only at 5% NG at 1 atm op press.**
- **Initially unstable, may cause intermittent blow-off, but transitions to stable detonation**
- **Detonation achieved only with larger annulus (0.2 in vs 0.3 in)**

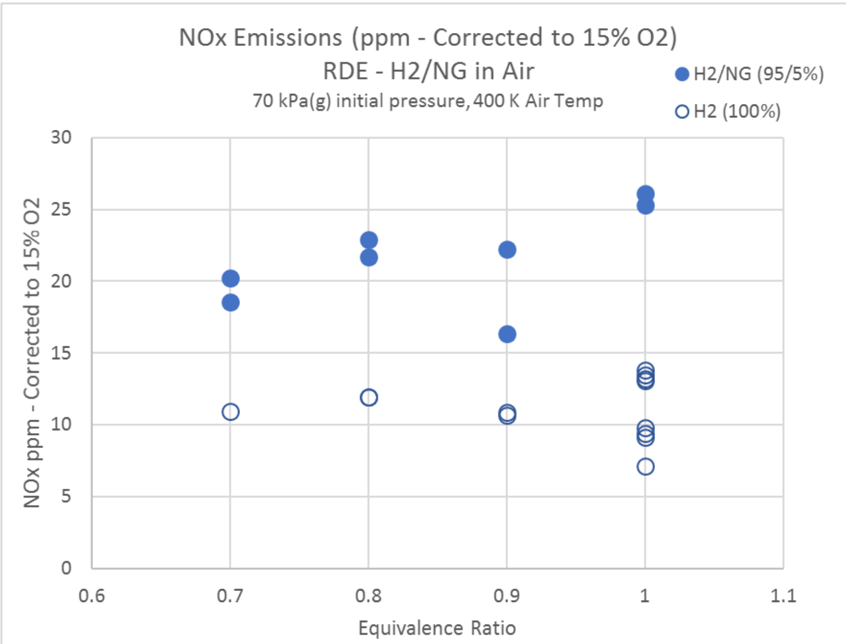
Chemical Reacting Network for RDE application



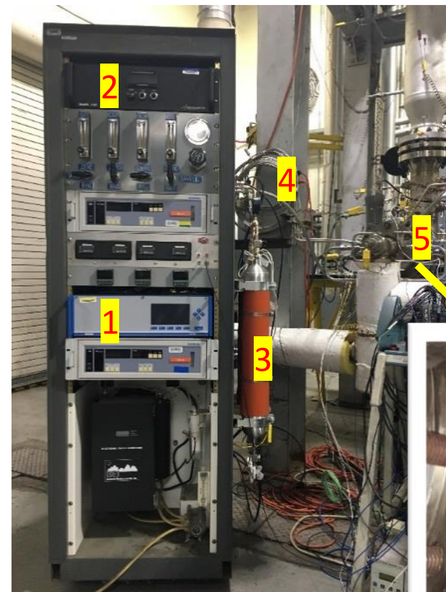


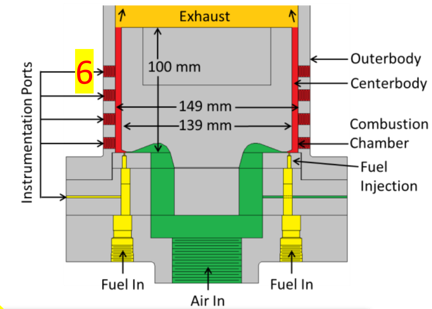
- CRN simplify the domain of combustor in “zones” that has similar conditions
- CFD with simplified global chemistry mechanism is solved From CFD data –
    - Reactors domain identified with their boundary , volume of each reactors
    - Mass flux between the reactors calculated
    - Reactor averaged T, P, density, species concentrations, velocity calculated
- In Cantera :
    - Reactor averaged properties supplied as input
    - Using detailed chemistry concentration of NOx is predicted

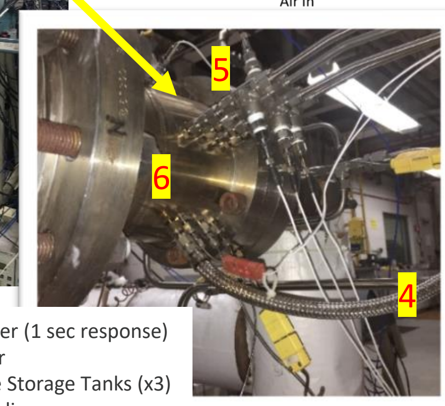
NOx Emissions (ppm) – Corrected to 15% O2



$$Oxygen\ referenced\ conc. = Measured\ conc.x\ \frac{20.9 - Oxygen\ Reference\ value\ (\%)}{20.9 - measured\ oxygen\ (\%)}$$





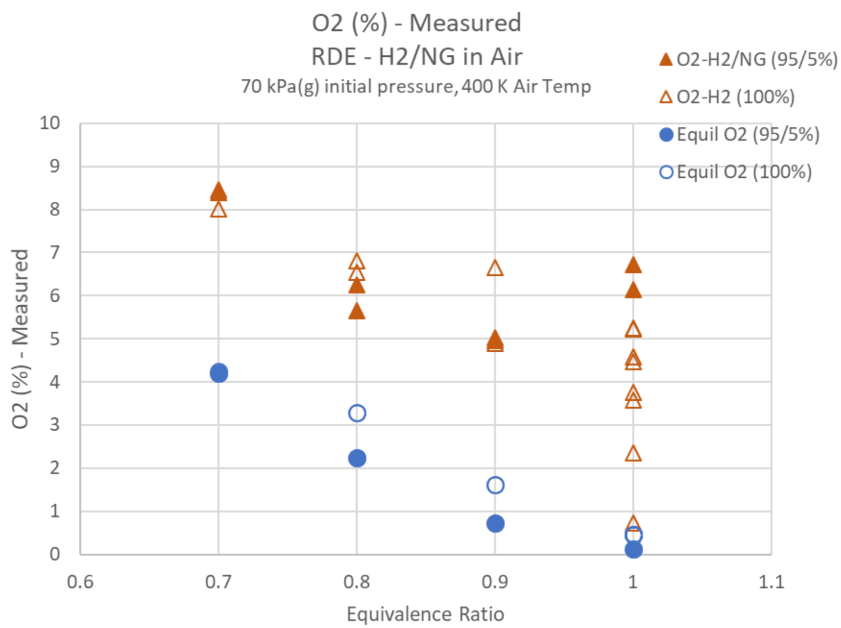


1. NOx Analyzer (1 sec response)
2. O2 Analyzer
3. Gas Sample Storage Tanks (x3)
4. Gas sample line
5. RDE
6. Gas sample port

Challenges

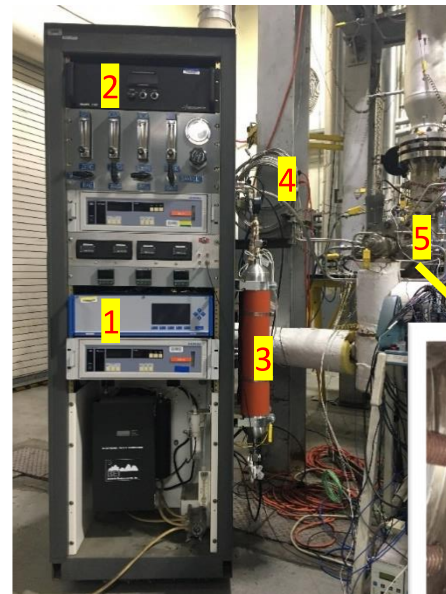
1. Unheated sample line permitted condensation (H2/Air) likely resulting in NO2 loss.
2. Some tests experiences periods of unstable and stable detonation.
3. Incomplete combustion (see O2 Emissions chart)

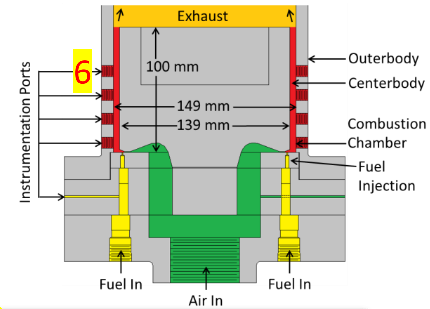
O2 Emissions (%) – Incomplete Combustion

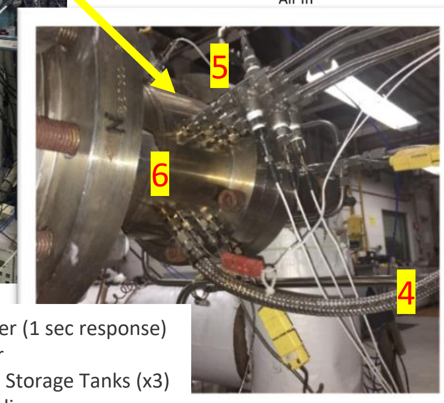


Challenges

1. High variability at phi = 1.0
2. High concentration of O2 at phi = 1.0 suggests incomplete combustion.







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Installation of Cooled RDE in HPC Test Facility

Combustor Assembly – Flow Paths

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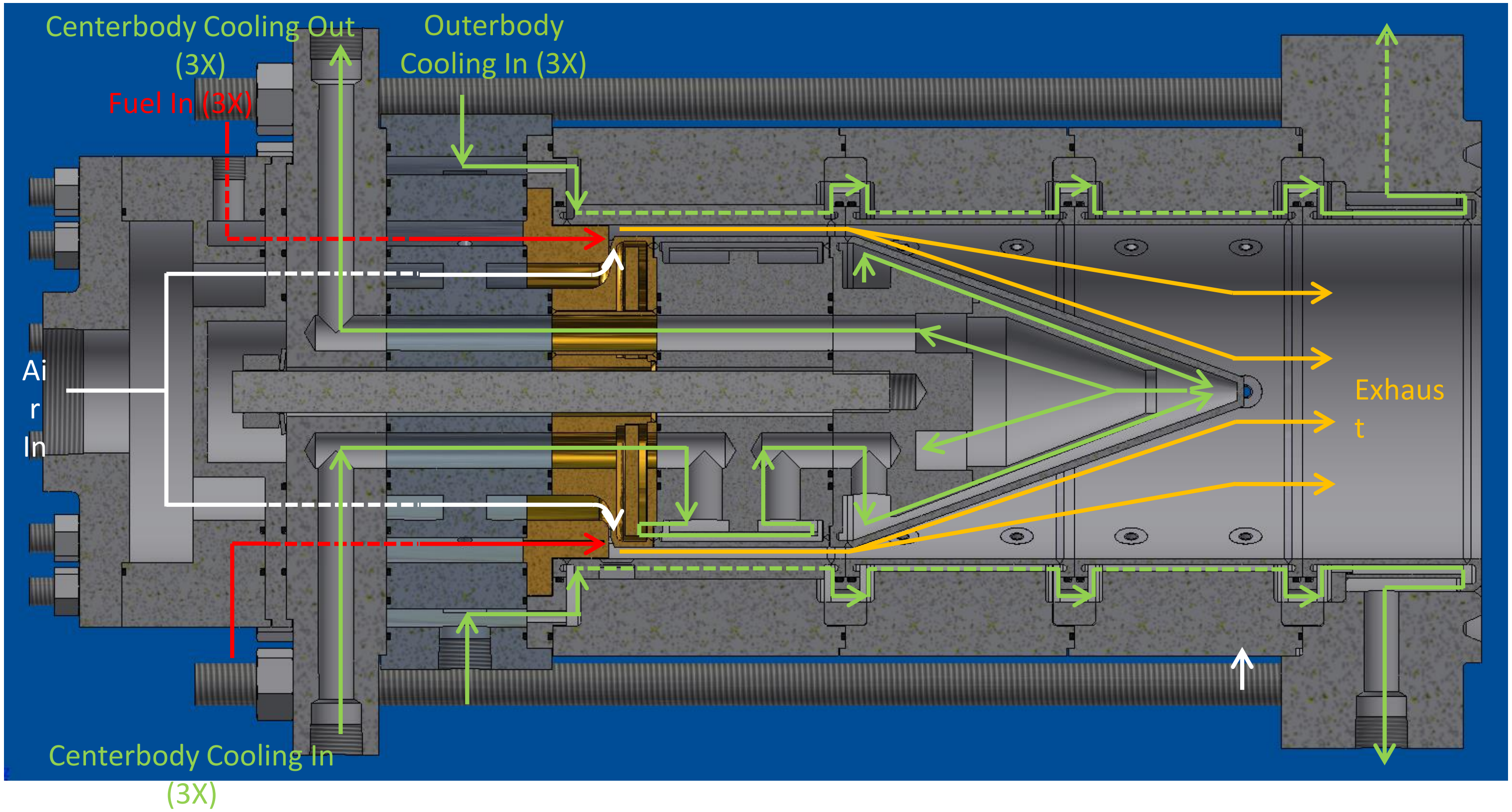
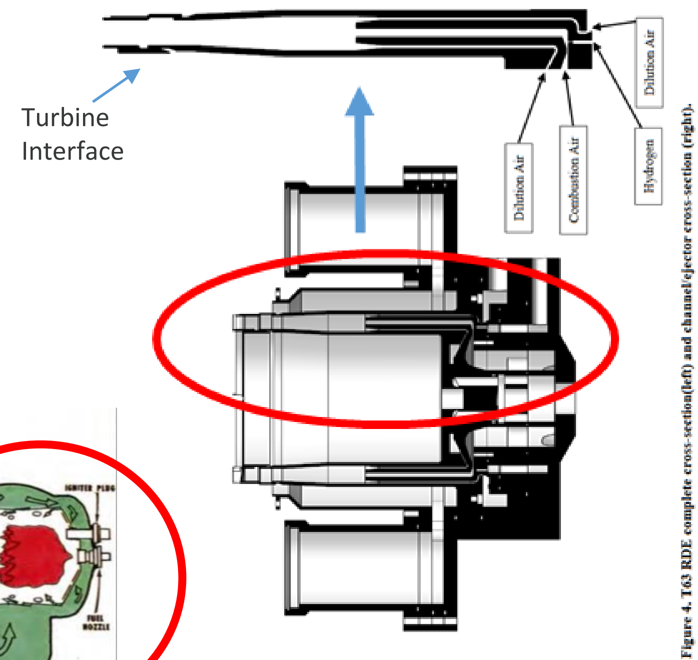
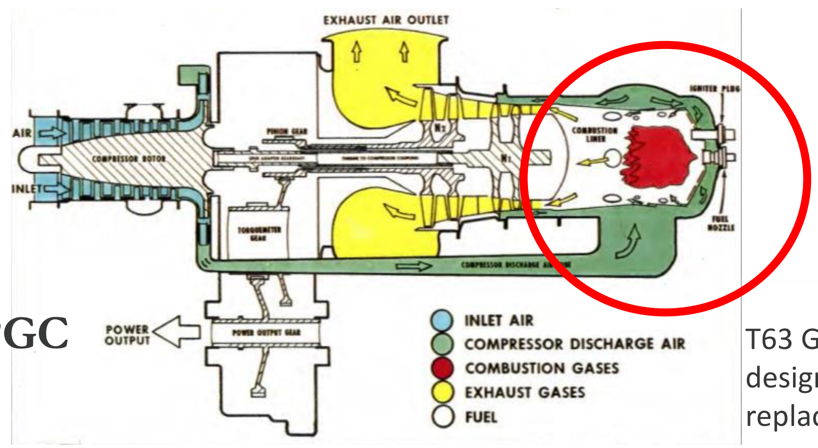


Short duration vs long duration tests (ignition and detonation wave stability, non-start)

Maximize Pressure Gain / Turbine Work Availability

- **Turbine / Engine Integration**
  - AFRL test of T63 gas turbine stock combustor replaced with RDE
  - Testing suggested no impact on turbine performance
  - Fully coupled testing is needed





T63 Gas Turbine reverse flow design with aft-engine combustor replaced with RDE.

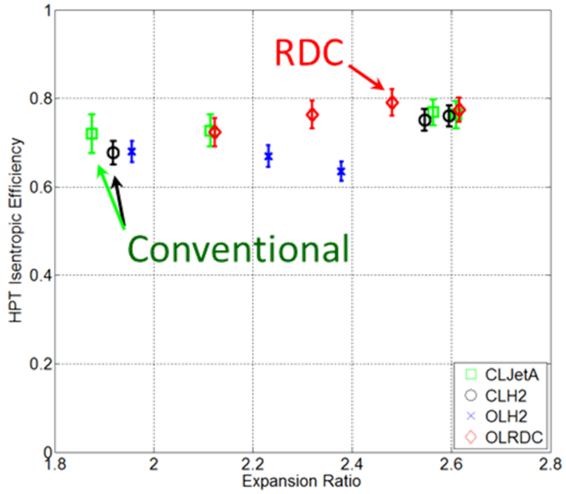
- **Expand awareness of PGC to Industrial / Power Turbine community**
  - Panel session at Turbo Expo 2018
  - Technical session at Turbo Expo 2019

Naples et al., "Rotating Detonation Engine Implementation into an Open-Loop T63 Gas Turbine Engine", AIAA SciTech 2017

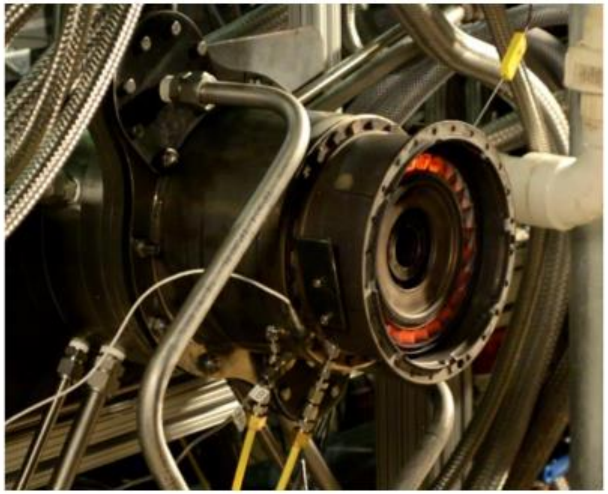
AFRL-DOE RDE T63 Turbine testing

- **Compare the adiabatic efficiency of a turbine driven with a conventional combustor and RDC**
  - No intention of pressure gain
  - Average efficiency, not time varying
  - No study of long term structural effects on turbine

- **RDC unsteadiness attenuated 65-85% in HPT**
- **No reduction in HPT efficiency measured with RDC setup**



Andrew Naples, Ryan T. Battelle, John Hoke and Frederick R. Schauer. "T63 Turbine Response to Rotating Detonation Combustor Exhaust Flow", GT2018-75534, 2018 ASME Turbo Expo, Oslo, Norway, 11-15 June 2018.

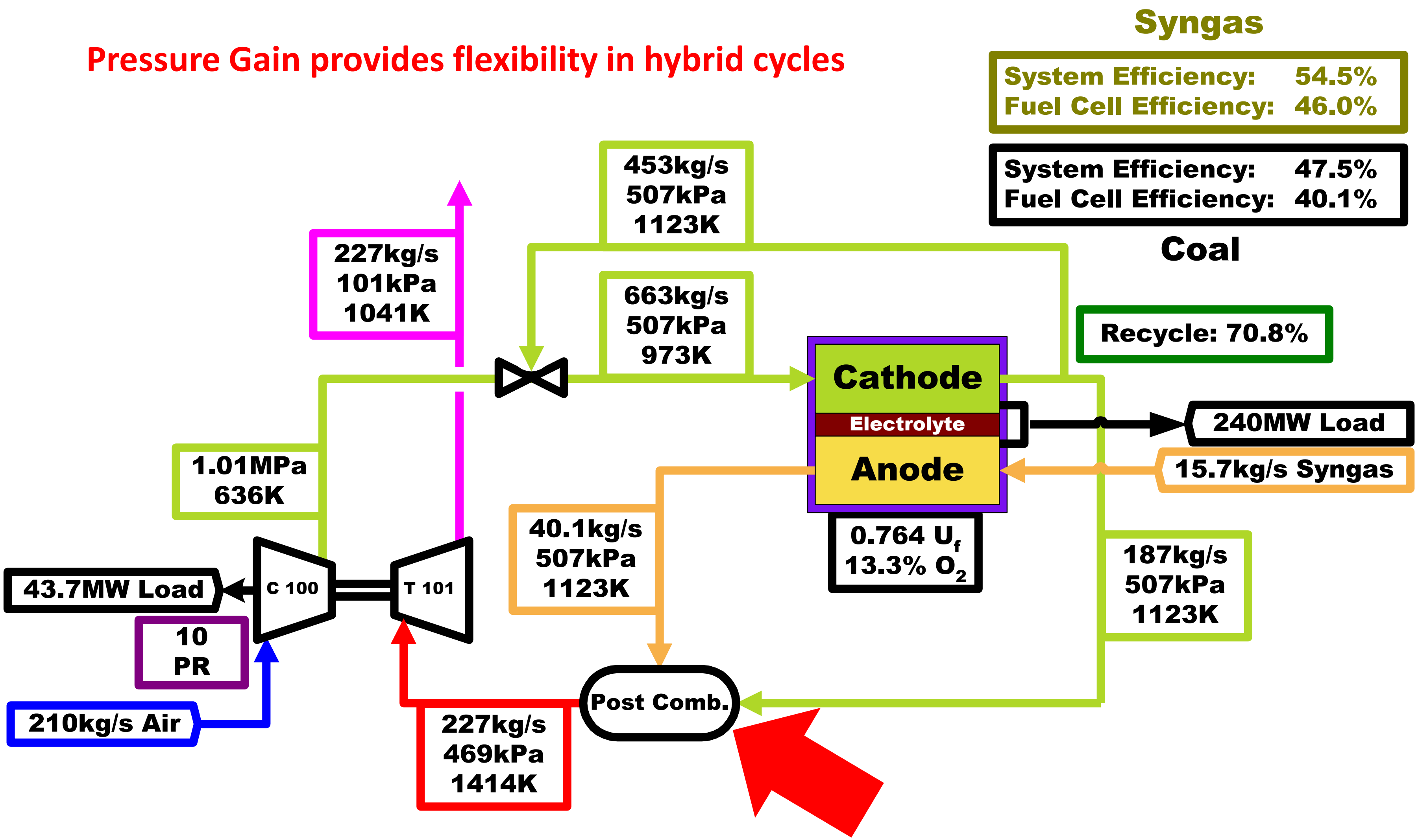


RDE coupled to T63 Turbine at AFRL

Andrew Naples, John Hoke, Ryan T. Battelle, Matthew Wagner, and Frederick R. Schauer. "RDE Implementation into an Open-Loop T63 Gas Turbine Engine", 55th AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, (AIAA 2017-1747)

Cathode Recycle Configuration with Ejector

Pressure Gain provides flexibility in hybrid cycles



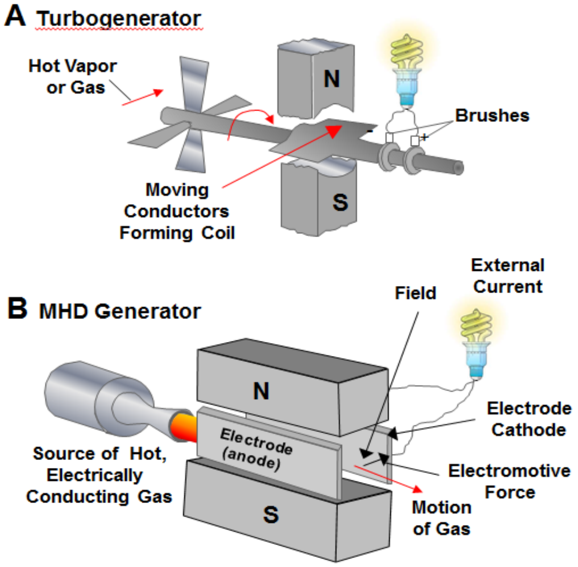
Making Oxy-fuel an Advantage

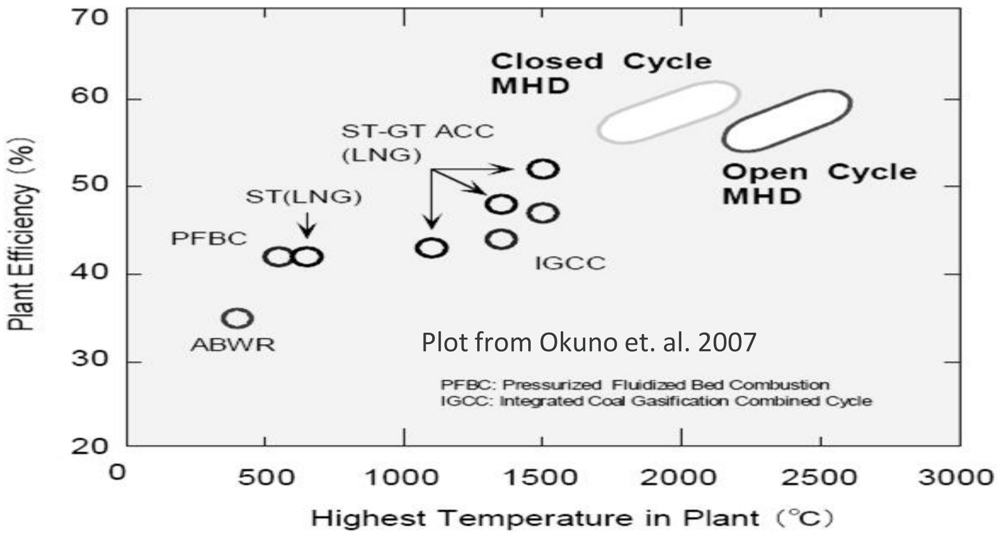
Direct Power Extraction (via MHD)

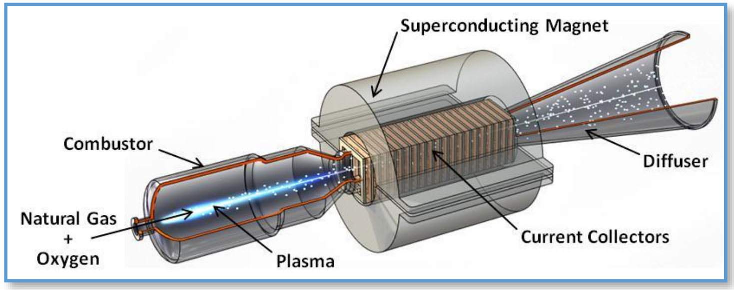
- **Magnetohydrodynamic (MHD) Power Generator:** Use a strong magn and convert kinetic energy of conductive gases directly to electric power

- **Higher plant efficiency – works at higher temperature**
  - Need to use in combined cycle
  - Synergy w/ oxy-fuel for CCUS
    - oxy-coal COE much higher than baseline COE primarily due to ASU
    - Legacy: MHD-steam coal has ASU (to combust to higher T) but COE lower than basel COE ->

MHD cycle turns having an oxygen production from efficiency disadvantage to efficiency advantage!







Summary

- In-house research effort are complementary to DOE externally funded activities
- In-house work focused on fundamental, computational and lab-scale studies.
- Low NOx appears to be consistent with preliminary modeling and expectations
- Alternative cycle considerations
- Two post-doc / post-grad positions available (Jan 2019 and Jul 2019)
  - https://orise.orau.gov/

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Questions?

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