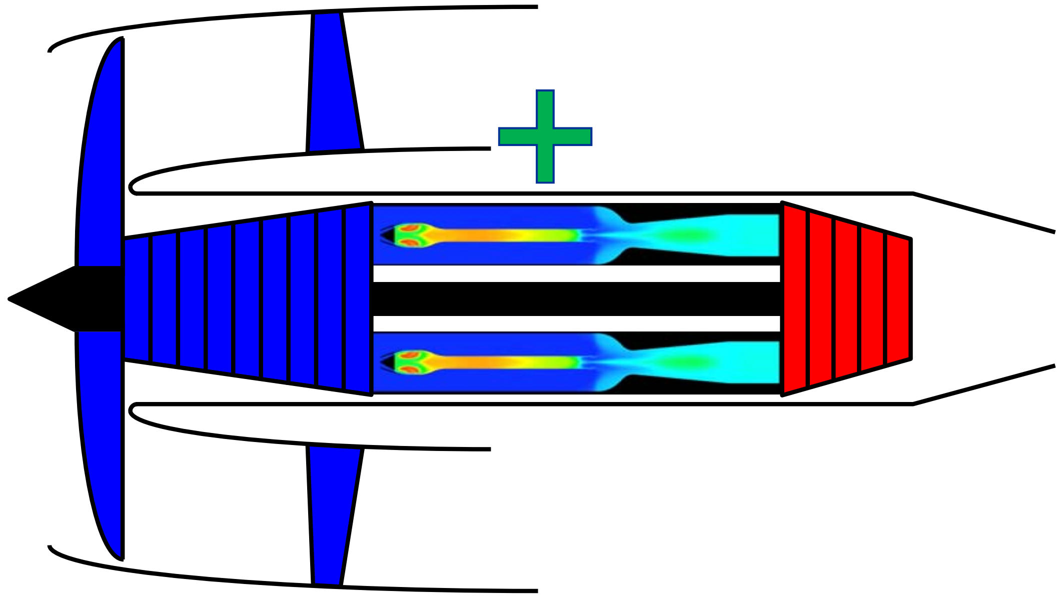


Pressure-Gain Combustion for Gas Turbines

Dan Paxson
NASA John H. Glenn Research Center
Cleveland, OH

ASME Turbo Expo
June 11-15, 2018
Oslo, Norway

Outline

- Motivation/Background
- Fundamental Thermodynamics of PGC (How It Works)
- Quantitative Benefit Examples
- **Approaches to Implementation (How It's Done)**
- The Role of Modeling
- Technology Challenges
- Closing Remarks

Some Preliminary Facts

Sources: Bureau of Transportation Statistics, Department of Energy, Environmental Protection Agency

The U.S. Consumes (Converts) **97,400,000,000,000,000** BTU of Energy Each Year

- *81% from fossil fuels (petroleum, natural gas, coal)*
- *66% from petroleum and natural gas*

Equivalent to 7.0 gallons of gasoline used by every U.S. citizen EVERY DAY!

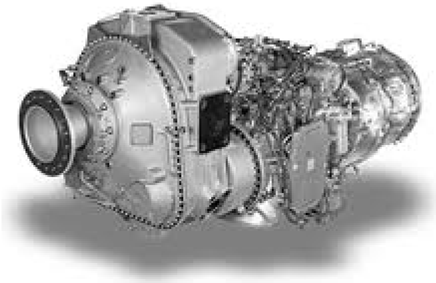
Resulting Issues

- *National & Economic security*
- *Pollution*
- *Climate Change*

The Response

- *Alternative fuels (biomass, etc.)* } 10%
- *Alternative conversion systems (wind, solar, hydroetc.)* } 10%
- *Conservation/ **EFFICIENCY** (use less)*

Today's Presentation Is All About This Response

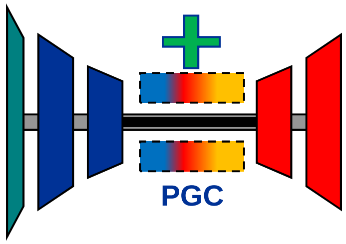


Gas Turbines Constitute an Astonishing 14% of Energy Consumption

- *3.4% from aviation*
- *10.5% from power generation (and growing if coal gasification and/or combined cycle plants are successful)*

A mere **1%** Improvement in Thermodynamic Efficiency is Equivalent to installing **17,300** commercial wind turbines, a 33% increase in the total number operating in 2016 on land.

Two Reasonable Conclusions:
Technologies to Improve Gas Turbine Performance Are Important
Those Applicable to Both Aviation and Ground Power are Critical



Pressure Gain Combustion is One Such Technology

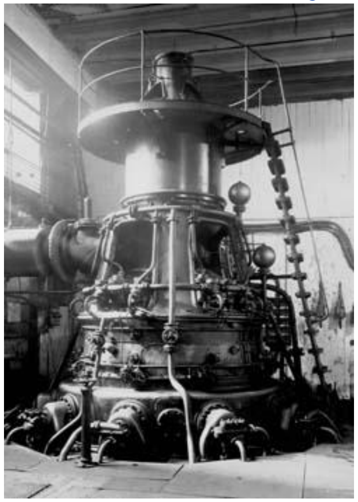
PGC†: A fundamentally unsteady process whereby gas expansion by heat release is constrained, causing a rise in stagnation pressure and allowing work extraction by expansion to the initial pressure.*

†The term "Pressure-Gain Combustion" is credited here to the late J.A.C. Kentfield

*Conventional combustion incurs a total pressure loss

The concept actually is old…

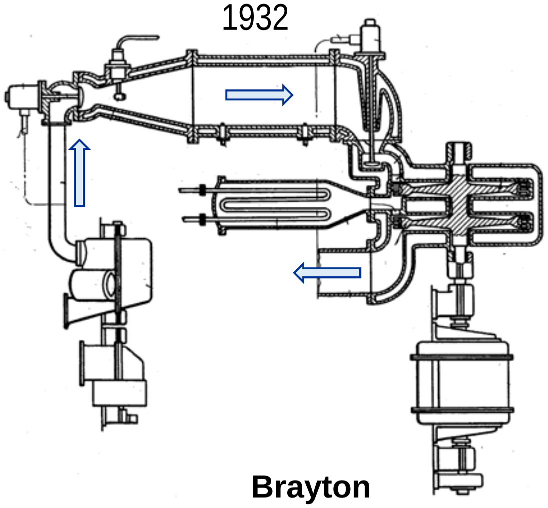
Holzwarth Explosion Turbine 1914



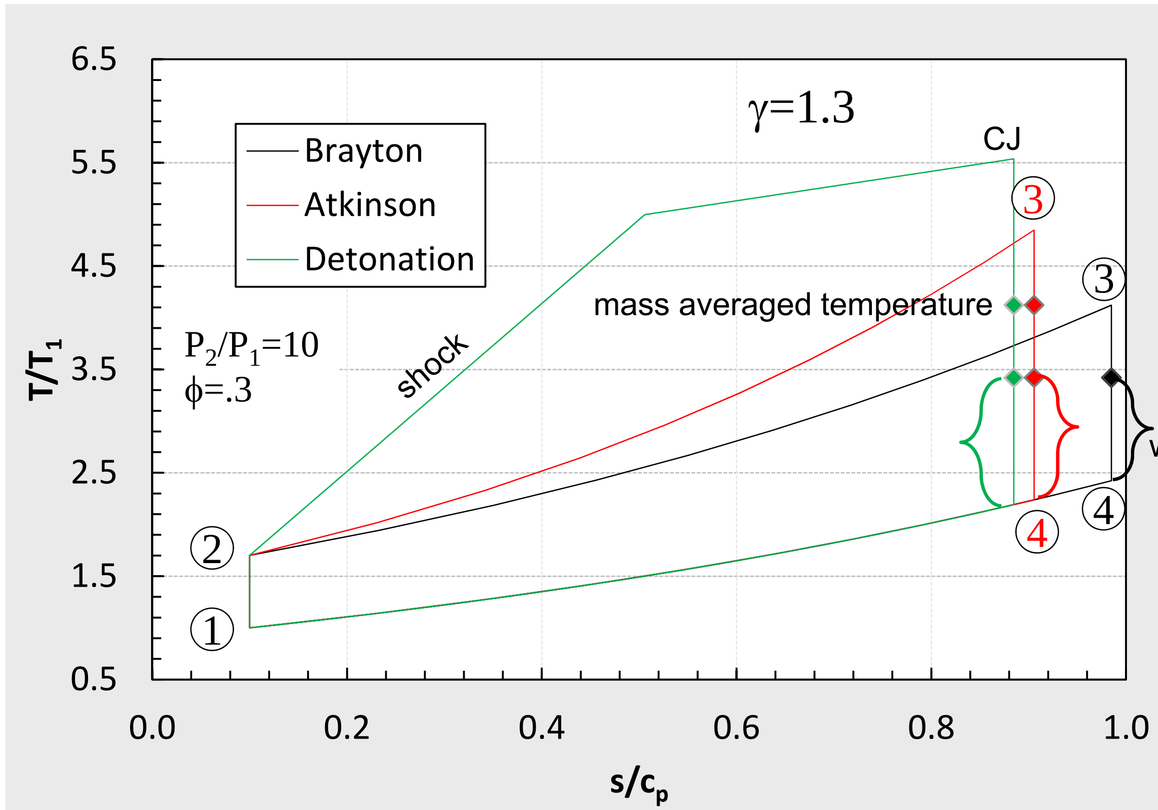
The Implementation Approaches, Analysis Tools, and Design Capabilities Are New

Fundamental Thermodynamics

Explosion Turbine (Holzwarth)
1932



Identical Mechanical Compression,& Heat Input



Brayton
1-2: Isentropic (adiabatic) Compression
2-3: Isobaric Heat Addition
3-4: Isentropic Expansion
4-1: Isobaric Heat Rejection

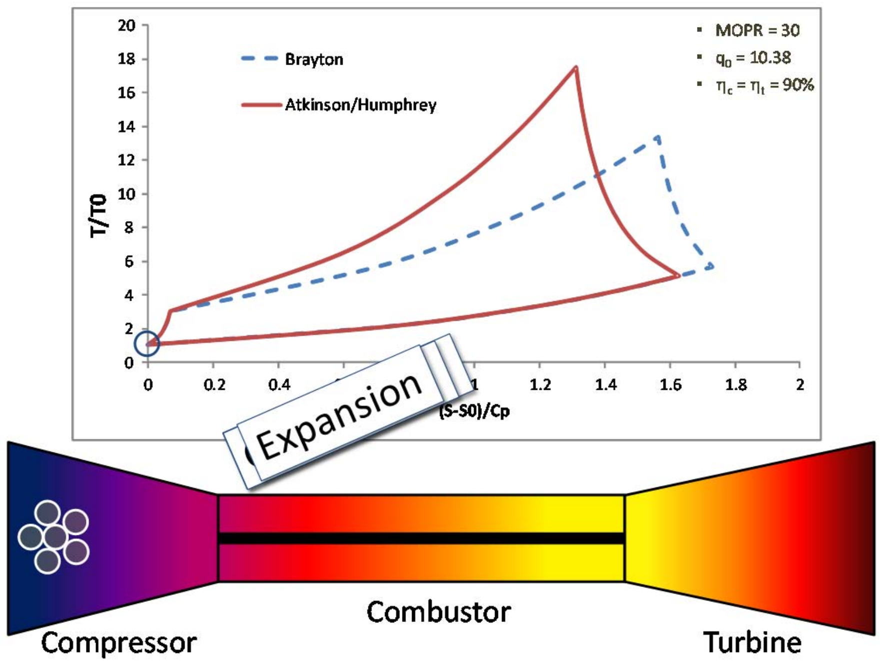
Atkinson
1-2: Isentropic (adiabatic) Compression
2-3: Isochoric Heat Addition
3-4: Isentropic Expansion
4-1: Isobaric Heat Rejection

- •PGC expands by gasdynamic conversion to kinetic energy (e.g. blowdown)
- •Flow to turbine is fundamentally unsteady, and/or spatially non-uniform

Fundamental Thermodynamics

Animation of a Representative PGC Cycle

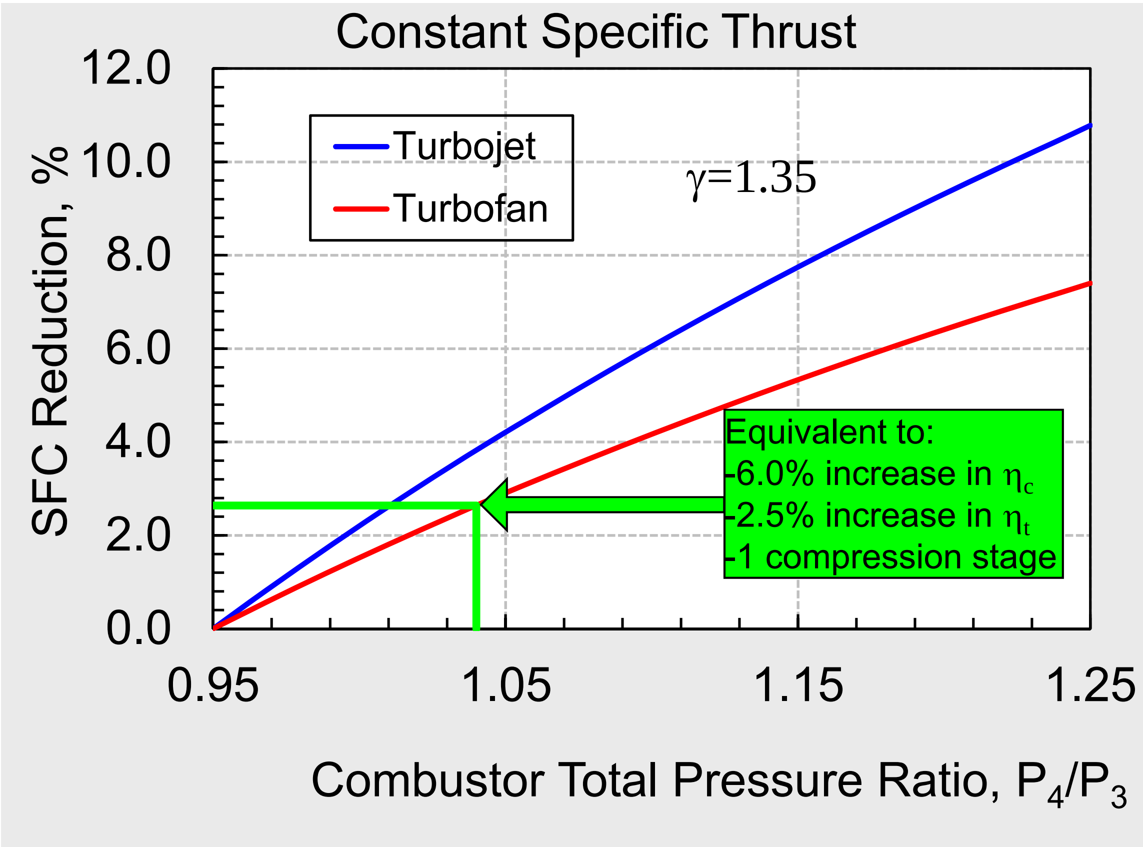
- Illustrates essential concepts
- Demonstrates the most basic acceptable level of modeling
- More quantitatively valuable than might be expected.

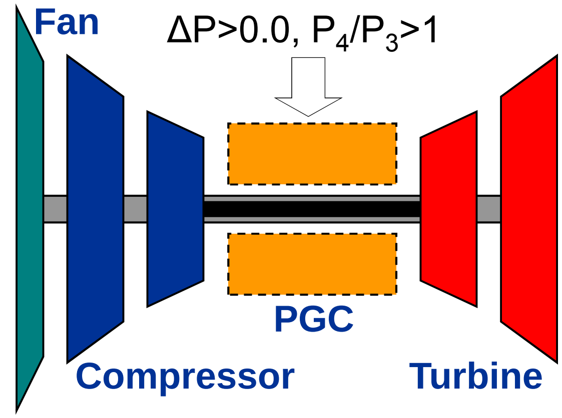


Quantitative Benefits

Pressure Gain Combustion Theoretically:

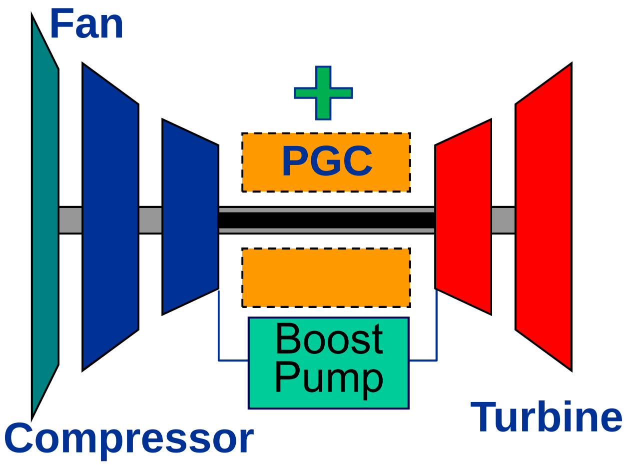
+Increases thermodynamic cycle efficiency
+Reduces SFC / fuel burn (NASA Objective)
+Reduces CO_2 gas emissions (NASA Objective)
+Competes with conventional cycle improvements



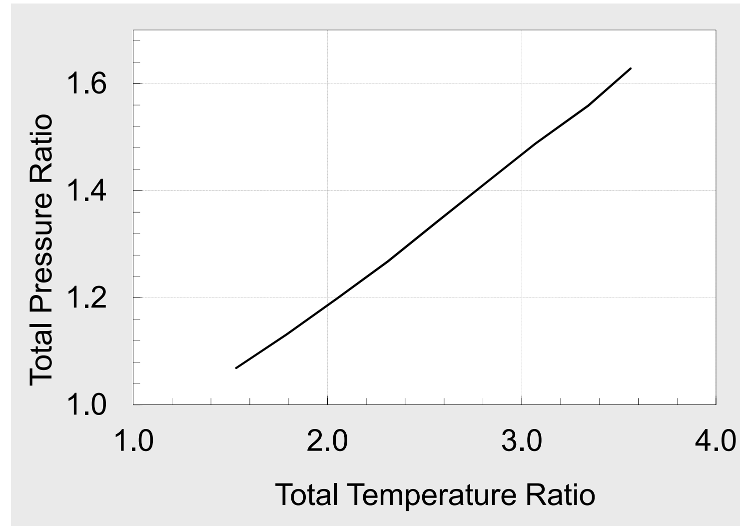


Engine Parameter	Turbofan	Turbojet
OPR	30.00	8.00
η_c	0.90	0.90
η_t	0.90	0.90
Mach Number	0.80	0.80
T_{amb} (R)	410	410
T_{t4} (R)	2968	2400
Burner Pressure Ratio	0.95	0.95
T_{sp} (lb_f-s/lb_m)	18.26	75.86
SFC (lb_m/hr/lb_f)	0.585	1.109

More Quantitative Benefits

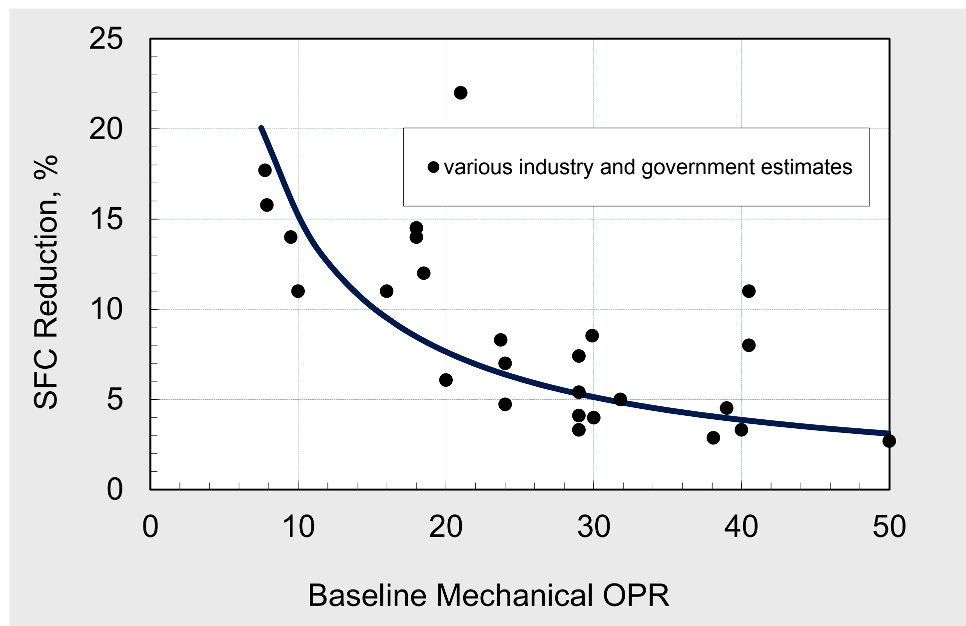


Example Modeled PGC Component Performance



- PGC component modeled by various methods
  - Typically assumed detonative or constant volume combustion
  - Temperature ratio indicates fuel added
  - Pressure ratio represents performance
  - Varied loss assumptions
- Results With Engine Cycle Decks Show Promise:
  - Non-ideal turbomachinery
  - Turbomachinery cooling air boost pump added.

These Are Large Reductions!



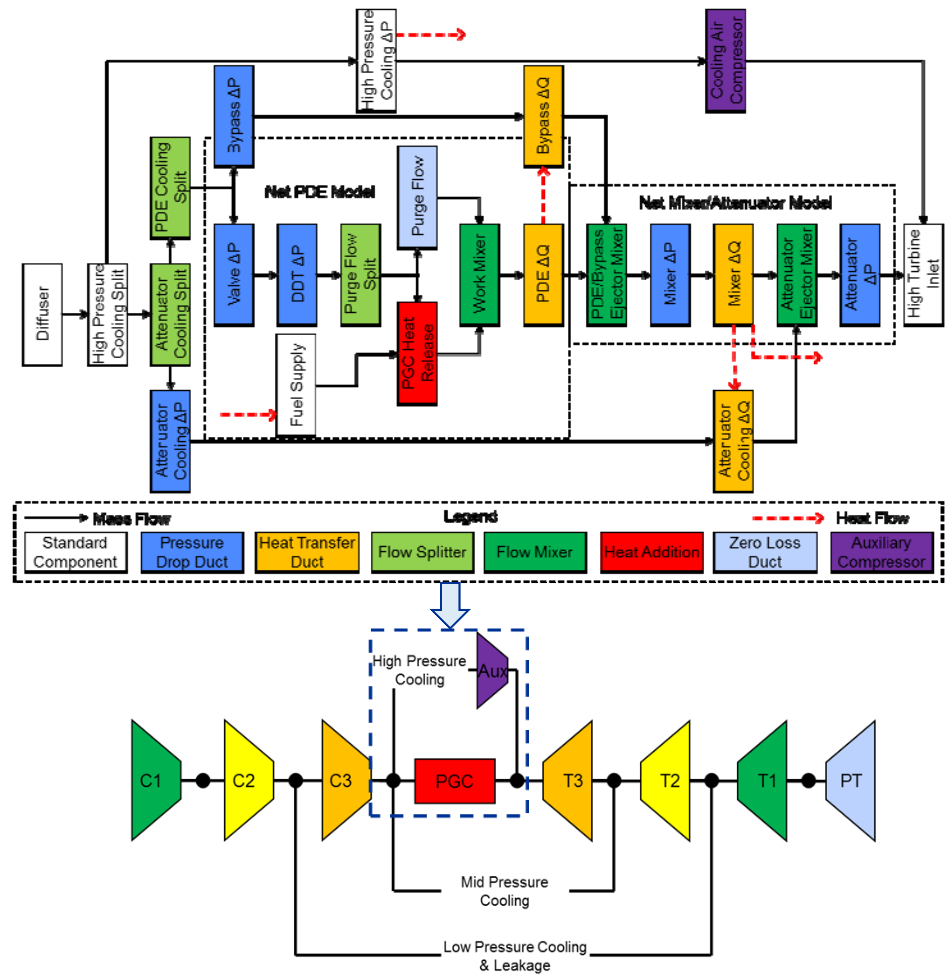
Still More Quantitative Benefits

Combined Cycle Power Generation Employing Pressure Gain Combustion

Department of Energy Award Number DE-FE0024011

All Information Courtesy of United Technologies Research Center

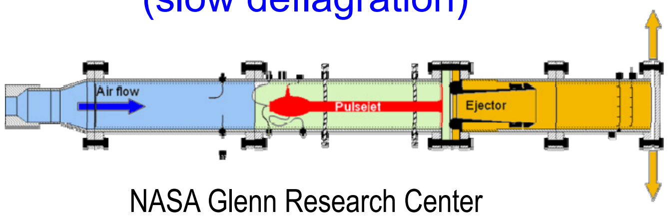
- Detonative PGC component model implemented in NPSS
  - Numerous known loss mechanisms incorporated
- PGC component integrated with other turbomachinery components
- Performance changes of gas turbine propagated through steam cycle.



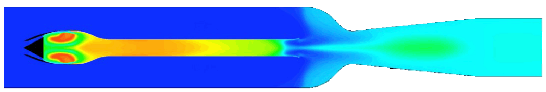
Power Plant Efficiency: +1.86%
Power Plant Power: +2.97%

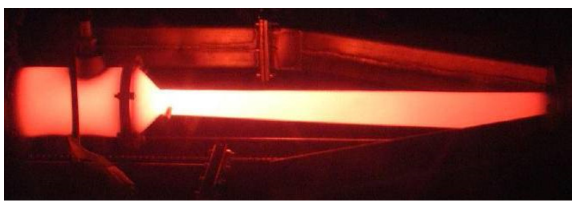
Recent Implementation Approaches

Resonant Pulse Combustor (slow deflagration)

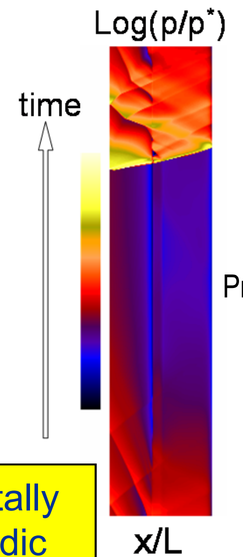


NASA Glenn Research Center





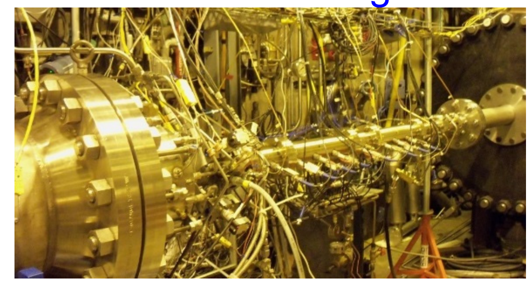
University of Cambridge



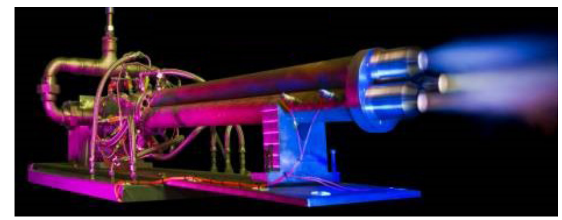
All Are Fundamentally Unsteady & Periodic

Fill →Burn →Blowdown →Repeat

Pulsed Detonation Engines



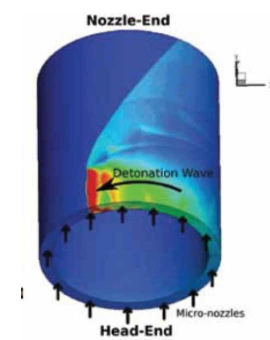
Pratt & Whitney/United Technologies Research Center



G.E. Global Research Center

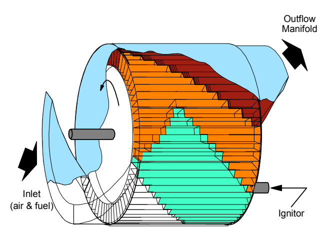
Rotating Detonation Engines

Air Force Research Laboratory

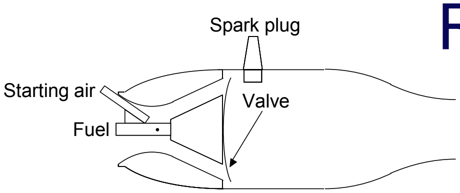


Naval Research Laboratory

Internal Combustion Wave Rotor ('Fast' Deflagration)

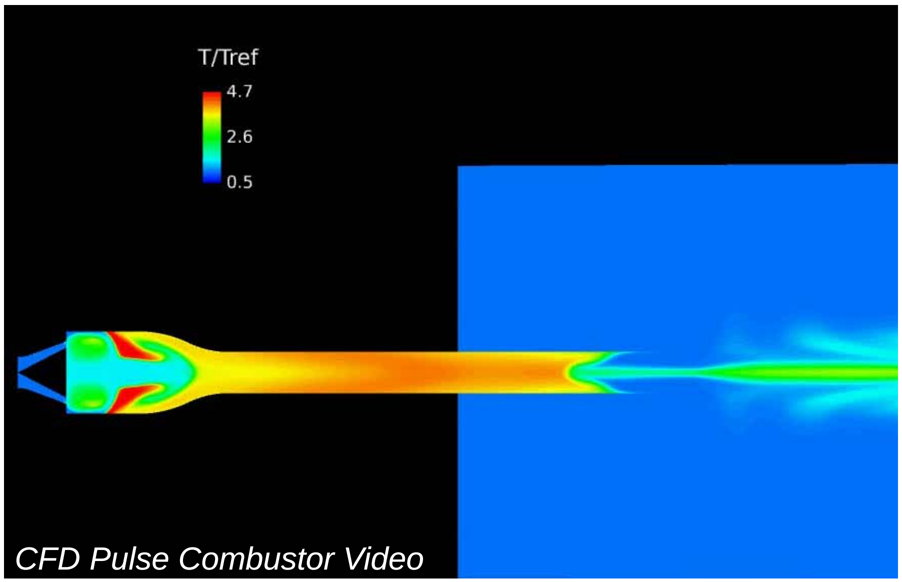


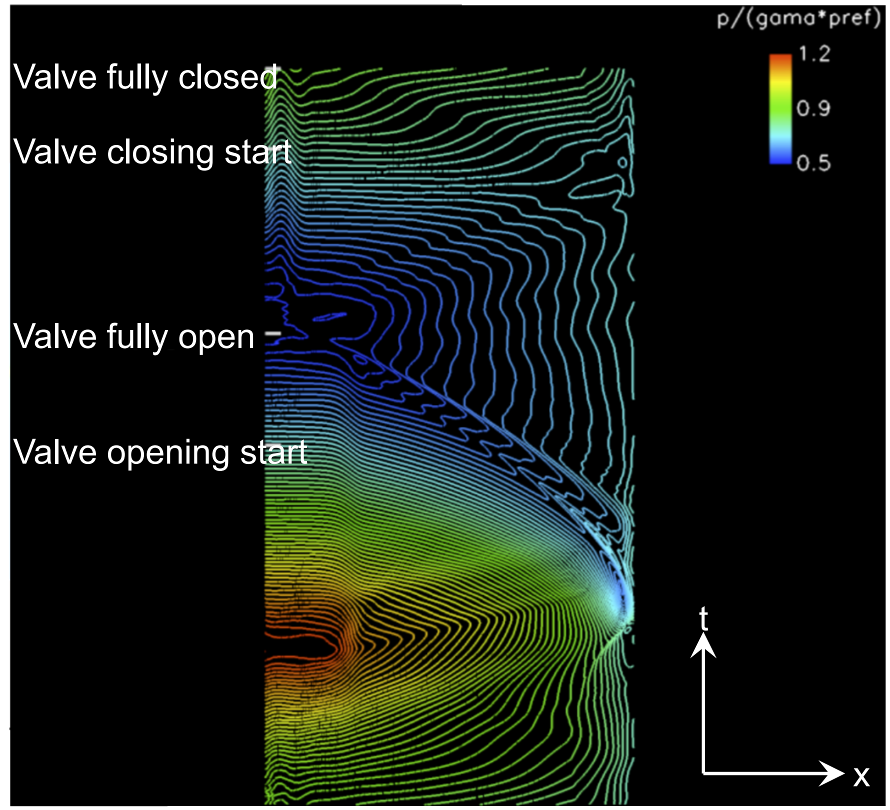
IUPUI/Purdue/LibertyWorks



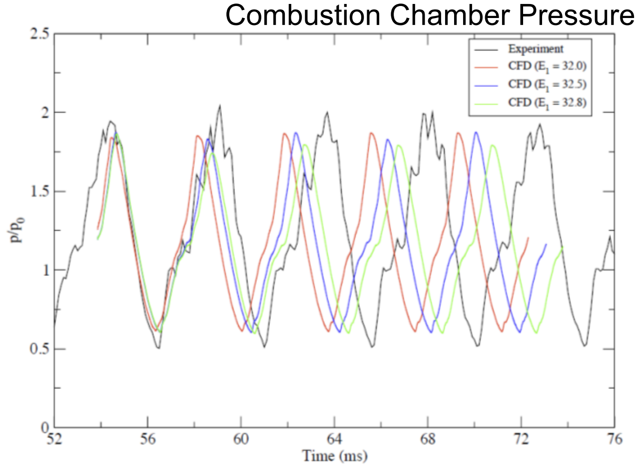
Recent Implementation Approaches

Resonant Pulse Combustor (RPC)





Combustion Chamber Pressure



Successful cycles balance:

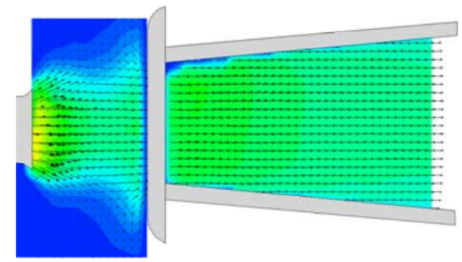
- Gasdynamic waves
- Large vortex dynamic
- Chemical kinetics
- Helmholtz phenomena

Recent Implementation Approaches

RPC as Gas Turbine Combustor

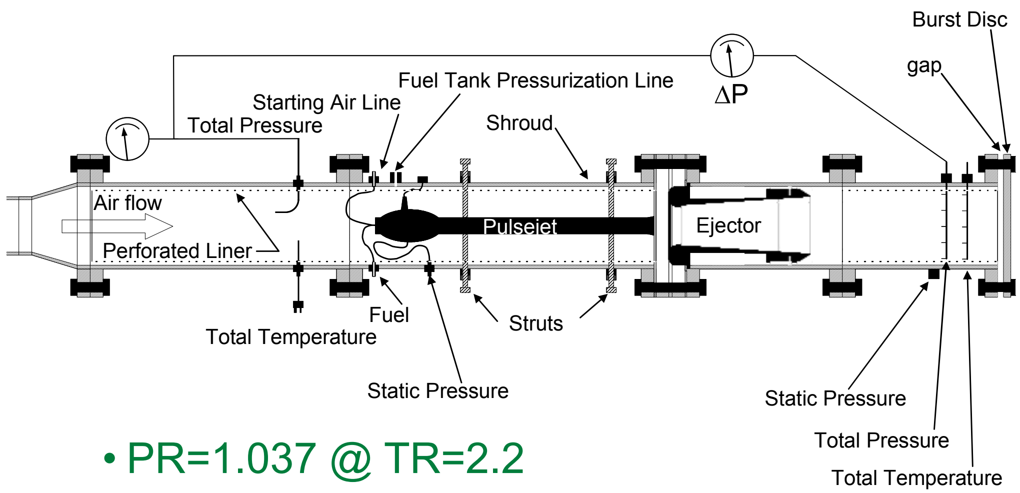
Effluent is too hot and impulsive for direct turbine coupling:

- Add optimized unsteady ejector
- Entrain bypass flow
- Mix efficiently
- Pump



PIV Measured Ejector Flowfield Video

Ejector Enhanced Resonant Pulse Combustor



- PR=1.037 @ TR=2.2
- rms p′/P=4.5% in the shroud
- Successful operation at 2 Atm. inlet pressure

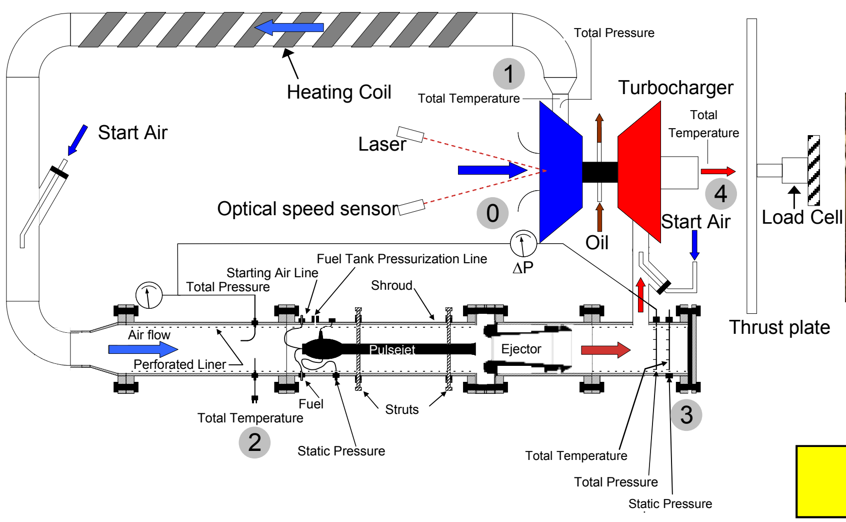
All Work Done With COTS Hobby Scale Pulse Combustor

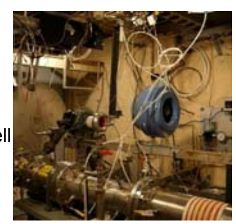
Recent Implementation Approaches

RPC as Gas Turbine Combustor

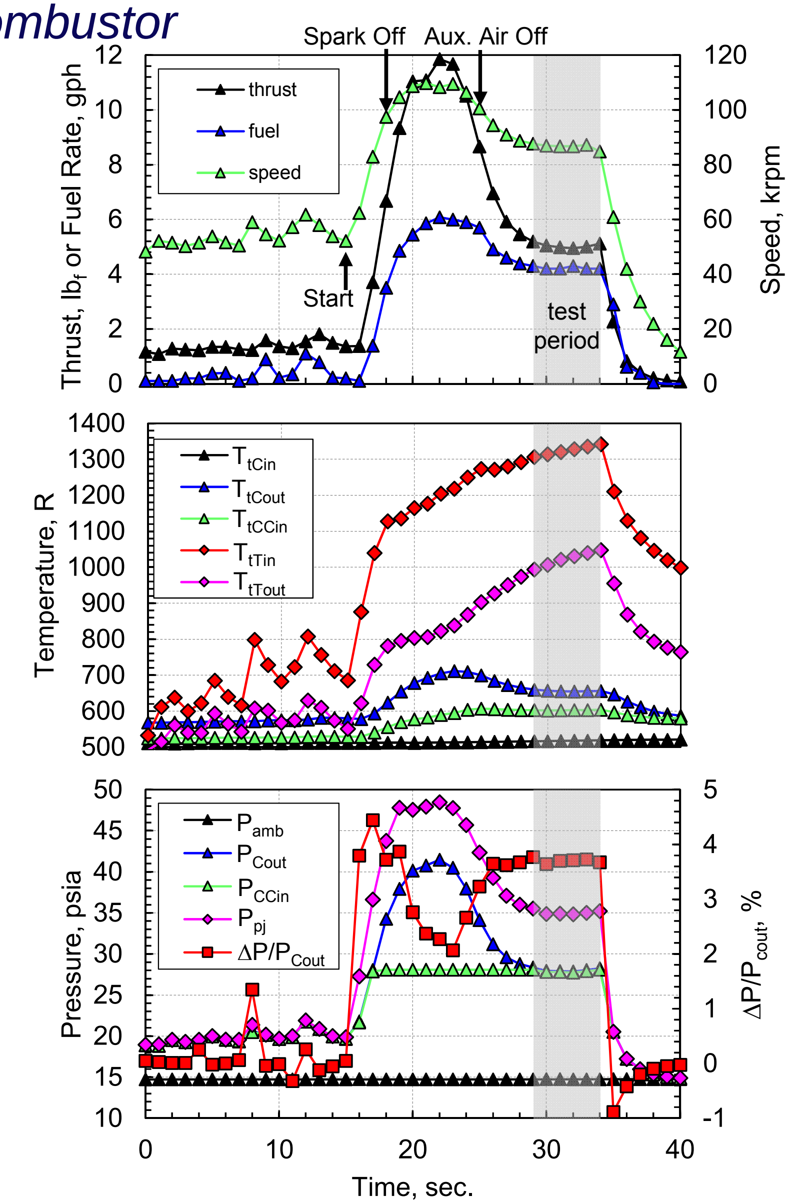
Lab Demo Results:

- True closed loop operation @ SLS
  - All air supplied by compressor
- $(P_4/P_3 - 1)=3.5\%$ @ $T_4/T_3=2.2$
- Sustained operation on liquid fuel
  - Limited only by COTS reed valve
- Successfully produced thrust
- Demonstrated Benefit
  - Turbine stops with conventional combustor at same T_4/T_3
- -20 dB noise reduction across Turbine
- 4% rms p'/P_4 at turbine inlet





Operational Rig Video

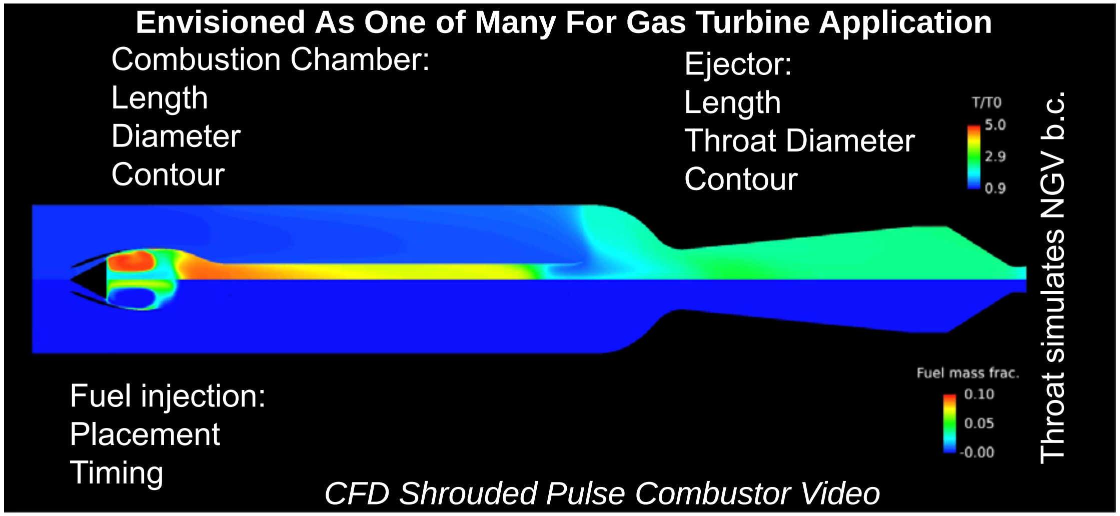


It Works!

Recent Implementation Approaches

RPC as Gas Turbine Combustor

High P_3, T_3 Operation and Optimization Through Simulation



Inflow Vortex Motion is Key

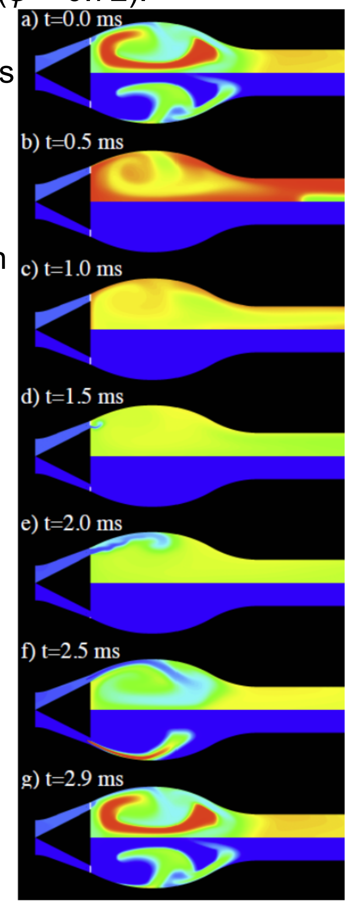
Temperature contours (top half) and fuel mass fraction contours (bottom half) at various times during one cycle (ϕ = 0.72).

Self-ignition via residual hot gas

Rapid confined combustion

Expansion/acceleration

refill



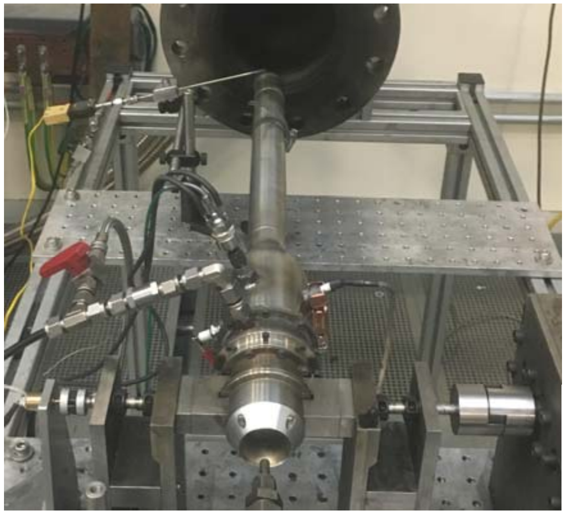
- Emission Index < 10 g_{NOX}/kg_{fuel}
  - Lower pressure gain configurations showed values below 1.0!
- $(P_{t4}/P_{t3} - 1)$=3.3% @ T_{t4}/T_{t3}=2.4
  - A large improvement considering T_{t3}=990 R
- Relatively benign station 4 conditions
  - 7% rms p'/P_{t4}
  - 23% rms u'/u_4
  - 1.7% rms T'/T_{t4}

Validated Models Are Essential For Design, Performance Assessment, and Diagnostics

Recent Implementation Approaches

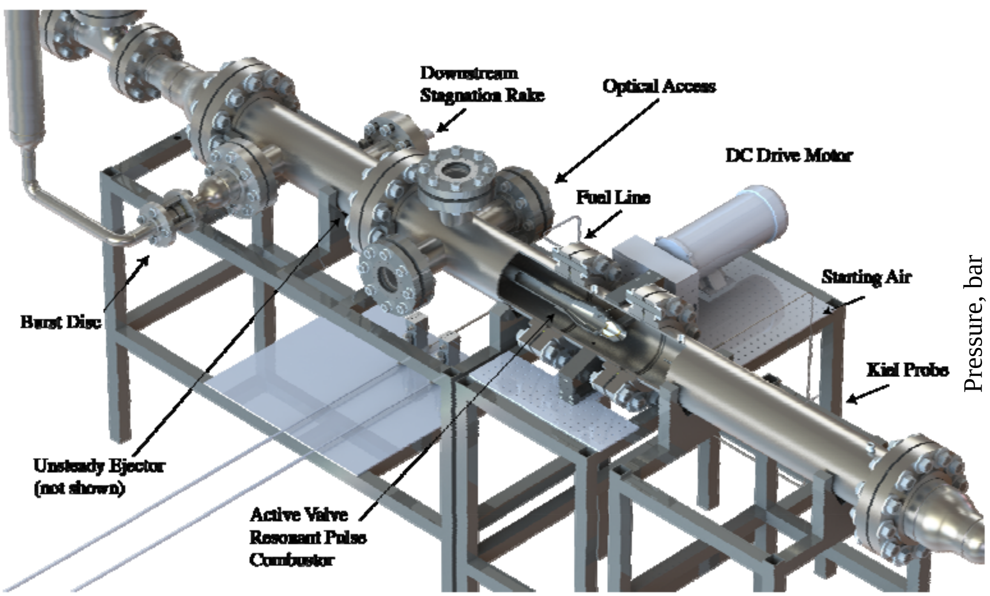
RPC as Gas Turbine Combustor

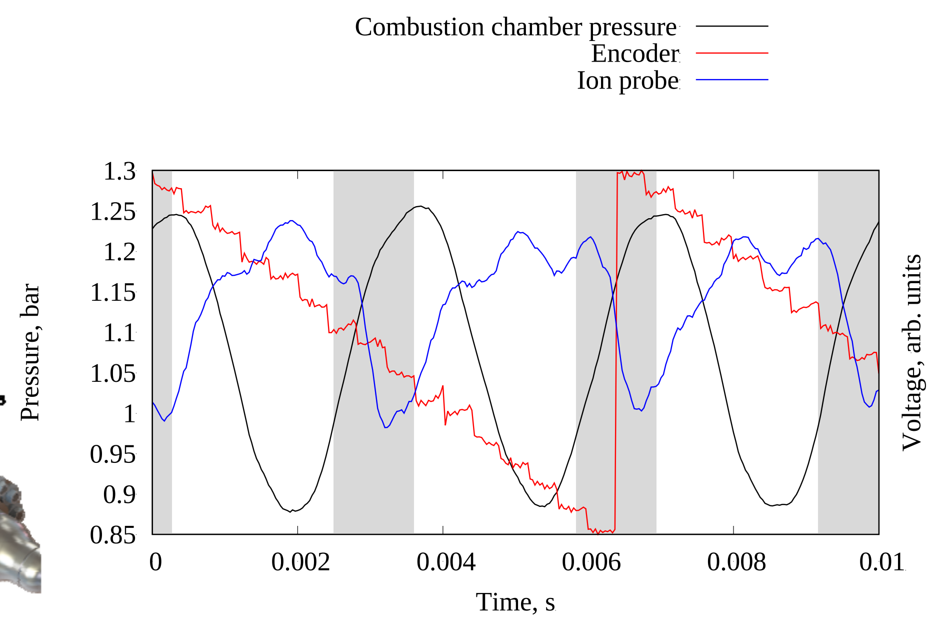
Images Courtesy of King Abdullah University of Science and Technology, Prof. William Roberts



Active Air Valve System
- *Successful self-sustained, self-aspirated operation*
- *Successful operation for long periods*

Shrouded High Pressure Test Bed
- *Heated air*
- *Extensive diagnostics*

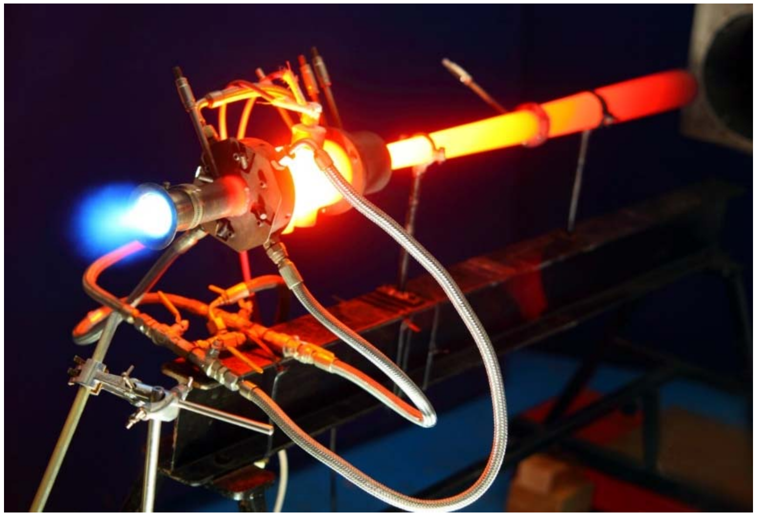


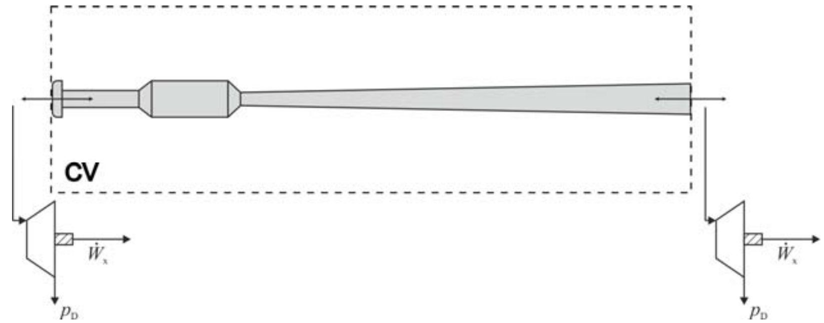


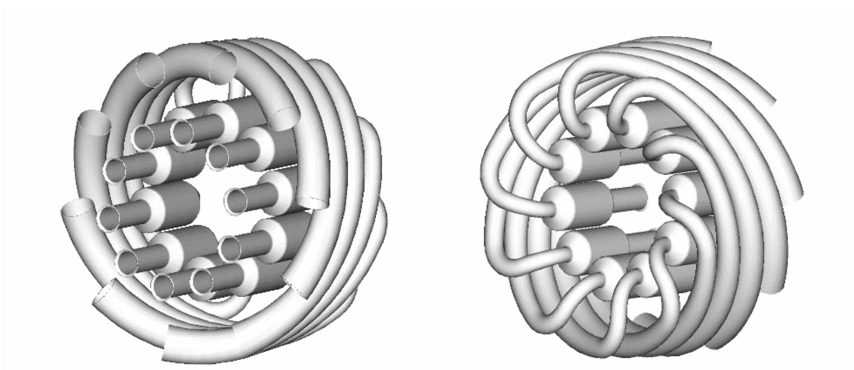
Recent Implementation Approaches

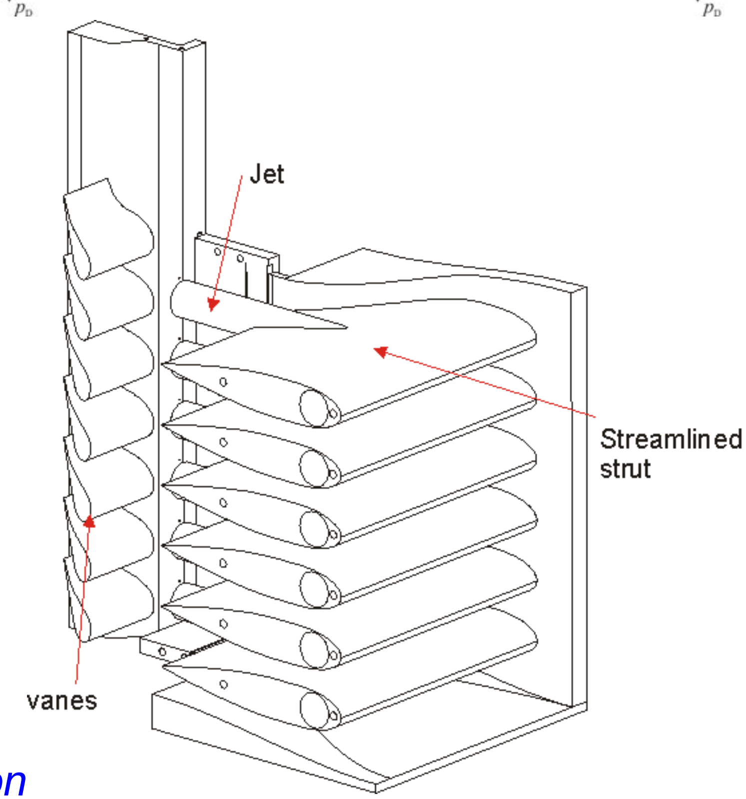
RPC as Gas Turbine Combustor

Images Courtesy of Whittle Laboratory and Rolls-Royce, Prof. Robert Miller









Aerovalved Configurations

- *Engine integration*
- *Defining and optimizing pressure gain*
- *Optimizing combustor/turbine interaction*

Recent Implementation Approaches

Internal Combustion Wave Rotor (ICWR)

('Fast' Deflagration)

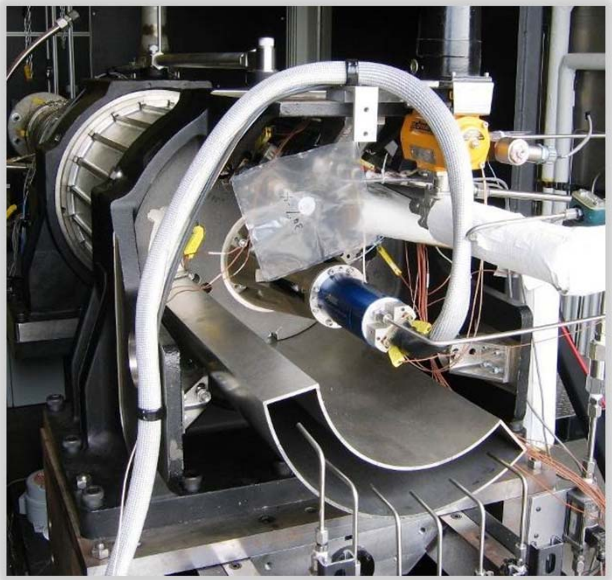
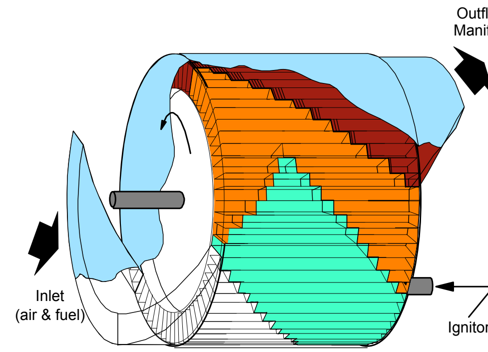
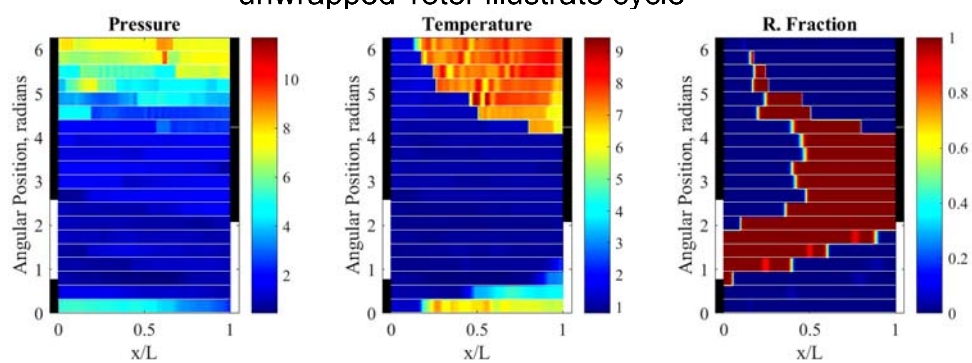


Photo and video courtesy IUPUI and LibertyWorks

Operational Rig Video



Contours of passage fluid properties in 'unwrapped' rotor illustrate cycle



1D CFD Wave Rotor Video

Characteristics

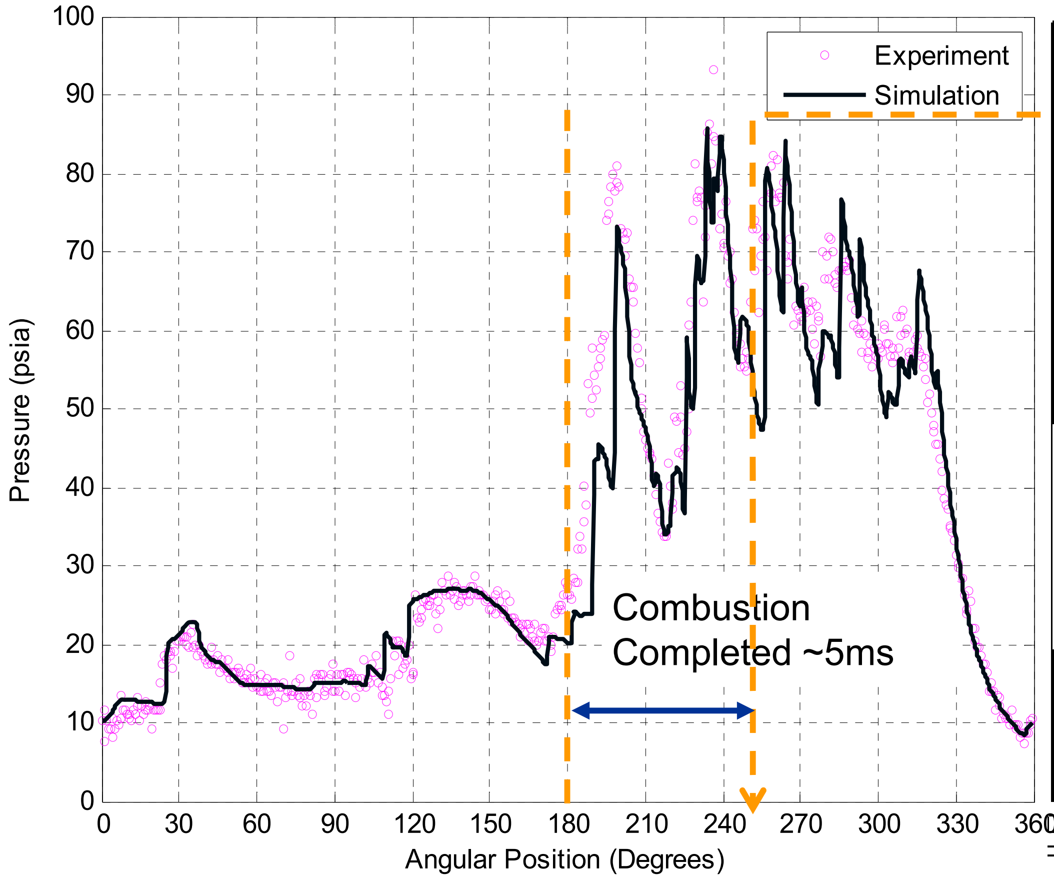
- Flow in ports is nominally steady, though spatially non-uniform
- Rotor is self-cooled
- Rotation provides valving not power extraction
- Valves implemented at both ends
- Closest to true constant volume combustion

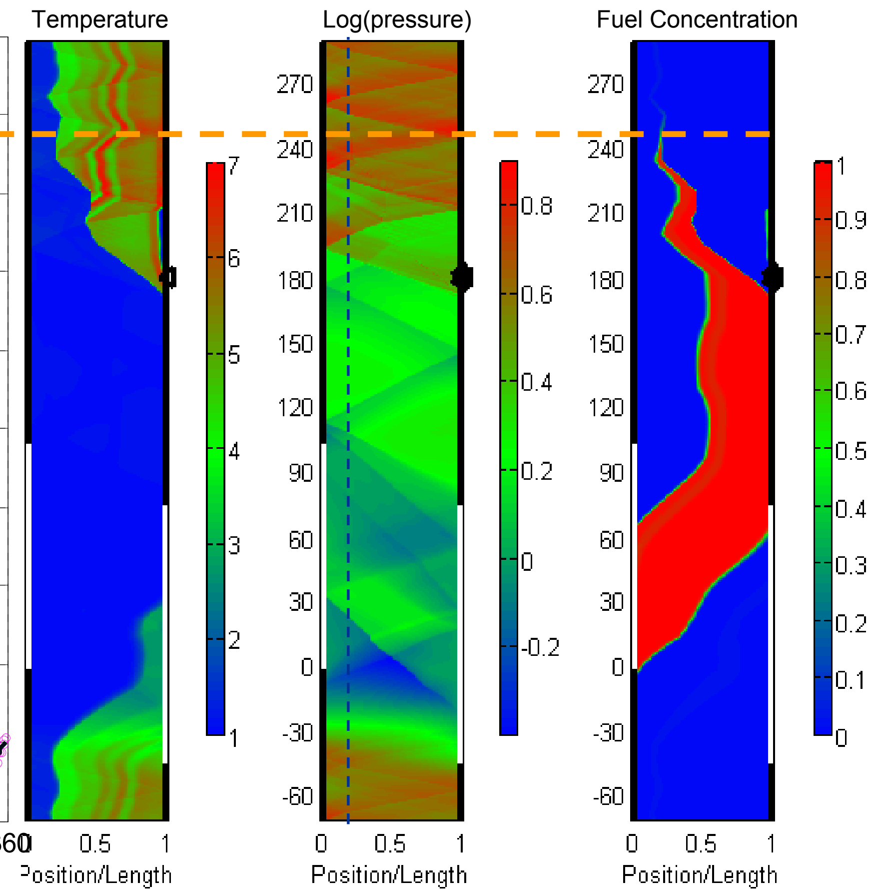
5%-17% Pressure Gain Measured on a 1st Generation, Concept Demonstrator Rig

Recent Implementation Approaches

Internal Combustion Wave Rotor

('Fast' Deflagration)



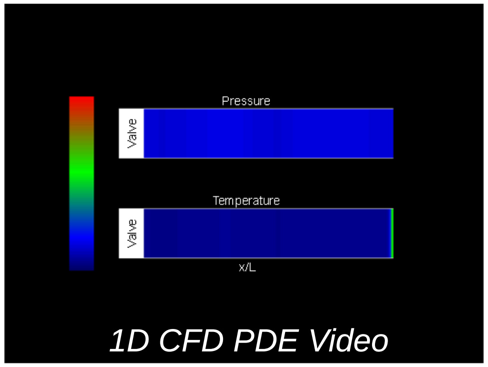


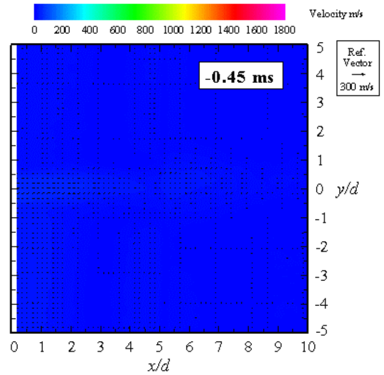
Pressure trace and contour plot courtesy IUPUI and LibertyWorks

Again, Validated Models Are Essential for Design, Performance Assessment, and Diagnostics

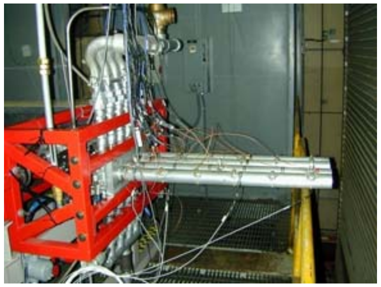
Recent Implementation Approaches

Pulsed Detonation Engines (PDE)

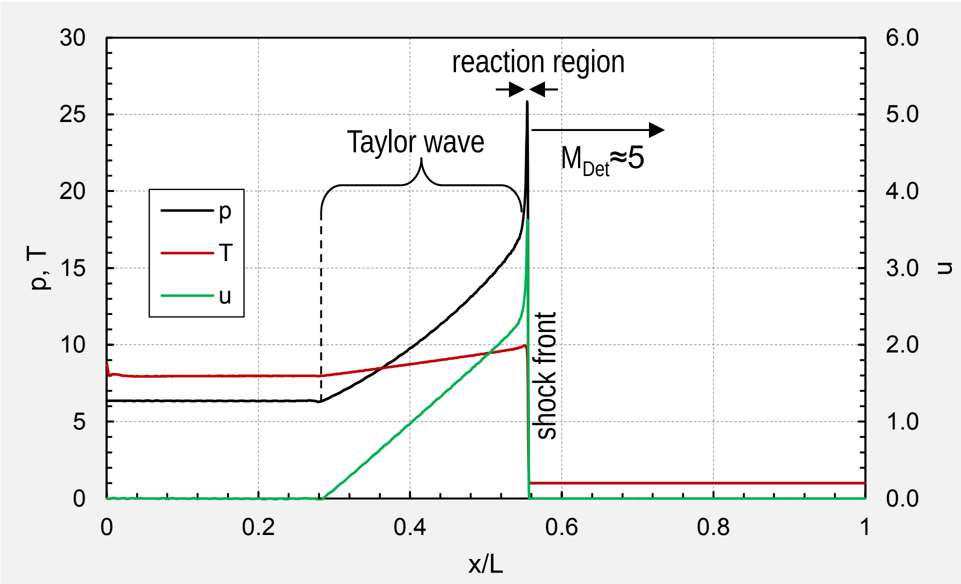




PIV Measured PDE Effluent Video



Courtesy Air Force Research Laboratory



A Detonation:

- Provides confinement by coupling shock wave with supersonic combustion wave
- Has a very thin reaction front
- Creates a supersonic wave front with subsonic fluid velocities
- Creates a large local pressure spike which is immediately reduced by a following Taylor wave that spreads in time
- Results in a fluid state in the tube that is similar to constant volume combustion

Recent Implementation Approaches

PDE's

Courtesy Naval Postgraduate School

Reliable PDE operation requires:

- Active valves
- Ignition source
- Deflagration to Detonation (DDT) mechanism
- Rapid fuel and air mixing
- Repeatability

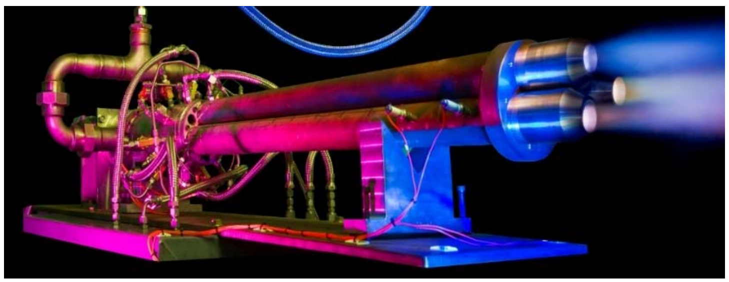


Image and details courtesy G.E. Global Research Center

Details

- Rotary air valve
- Schelkin type spiral for DDT
- Exit nozzles for back pressure
- 20 Hz per tube operation
- Stoichiometric C_2H_4-Air
- **Pressure gain demonstrated**

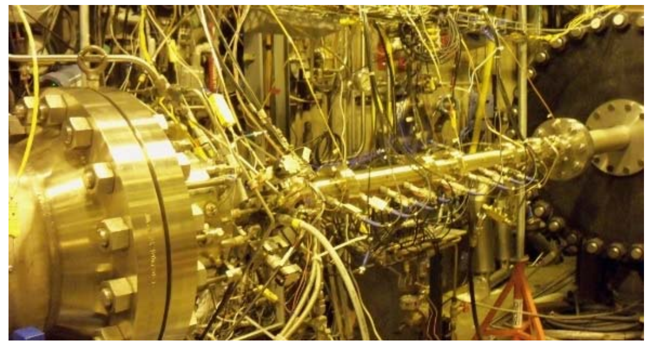


Image and statement courtesy Pratt & Whitney/United Technologies Research Center

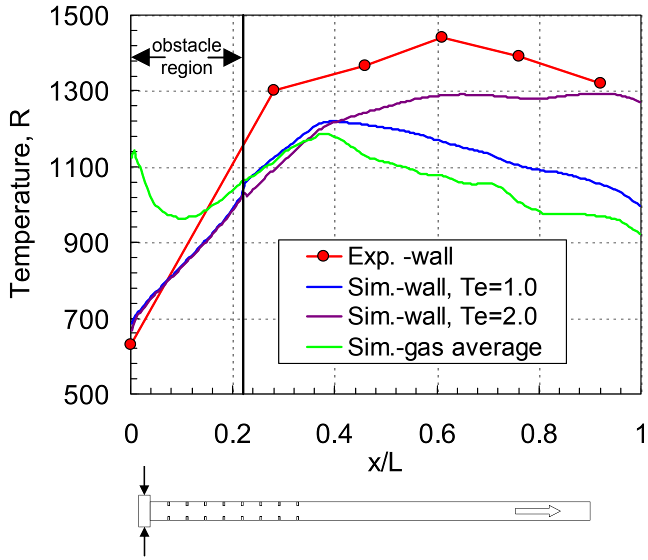
*"A pulse detonation engine developed by the Pratt & Whitney/United Technologies Research Center **demonstrates pressure gain** at turbine conditions."*

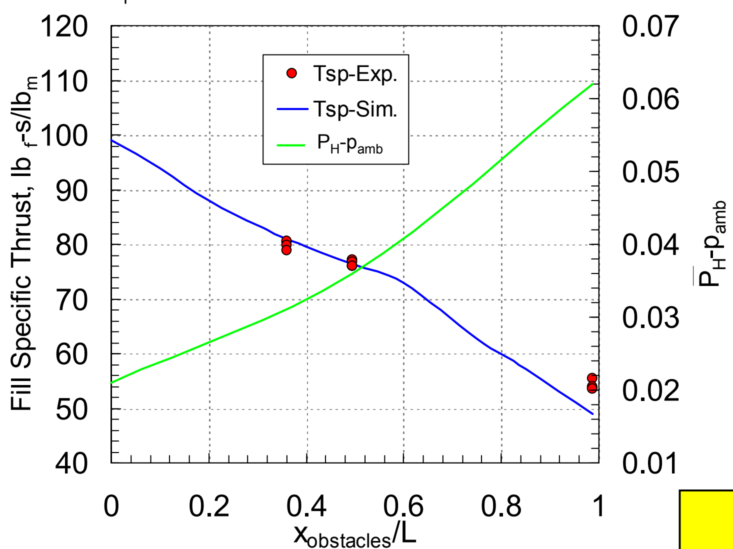
– AIAA 2014 Year In Review

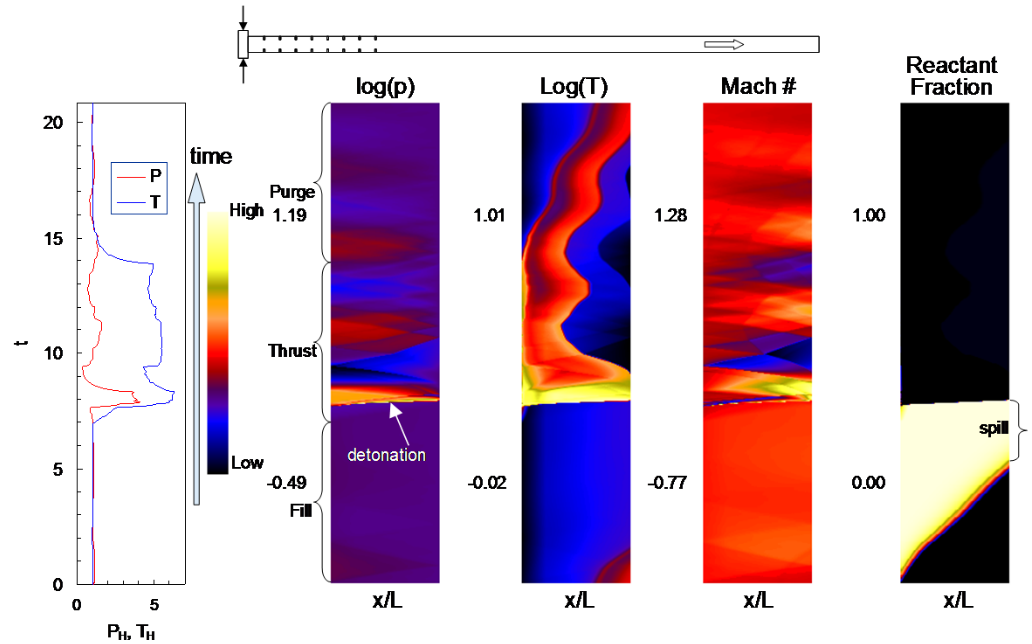
Numerous Research Efforts Have Yielded Significant Progress

Recent Implementation Approaches

PDE's







Details

- Premix H_2/Air PDE
- Automotive valve system
- 1D CFD Model
  - Valve Sub-Model
  - Heat transfer sub-model
  - Viscous sub-model

Did I Mention:Validated Models Are Essential for Design, Performance Assessment, and Diagnostics

Recent Implementation Approaches

PDE's As Gas Turbine Combustors

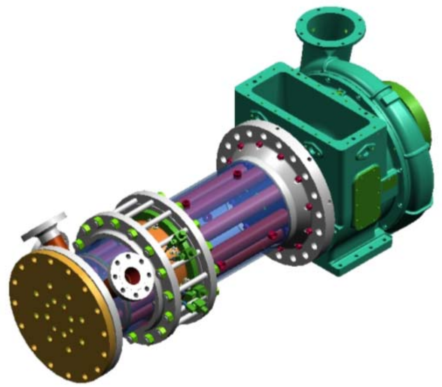
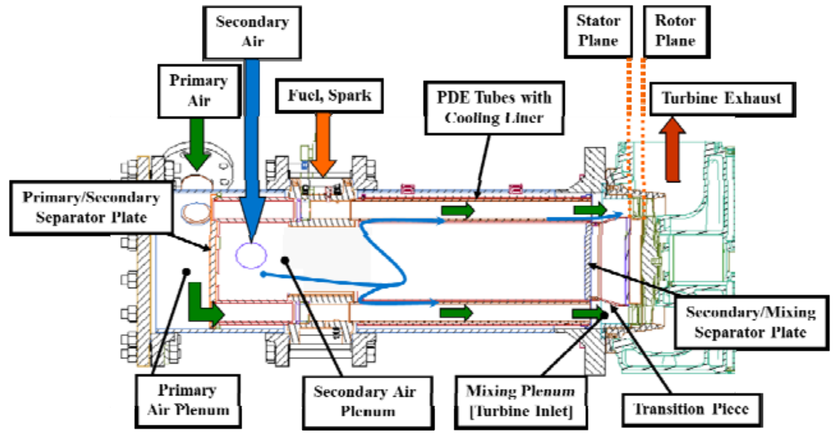
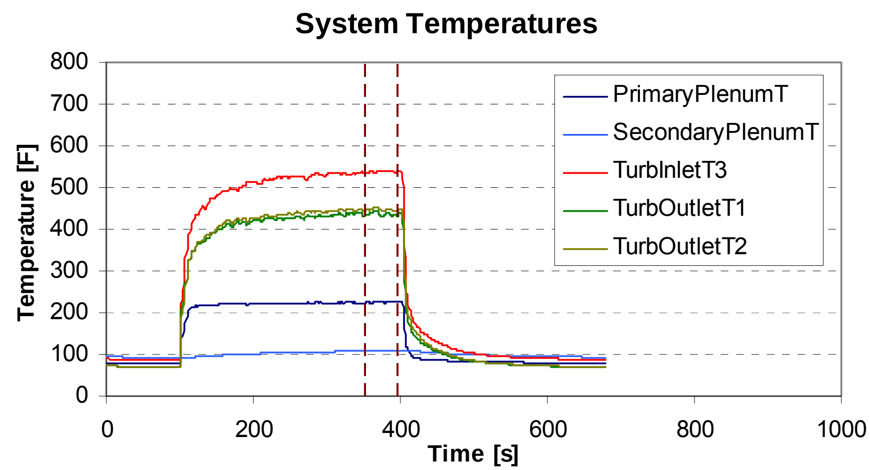


Image and details courtesy G.E. Global Research Center



Details

- Goal was to study turbine/PDE interactions, not PDE performance
- 8 tube "can-annular" configuration
- 1000 hp, 25000 RPM single stage axial turbine
- Airflow ≈ 10 lbm/s (50% secondary flow)
- Constant air flow, fuel is valved
- C_2H_4 – Air, stoichiometric conditions
- Detonations verified at 10 Hz and 20 Hz
- Long duration operation to thermal steady state
- 10 dB broadband acoustic noise reduction



"The turbine component efficiency was indistinguishable under steady and PDC fired operation with the present measurement resolution."– AIAA JPP V.27, 2011

Recent Implementation Approaches

PDE's As Gas Turbine Combustors

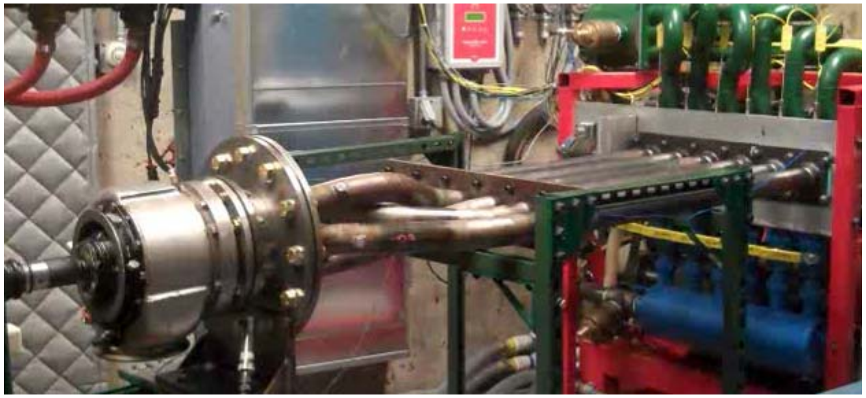


Image and details courtesy Air Force Research Laboratory

Details

- 6 tube linear PDE array
- Single stage axial turbine
- Airflow ≈ 1.5 lbm/s
- H_2/Air
- 10 Hz. per tube operation
- **Similar turbine efficiencies measured for steady and PDC fired operation**

While It Is Understood That:

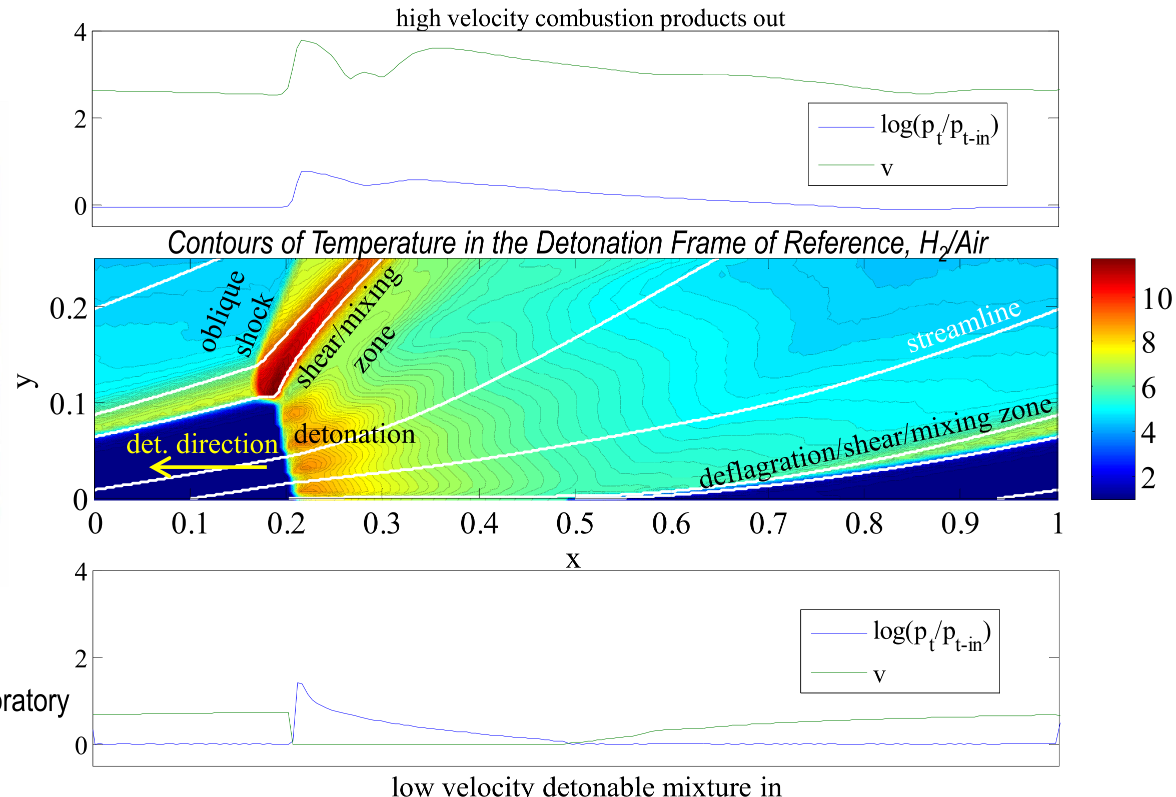
- There are many caveats to these and other investigations (some to be discussed later)
  - How are requisite P_4, T_4, etc. measured in an unsteady environment?
  - What does the partial admission nature of PDE tubes do to a turbine that wasn't built for it?
  - Etc.
- These were not high performance turbines to begin with
- The results seem to contradict much of what we expect in terms of the impact of unsteadiness

These <u>Preliminary</u> Investigations Indicate That PDE Combustors for Gas Turbines <u>Are</u> Feasible

Recent Implementation Approaches

Rotating Detonation Engines (RDE)

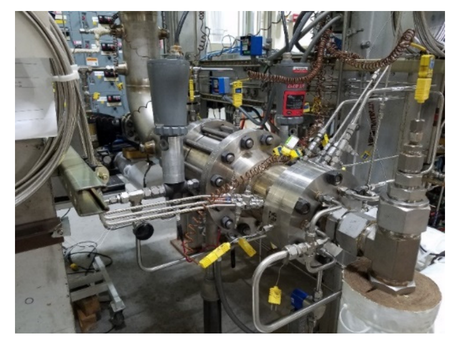
CFD RDE Video
Courtesy Naval Research Laboratory



Courtesy AFRL

Rotating Detonations:

- Supersonic detonation propagates circumferentially
- Fluid travels axially
- No ignition source required (after startup)
- No DDT obstacles required
- Very high frequency operation (kHz)
- Inlet often aero-valved to reduce/prevent backflow

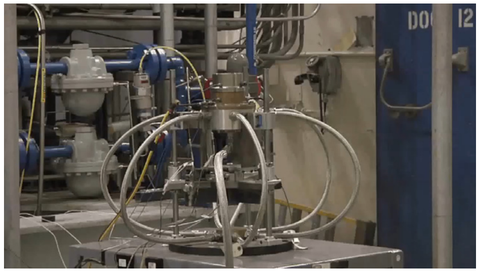


Courtesy DOE/NETL

Recent Implementation Approaches

RDE's

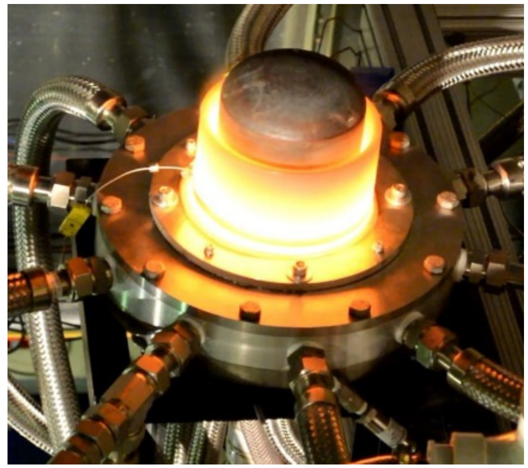
Upper images and videos courtesy Air Force Research Laboratory (AFRL)



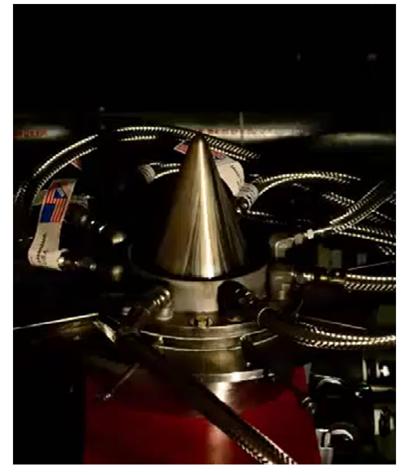
Exhaust End Operational Video

Details

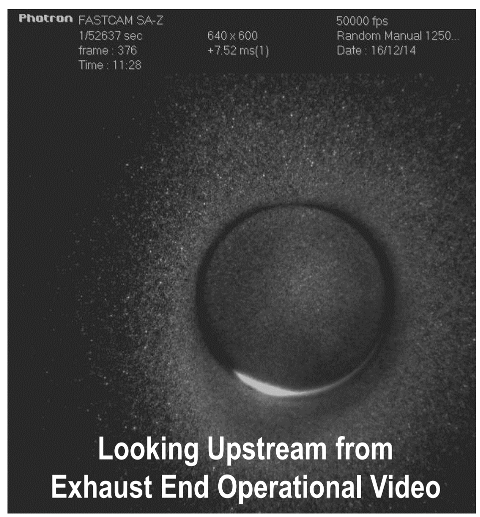
- All operation shown H_2/Air
- Audible screech is operational frequency
- No premix
- Throttling demonstrated



RDE Run to Thermal Steady State



Exhaust End Operational Video



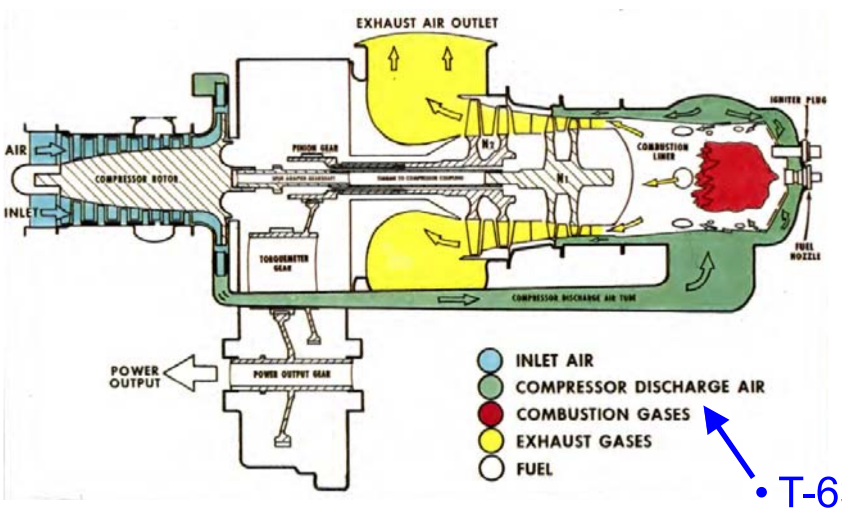
Significant Progress Since First Widely Reported Operations in 2012

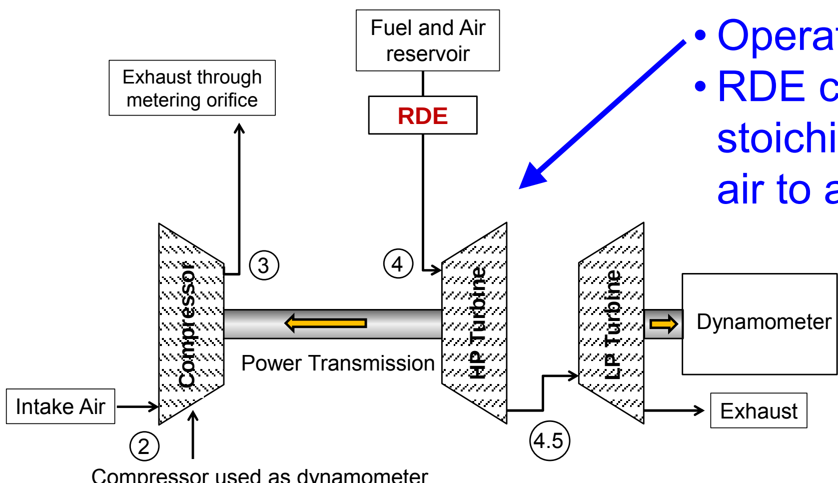
Courtesy Department of Energy/National Energy Technology Laboratory

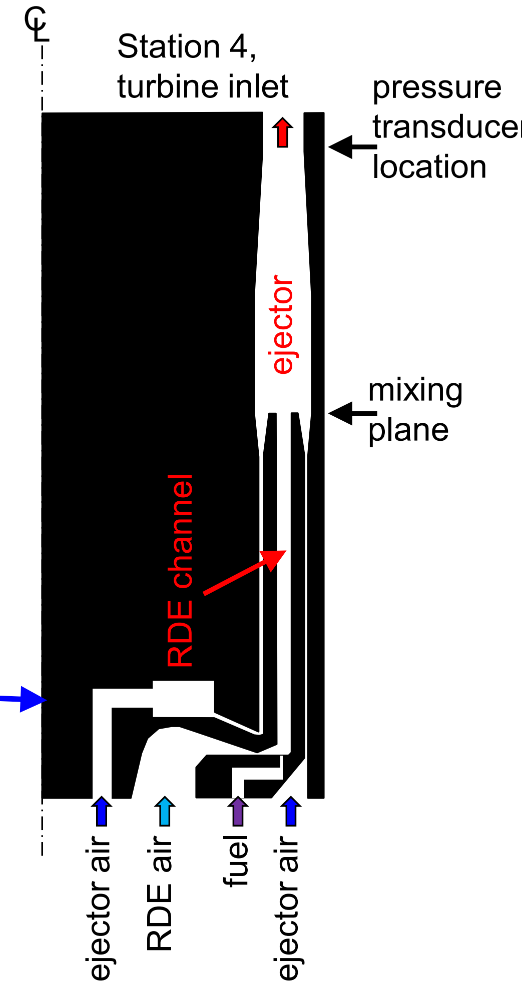
Recent Implementation Approaches

RDE's As Gas Turbine Combustors

Images and details courtesy Air Force Research Laboratory







Details

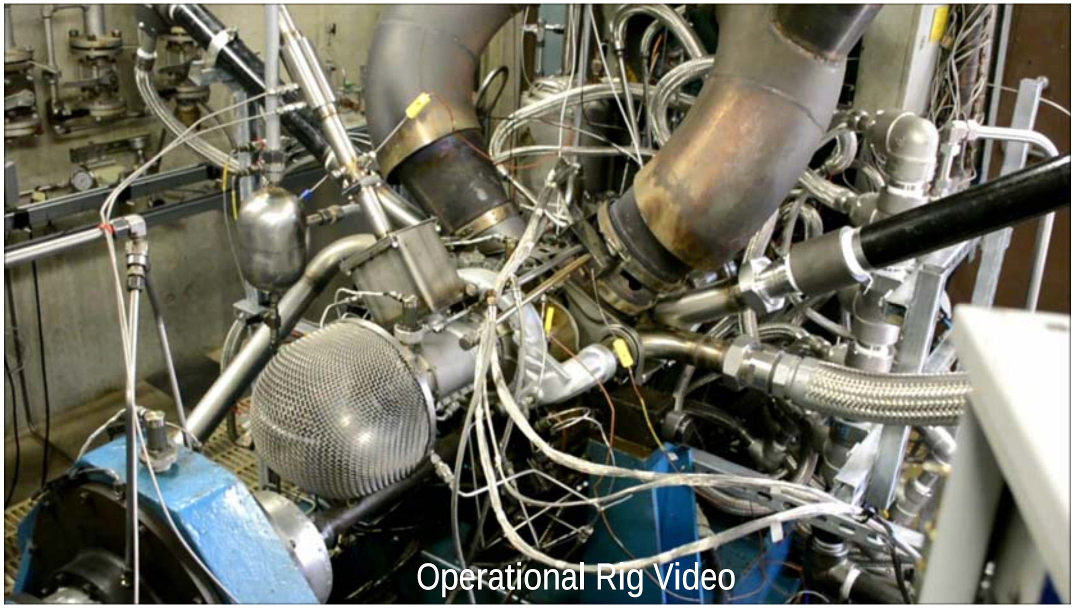
- T-63 engine selected
- Operated in open-loop mode
- RDE combustor run stoichiometrically with bypass air to achieve T_4

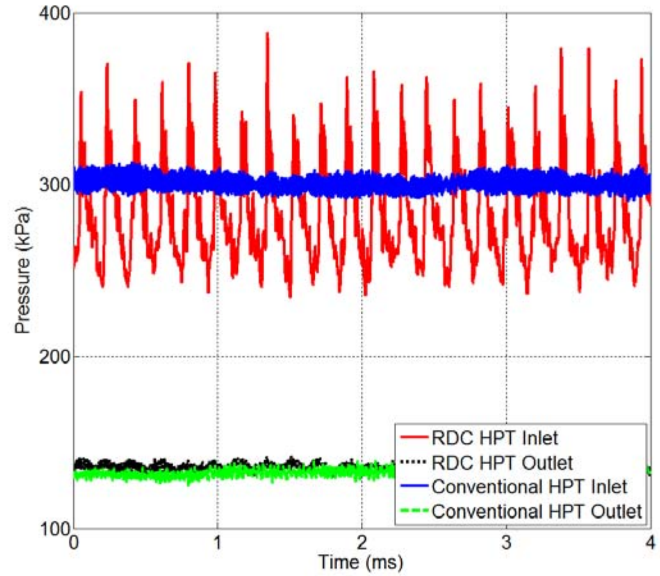
Non-Optimized Laboratory RDE Used
This Was A Turbine Performance Test NOT A Pressure Gain Test

Recent Implementation Approaches

RDE's As Gas Turbine Combustors

Images, video, and details courtesy Air Force Research Laboratory





Details

- H2/air
- 3/6 kHz detonation frequency
- Operation from light-off to Rated Power
- Each operating point at thermal steady state
- Compressor discharge always matched core flow
- Combustor efficiency 97-100%
- NOx emissions very low
- **Turbine efficiency unaffected**

This Preliminary Investigation Indicates That RDE Combustors for Gas Turbines Are Feasible

The Role of Models

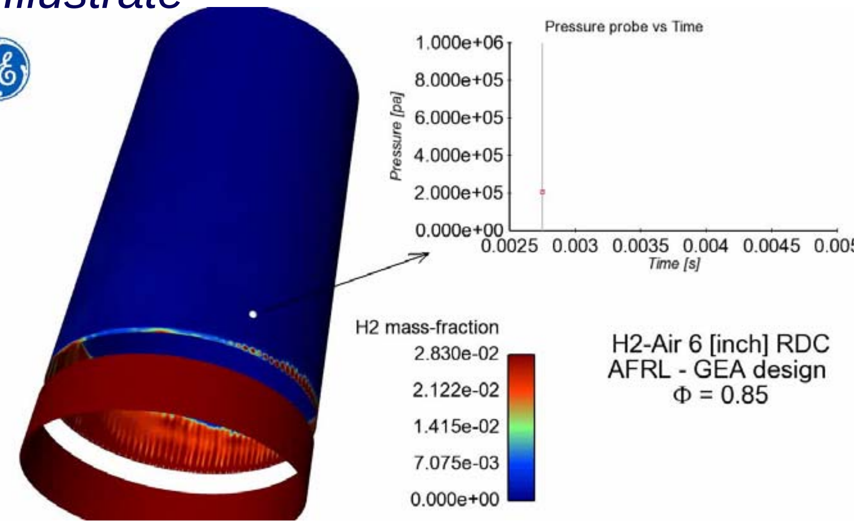
Using RDE's to Illustrate

In PGC Devices:

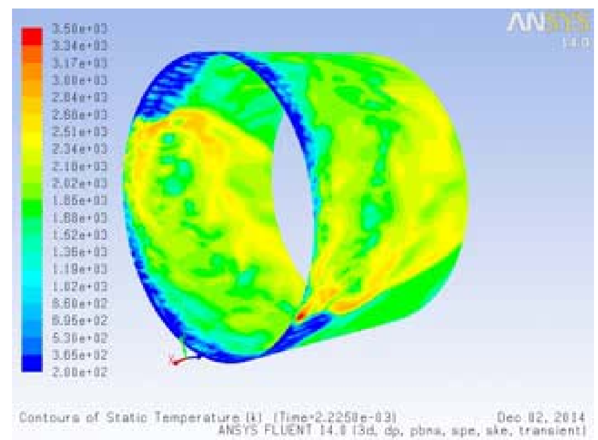
- Flowfields are extraordinarily complex
- Instrumentation is difficult
  - Harsh environment
  - Orders of magnitude variations
  - Very high frequency
  - Average flow rates, pressures, thrust, are typically all that's available in the lab
- Highly coupled processes
- No conventional 'stations' (i.e. locations fixed in time and space)

Models Serve To:

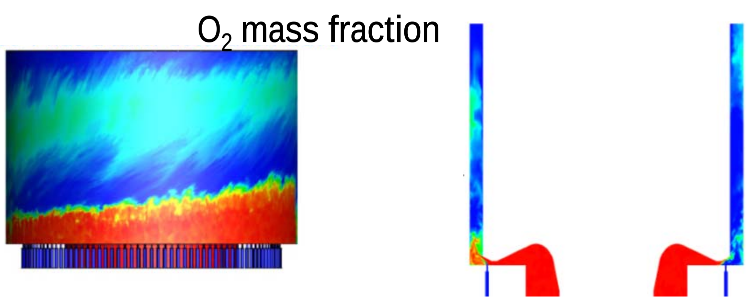
- Interpret typically averaged readings
- 'Measure' where instruments can't
- Literally allow us to see what's going on
- Guide optimization in experiments



3D CFD RDE Video Courtesy G.E. Global Research Center



3D CFD RDE Video Courtesy DOE/NETL



3D CFD Image Courtesy UTRC

PGC System Development Requires Strong Model, Experiment, Measurement Collaboration

Example Effort

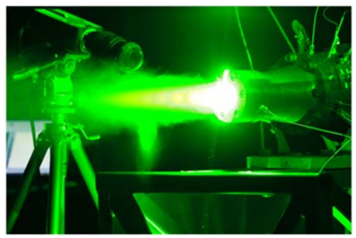
Using RDE's to Illustrate

Images and details courtesy Aerojet Rocketdyne

- Phase II National Energy Technology Laboratory funded, multi-team research effort characterizing and optimizing the fluid and mechanical interface between the RDE and a turbine cascade.
  - Aerojet Rocketdyne lead and integrator

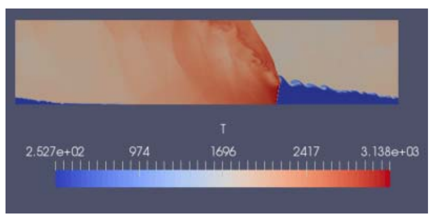
University of Alabama

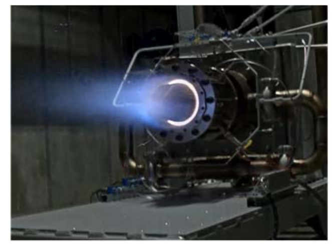
- Testing 10-cm RDE with optical diagnostics for combustor & diffuser exhaust flow characterization.



University of Michigan

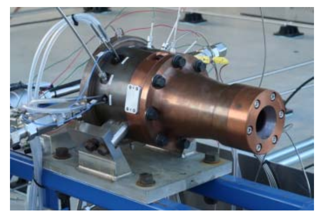
- Lab-scale testing and CFD modeling of RDE for injector & combustion physics





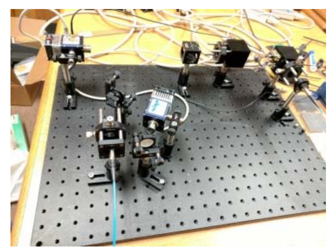
Purdue University

- Flow effects on turbine efficiency
- 21-cm and 31-cm RDE testing with air/natural gas.



Southwest Research Institute

- Testing 10-cm RDE and various diffuser geometries with optical diagnostics



University of Central Florida

- High fidelity TDLAS optical diagnostic for composition & unsteady flow analysis

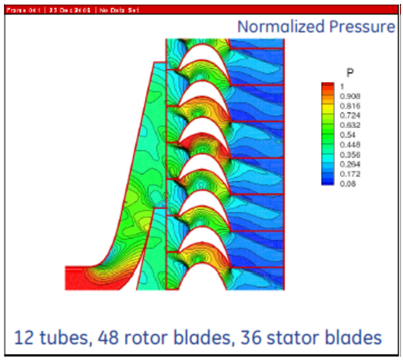
Duke Energy

- NGCC integrated plant study support and funding partner

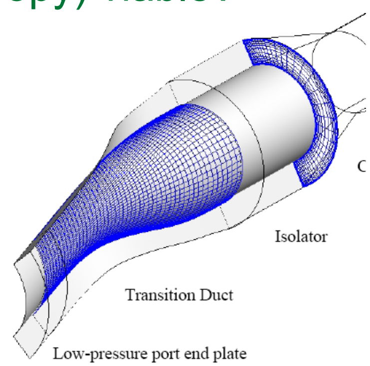
Technology Challenges

(aka What Makes it Fun!)

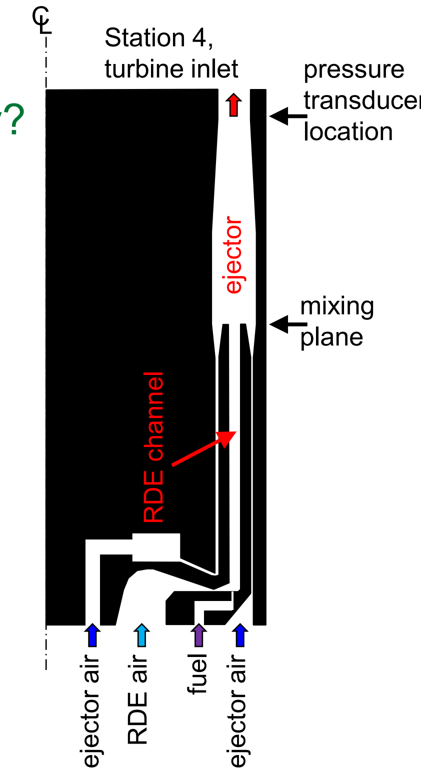
- Turbine/PGC Component Interactions
  - –How is turbine performance quantitatively affected by non-uniformity?
  - –Can unsteadiness-tolerant turbines be designed?
  - –Is efficient bypass mixing (with associated entropy) viable?
  - –Where does turbine cooling flow come from?



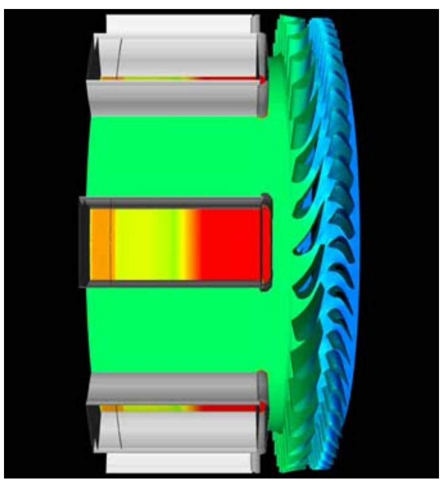
2D CFD Video Courtesy G.E. Global Research Center



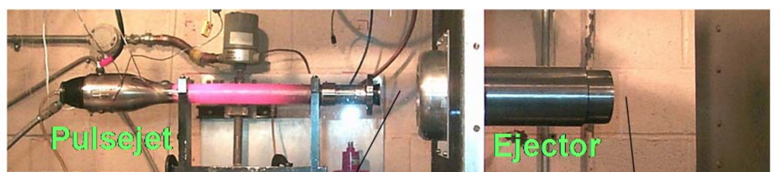
Wave Rotor Transition Duct

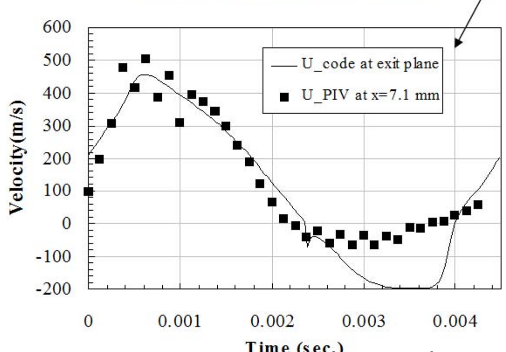


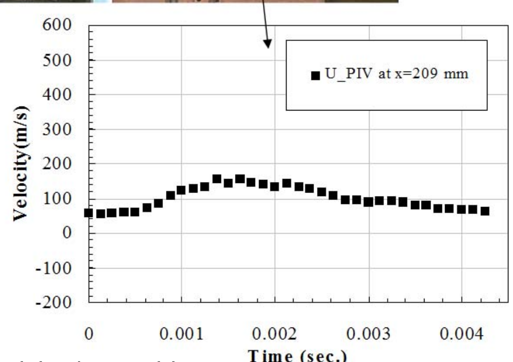
RDE Bypass Ejector for Mixing/Smoothing



3D CFD Video



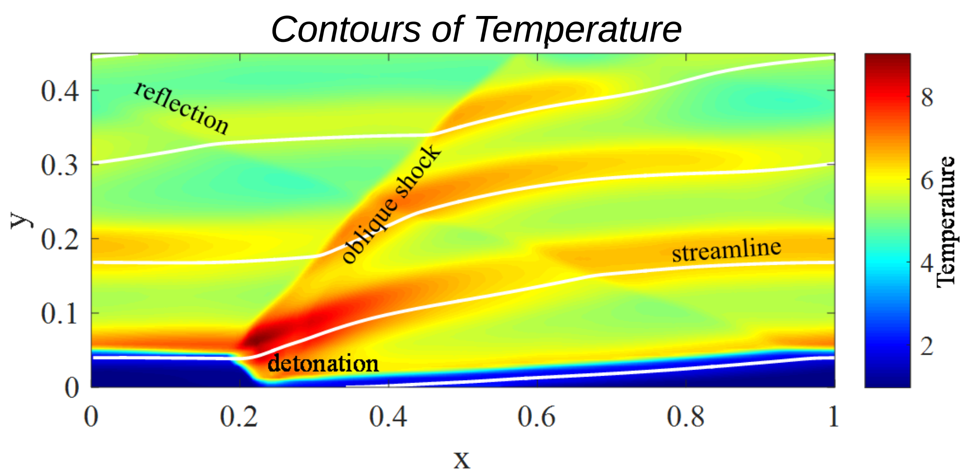




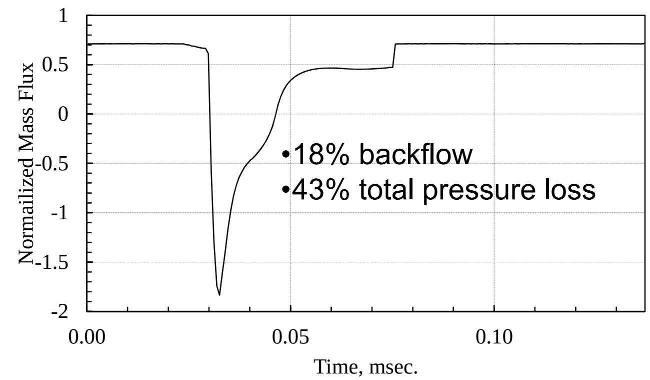
Ejector Mixing/Smoothing

Technology Challenges
(aka What Makes it Fun!)

- Inlet Valves
  - All PGC methods require robust mechanical or aero-valve systems which:
    1. Prevent backflow into inlet and/or seal
    2. Have low loss to forward flow
    3. Operate at high frequency
    4. Don't fail
    5. Tolerate high thermal and stress loads (though they are at least intermittent)



1950's era RPC Reed Valves After 15 sec. Operation in Gas Turbine



Computed Inlet Plane Mass Flux of a Research RDE Using Validated CFD

Technology Challenges

(aka What Makes it Fun!)

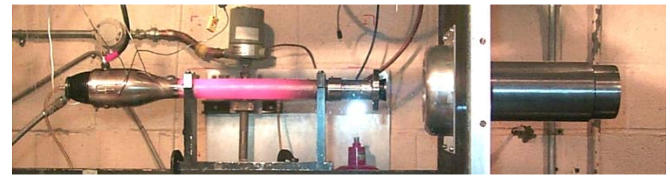
- Thermal Management
  - PGC devices have very high associated thermal loads
  - They are intermittent, but still require attention
- Instrumentation and Measurement
  - High frequency, large amplitude range, harsh environment tolerant capabilities required
  - Methodologies for assessing meaningful averages for P_{t4}, T_{t4} *(Hint: time-average won't work)*
- Controls and Actuation
  - Many PGC devices do not operate (well) passively
- Modeling and Validation
  - PGC environment is computationally challenging (fundamentally unsteady, multiple time scales, chemical kinetics uncertain, turbulence models uncertain)
  - Validation is difficult due to instrumentation limits and lack of canonical flows
- Emissions?
  - Some approaches are problematic due to near stoichiometric operation, exceptionally high temperatures, and long residence time.
  - Several approaches have shown competitive levels due to rapid expansion following reaction

Recent Research Efforts Have Yielded Substantial Progress in All Areas
No Show Stoppers Identified to Date

Concluding Remarks

Pressure Gain Combustion is a promising technology area for improving gas turbine performance

- *Competitive with conventional improvement strategies*
- *Targets improvement at the major source of entropy generation*



There are numerous promising implementation strategies under investigation

- *Resonant Pulsed Combustion*
- *Internal Combustion Wave Rotor*
- *Pulse Detonation Engine*
- *Rotating Detonation Engine*
- *Aero or mechanical valves*
- *Valves fore and aft, or just fore*
- *Mixing, bypass, lean, etc. operational modes to achieve acceptable TR*

There are technology challenges however:

- *None have yet been identified as insurmountable*
- *Analysis tools have advanced significantly*
- *Understanding has increased dramatically*

"Great things are done by a series of small things brought together."
- Vincent Van Gogh

QUESTIONS?

"Nothing in this world can take the place of persistence. Talent will not: nothing is more common than unsuccessful men with talent. Genius will not; unrewarded genius is almost a proverb. Education will not: the world is full of educated derelicts. Persistence and determination alone are omnipotent."

-Calvin Coolidge