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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NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY

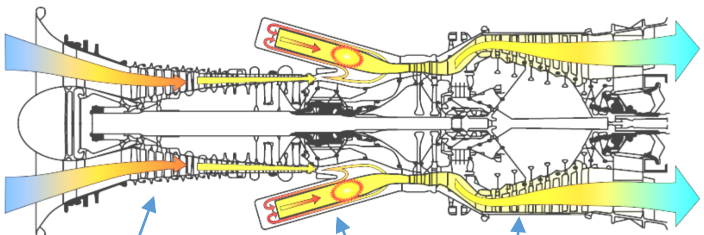
Outline

- **Background**
  - Rotating Detonation Engine
  - Current DOE Pressure Gain Combustion
- **DOE R&IC PGC**
  - DOE RDE Roadmap
- **Looking Forward**
- **Summary**

Pressure Gain Combustion

Convention gas turbines relies on Constant Pressure Combustion (Brayton cycle)

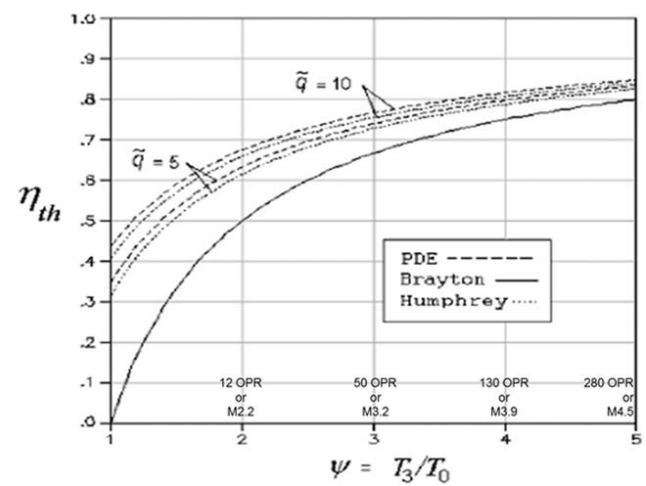
- Utilizes Deflagration (slow combustion – subsonic)
- Actually results in a pressure loss across the combustor due to viscous effects



Conventional approach to improve efficiency is to increase the temperature at the turbine inlet

Constant volume combustion through detonation is more efficient than deflagration

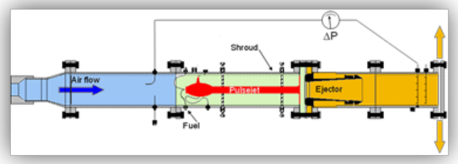
- Similar (high) temperature as conventional gas turbine combustion with less entropy generation
- Elevated pressure at turbine inlet or less work to compressor



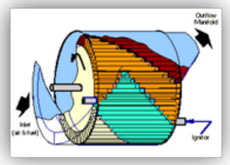
Current Technology Trends in PGC

	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)

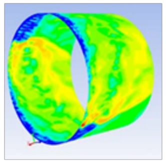


Wave Rotor Engine (IUPUI)



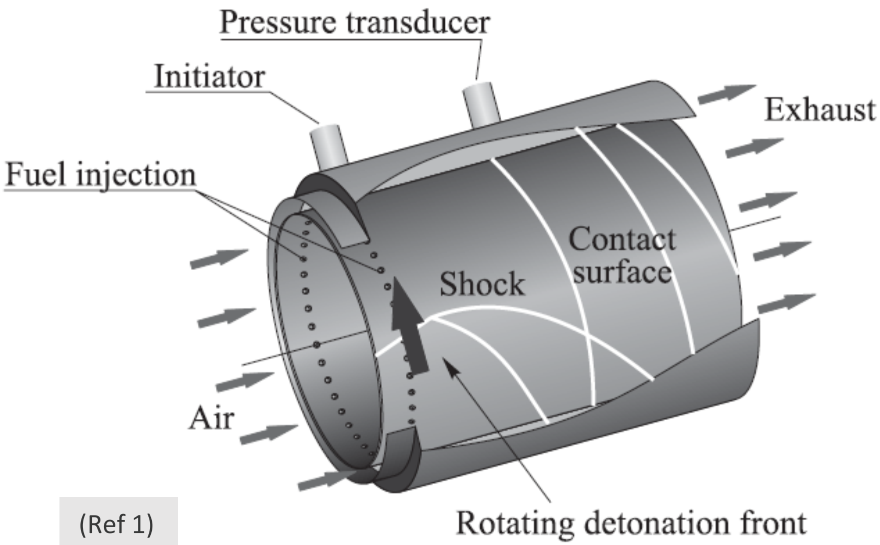
Multi-Tube PDE
G.E. Global Research Center 2005

RDE Simulation
NETL - 2016

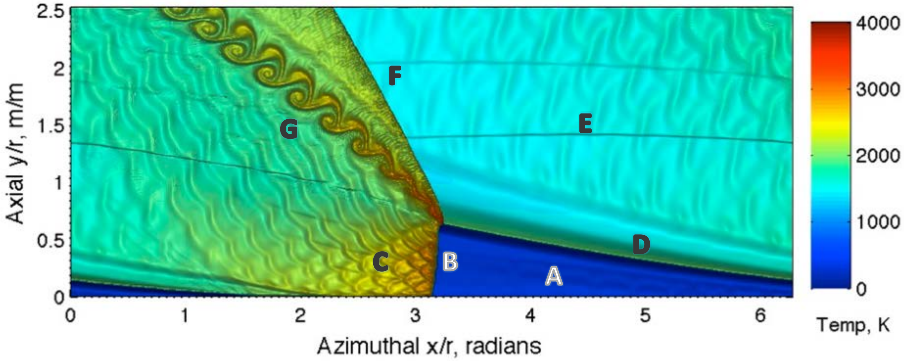


Rotating Detonation Engines

Application and Advantages



(Ref 1)



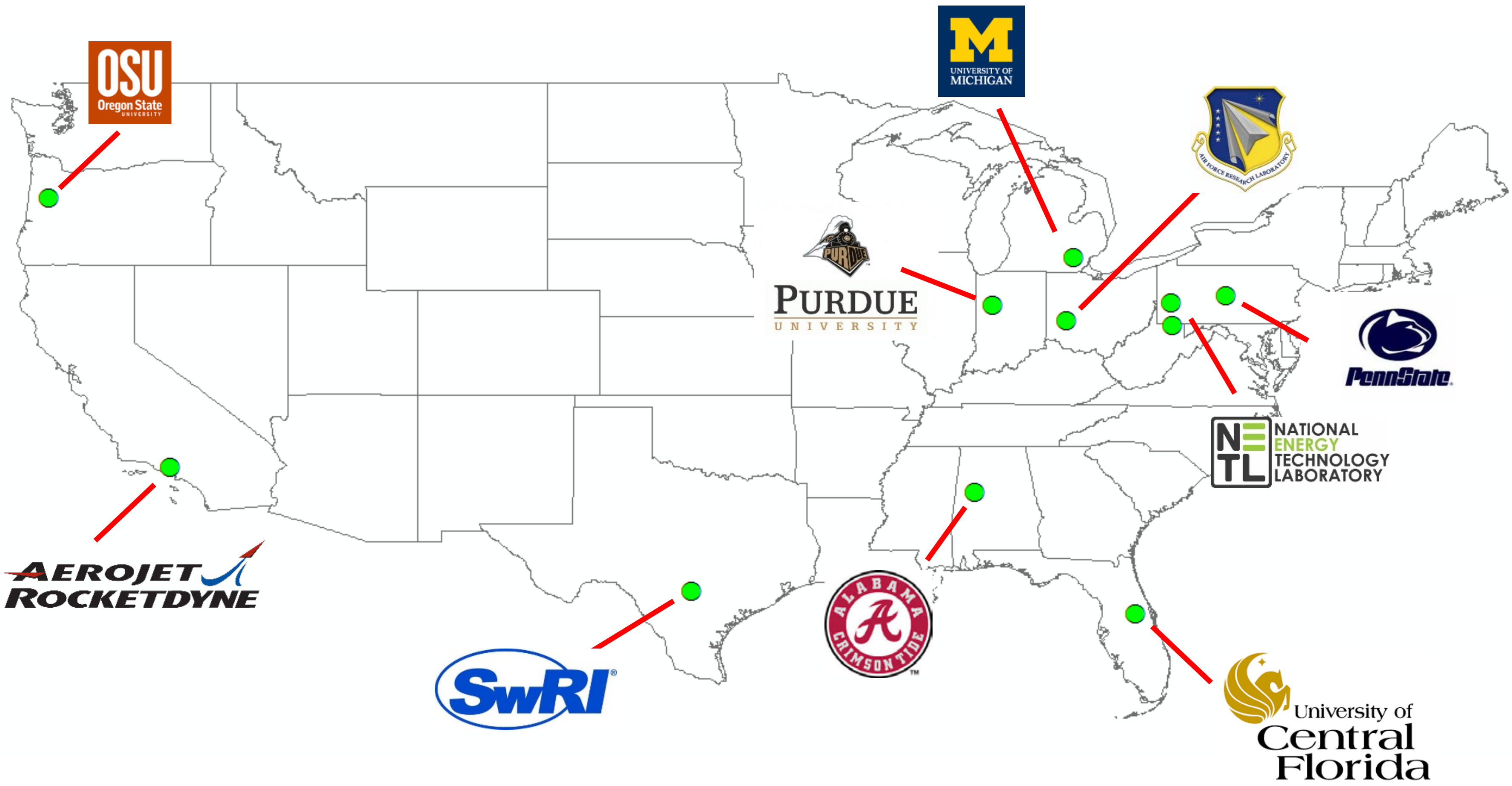
A. Fresh Reactants
B. Detonation wave
C. Post-Detonation / Transverse Waves
D. Contact Surface (Def)
E. Product Expansion (Det, Det+Def)
F. Oblique Shock Wave
G. Shear Layer

(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.**
- **Flow exits the flow quasi-steady do to high speed detonation wave (3-5 kHz).**
- **Potential for low NOx (less residence time)**

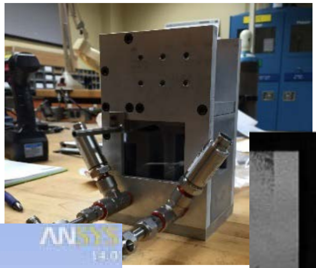
1. *Wolanski, P., Proc. Comb. Institute, 2013*
2. Nordeen et al, 49th AIAA Aerospace Sciences Meeting, Orlando, FL:, 2011.

Current DOE Pressure Gain Combustion Funded Activities (2017)

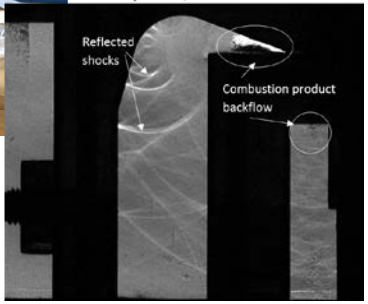


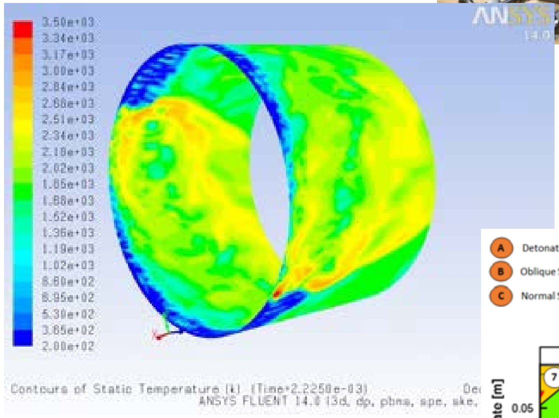
NETL In-House Research Activities

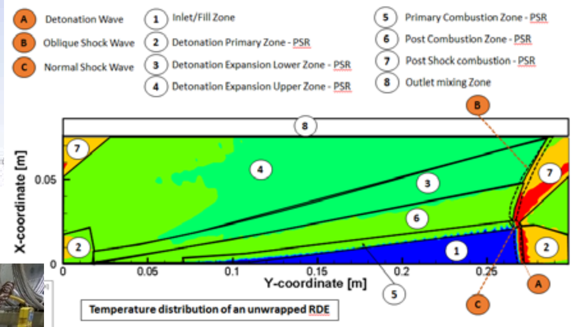
- **RDE Sector / Inlet Lab-Scale Test Rig**
  - Rapid evaluation of inlet concepts with correlation to lab-scale combustor.
- **Computational Studies**
  - Chemical Reactor Network (CRN)
    - Reduced order model with emissions
  - CFD
    - Fundamental aspects of detonation
    - Inlet / geometry physics
    - 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

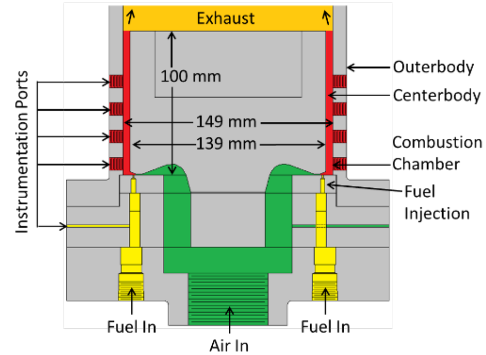


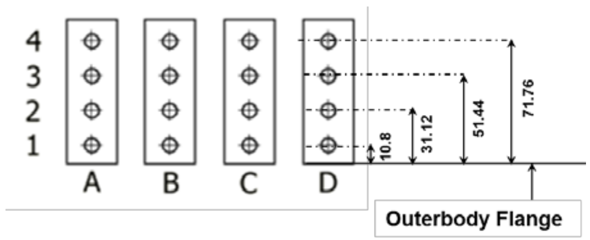


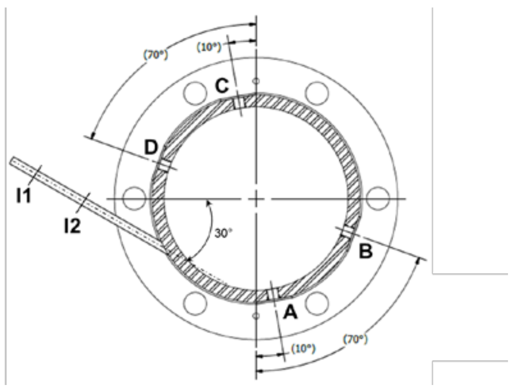


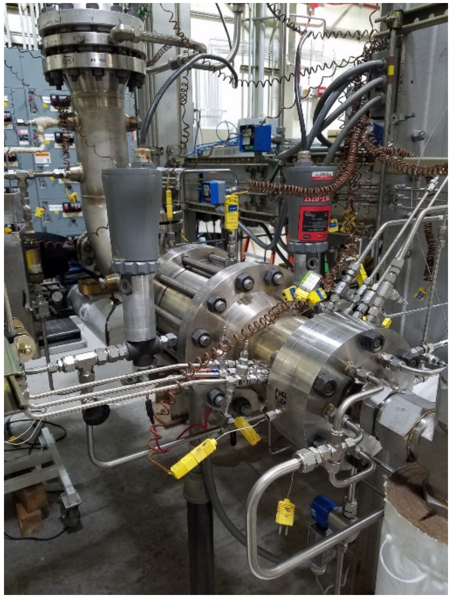
NETL Lab-Scale Full RDE

- **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





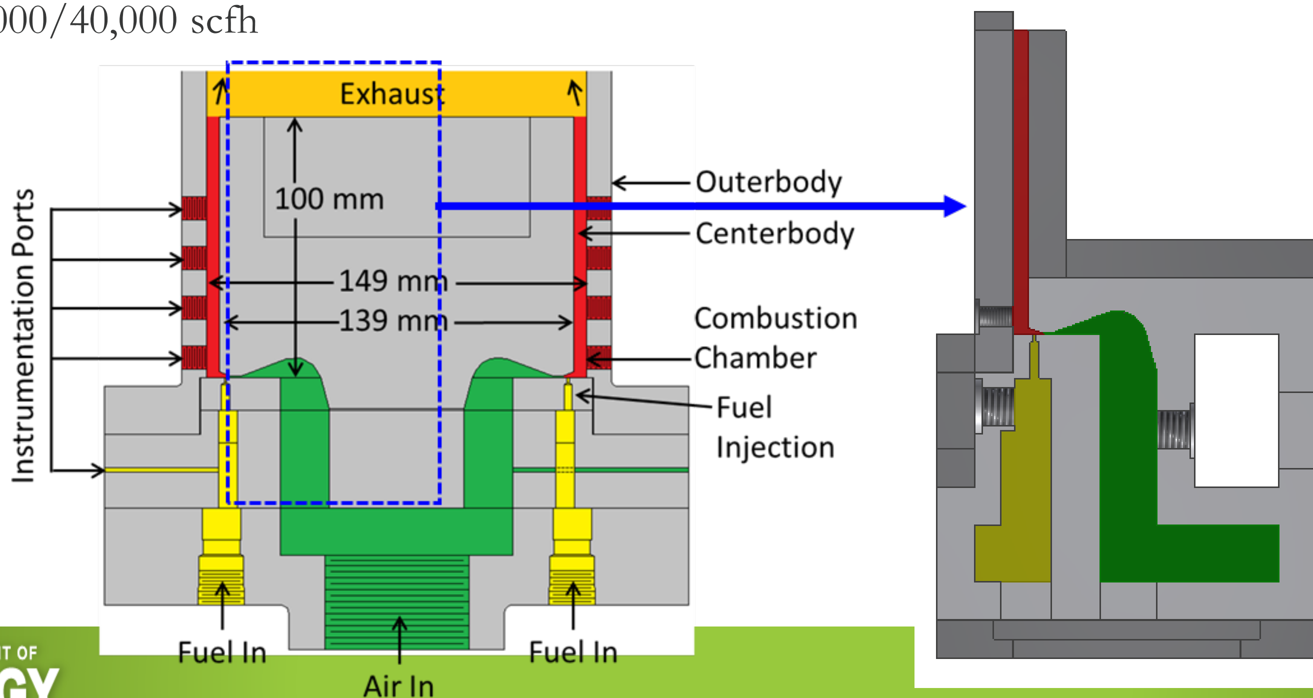




NETL Lab-Scale RDE Inlet Sector Rig

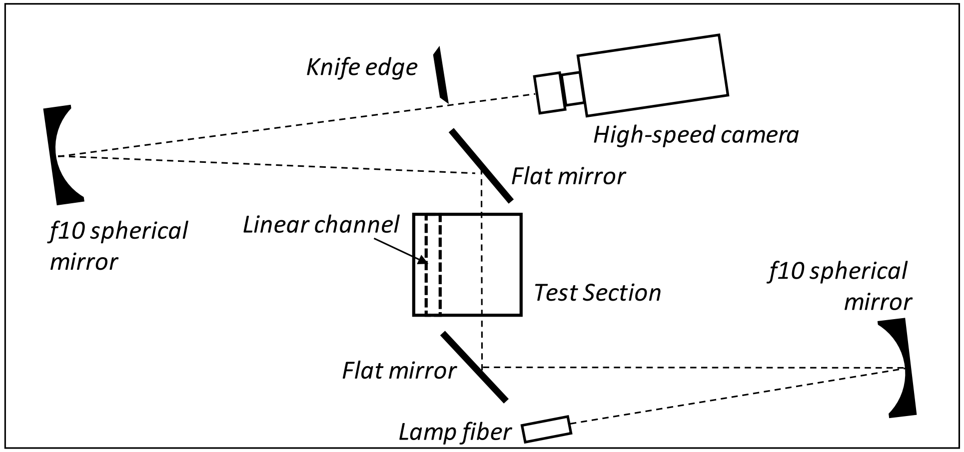
- **Small Pilot-scale 6 in diameter RDE presently operated**
  - Combustion annulus width 0.02 in
  - Continuous air slot between fuel plate and centerbody (gap size 0.022 in)
  - 80 discrete fuel injectors (ID 0.035 in)
  - Nominal H_2/air flow rates of 10,000/40,000 scfh

- **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



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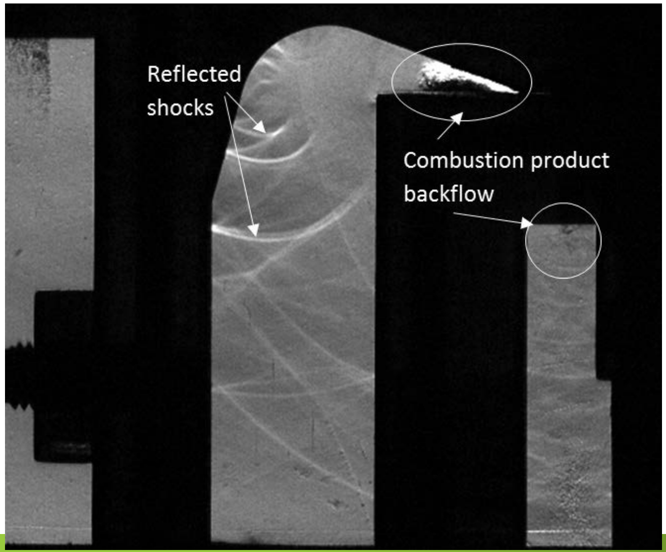


DOE Pressure Gain Combustion Objectives

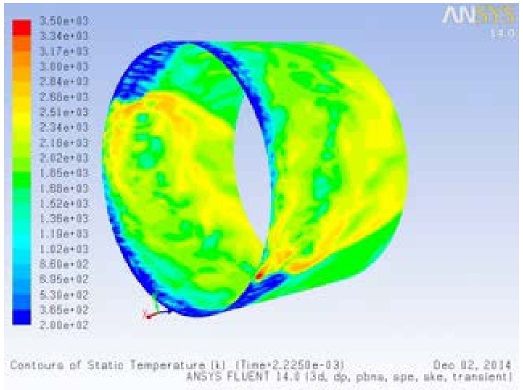
- Improve fundamental understanding of stable continuous wave detonation in a semi-enclosed channel

- Develop scaling laws to better understand the parametric impacts

- Maximize pressure gain / turbine work availability and reduce emissions

- Improve Modeling / Validation Data

- Align programs across agencies (as possible)



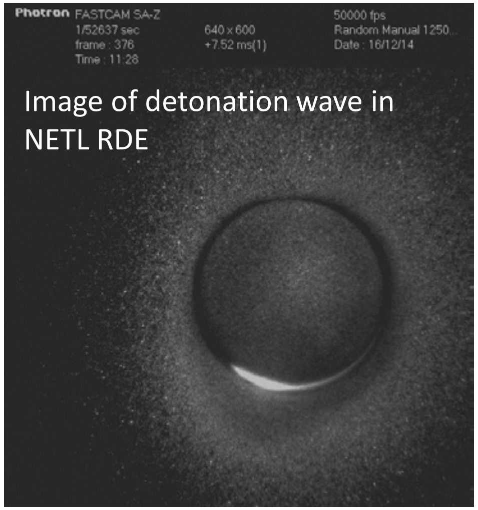
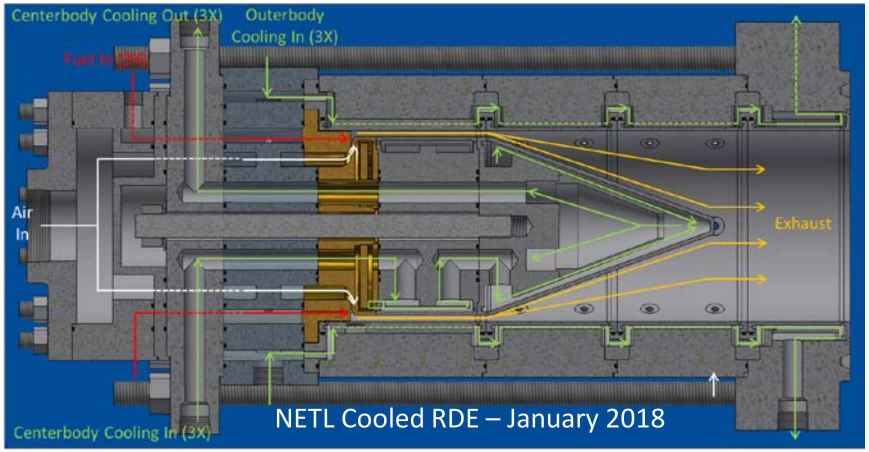
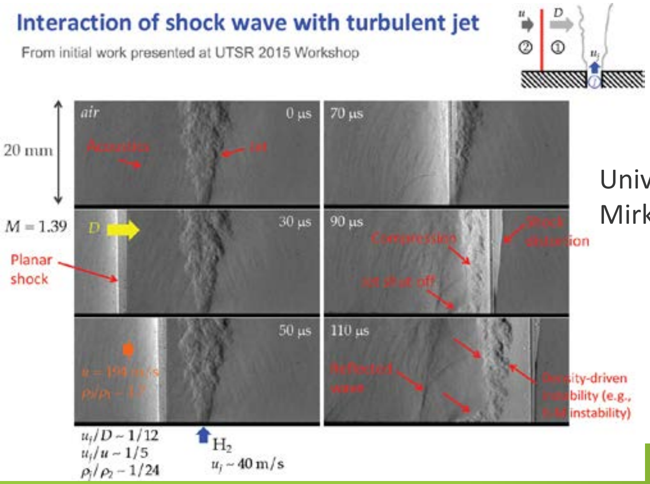


Image of detonation wave in NETL RDE

Improve Fundamental Understanding of Stable Continuous Wave Detonation

- **Short duration vs long duration tests (ignition and detonation wave stability, non-start)**
  - Cooled RDE installed at NETL in Jan '18
- **Influence of unmixedness on shock / rarefraction wave**
  - Wave directionality, bifurcation, translation speed (~CJ)
- **Additional Test Facilities (FY18)**
  - New NETL Shock Tube
  - New Small Scale RDE (~60 mm dia)

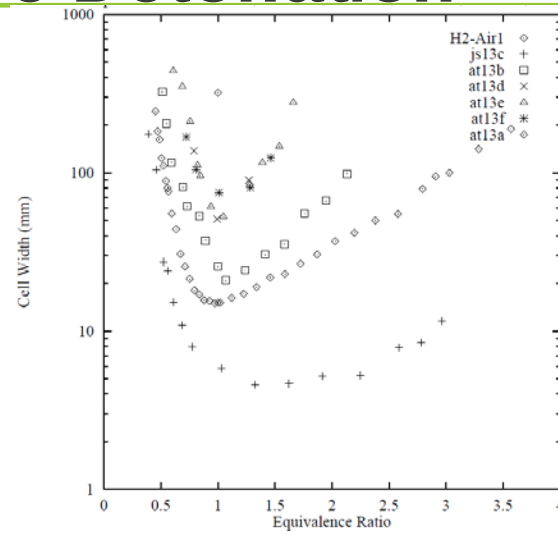




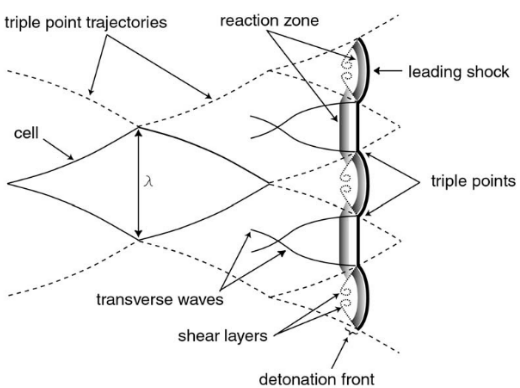
University of Michigan
Mirko Gamba / Venkat Raman

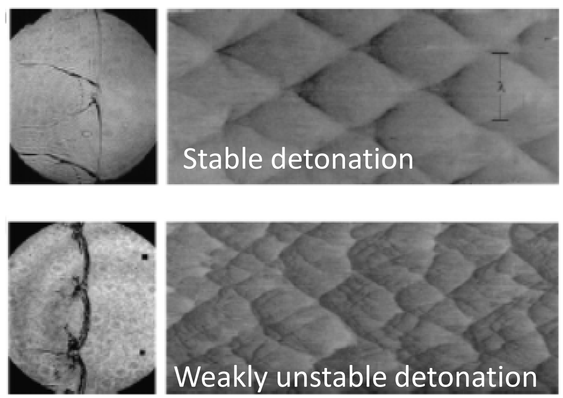
Improve Fundamental Understanding of Stable Continuous Wave Detonation

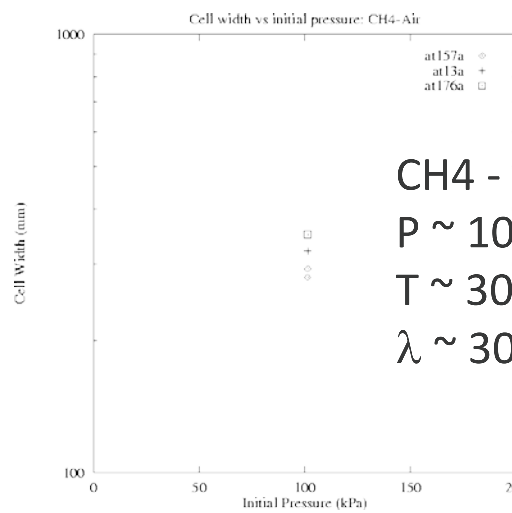
- **Detonation wave stability and operation on natural gas**
  - Detonation cell size of methane – air is much larger than RDE length scales
    - Pressure and temperature help
  - Can we ignore cell size and focus on induction time??



H2-Air
P ~ 101.3 kPa
T ~ 300 K





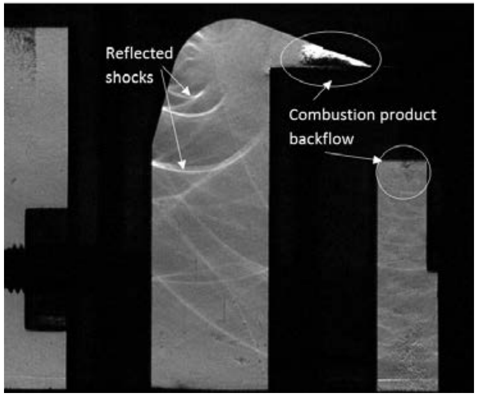


CH4 - Air
P ~ 101.3 kPa
T ~ 300 K
λ ~ 300 mm

M. Kaneshige and J.E. Shepherd. **Detonation database.** Technical Report FM97-8, GALCIT, July 1997

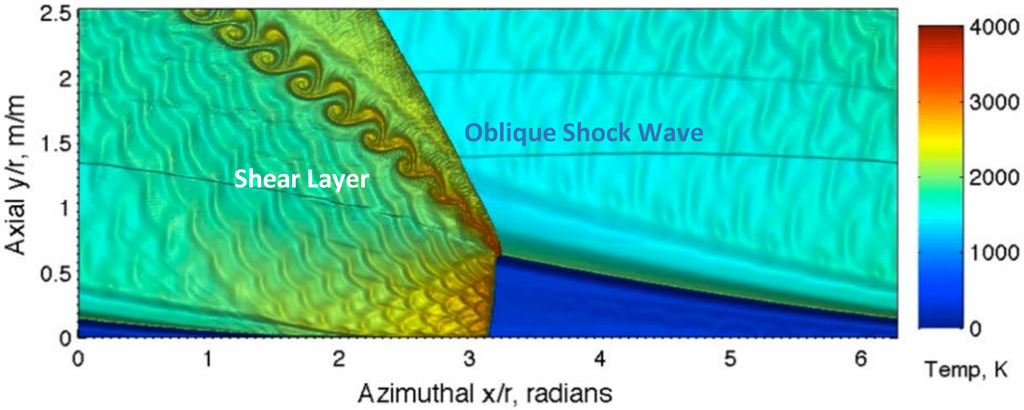
Maximize Pressure Gain / Turbine Work Availability

- **Inlet studies**
  - Expanding the Area Ratio (> 0.2)
  - Reduce the impact of shock wave/back flow on fuel/air mixing
  - Reduce ratio of deflagration/detonation
  - Theoretical study of nozzle / inlet performance



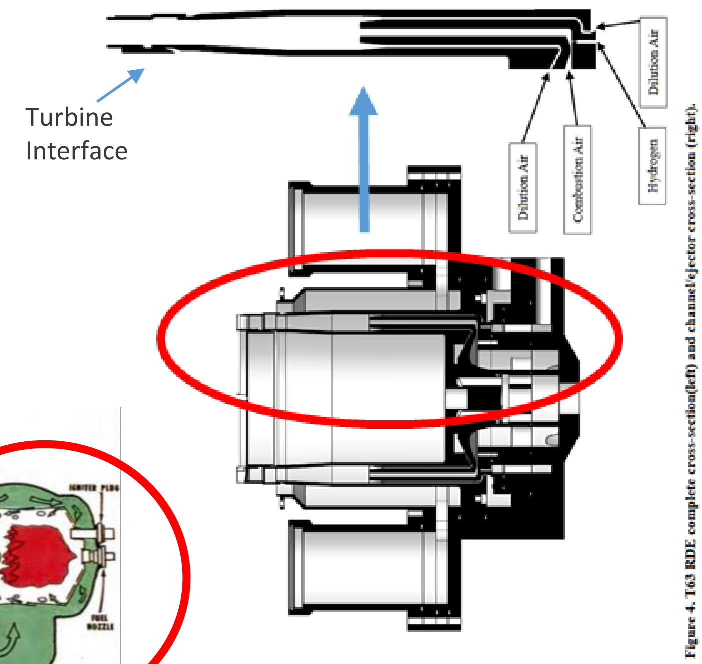
- **Diffuser studies**
  - Transition exhaust flow to maximize available work

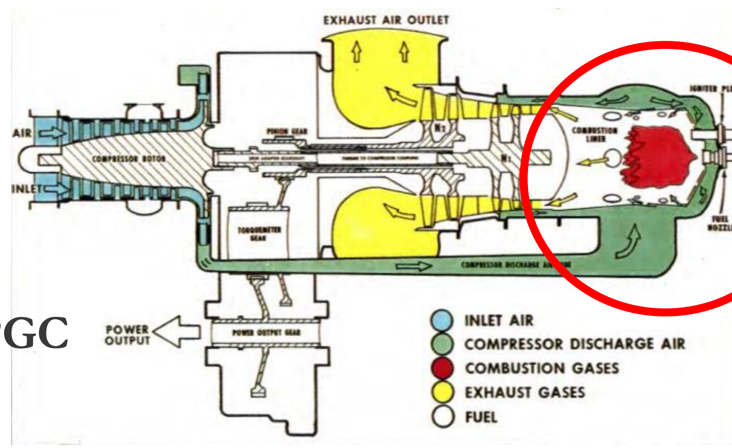
- **Combustor length impact on oblique shock**
  - What does an "optimal" RDE look like?
  - Should we focus on practical before we think about optimal?



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





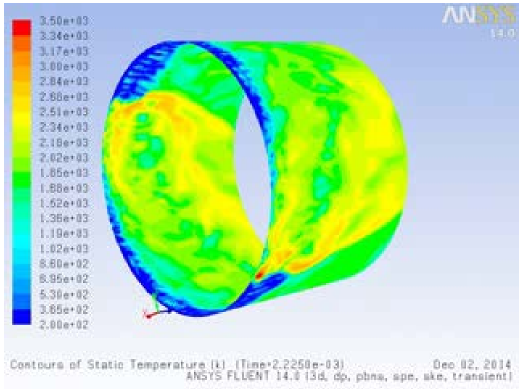
T63 Gas Turbine reverse flow design with aft-engine combustor replaced with RDE.

- **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

Improve Modeling / Better Utilize (Modeling needs to drive experiments)

- **Inlet studies (Area Ratio, Mixing, Loss Reduction)**
- **Influence of mixedness on wave directionality**
  - What influences wave stability and bifurcation
  - Alter spacing between fuel jets or eliminate discrete jets (like air inlet)
- **Natural gas simulations**
  - Pressure / Temperature / Ignition / Fuel Composition
- **Exhaust Transition**



- **Develop database of experimental results for model validation**

Relationship with DOD

NATIONAL ENERGY TECHNOLOGY LABORATORY

- **PGC plays a major role in DOD ATTAM (next gen VAATE) Technology Plan across multiple platforms**
  - Opportunities for "Dual Use Science and Technology" (DUST)
- **PGC "Blue Collar" Working Group (Unofficial)**
  - Monthly teleconf with federal researchers from NETL (DOE), AFRL (Air Force), NRL (Navy), NPS (Navy) and NASA-Glenn to share findings and identify opportunities for collaborations
- **T63 Turbine Integration Tests – Official collaboration between NETL and AFRL**
  - Coupled RDE to turbine
- **Collaborated on PGC Working Group Mini-Symposium hosted at NETL in Morgantown**
  - 50+ top researchers from around the country (Gov, Academia and Industry).


PGC WG Mini-Symposium, July 22-23, 2017

Elements of PGC / RDE Considered Export Controlled/ITAR for ***critical enabling technologies***

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PGC InfoSec Guidelines

AIR FORCE RESEARCH LABORATORY

Current Documents

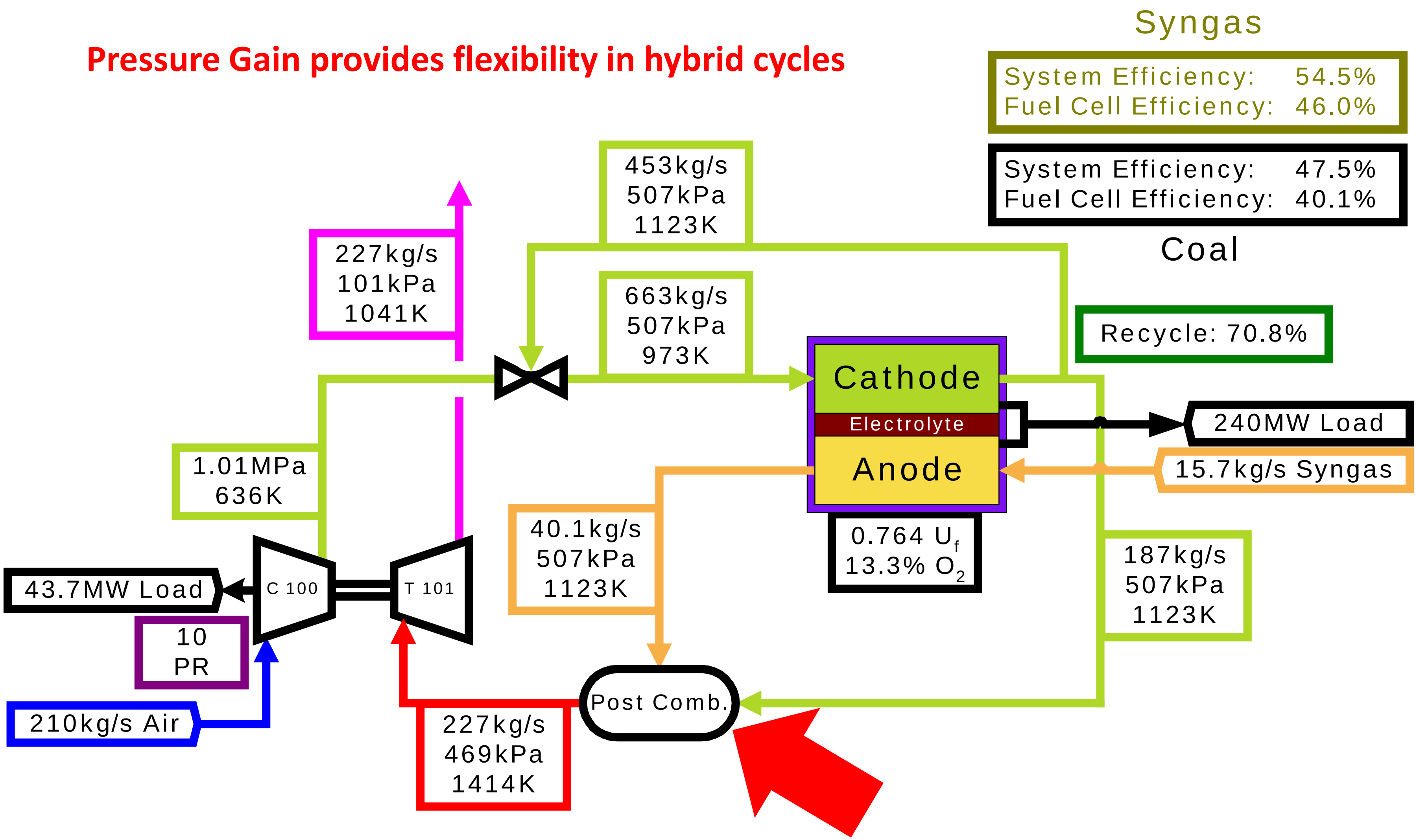
- USAF Security Classification Guidelines (Propulsion)
- AFRL Letter of interpretation
- Export Control Reform: ITAR/USML Categories IV/XIX
- AFRL PGC InfoSec Guidelines (this document)

Guidelines proposed 13 June 2005 at JANNAF workshop on Pulse Detonation Combustion for Propulsion. Input from industry and government solicited and considered in 2010, 2014, and 2015 Revisions.

Following PGC infosec guidelines are AFRL policy as of revision date on title page.

Cathode Recycle Configuration with Ejector

Pressure Gain provides flexibility in hybrid cycles

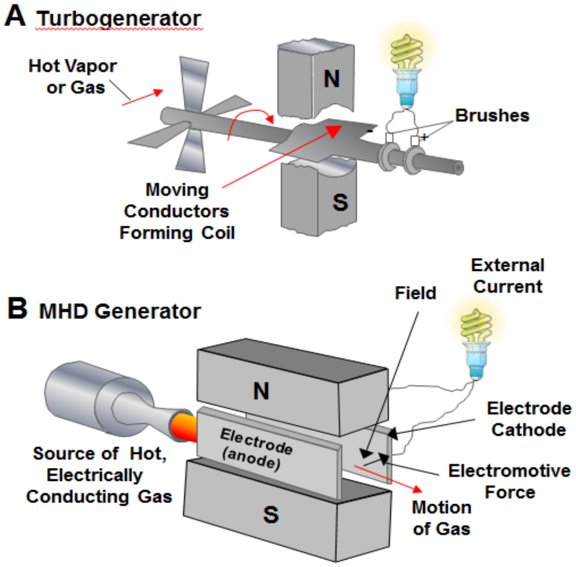


Making Oxy-fuel an Advantage

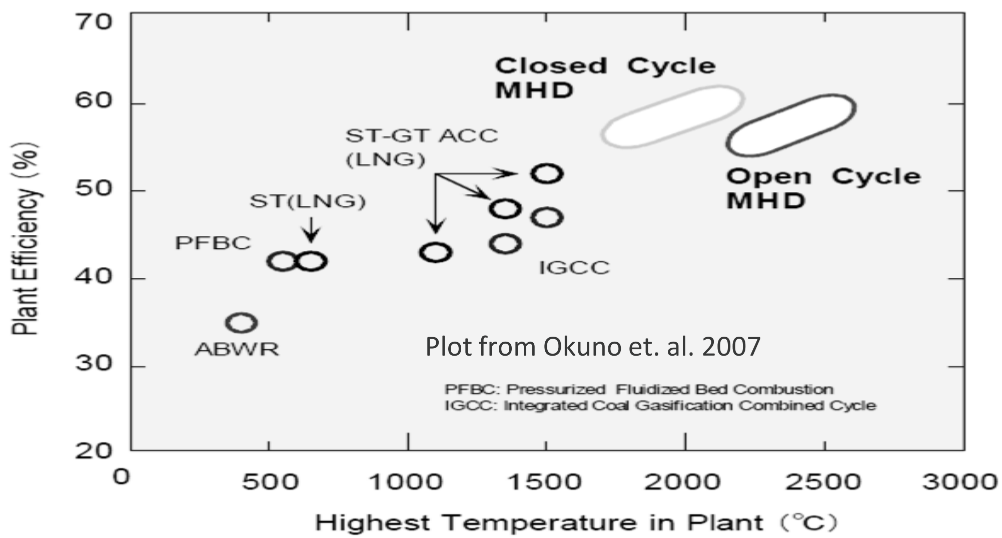
Direct Power Extraction (via MHD)

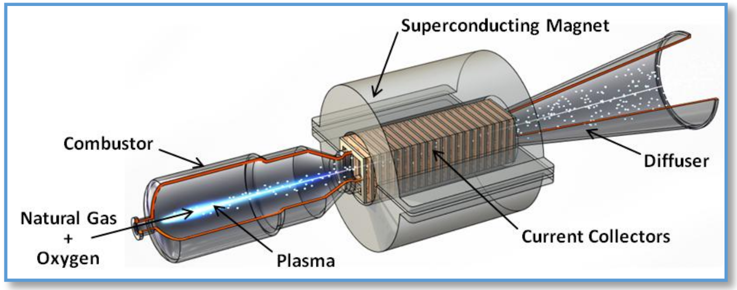
- **Magnetohydrodynamic (MHD) Power Generator:** Use a strong magn and convert kinetic energy of conductive gases directly to electric power

- **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!





Acknowedgements

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- **Project Funding (DOE – NETL)**
  - Richard Dennis – Advanced Turbine Program
  - John Rockey – Advanced Combustion Program

Questions?

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