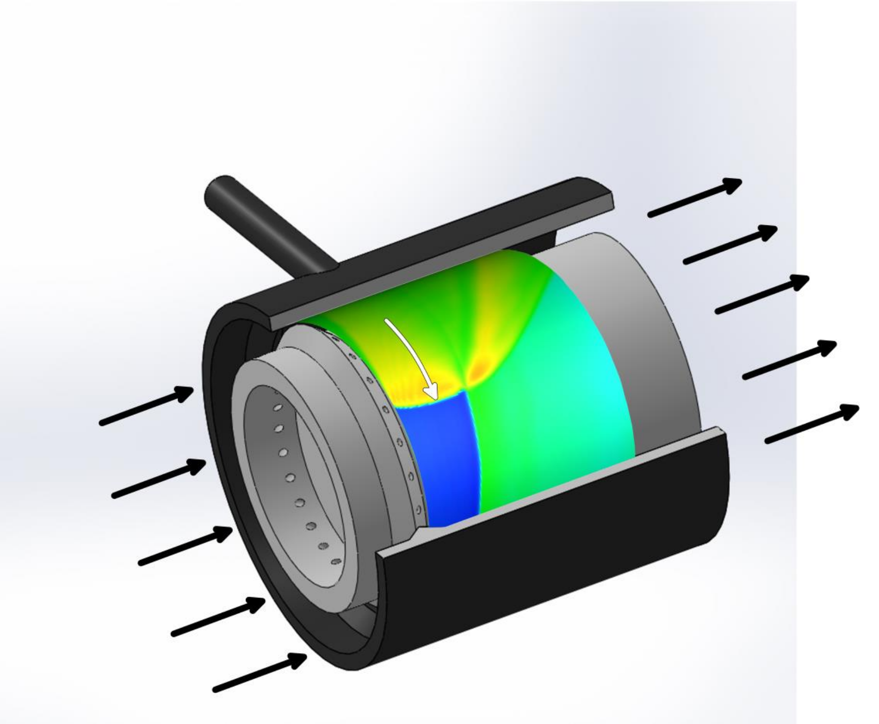
Pressure Gain Combustion for Land Based Power Generation



NETL – Office of Research and Development (ORD) and Advanced Energy Systems Program (AES)
Providing Clean Energy Technology Through Innovative Ideas

Don Ferguson (PhD)
Todd Sidwell, Pete Strakey (PhD), Arab Roy (PhD), Andrew Sisler

Cost of Carbon Capture

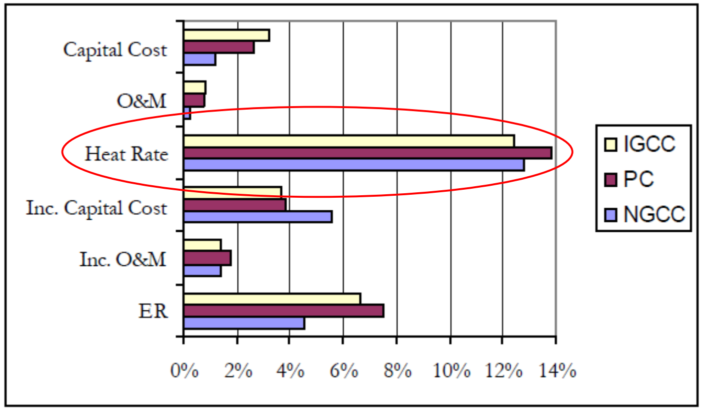
David, J. and Herzog, H., "The Cost of Carbon Capture", NETL Workshop on Carbon Capture, 2001

- **Comparative analysis of the increased Cost of Electricity with 90% capture**
  - PC and NGCC with post-combustion MEA capture
  - IGCC with pre-combustion absorption

Difference from Ref with no capture.	PC	NGCC	IGCC
Therm Efficiency (%Change)	-6.3%	-6.0%	-4.3%
COE (% Change)	+53%	+40%	+25%

- **Analysis considers the sensitivity of COE to changes in parameters such as Heat Rate (fuel consumed)**
  - For a 10% decrease in fuel consumed (Heat Rate) for NGCC with CC, estimated COE would decrease by 13%

- **Subsequent benefit of reducing the size of the CC with a reduction in fuel consumed**



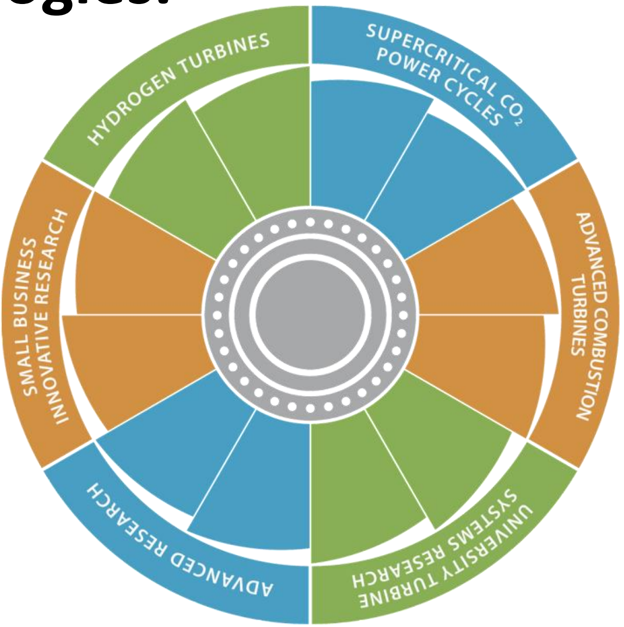
Decrease in COE with 10% decrease in parameter. A 10% decrease in HR could have a 13% decrease in COE for NGCC.

DOE/NETL Turbines Program

- **Manages a research, development, and demonstration (RD&D) portfolio of projects designed to remove environmental concerns about the future use of fossil fuels through development of revolutionary, near-zero-emission advanced turbine technologies.**

Advanced combined cycle turbine

- Applicable to natural gas and H_2
- T3 of 1900 K
- Adv. components: pressure gain combustion, advanced transition, air foils w/ decoupled thermal & mechanical stresses
- Delivers another \$20/T reduction in CO_2 capture cost
- NG CC (LHV) efficiency approaching 65%

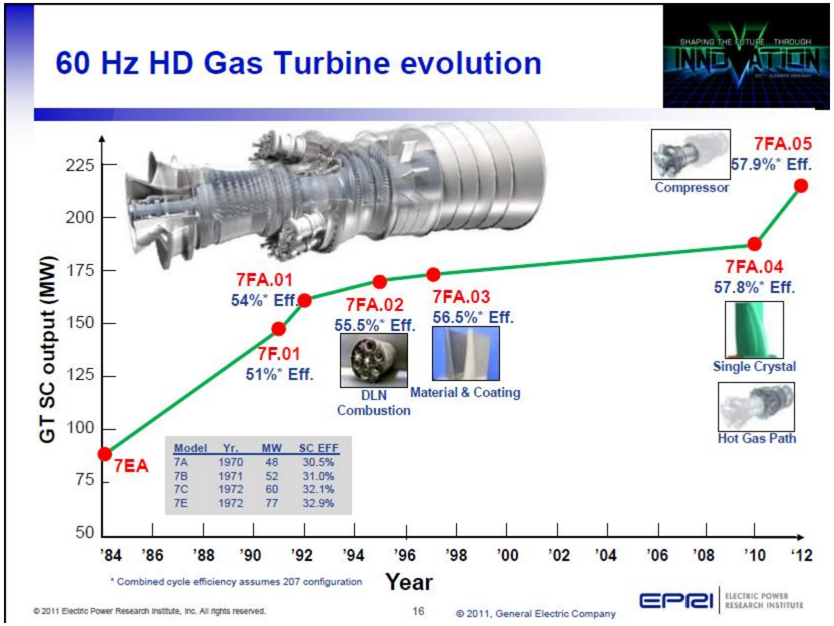


Gas Turbine Technology Development

Evolution to Revolution

- **Recent technology advancements have resulted in incremental improvements in efficiency. For example consider the GE F class engine.**

Model	Year	CC Eff	Technology
7FA.01	1992	54%	Combined cycle advancement
7FA.02	1995	55.5%	DLN Combustion
7FA.03	1997	56.6%	Materials and Coatings (> T_3)
7FA.04	2010	57.8%	Hot gas path, single crystal blades
7FA.05	2012	57.9%	Compressor improvements



60 Hz HD Gas Turbine evolution

Model	Yr.	MW	SC EFF
7A	1970	48	30.5%
7B	1971	52	31.0%
7C	1972	60	32.1%
7E	1972	77	32.9%

* Combined cycle efficiency assumes 207 configuration

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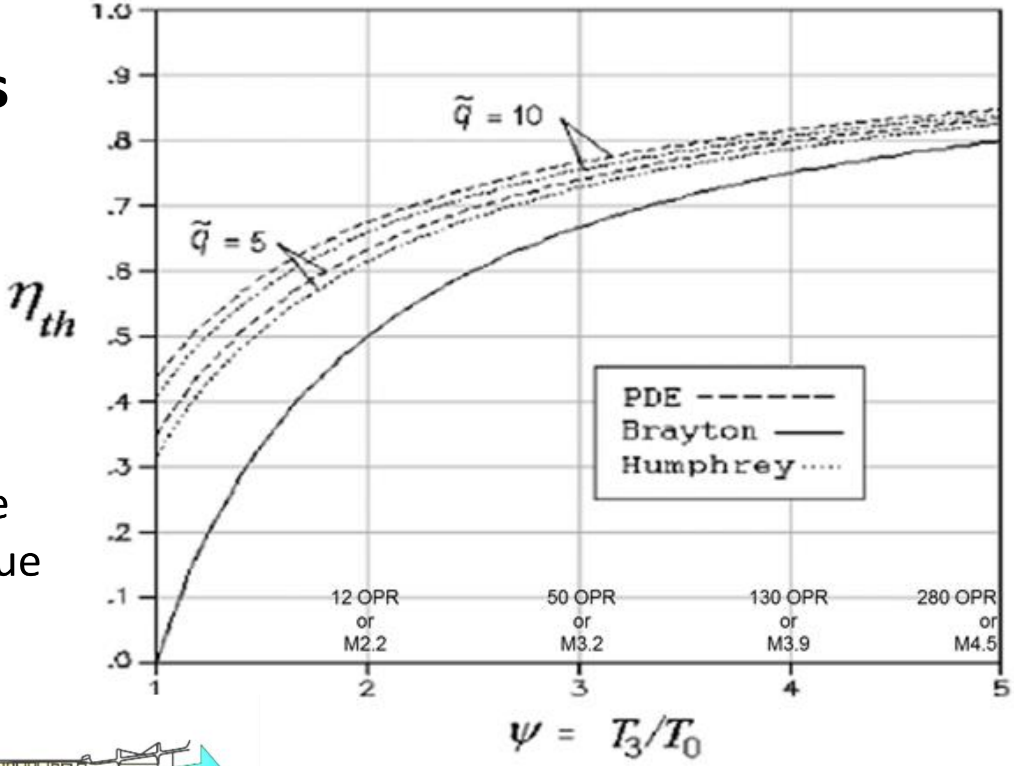
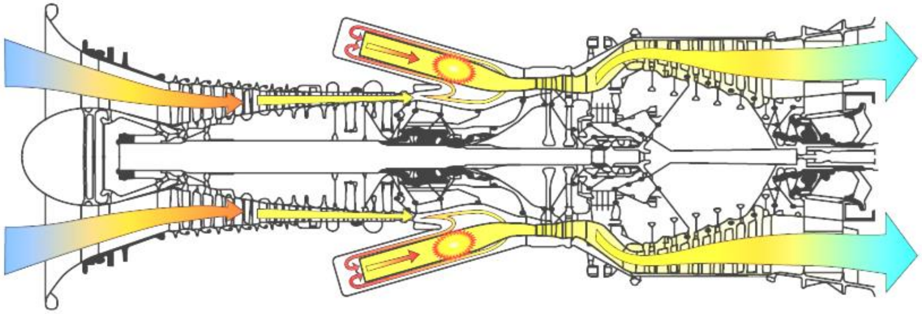
- **The need for transformational technology!!**
  - **Combustion**

Constant Pressure vs Constant Volume Combustion

- **Convention gas turbines relies on Constant Pressure Combustion (Brayton cycle)**
  - Utilizes Deflagration (slow combustion – subsonic)
  - Actually results in a pressure loss across the combustor due to viscous effects

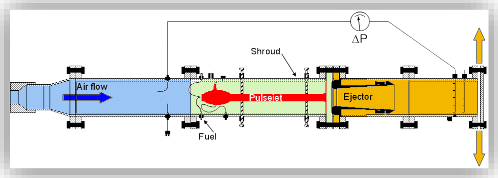




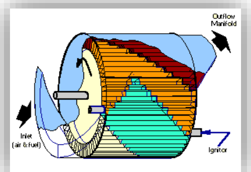
Constant volume combustion through detonation offers a pathway to improved efficiency compared to deflagration

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

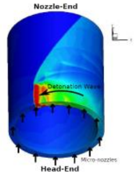


Resonant Pulse Combustor (NASA-Glenn)



Wave Rotor Engine (IUPUI)

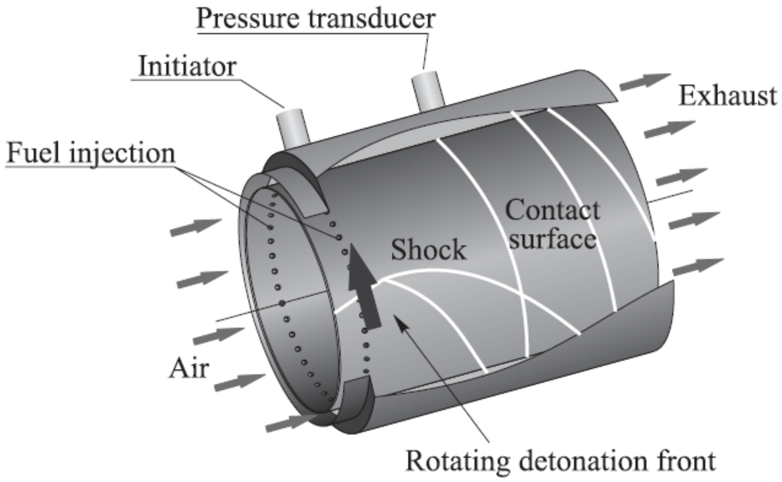

Multi-Tube PDE
G.E. Global Research Center 2005



RDE Simulation
Naval Research Laboratory - 2011

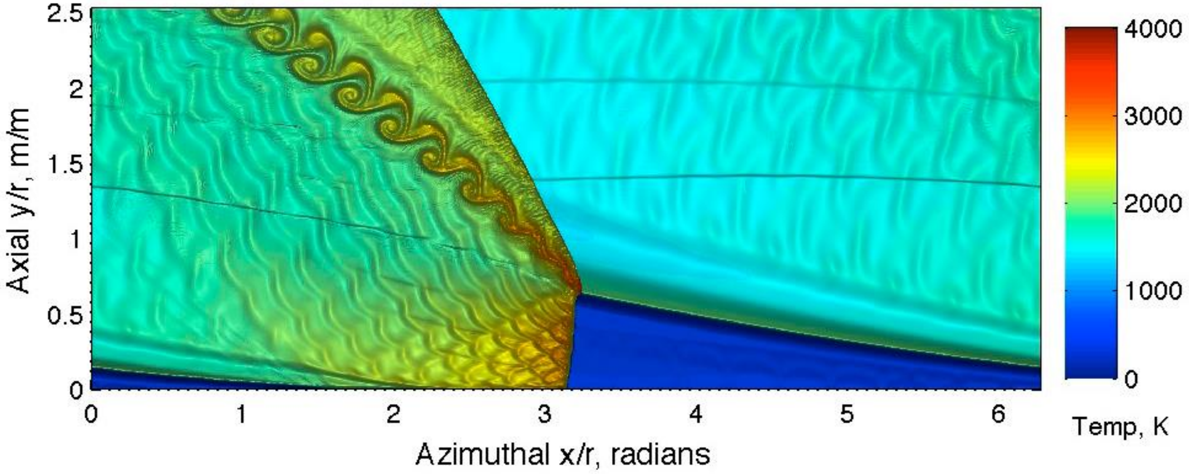
RDC Potential Advantages

- Benefits are in addition to other gas turbine improvements
- Unlike related pressure gain combustion technology, RDE offer continuous flow eliminating the need to Purge and Fill events and complicated valving.
- Once initiated, detonation wave is self-sustaining (limited DDT)
- High frequency detonation results in quasi-steady flow through combustor exhaust.
- Scalable and good turn-down performance

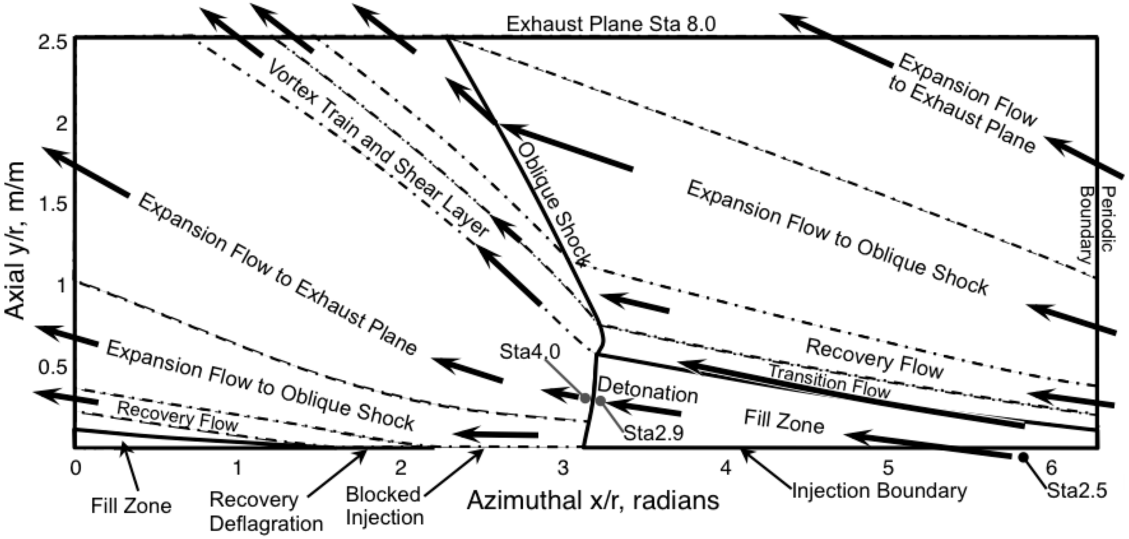


Physical Characteristics of RDE Combustion

- **Complex fluid and thermodynamic feature occur throughout the flow field (Nordeen, 2013)**



Temperature with Density shading highlights complexity
(Induction Parameter Model)



Different regions of the flow experiences different thermodynamic cycles

Thermodynamic Analysis of RDE

- **Individual streamlines exhibit unique thermodynamic cycles.**

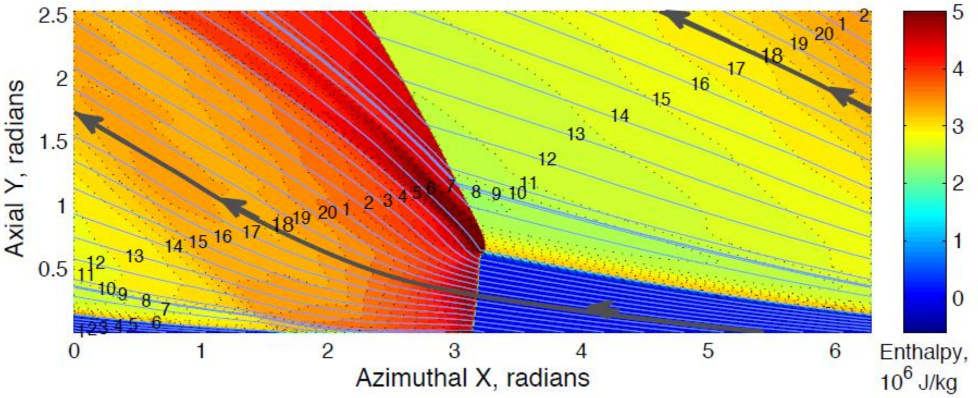
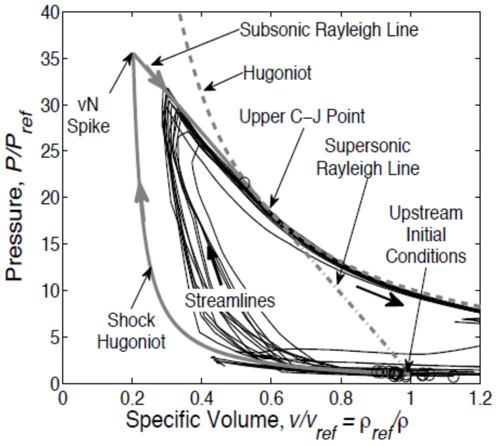
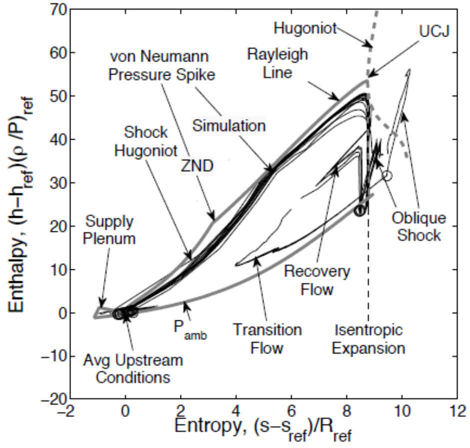


Figure 1–4 Time-averaged enthalpy with streamlines in rotating frame of reference [13]

One approach is to model flow along streamlines as individual thermodynamic cycles (Nordeen, 2013). But over-simplifies the chemistry.



a)



b)

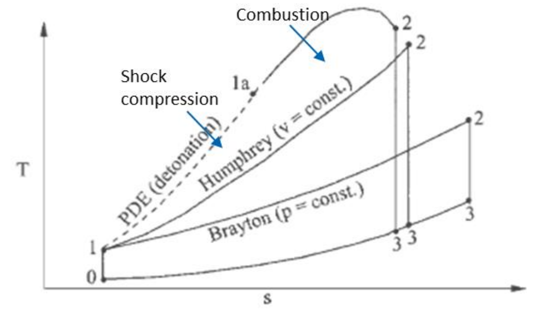


Fig. 2 Temperature–entropy diagram of ideal PDE, Humphrey, and Brayton cycles.

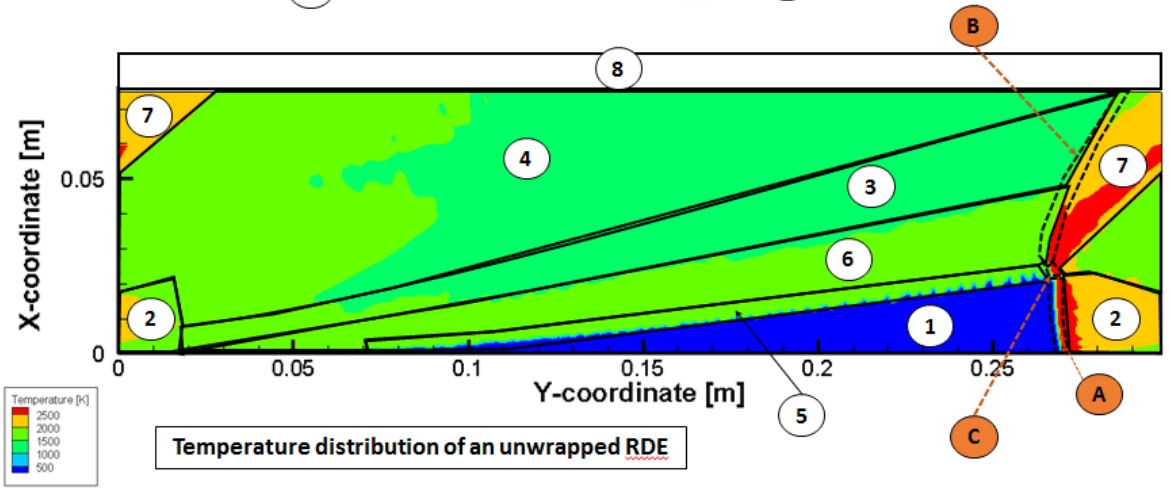
Chemical Reactor Network Approach (NETL)

Thermodynamic Model

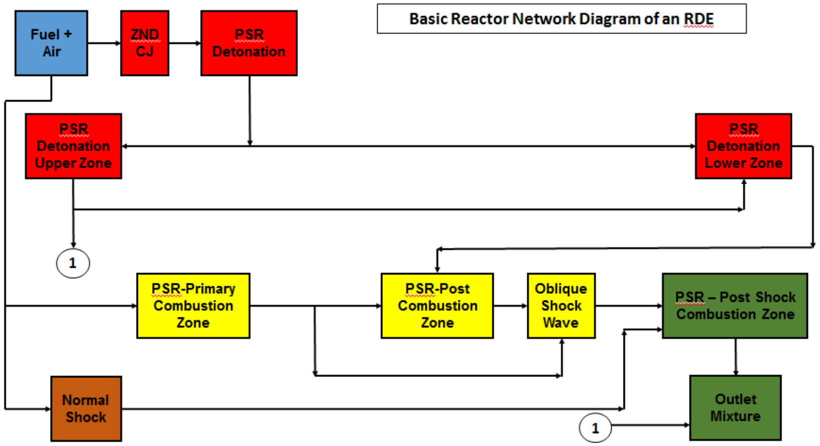
- A Detonation Wave
- B Oblique Shock Wave
- C Normal Shock Wave

- 1 Inlet/Fill Zone
- 2 Detonation Primary Zone - PSR
- 3 Detonation Expansion Lower Zone - PSR
- 4 Detonation Expansion Upper Zone - PSR

- 5 Primary Combustion Zone - PSR
- 6 Post Combustion Zone - PSR
- 7 Post Shock combustion - PSR
- 8 Outlet mixing Zone

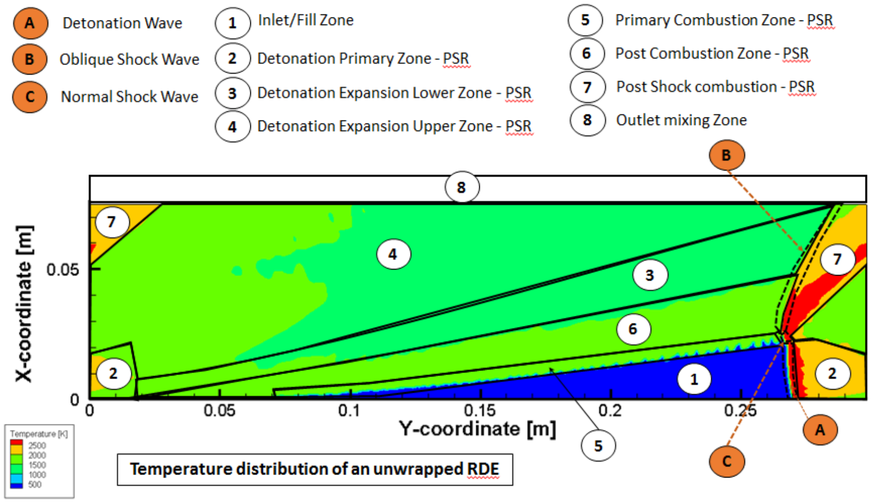


Temperature distribution of an unwrapped RDE



Basic Reactor Network Diagram of an RDE

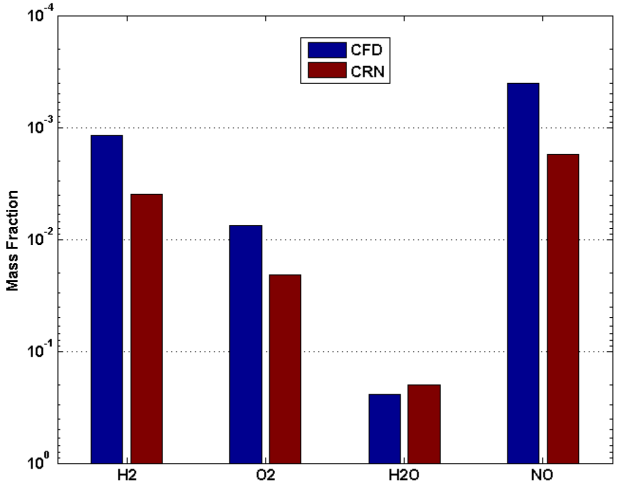
Comparison of CRN with CFD



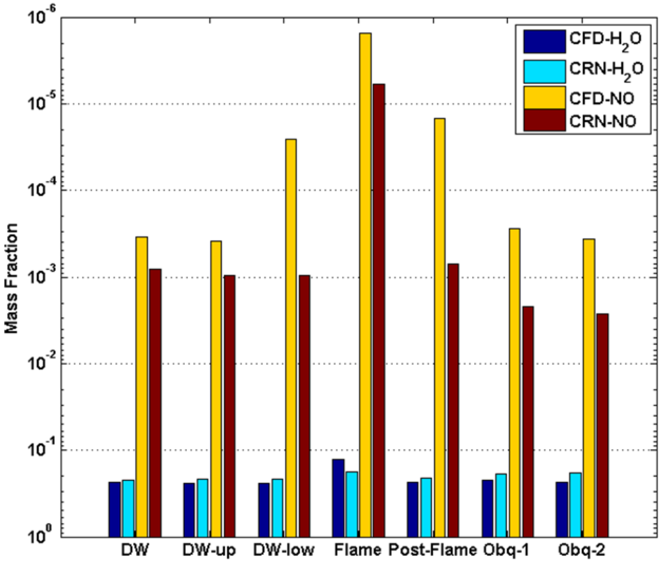
Temperature distribution of an unwrapped RDE

Zone	T(avg) [K]	P(avg) [Pa]	Reactor Volume /Total Volume	Fraction mass flow (Fig. 5)
PSR_DW	2585	7.0948E+05	0.05638	
PSR_DW_up	1935.4	1.658E+05	0.48411	
PSR_DW_low	1686.2	1.0758E+05	0.20616	x1 = 0.95
PSR_Flame	1144.6	1.135E+05	0.01403	
PSR_Post_flame	1816.4	1.0108E+05	0.07777	y1 = 1-x1
PSR_Obq_1	2682.2	3.5188E+05	0.0164	
PSR_Obq_2	2778.29	2.77829E+05	0.04614	

Reactor zone properties



Comparison of CRN predicted mass fractions with 2-D CFD results at RDE outlet



Reactor wise product mass fraction comparison with CFD

Rotating Detonation, Continuous Wave, Combustion offers a set of unique challenges

- Combustor
  - Inlet/Injector design
    - Low-loss injectors
  - Combustion stability / Efficiency
    - Mixing
    - Limiting deflagration
    - Wave bifurcation
    - Directionality
  - Exhaust Transition
    - Maintain pressure gain
    - Sub-Sonic vs Super-Sonic
  - Unsteady Heat transfer
  - Emissions
    - High or low NOx

Rotating Detonation, Continuous Wave, Combustion offers a set of unique challenges

- Compressor (unsteady flow or backflow from combustor) – could this induce surge / stall on the compressor

- Turbine
  - Turbine blade film cooling with PGC
  - Integration of Combustor to Turbine to minimize pressure loss.

- Cycle benefit from pressure gain
  - Hybrid cycles
  - Coupled with reciprocating engine for turbo-compounding in a PDE arrangement taking advantage intermittent flow from cylinders.

NETL-ORD Program Objectives

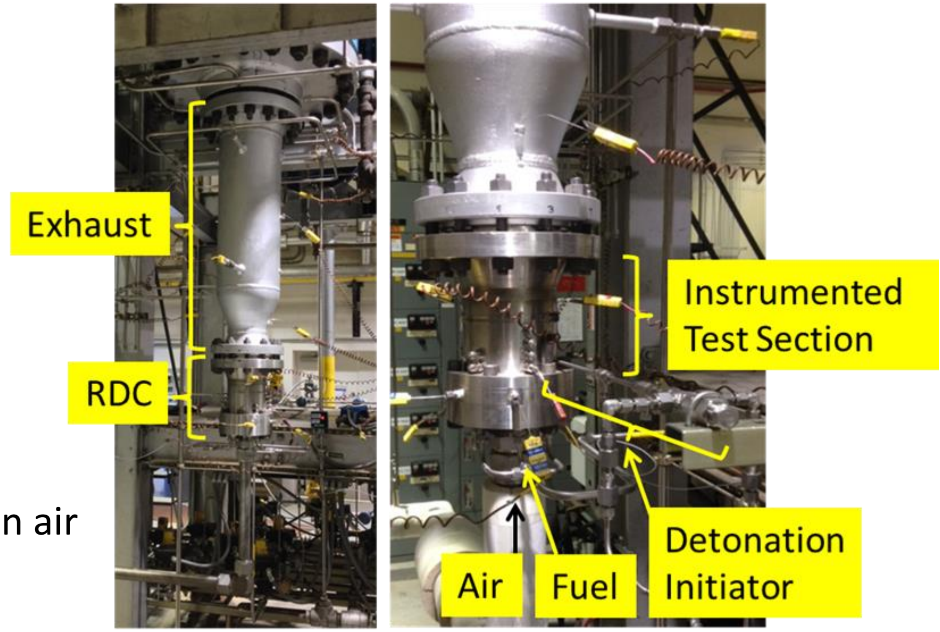
- Identify and address knowledge gaps relative to detonation and shock wave management for sustained combustion in land based power generation applications.

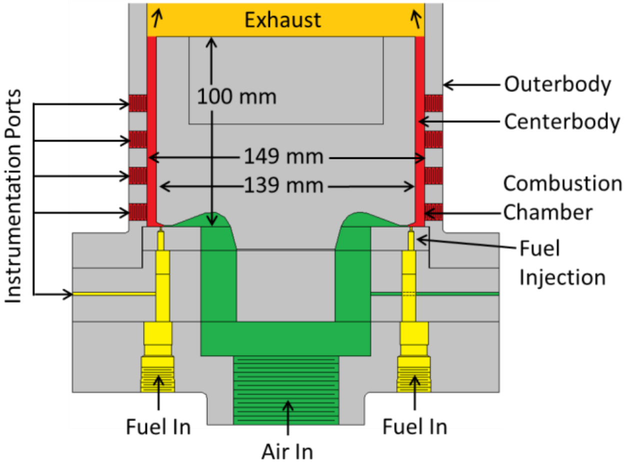
- Define a realistic pathway for implementing pressure gain combustion in a gas turbine engine for land based power generation.

- Provide experimental data for model validation

NETL Bench-Scale Experimental Research

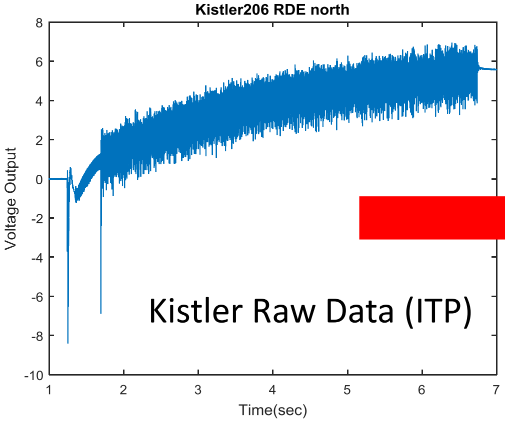
- **Hardware / Facilities**
  - AFRL 6” RDE, H2-Air
  - Facility capabilities
    - 30 bar (30 atm)
    - 800 K (1000 F) preheat
    - 2100 K (3100 F)combustion temperatures
    - 1.5 kg/sec (3.2lb/sec) combustion air
    - H2, NG, Propane, Ethane
- Objectives
  - Influence of pressure on RDE
  - Low loss inlet and wave directionality
  - Exhaust flow transition for turbine
  - Heat transfer
  - NOx Emissions
  - Generate validation data for models

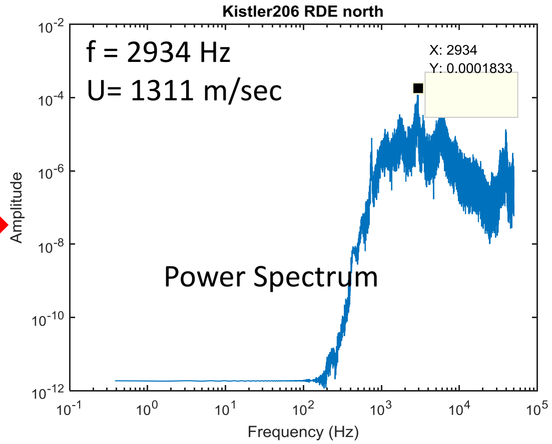




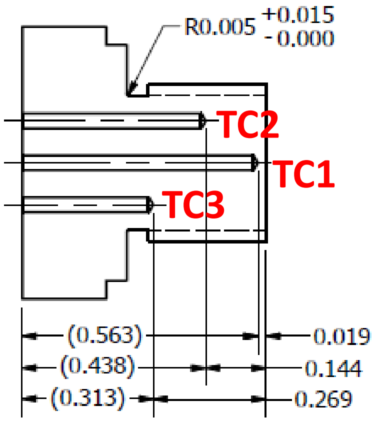
Preliminary Data Analysis

- Dynamic Pressure measurements using fast response transducers in ITP (Infinite Tube Pressure) and flush mounted configuration





- **Transient Heat Flux estimate**

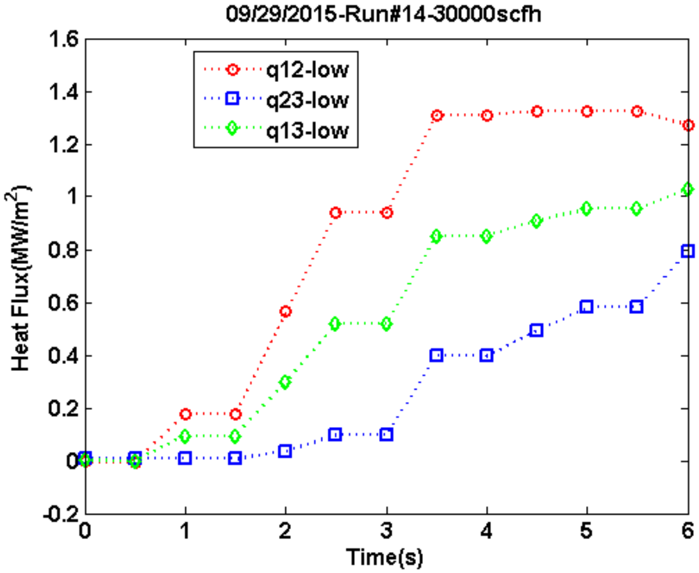


Simplification: 1-D Semi-infinite Transient Conduction

- **Transient heat flux[1,2] @ $x = 0$**

$$q(t_N) = 2\sqrt{\frac{\rho C k}{\pi}}\left[\sum_{i=1}^{N}\frac{T_S^*(t_i) - T_S^*(t_{i-1})}{(t_N - t_i)^{1/2} - (t_N - t_{i-1})^{1/2}}\right]$$

q12 -> Heat flux using TC2-TC1



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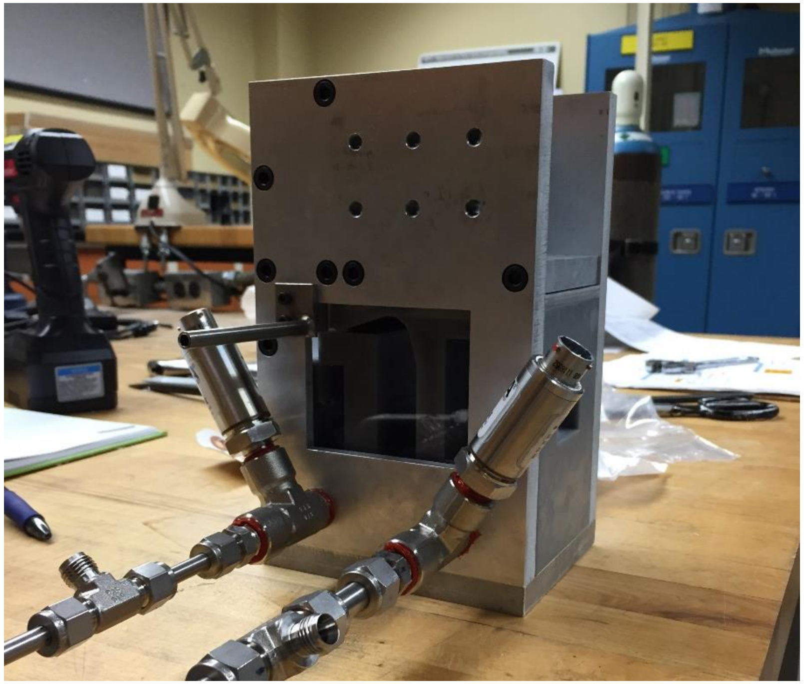
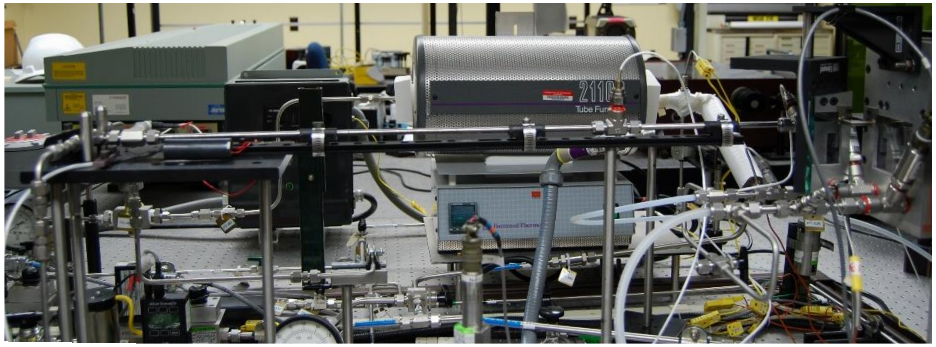
[1] *Dennis E. Lilelkis, AFRL, MS thesis, 1986*

[2] *Cook and Felderman, AIAA, 1966*

NETL RDE Inlet Experiments

- **Linear RDE apparatus designed and fabricated to facilitate development of improved inlets**
  - Inlet and plenum optically accessible from multiple sides
  - Detonation pressure wave created by accompanying H_2/air detonation tube
  - 3D printed inlet geometries for rapid evaluation of designs

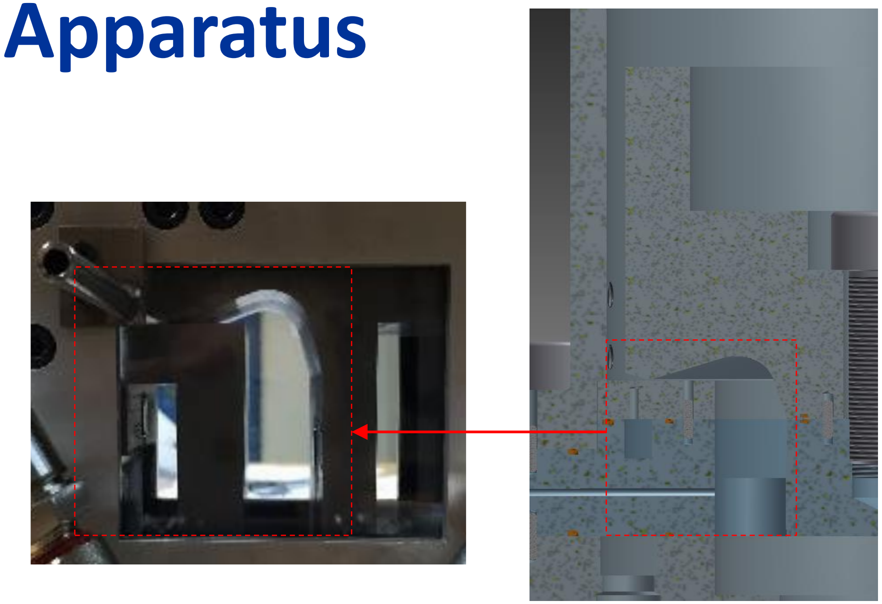




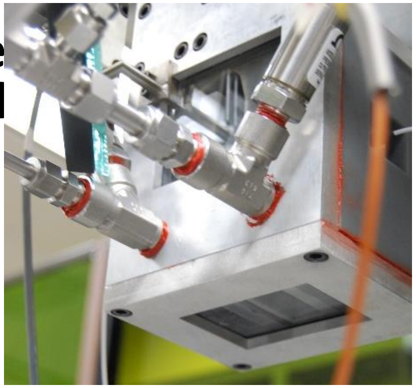
- **Scaling and similitude used to maintain relevance to full-scale, fired RDE at NETL MGN**

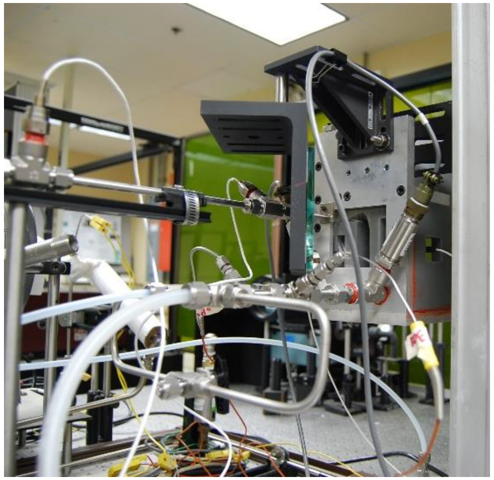
Linear RDE Apparatus

- **Non-reacting gases within inlet passages (He/air)**
  - H_2/air detonation tube connected to end of linear RDE channel
  - 3D printed inlet geometry mimics RDE cross section at 1:1 scale
  - Optical accessibility permits non-intrusive data collection

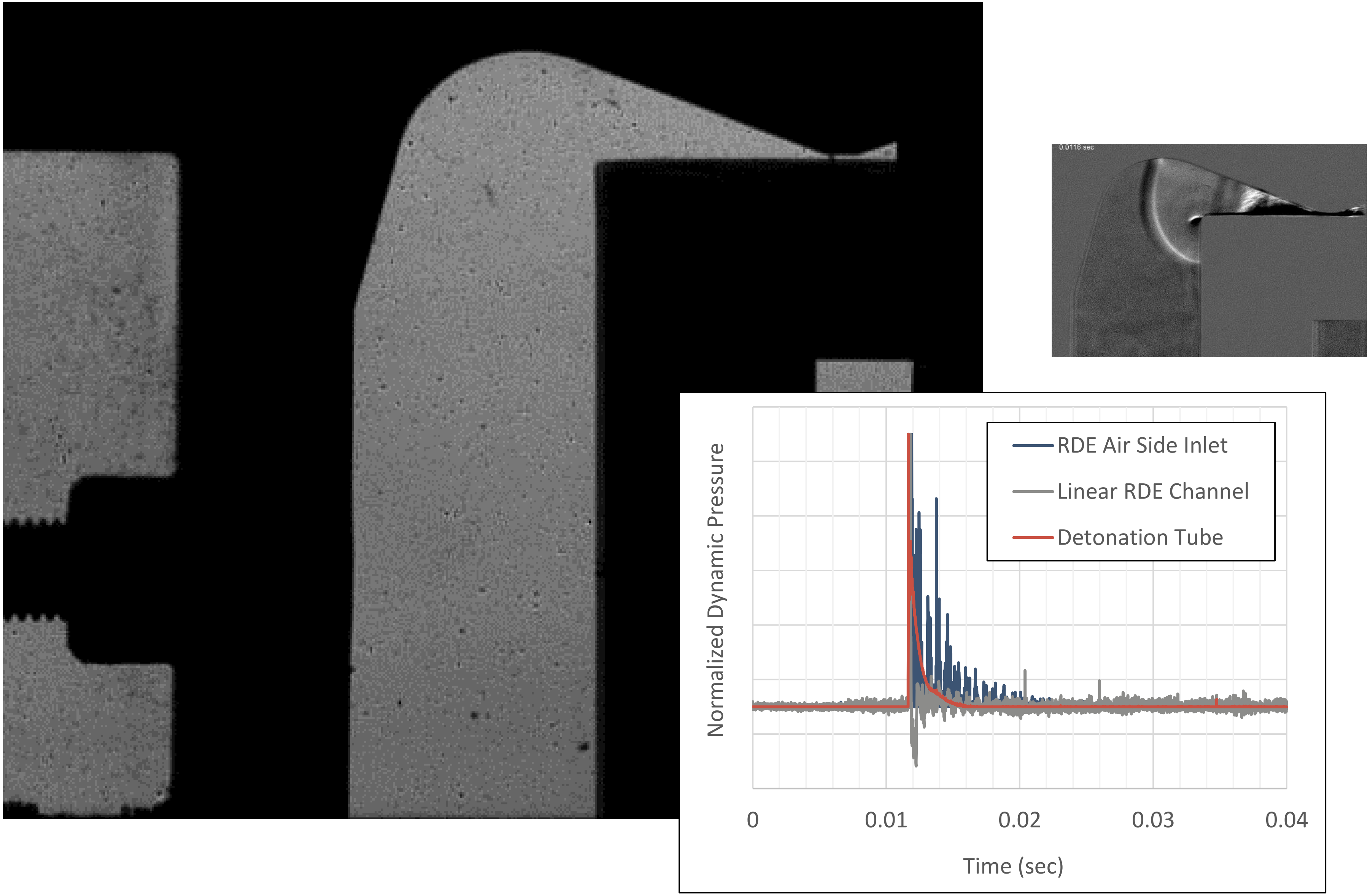


- **Rapidly propagating pressure wave creates characteristic backflow and recovery behavior seen in full-scale, fired RDE**
  - Diagnostics include dynamic pressure measurements and high-speed Schlieren imaging to evaluate inlet dynamics, acetone PLIF for fuel/air mixing within channel





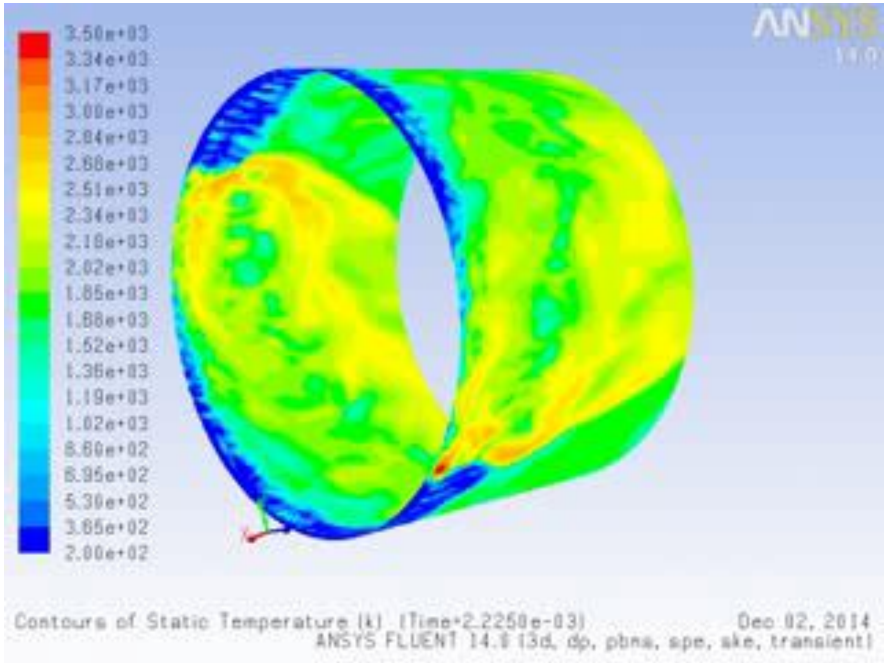
Synchronized Measurements



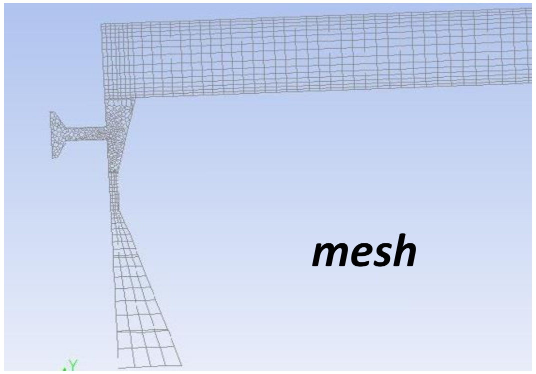
CFD Modeling of NETL RDE

- Fluent being used to simulate RDE operation.
  - 3D grid (~1.8M cells) includes discreet fuel injection and air slot with partial manifolding.
  - 1 step H2/Air mechanism, no combustion model.
  - k-e turbulence model.
- Characterizing overall thermal efficiency, pressure gain/loss, potential turbine work, etc…

Temperature Contours (ϕ = 1.0)



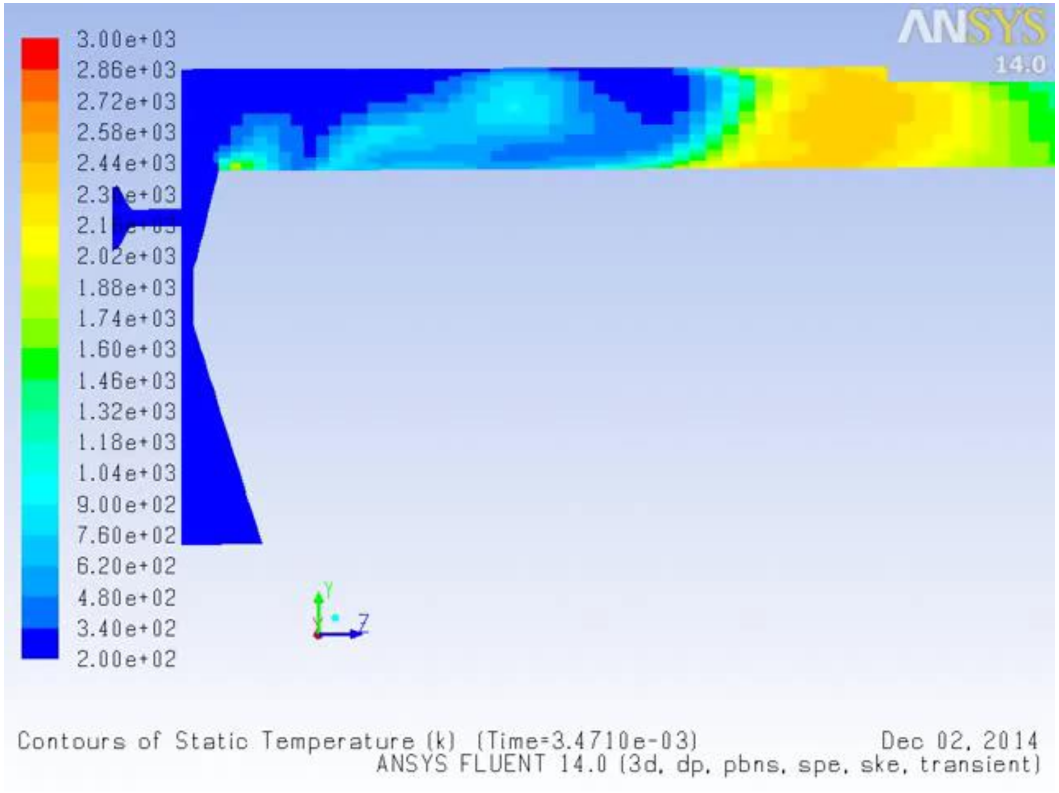
Simulation shows significant interface burning (~40% of fuel). Turbulence chemistry interaction models are not valid for both deflagration and detonation zones.



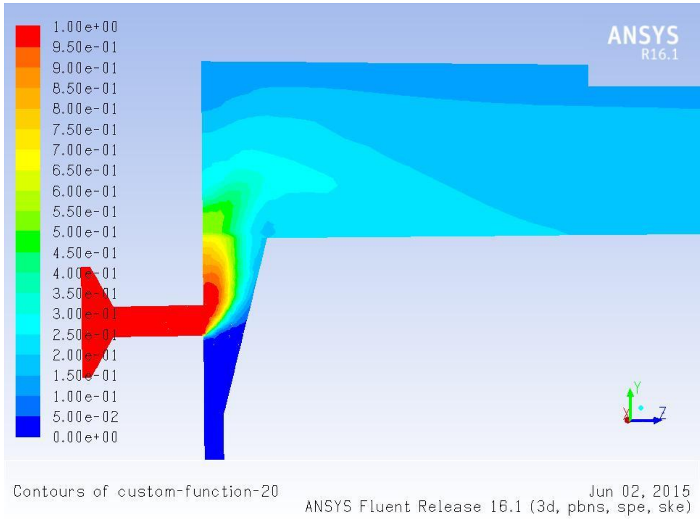
- *Includes Air and Fuel Injectors and Partial Manifolding*

Modeling Upstream at the Inlet

Temperature



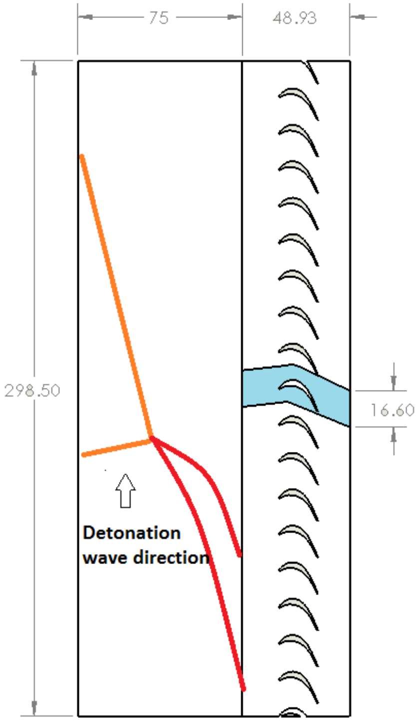
$H_2^{.5}$ Cold Flow



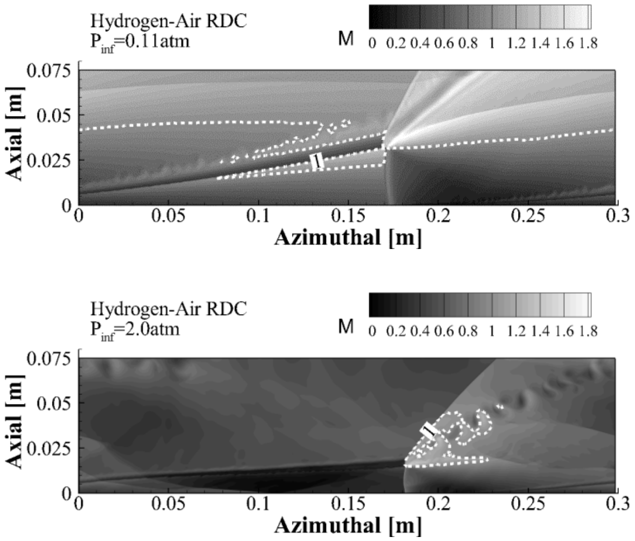
- **Combustion gasses and shock waves propagate back into manifolding.**

CFD Modeling of NETL RDE

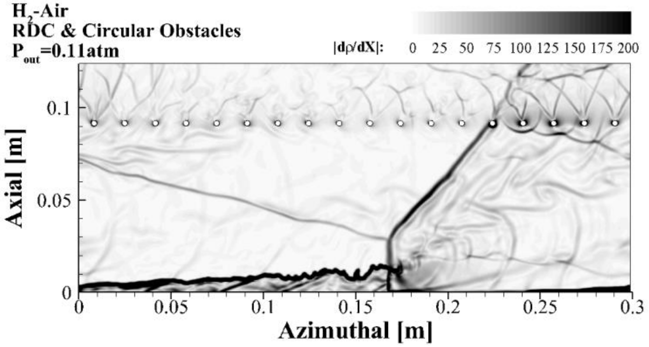
Simulations to evaluate turbine integration, effect of pressurized operation *(S. Escobar, I. Celik, West Virginia University).*



Schematic of simulation of interaction of RDE and integrated turbine exit.



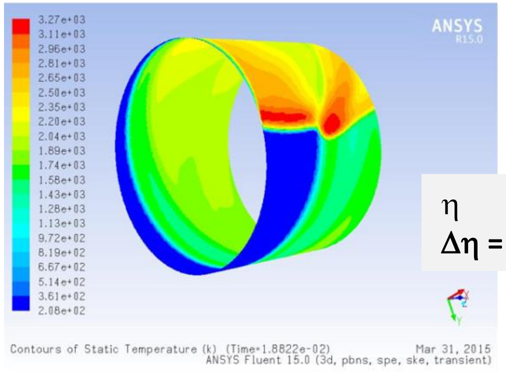
Mach number contours for Pout=0.11atm (top) and Pout=2atm (bottom)



Parametric study to define loss mechanisms

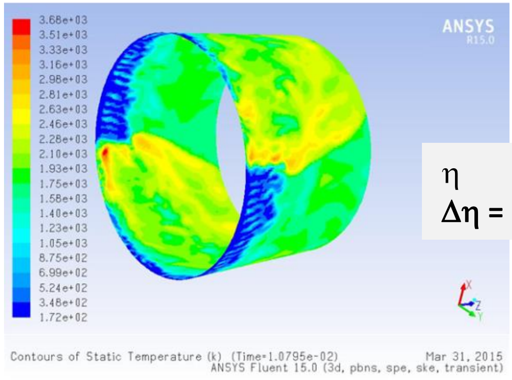
Baseline case, steady, premixed combustion at 6 bar: η = 33%

No inlet, premixed, no heat loss



η = 37.6%
Δη = +4.6 pts

With inlet, no heat loss



η = 30.6%
Δη = -2.4 pts

DOE / NETL PGC Funded Activities

- **Aerojet Rocketdyne (FY15-16)**
  - Develop, validate, and integrate a systems model for a rotating detonation combustor into an overall systems model of a power plant and define the path to configurations that exceed 65 percent combined-cycle efficiency.

- **UTRC (FY15-16)**
  - Assess the potential benefit of PGC system technology for combined-cycle gas turbines and compare it to the DOE goals.

- **Penn State University (FY15-17) - UTSR**
  - Impact of fuel-oxidizer mixture concentration inhomogeneity on detonation wave quality and stability in a hydrogen and hydrogen/natural gas with air fueled RDE.
  - Parametric study to better understand relationship between combustor geometries and injector performance.

DOE / NETL PGC Funded Activities

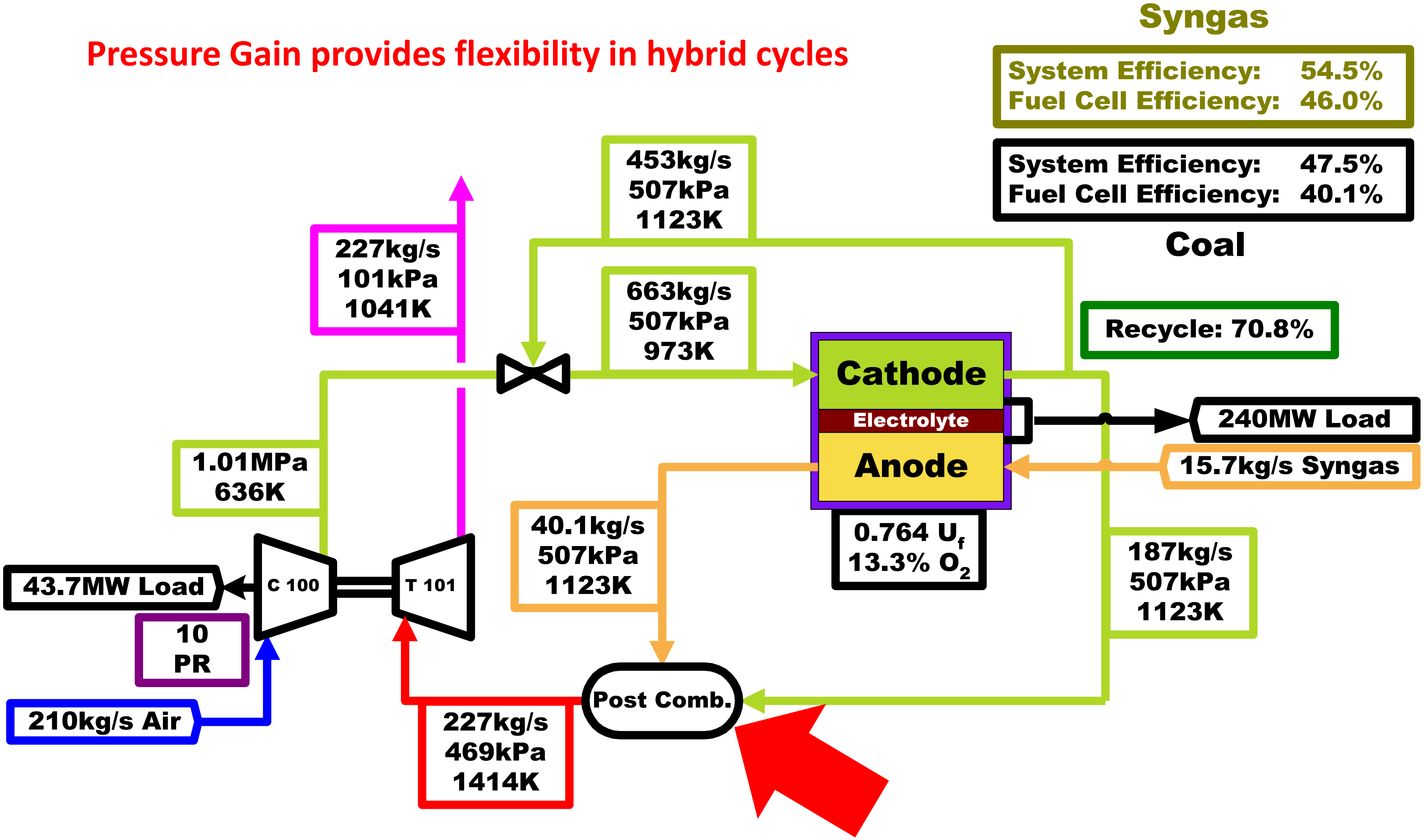
- **University of Michigan (FY15-17) - UTSR**
  - Explore fundamental physics governing non-idealities and impacted performance in a linear RDE analogue.
  - Develop detailed computational tools (DNS & LES) for studying detonation wave propagation processes in RDEs.

- **Purdue University (FY15-17) – UTSR**
  - Characterize the performance of RDE injection/mixing systems using an optically-accessible, linear platform with actual injector geometry.
  - Evaluate the operability of an RDE combustion chamber relative to installation in a gas turbine system

- **Oregon State University (FY15 – FY 17)**
  - Evaluate the performance of a Pulse Detonation Engine for an application in a MHD System.

Cathode Recycle Configuration with Ejector

Pressure Gain provides flexibility in hybrid cycles



Syngas

System Efficiency: 54.5%
Fuel Cell Efficiency: 46.0%

System Efficiency: 47.5%
Fuel Cell Efficiency: 40.1%

Coal

Recycle: 70.8%

453kg/s
507kPa
1123K

663kg/s
507kPa
973K

227kg/s
101kPa
1041K

1.01MPa
636K

Cathode

Electrolyte

Anode

240MW Load

15.7kg/s Syngas

0.764 U_f
13.3% O_2

40.1kg/s
507kPa
1123K

187kg/s
507kPa
1123K

43.7MW Load

C 100

T 101

10
PR

210kg/s Air

Post Comb.

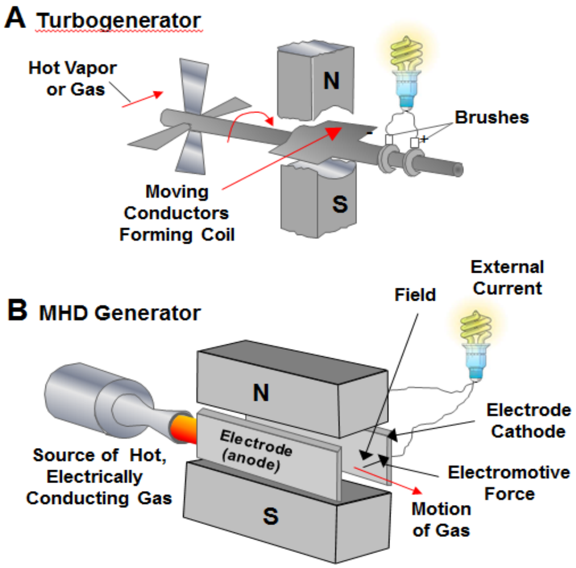
227kg/s
469kPa
1414K

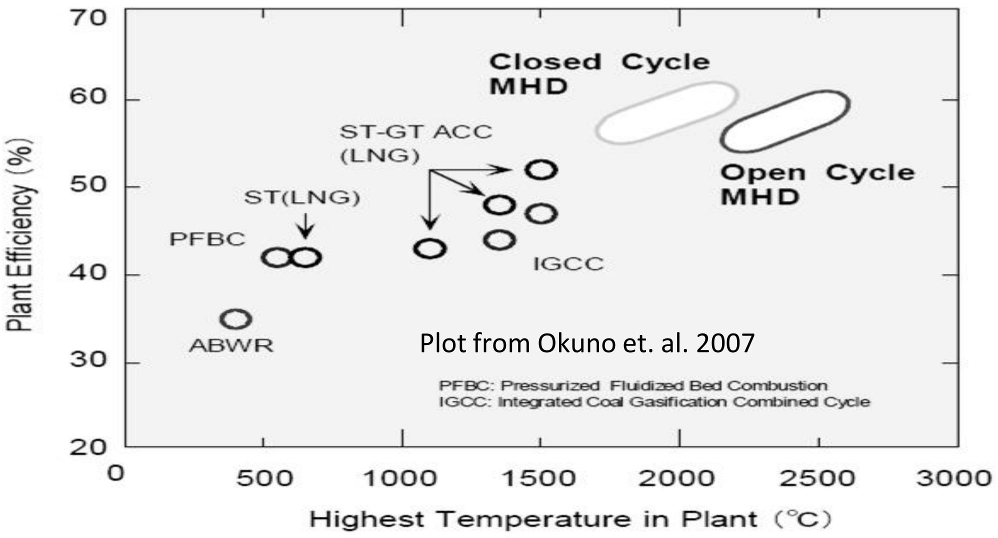
Making Oxy-fuel an ***Advantage***

Direct Power Extraction (via MHD)

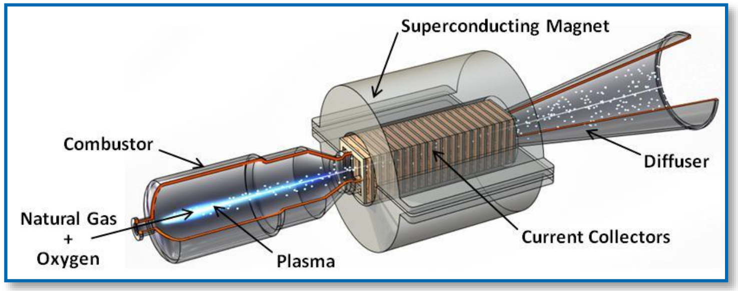
- **Magnetohydrodynamic (MHD) Power Generator:** Use a strong magnet and convert kinetic energy of conductive gases directly to electric power
- **Higher plant efficiency – works at higher temperature**
  - Need to use in combined cycle
  - Synergy w/ oxy-fuel for CCUS
    - oxy-coal COE much higher 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



Questions??