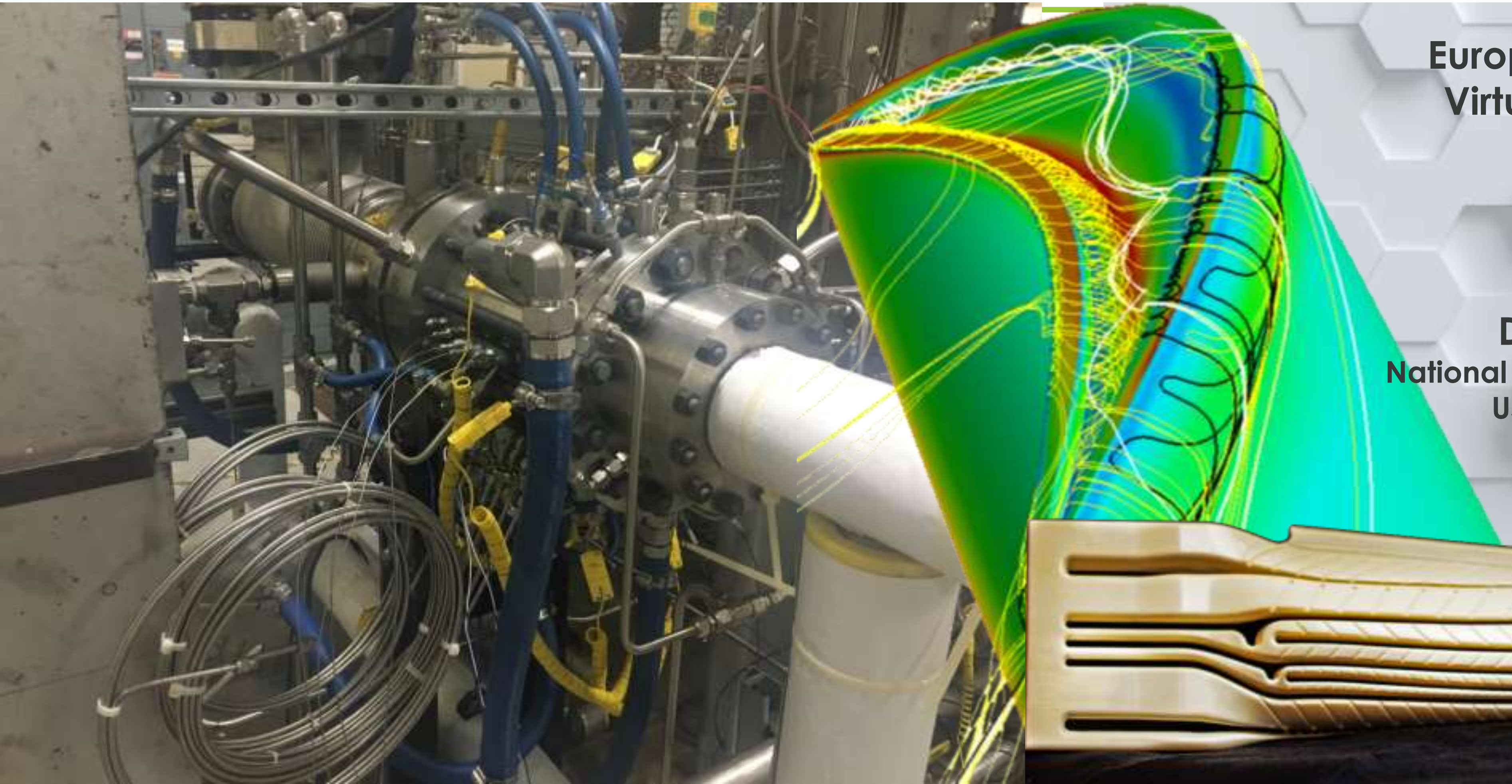
Pressure Gain Combustion Technology Development for Gas Turbine Engines

Solutions for Today | Options for Tomorrow



European Turbine Network
Virtual AGM & Workshop

March 16, 2021

Don Ferguson, PhD
National Energy Technology Laboratory
US Department of Energy

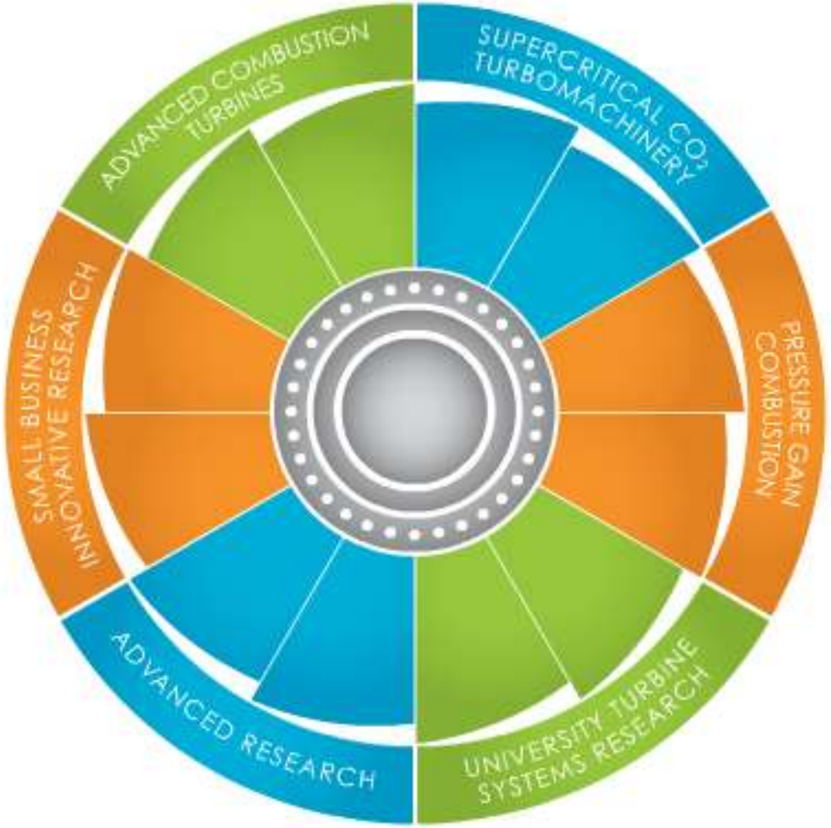
DOE's Advanced Turbines Program

Technology Manager: Rich Dennis

- **SCO2 power cycles (CO2 storage ready)**
  - Indirect and Direct cycle considerations

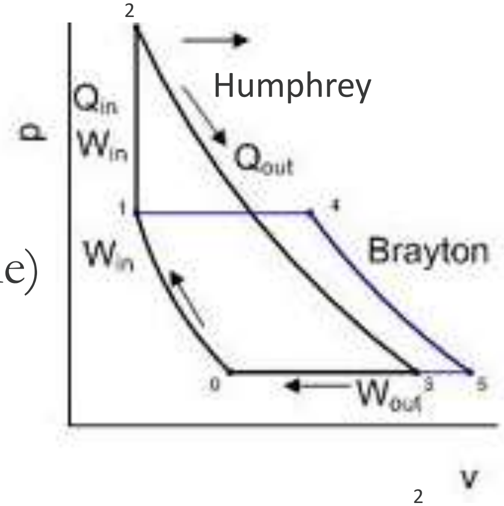
- **Advanced Combustion Turbines** - Combined cycle machines for pre- and post-combustion capture
  - Technologies applicable to natural gas, hydrogen and super critical CO2 cycles.
  - Reducing the cost of CO2 capture.
  - Combined Cycle (LHV) efficiency approaching 65%
  - Adv. components: advanced transition, air foils w/ decoupled thermal & mechanical stresses
  - T3 of 2,100 K (3,100^{o} F) – improved cooling, materials, CMCs, Low NOx combustion

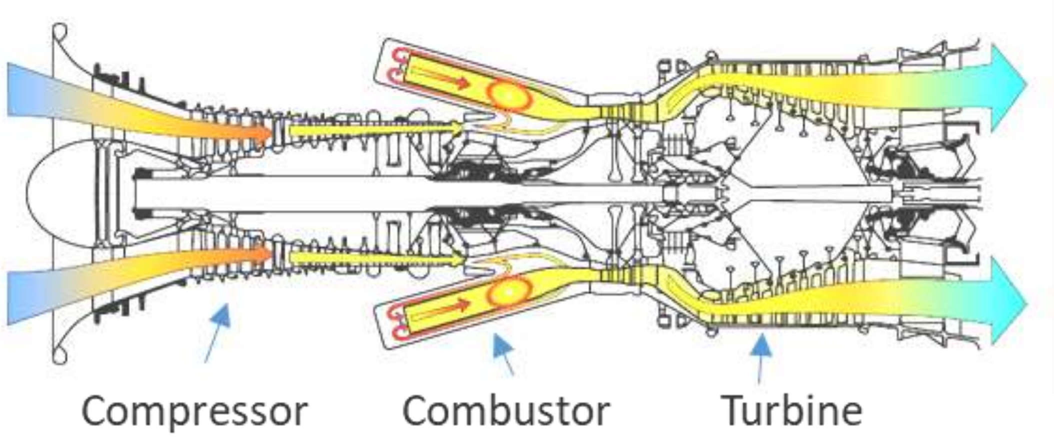
- **Pressure Gain Combustion**
  - Hybrid-bas turbine cycle that permits greater work availability achieved through combustion



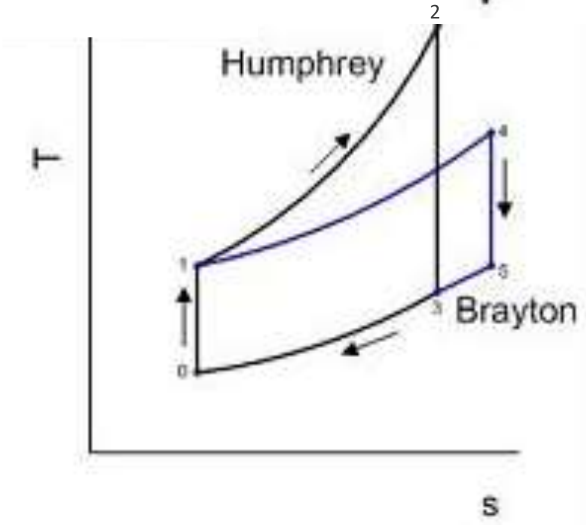
Constant Pressure vs Constant Volume Combustion

- **Constant volume combustion offers greater thermodynamic availability than constant pressure combustion**
  - Heat added at constant volume (1->2) allows for greater increase in pressure within the combustor compared to Constant Pressure Combustion (1->4). Both approaches can achieve similar temperatures but CVC (Humphrey Cycle) can reach higher temperatures while generating less entropy.
  - Heat addition through constant volume permits the cycle to utilize higher pressure through the expansion stage (2-3)





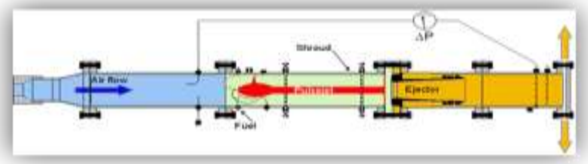
6->1	1->4 (CP) 1->2 (CV)	4->5 (CP) 2->3 (CV)



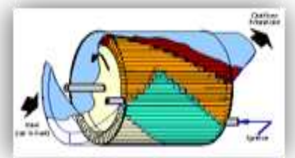
Current Technology Trends in PGC

	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)

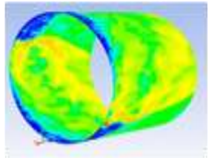


Wave Rotor Engine (IUPUI)

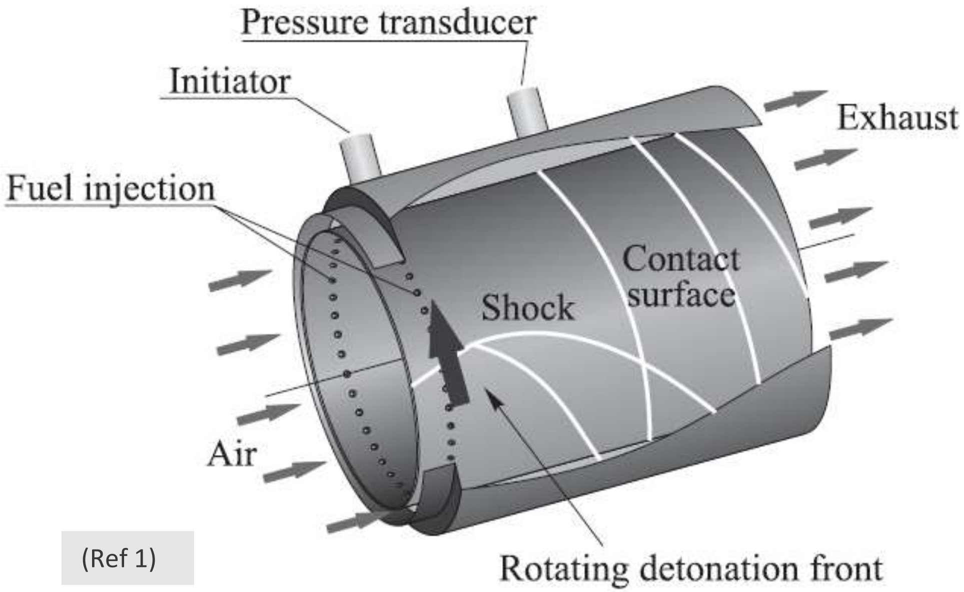


Multi-Tube PDE
G.E. Global Research Center 2005

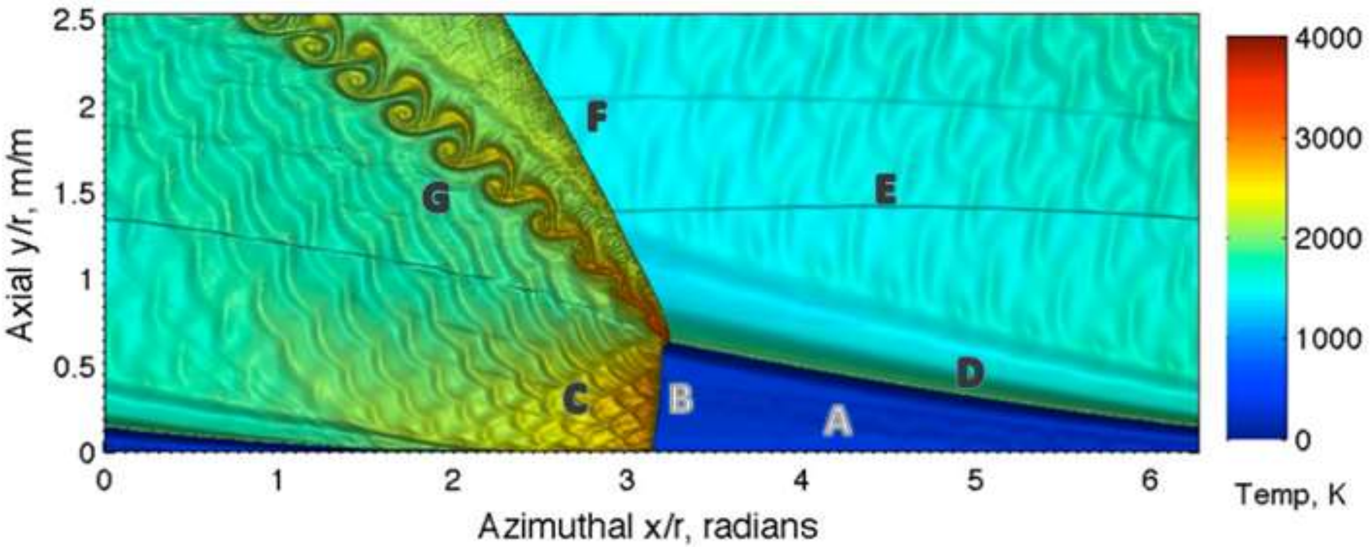
RDE Simulation
NETL - 2016



Rotating Detonation Combustion



(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

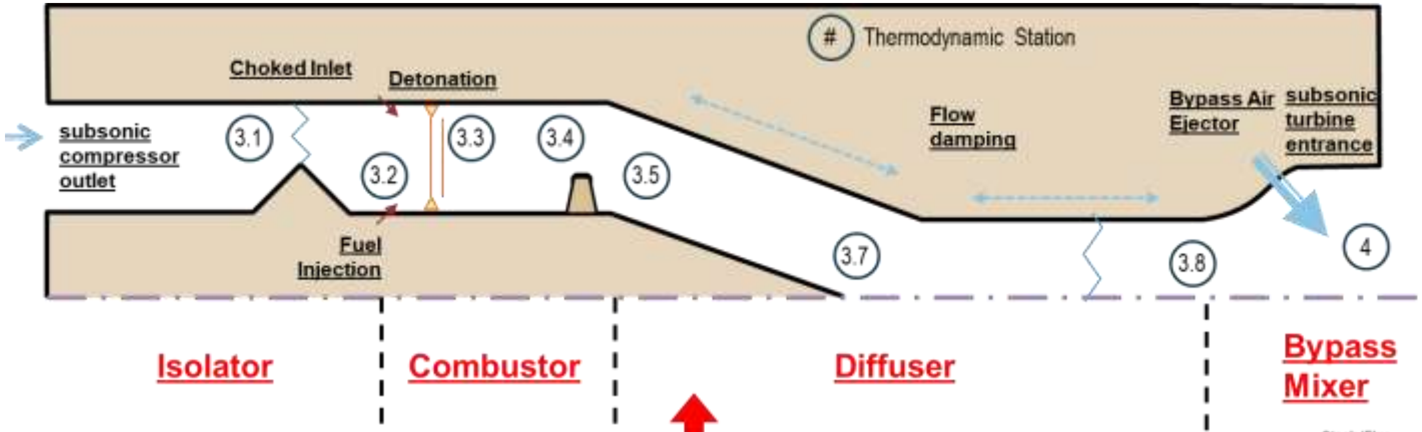
(Ref 2)

- **Bulk axial flow with circumferential detonation wave**
- **Detonation wave, once initiated, is self-sustained.**
- **No moving parts – No complex valving required at the inlet compared to PDE's**
- **Unsteady flow at high frequency may have minimal impact on turbine performance.**
- **Estimated 49% increase in pressure [3]**
- **Potential for low NOx**

1. *Wolanski, P., Proc. Comb. Institute, 2013*
2. Nordeen et al, 49th AIAA Aerospace Sciences Meeting, Orlando, FL:, 2011.
3. Kaemming, T.A. and Paxson, D., 2018 AIAAJoint Propulsion Conf., Concinnati, OH.

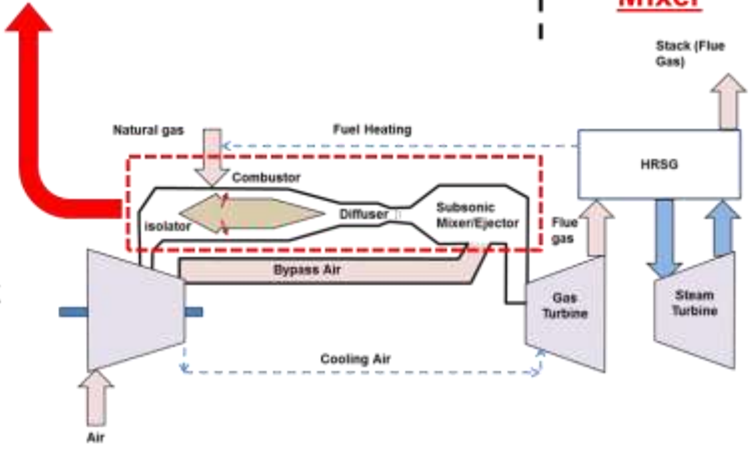
Hybrid RDE-Gas Turbine Cycle

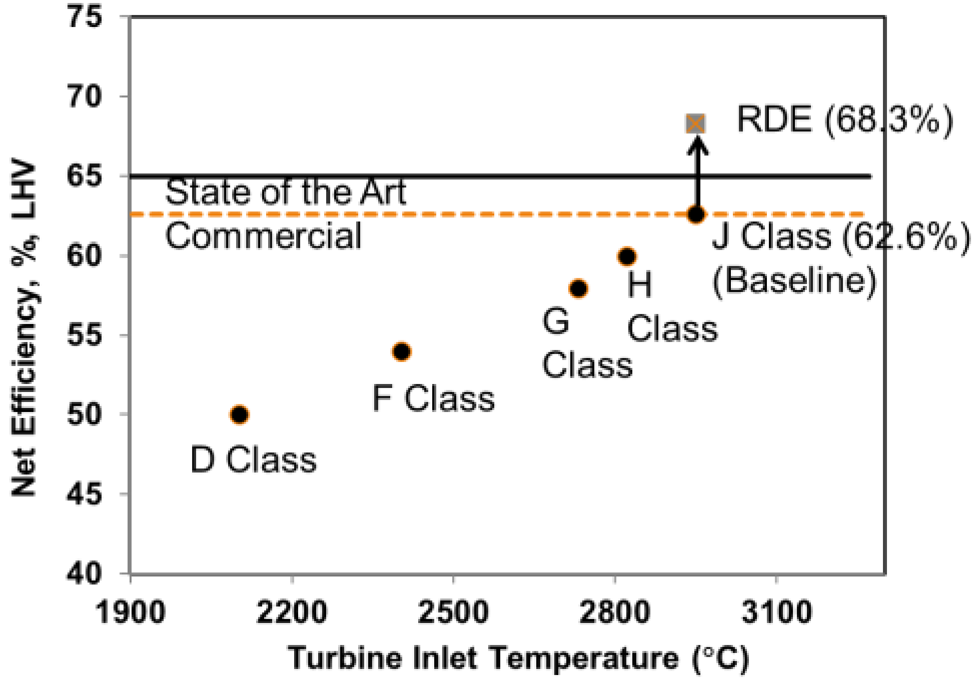
Comparison of NGCC Plant Efficiency with Various Gas Turbines



Trade Study Parameters:

1. Isolation shock strength
2. Equivalence ratio
3. Combustion efficiency
4. Flow compression ΔPt
5. Flow transition normal shock
6. Bypass mass flow / mixing





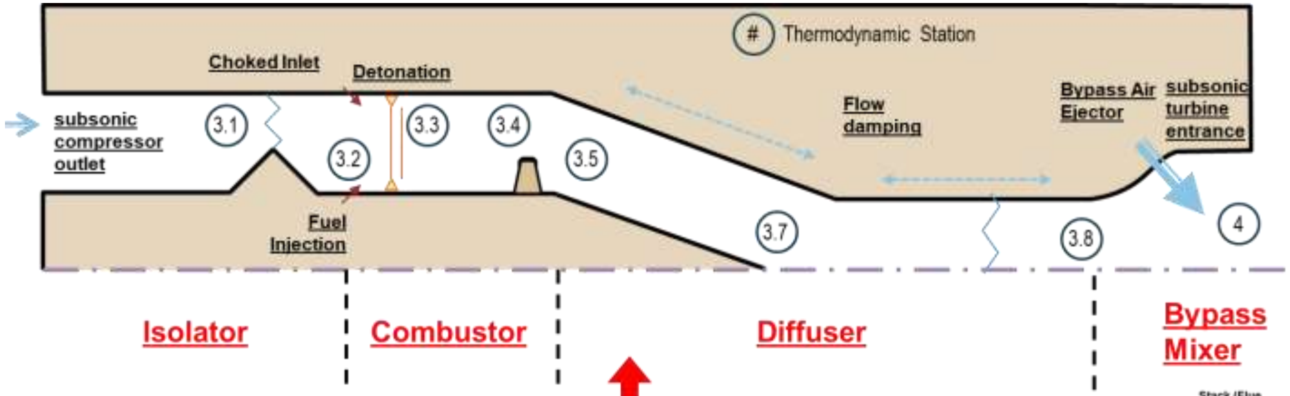
Courtesy: Aerojet Rocketdyne, Inc.

Baseline: MHI's J Class Turbine with 62.6% LHV efficiency (Case 3a, DOE/NETL-341/061013, Walter Shelton, Current and Future Technologies for Natural Gas Combined Cycle (NGCC) Power Plants)

Performance Results

Comparison of NGCC Plant Efficiency with Various Gas Turbines

Power Plant Details	Baseline	RDE
Net Plant Power, MWe	982	1073
Net Plant Efficiency, LHV	**62.6%**	**68.3%**



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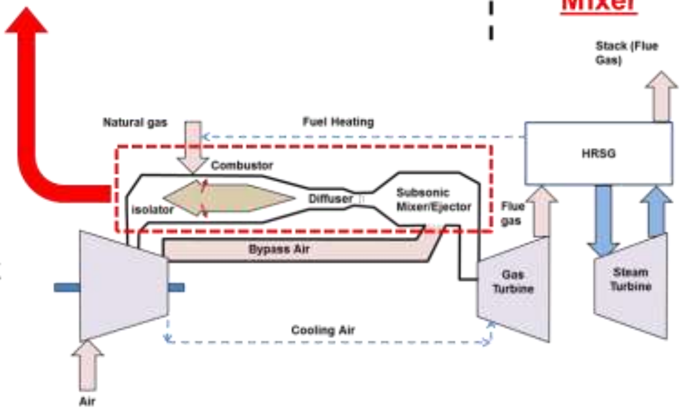
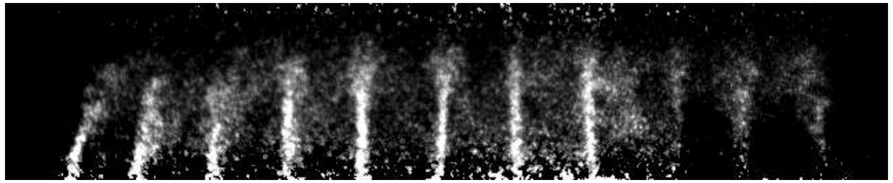


Baseline Cycle Data taken from Case 3a, DOE/NETL-341/061013, Walter Shelton, Current and Future Technologies for Natural Gas Combined Cycle (NGCC) Power Plants

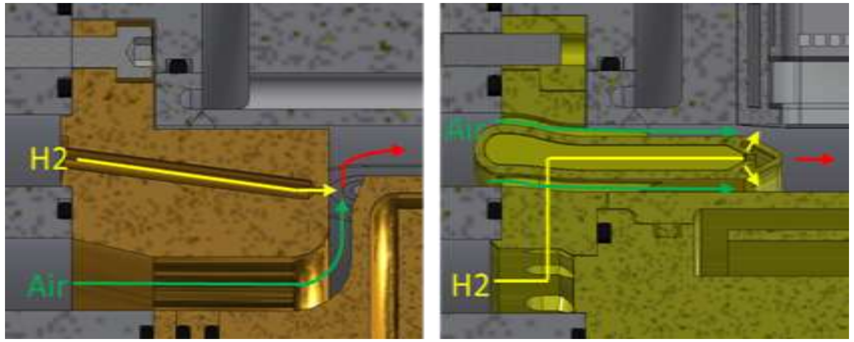
Power Plant Details	Baseline	RDE
Natural Gas Feed, lb/hr	263,520	263,520
Lower Heating Value LHV, Btu/lb	20,201	20,201
Thermal Input, MWt	1,567	1,567
Plant Capacity Factor	85%	85%
Power Output		
Gas Turbine Power, MWe	690	785
Steam Turbine Power, MWe	315	310
Total Gross Power, MWe	**1,005**	**1095**
Auxiliary Loads		
Boiler Feedwater Pumps, MWe	6.7	6.7
Circulating Water Pumps, MWe	2.9	2.9
Ground Water Pumps, MWe	0.3	0.3
Cooling Tower Fans, MWe	2.2	2.2
SCR, MWe	0.01	0.01
Gas Turbine Auxiliaries, MWe	1.1	1.1
Steam Turbine Auxiliaries, MWe	0.7	0.7
Miscellaneous BOP, MWe	3.4	3.4
Transformer Losses, MWe	5.0	5.0
Total Auxiliary Load, MWe	**22.4**	**22.4**

DOE PGC Roadmap

- **Improve fundamental understanding stable continuous wave detonation**
  - Wave directionality, bifurcation, translation speed (~CJ)
  - Det wave influence on operational parameters (i.e fuel injection/mixing)
- **Develop scale 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 emissions
- **Improve modeling capabilities**
  - Simultaneous detonation and deflagration
  - Grid dependences, chemical kinectics
  - Reduced order thermo and chemical models



NETL Characterization of Injector Response using Acetone PLIF



Varying the Fuel / Oxidizer injection schemes and sizes

RDE coupled to T63 Turbine at AFRL
Naples et al., AIAA 2017-1747

Current DOE Pressure Gain Combustion Funded Activities (2014 - 2021)

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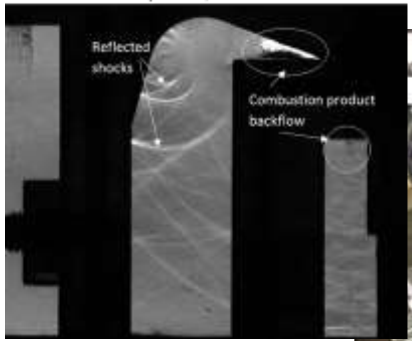
NETL In-House Research Activities

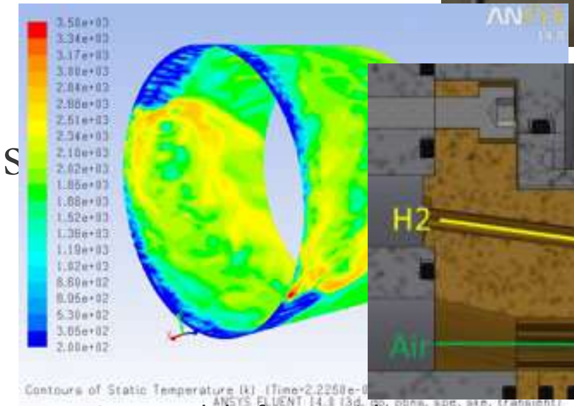
- **Lab-Scale Experiment**
  - Water-cooled for long duration testing
    - H2-Air, H2/NG-Air
    - Combustion stability, emissions, heat transfer
  - Optically accessible RDE

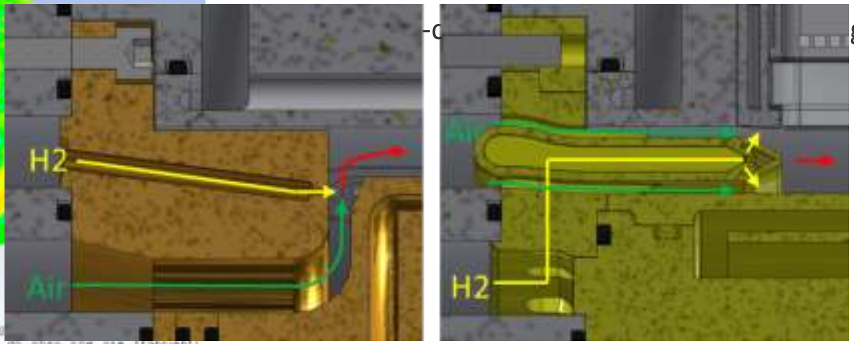
- **Computational Studies**
    - Model validation
    - Fundamental aspects of detonation
    - Low loss injector / geometry physics
    - Turbine integration

300 slpm air, no He flow



NETL Lab-Scale RDE Inlet Sector Rig



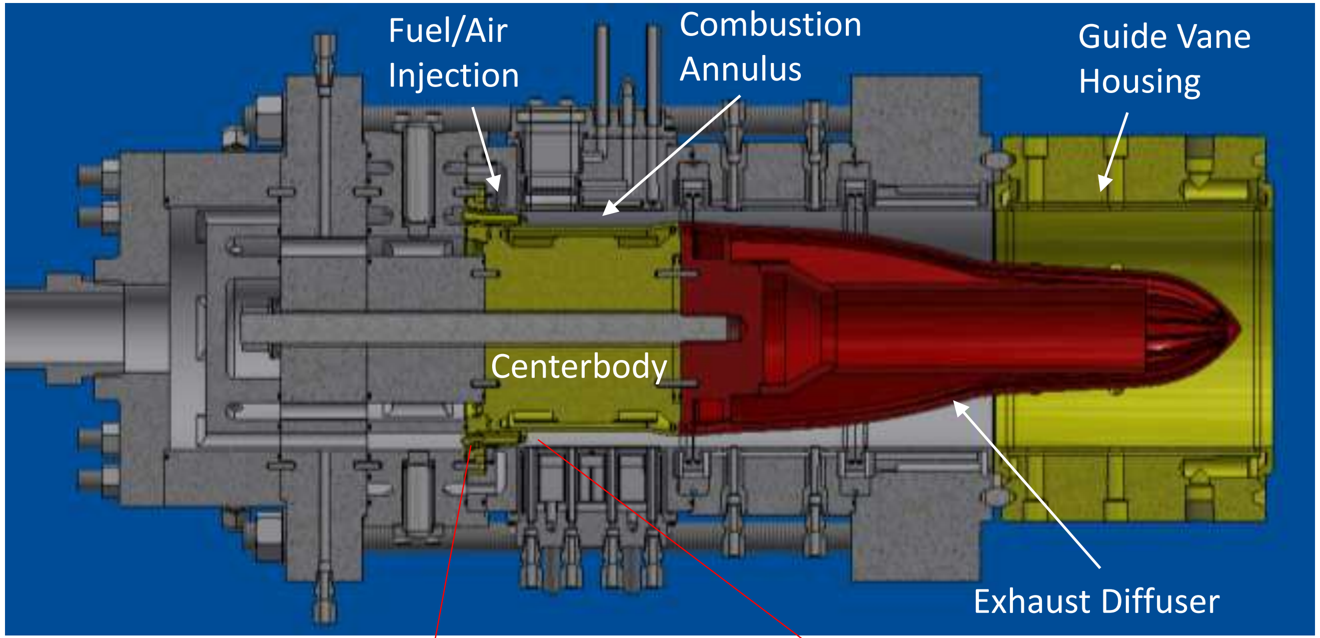


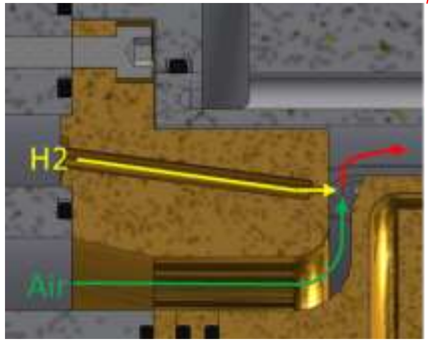
CFD model of RDE with temperature contours (H2/Air)

NETL Water-Cooled, High Pressure RDE

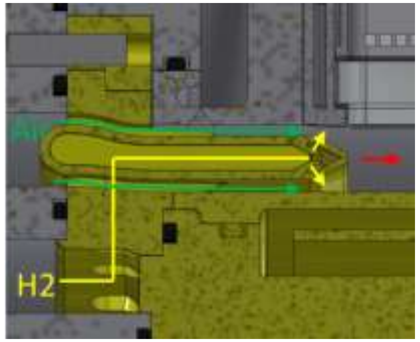
Design Basics and Operational Envelope

- **Modular Geometry**
  - 152.4 mm diameter, 7.62 mm combustion annulus, 152.4 mm length
  - Radial air injection (AFRL design)
  - Accommodate changes to fuel/air routing, injector, centerbody, outerbody, exhaust, instrumentation ports
- **Operating Conditions**
  - Cooling: water @ 150 lpm, 11 Bar
  - Max. shell T. P ≈ 477K, 16 Bar
  - air flow rate @ 600 K – 1 kg/sec
- **Instrumentation** **(1 MHz sampling)**
  - Dynamic Pressure, OH Chemi, Combustion Ionization
  - High Speed Imaging (60 kHz)





Radial Air Injection

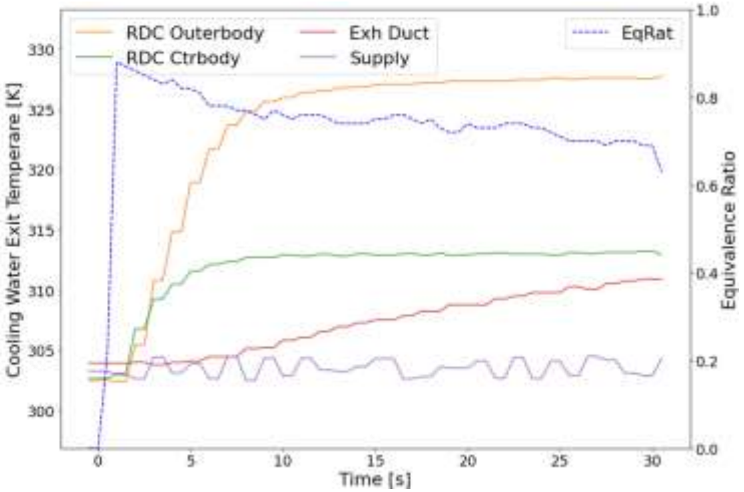


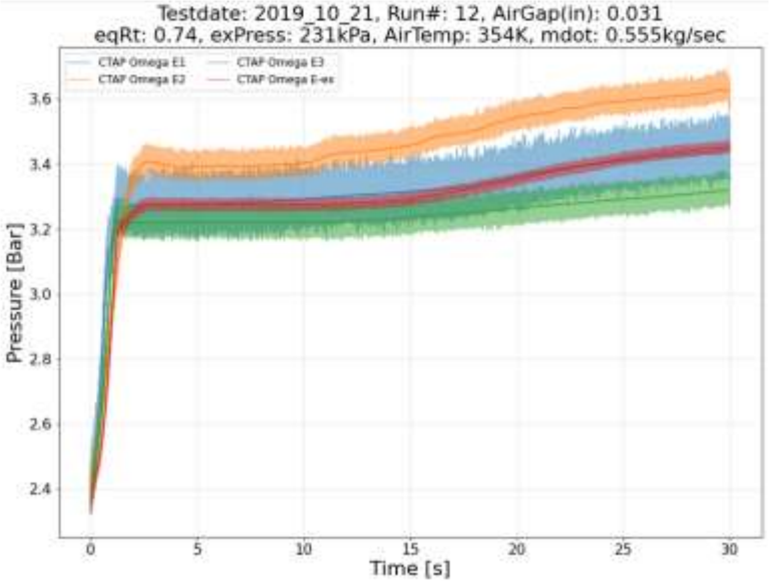
Axial Air Injection

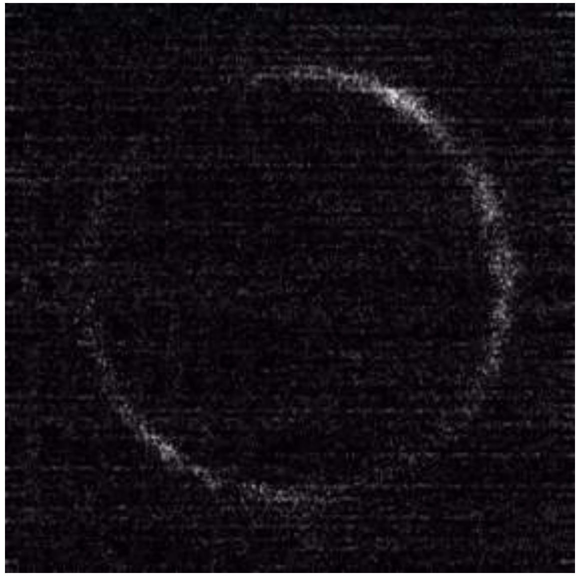
Air Injector Gap Size (mm)
0.56
0.79
1.75
2.8

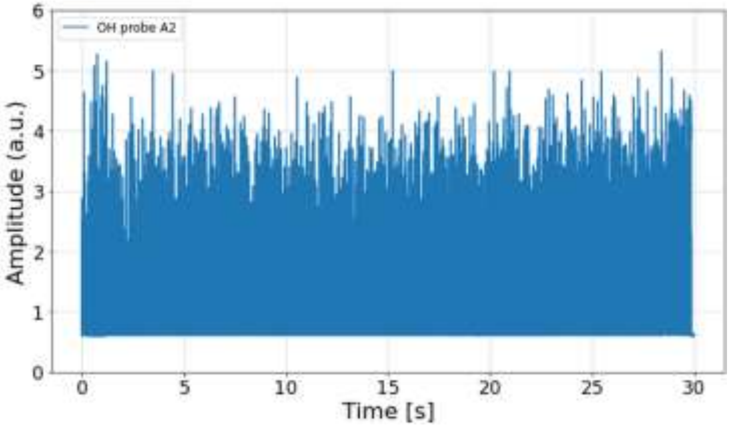
NETL Lab Scale RDC – H2/Air

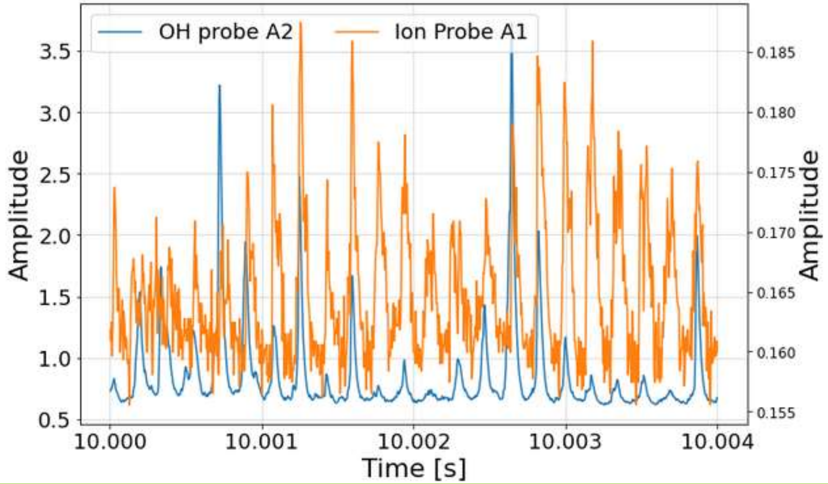
phi=0.74, Total mass flow ~ 0.555kg/sec P = 2.3 Bar, Tair = 354 K

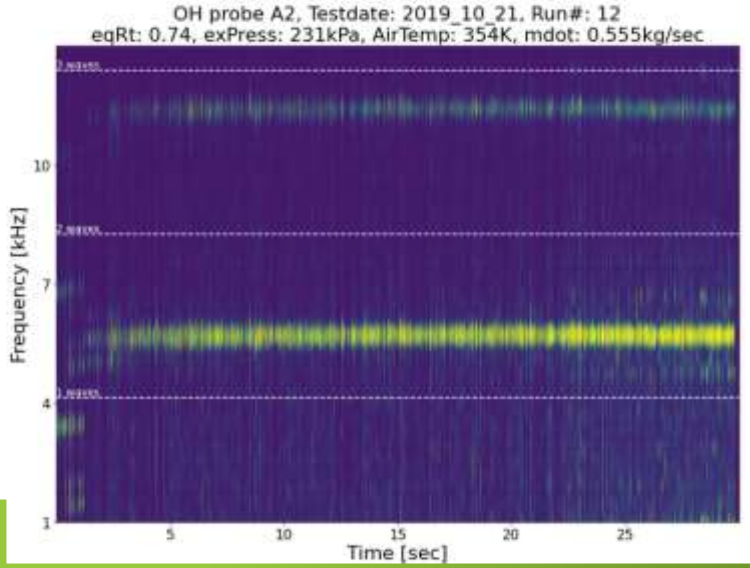






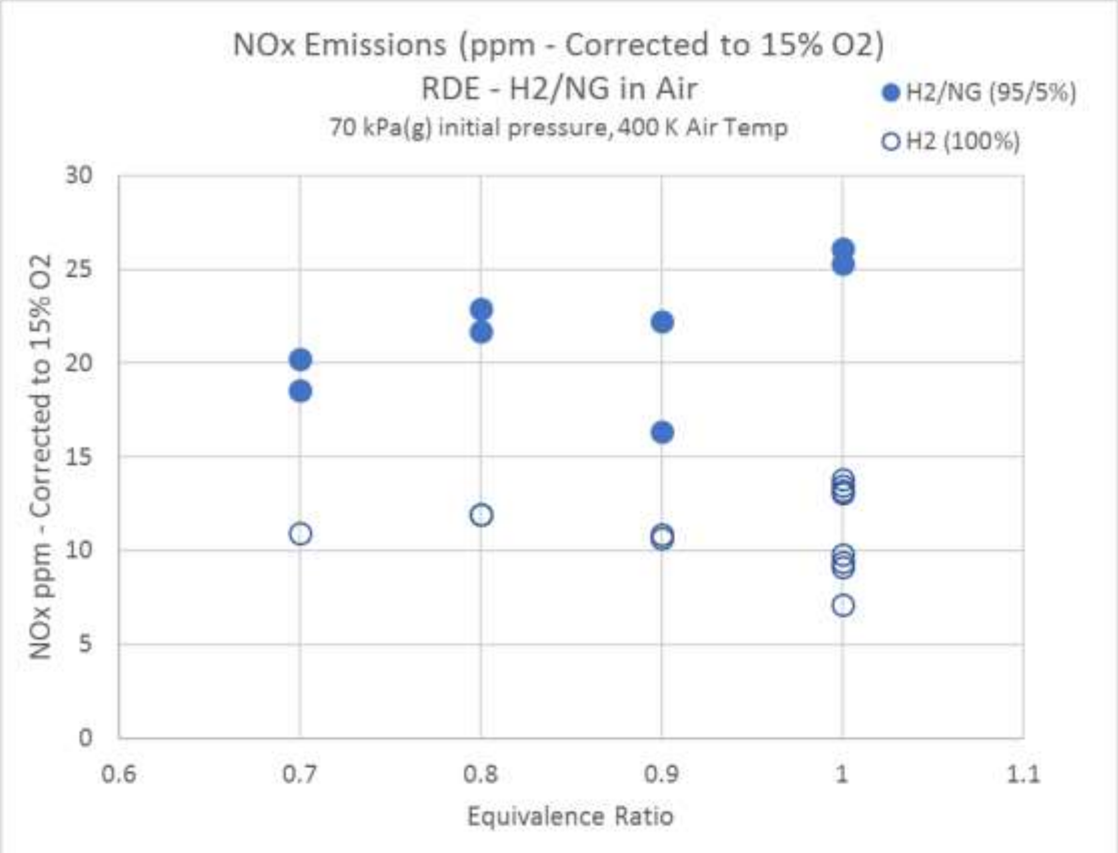




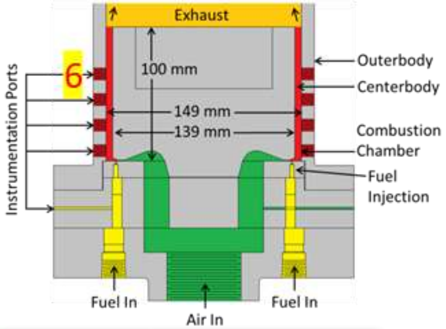


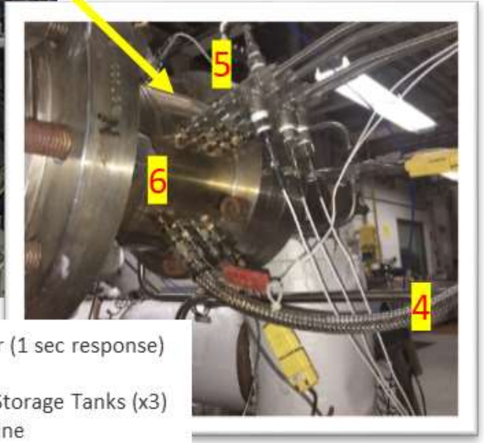
NOx Emission (ppm) – NETL RDE on H2-Air

NOx Emissions (ppm) – Corrected to 15% O2



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





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

Results shown are from NETL uncooled RDE

Ferguson, Donald H., Bridget O'Meara, Arnab Roy, and Kristyn Johnson. "Experimental Measurements of NOx Emissions in a Rotating Detonation Engine.", AIAA2020-0204, *AIAA Scitech 2020 Forum,* Orlando, FL, January 2020, https://doi.org/10.2514/6.2020-0204.

Real-time sensor for RDE Mode and Wave Speed

Machine Vision – Deep Learning Application

- Train convolutional neural network (CNN) on large pool of images with multiple modes
- Utilize CNN to predict wave mode (wave number and direction of rotation) from a single image
- Machine vision approach is being combined with conventional instrumentation (p') to add instantaneous wave speed.

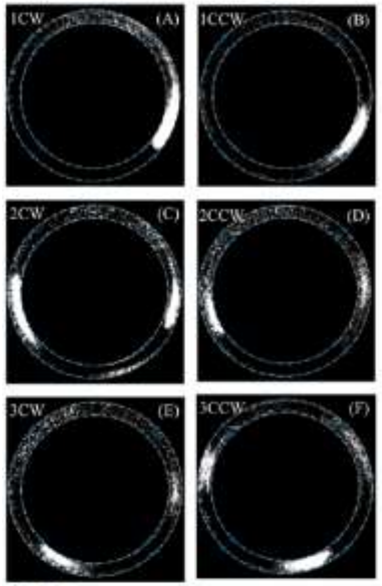


FIGURE 6: Downstream images of modes (A) 1CW, (B) 1CCW, (C) 2CW, (D) 2CCW, (E) 3CW and (F) 3CCW

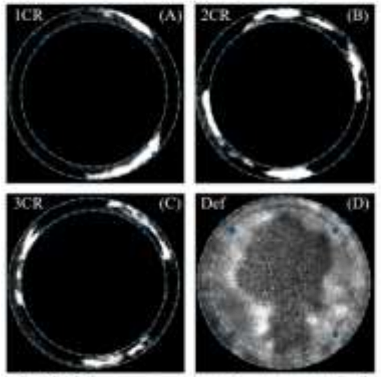


FIGURE 15: Downstream images of additional modes (A) 1CR, (B) 2CR, (C) 3CR, and (D) Def

Purdue images

NETL images

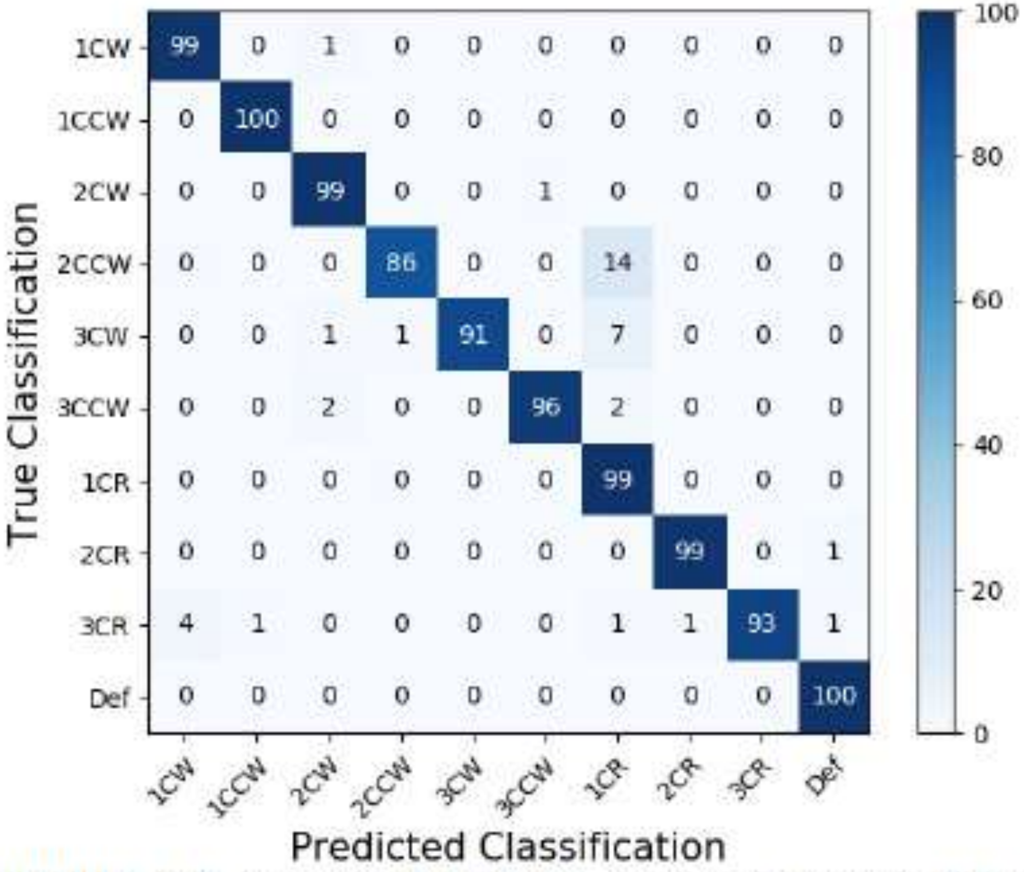


FIGURE 16: Normalized confusion matrix of extended dataset containing counter-rotating waves and deflagrative behaviors

Johnson, Kristyn B, Donald H Ferguson, Robert S Tempke, and Andrew C Nix. "Application of a Convolutional Neural Network for Wave Mode Identification in a Rotating Detonation Combustor Using High-Speed Imaging.", GT2020-15676 In ASME 2020 Turbo Expo. Virtual, Online: ASME Turbo Expo, 2020.

Summary

- **Rotating Detonation Combustion / Engines has the potential for producing significant gains in cycle efficiency through near constant volume combustion.**
  - Research has focused on Hydrogen-Air combustion

- **Challenges exist**
  - Reducing the pressure drop across the inlet, maintaining combustion stability, understanding performance characteristics, compressor / turbine integration

- **DOE continues to provide support for PGC and collaborates with other funding agencies when appropriate.**

- **Consideration for Pressure Gain Combustion in new hybrid cycles.**

NATIONAL ENERGY TECHNOLOGY LABORATORY

Thank You.

Questions??

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U.S. DEPARTMENT OF ENERGY

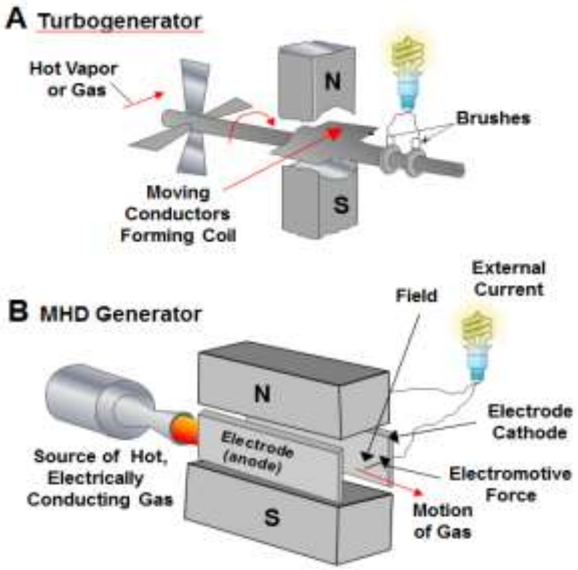
Backup slide

Making Oxy-fuel an Advantage

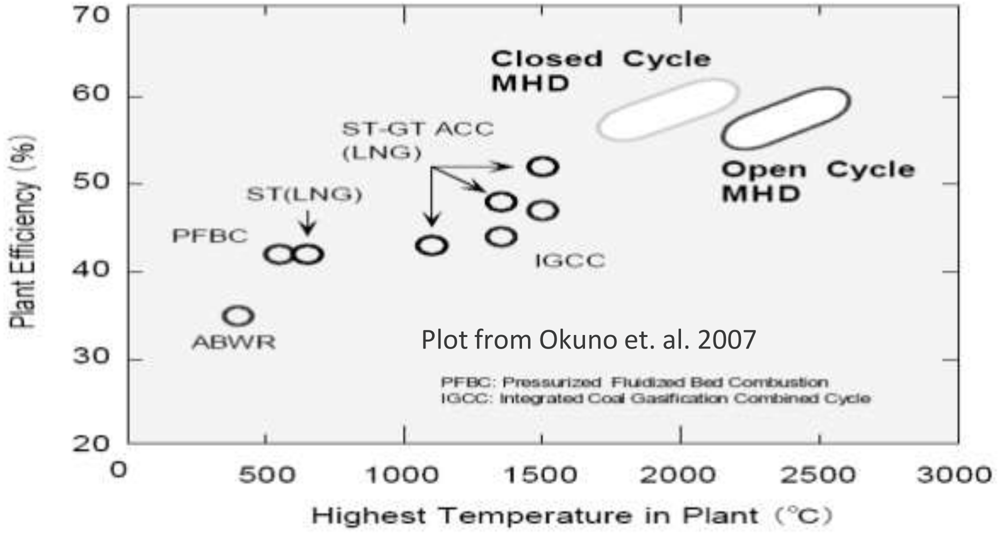
Direct Power Extraction (via MHD)

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

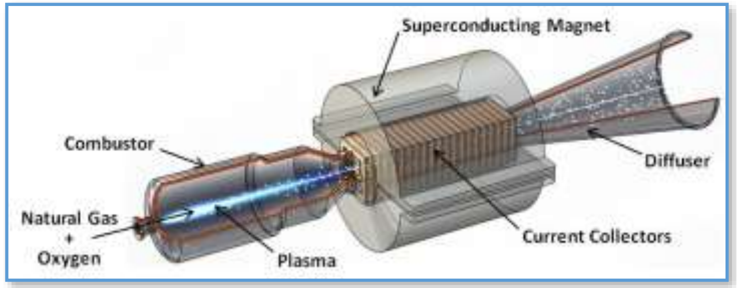
- **Higher plant efficiency – works at higher temperature**
  - Need to use in combined cycle
  - Synergy w/ oxy-fuel for CCUS
    - oxy-coal COE much higher than baseline COE primarily due to ASU
    - Legacy: MHD-steam coal has ASU (to combust to higher T) but COE lower than baseline COE ->



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

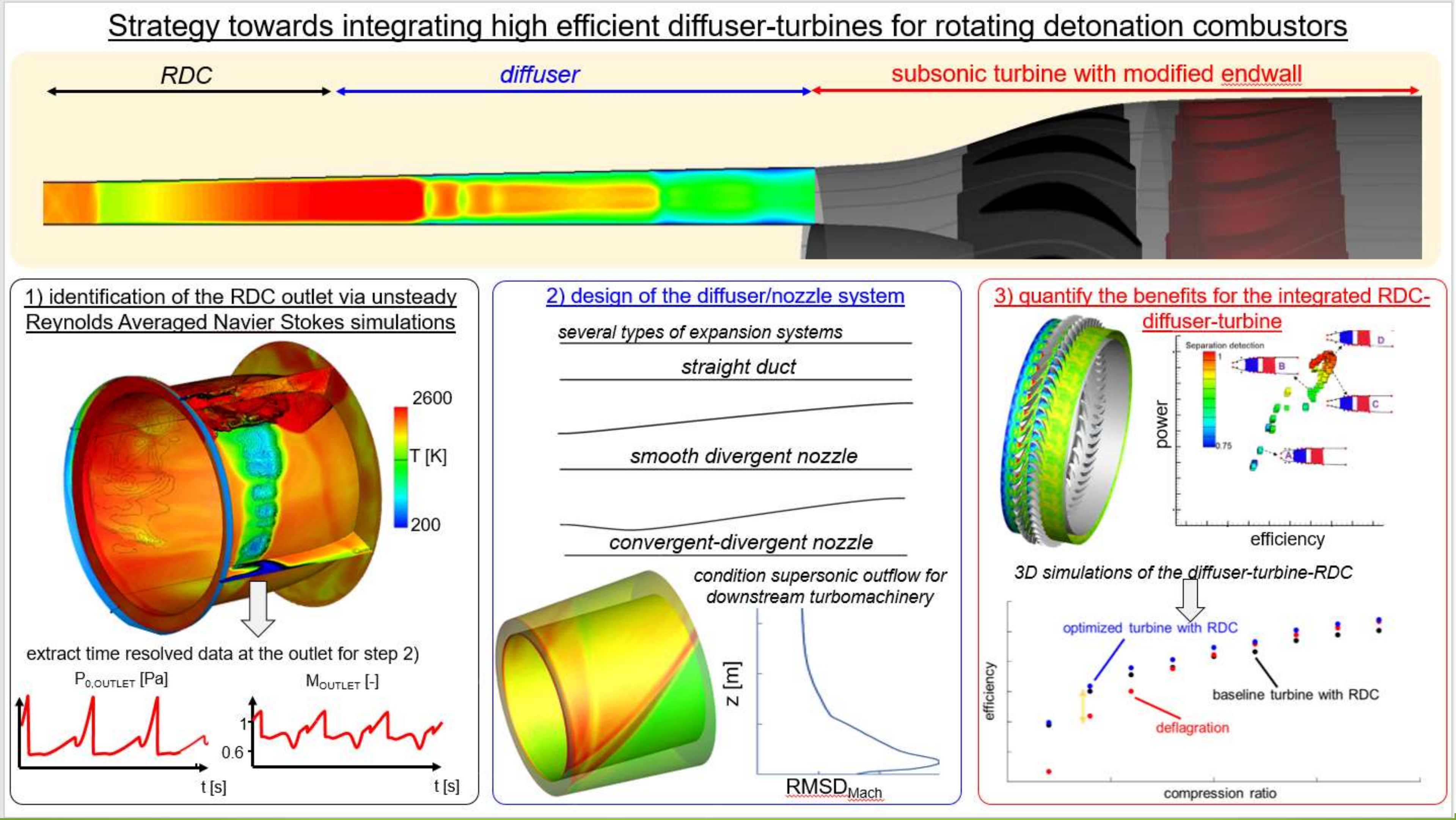


Plot from Okuno et. al. 2007



Turbine Integration – High efficiency Diffuser

Guillermo Paniagua and James Braun (Purdue University)



Improved Sensors: TDLAS (T and species)

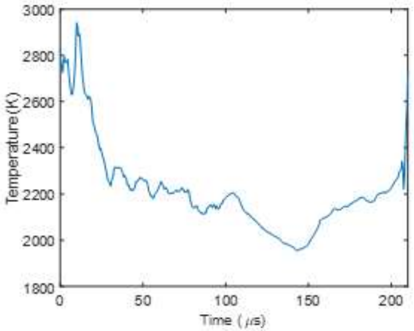
Subith Vasu (UCF)

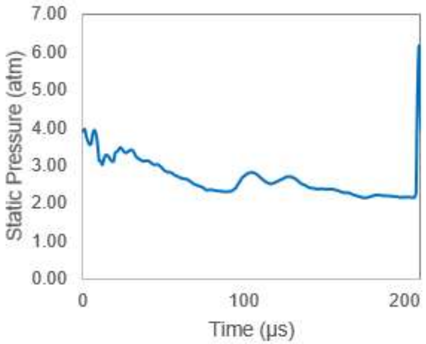
Measurement Results Inside Detonation Channel: H_2 vs. CH_4 RDE Operation

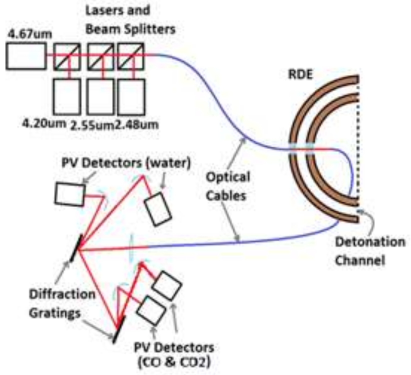
2

H_2-Air/O_2 Fueled (2017)

Location: SwRI, San Antonio, TX



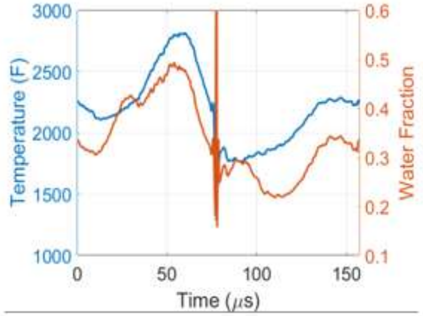


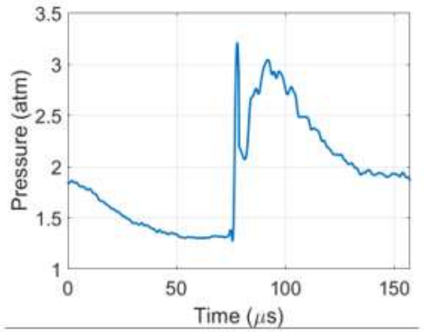


- Same engine (10cm OD, 1cm channel).
- Target, temperature and H_2O
- 2017 measurements resembled CFD simulations. Captured high-speed features.
- Uncertainty greatly reduced for 2018 measurements.
- 2018 measurements revealed incomplete combustion during detonation. Secondary combustion occurs after shock heating.

CH_4-Air/O_2 Fueled (2018)

Location: Univ. of Alabama





Upgrades to NETL Water-Cooled RDE

- Radial to axial air injection
- Exhaust diffuser with ability to add instrumented guide vanes

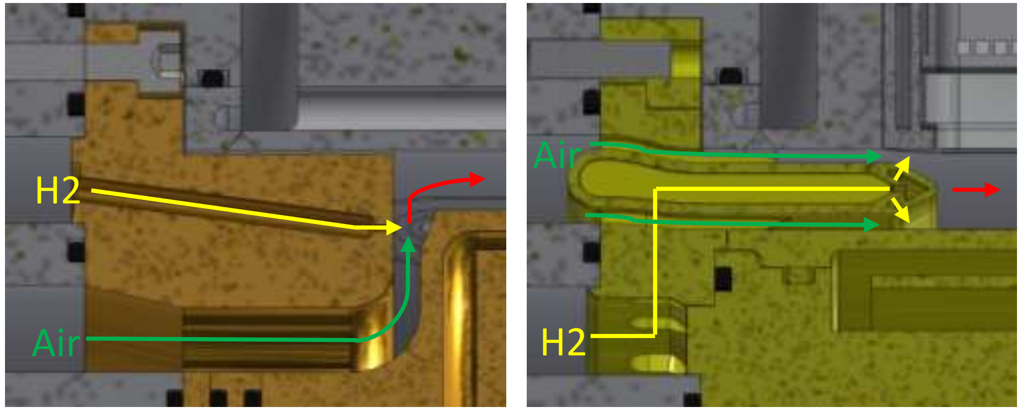


Figure 8: Baseline Fuel-Air Injector with Turning, Radial-Outward Air Flow (Left) and Pintle Fuel-Air Injector with Axial Air Flow (Right). Baseline Injector shown with widest tested air gap of .111" and annulus gap of .300". Pintle Injector shown with new .400" annulus gap.

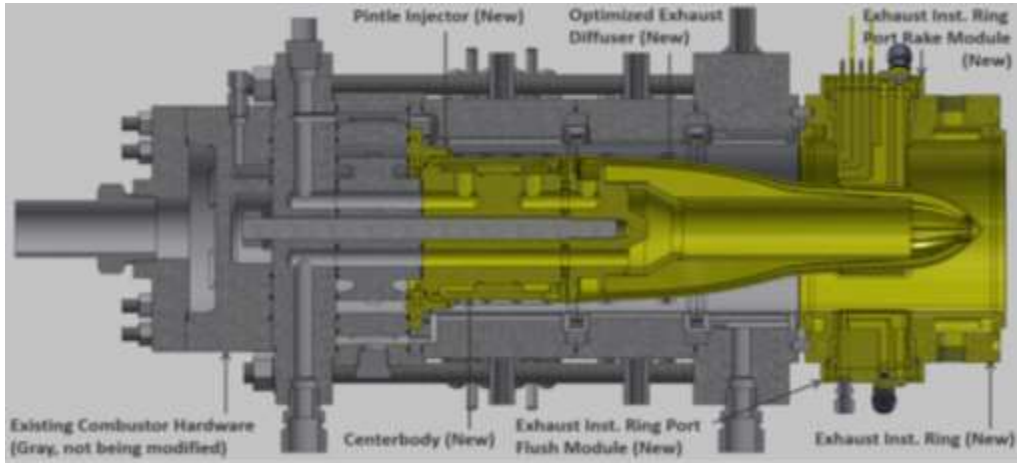
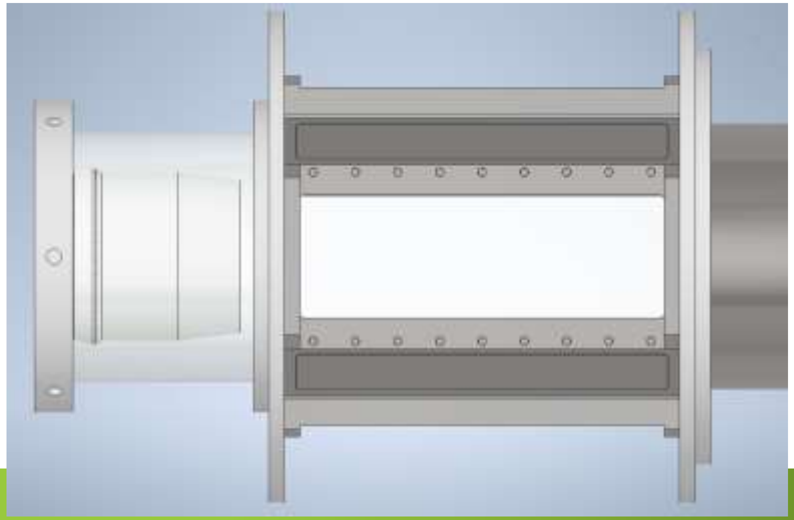


Figure 9: NETL RDE Combustor as Reconfigured with New Pintle Fuel-Air Injector, Centerbody, Exhaust Diffuser and Exhaust Instrumentation Ring

Conceptual design on new optically accessible RDE and exhaust



CFD for PGC

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