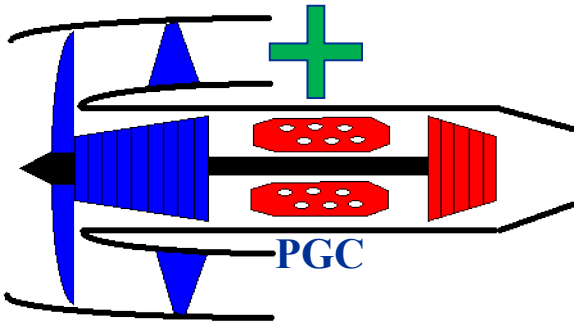


Pressure-Gain Combustion for the Gas Turbine

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

University Turbine Systems Research Workshop

October 20, 2010

Pennsylvania State University

State College, PA

Some Preliminary Facts

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

The U.S. Consumes (Converts) **99,200,000,000,000,000** BTU of Energy Each Year

- *84% from fossil fuels (petroleum, natural gas, coal)*
- *61% from petroleum and natural gas*

Resulting Issues

- *National & Economic security*
- *Pollution*
- *Global warming*

How Are We Responding

- *New fuels (biomass, etc.)*
- *New conversion systems (wind, solar, etc.)*
- *Conservation/ **EFFICIENCY** (use less)*

Gas Turbines Constitute an Astonishing 9.4 % of Energy Consumption

- *2.5% from aviation*
- *6.9% from power generation (much more if coal gasification is successful)*

Thus, a **1%** Improvement in Thermodynamic Efficiency is Equivalent to **1,360,000** fewer cars

A Reasonable Conclusion

Improving Gas Turbine Performance by Any Means is Critical

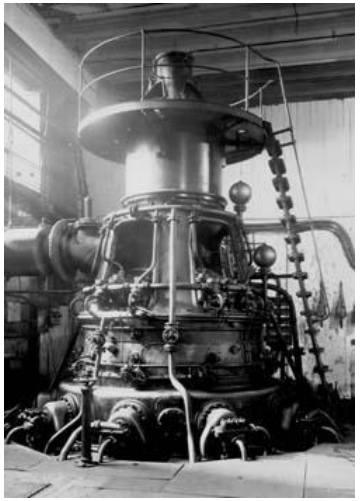
WORKING DEFINITION

PGC†: *A combustion process whereby the total pressure of the exit flow, on <u>an appropriately averaged basis</u>, is above that of the inlet flow.*

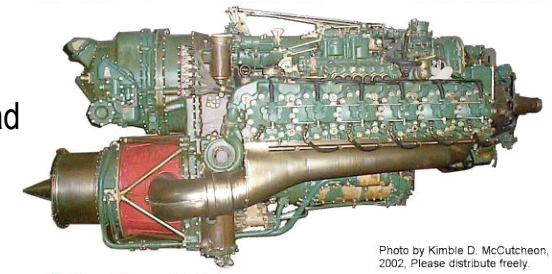
†The term "Pressure-Gain Combustion" is credited here to J.A.C. Kentfield

The concept is old…

Holzwarth
Explosion Turbine
1914



Napier Nomad
1949

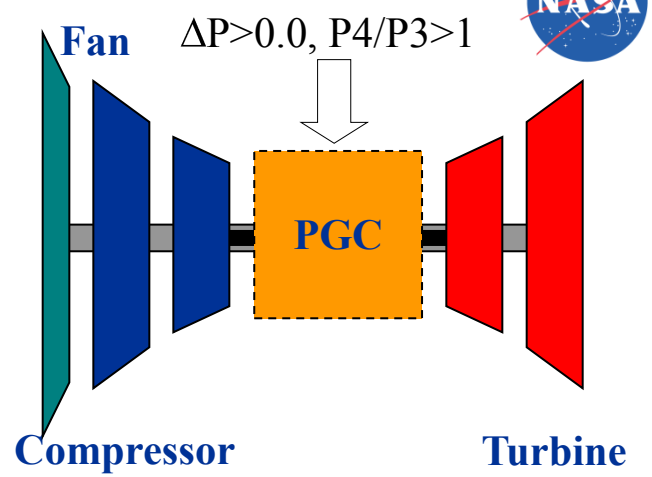


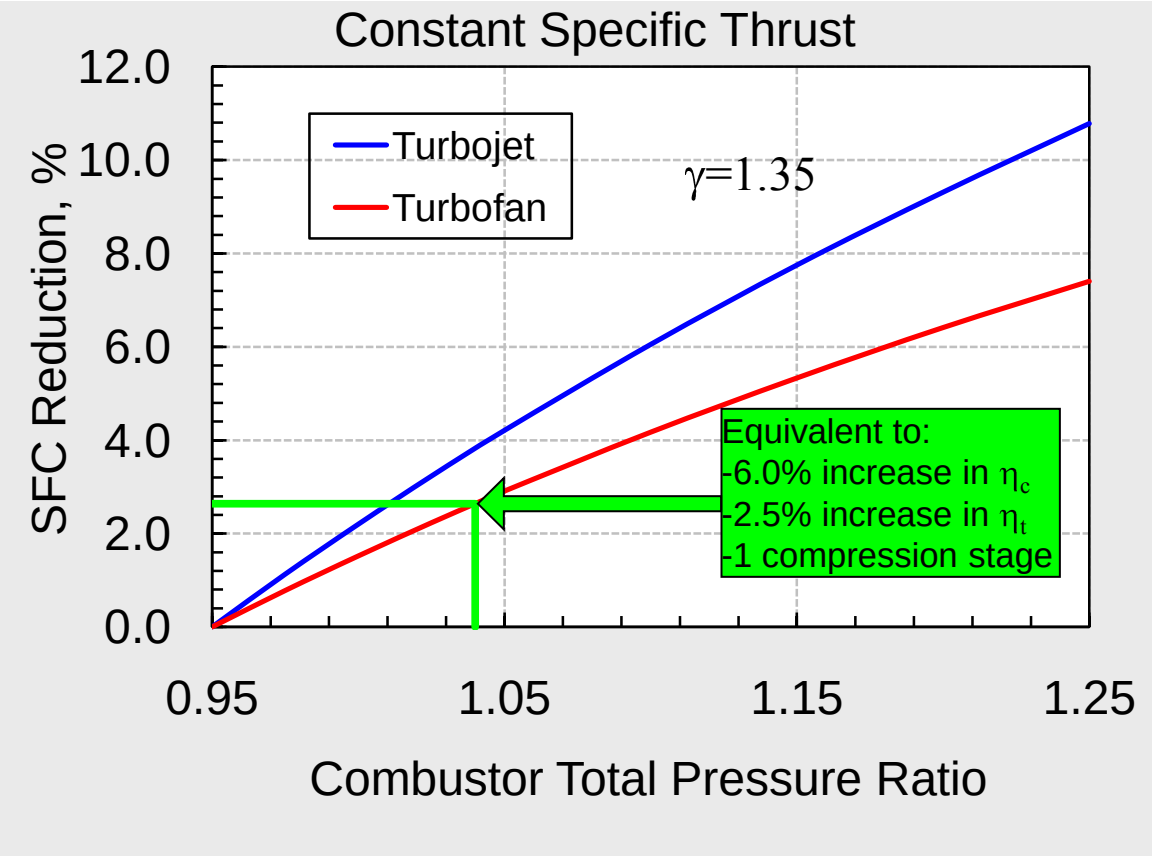
The application, analysis, and implementation are relatively new.

PGC-Why?

Pressure Gain Combustion Theoretically:

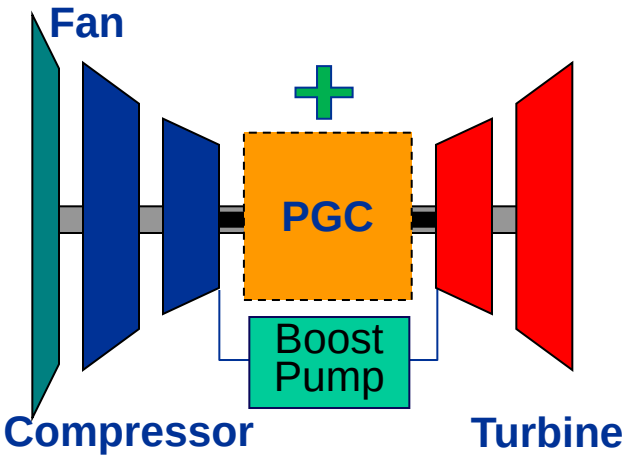
+Increases thermodynamic cycle efficiency
+Reduces SFC / fuel burn (NASA Objective)
+Reduces greenhouse gas emissions (NASA Objective)
+Competes with conventional cycle improvements

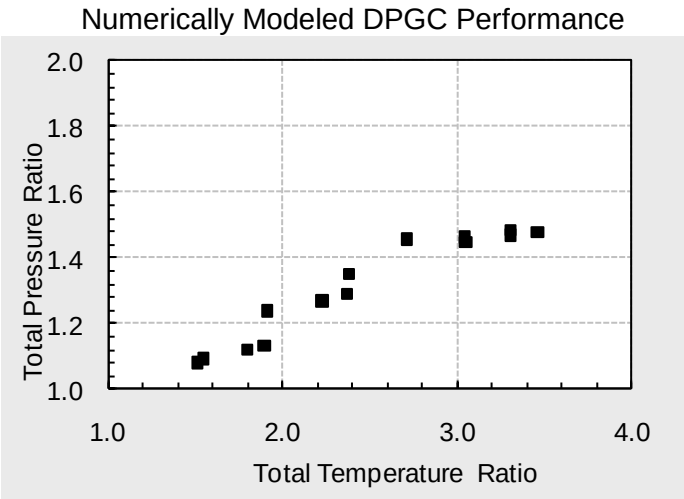




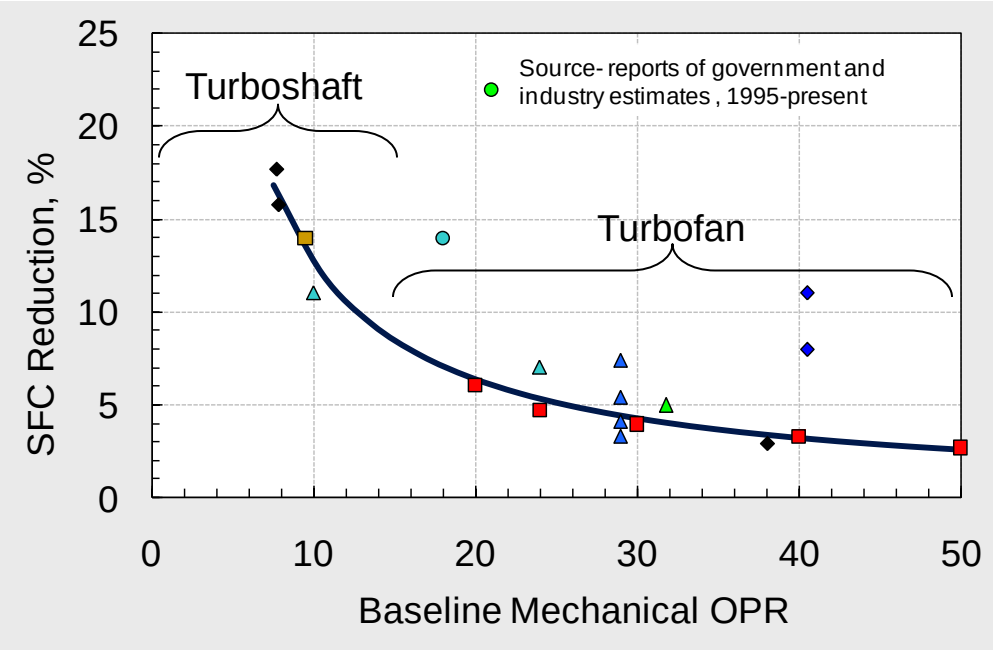
Engine Parameter	Turbofan	Turbojet
OPR	30.00	8.00
η_c	0.90	0.90
η_t	0.90	0.90
Mach Number	0.80	0.80
T_{amb} (R)	410	410
$T_{combustor\ exit}$ (R)	2968	2400
Burner Pressure Ratio	0.95	0.95
T_{sp} (lb_f-s/lb_m)	18.26	75.86
SFC (lb_m/hr/lb_f)	0.585	1.109

PGC-Why?





- Detonation-Based PGC
  - Detonative Device Replaces Conventional Combustor
  - Essentially a Topping Cycle
- Analyses Show Promise:
  - Semi-Idealized Combustor
  - Non-Ideal Turbomachinery
  - Turbomachinery Cooling Air Boost Pump Added.
  - Various loss assumptions (e.g. mixing).



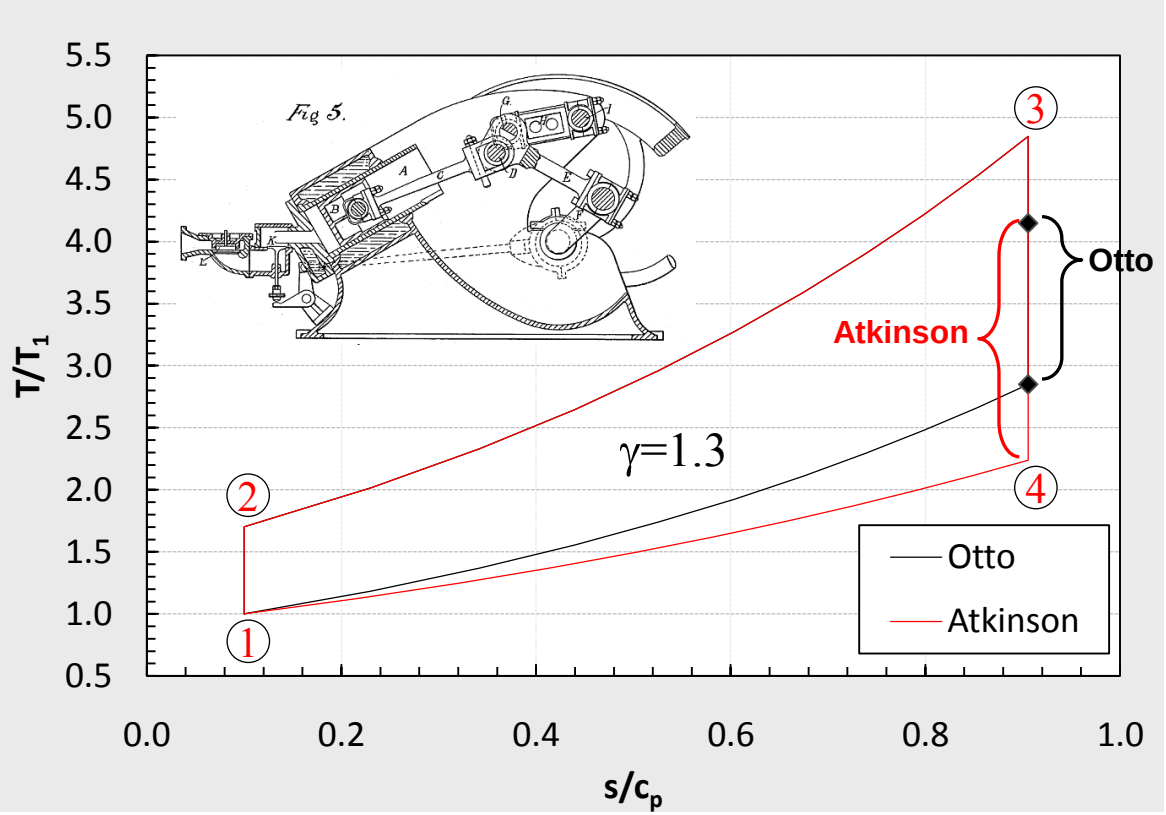
PGC-How?
Fundamental Thermodynamics and Implementation

Positive Displacement Atkinson Cycle

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

Atkinson (aka Humphrey)-1882
1-2: Isentropic (adiabatic) Compression
2-3: Isochoric Heat Addition
3-4: Isentropic Expansion
4-1: Isobaric Heat Rejection

$\eta_A/\eta_O=1.19$
$P_2/P_1=10$
$\phi=.3$

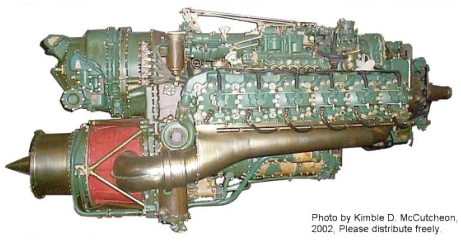


Additional Work Originally Extracted Via Asymmetric Piston Travel

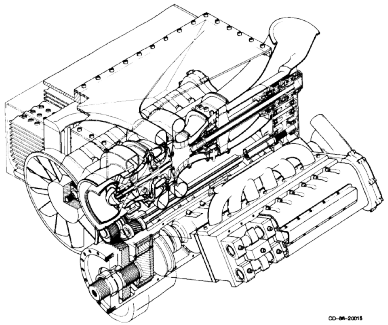
- *Utilizes otherwise wasted energy*
- *Asymmetric linkage is troublesome (apparently, a rotary version exists)*
- *Auto manufacturers have achieved Atkinson via valve timing on hybrids (e.g. Prius, Escape)*

PGC-How?
Fundamental Thermodynamics and Implementation

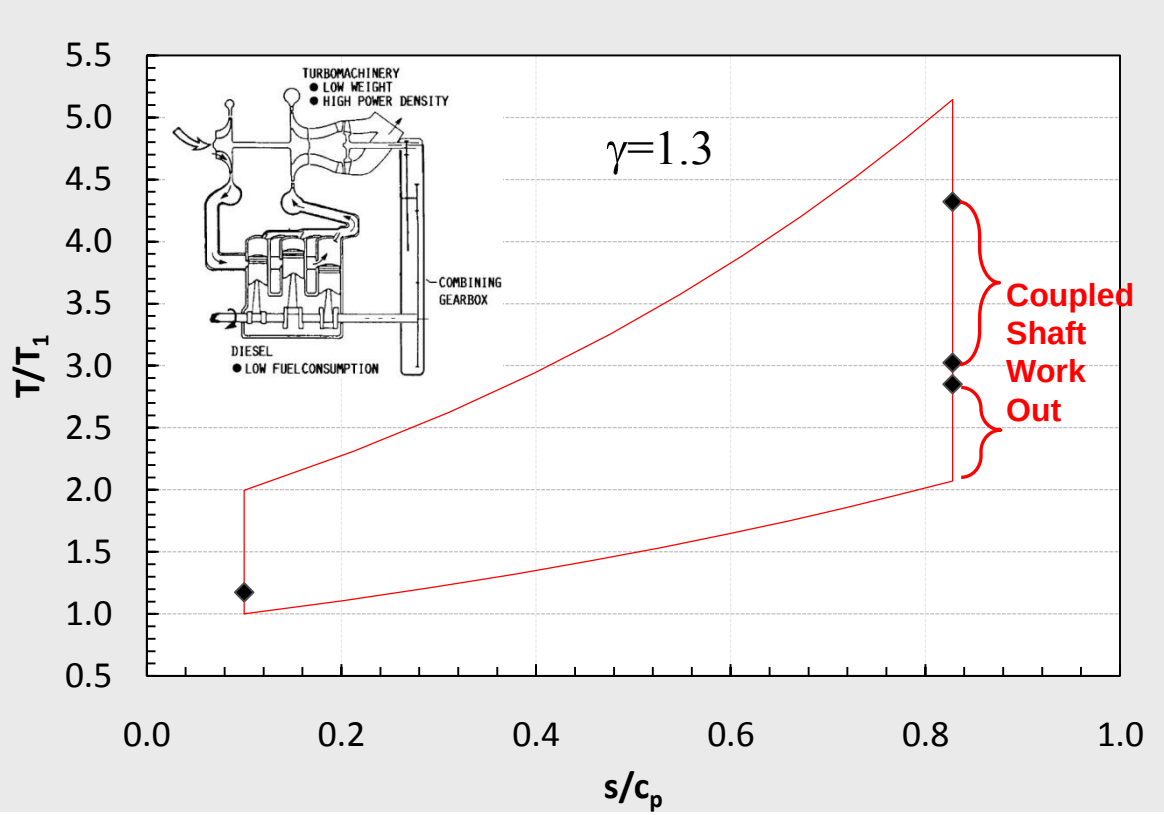
Napier Nomad
1949



Army
Compound Cycle Engine
1986



Compound Atkinson Cycle



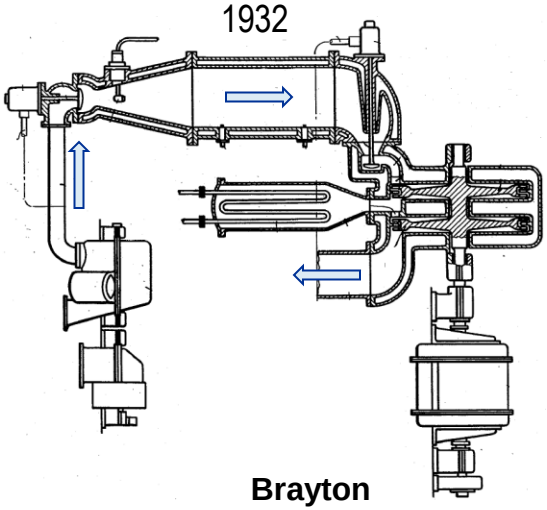
Additional Work <u>Could</u> be Extracted Via Turbomachinery

- Exceptionally low SFC
- Gearbox and IC engine are heavy and impose large losses
- Low throughflow and thrust-to-weight

PGC-How?

Fundamental Thermodynamics and Implementation

Explosion Turbine (Holzwarth)
1932



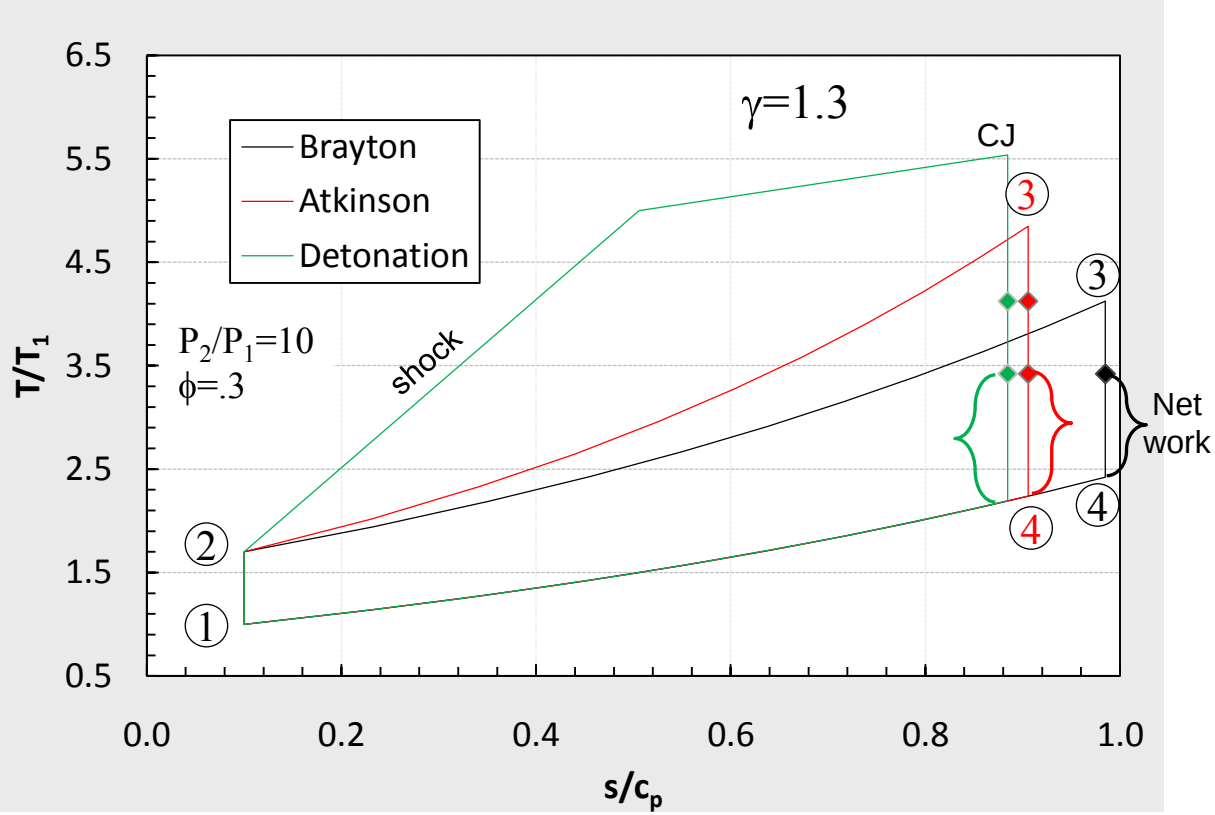
Brayton

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

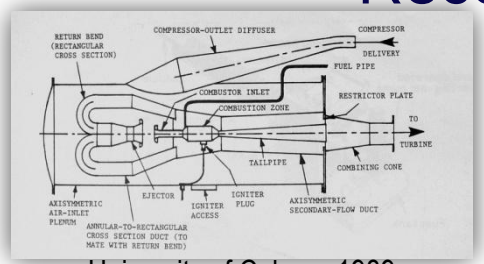
Identical Mechanical Compression,& Heat Input



All Work Could be Extracted Via Turbomachinery

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

Recent Implementation Approaches

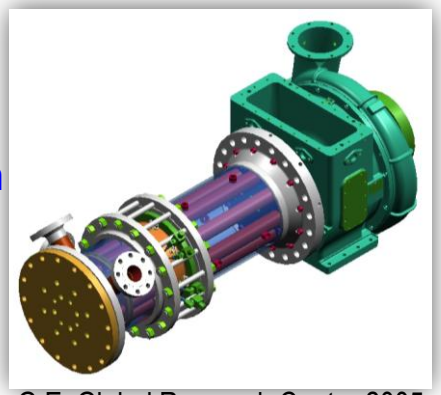


University of Calgary 1989

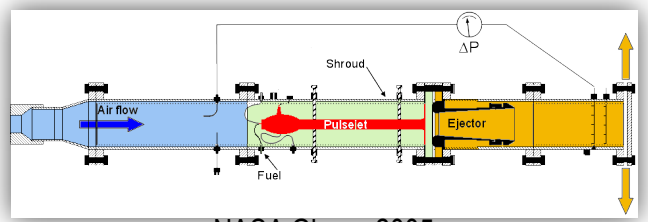
Resonant Pulsed Combustion (slow deflagration)†

†*Envisioned as a canular arrangement*

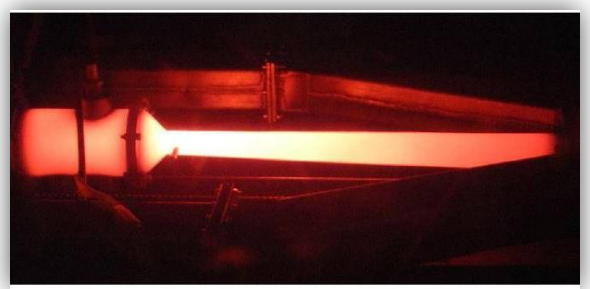
Detonation or 'Fast' Deflagration (gasdynamic)



G.E. Global Research Center 2005

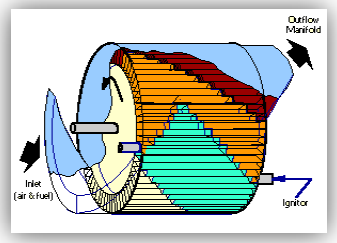


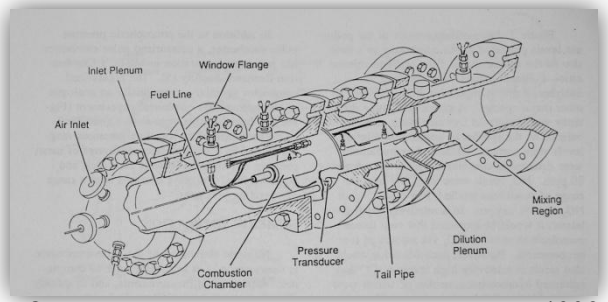
NASA Glenn, 2005



University of Cambridge, 2008

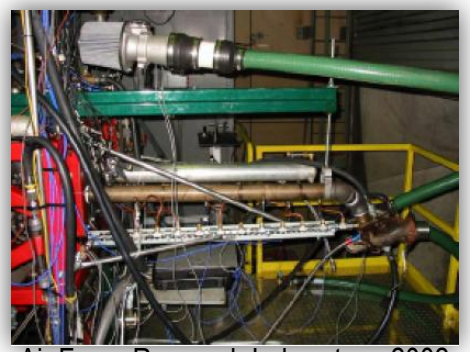
IUPUI/Purdue/LibertyWorks, 2009





DOE National Energy Technology Laboratory, 1993

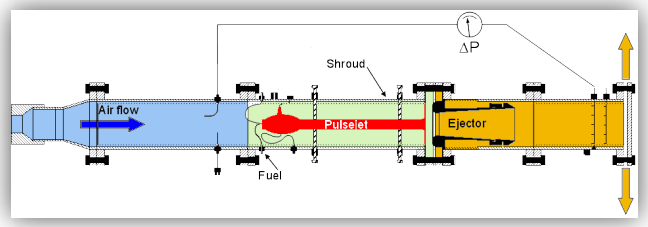
ALL ARE FUNDAMENTALLY UNSTEADY & PERIODIC

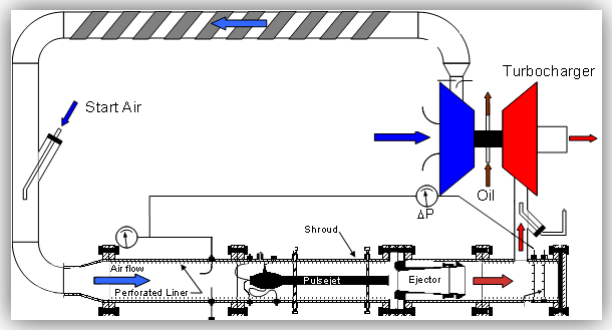


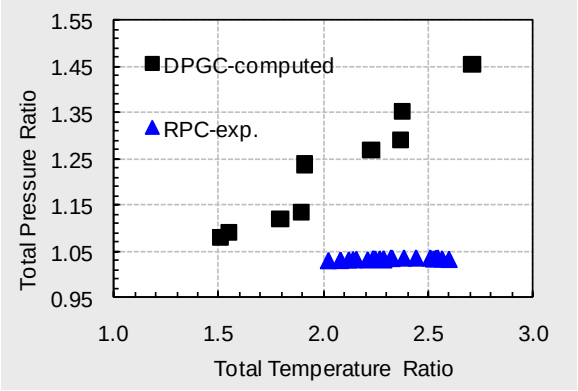
Air Force Research Laboratory, 2002

Recent Implementation Approaches

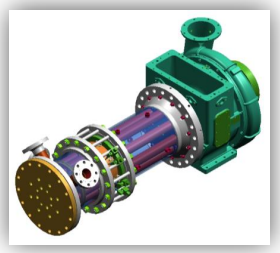
RPC

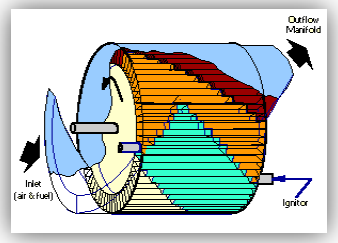






DPGC





- Demonstrated pressure gain during closed loop operation in gas turbines using liquid fuels
- Few or even no valves required

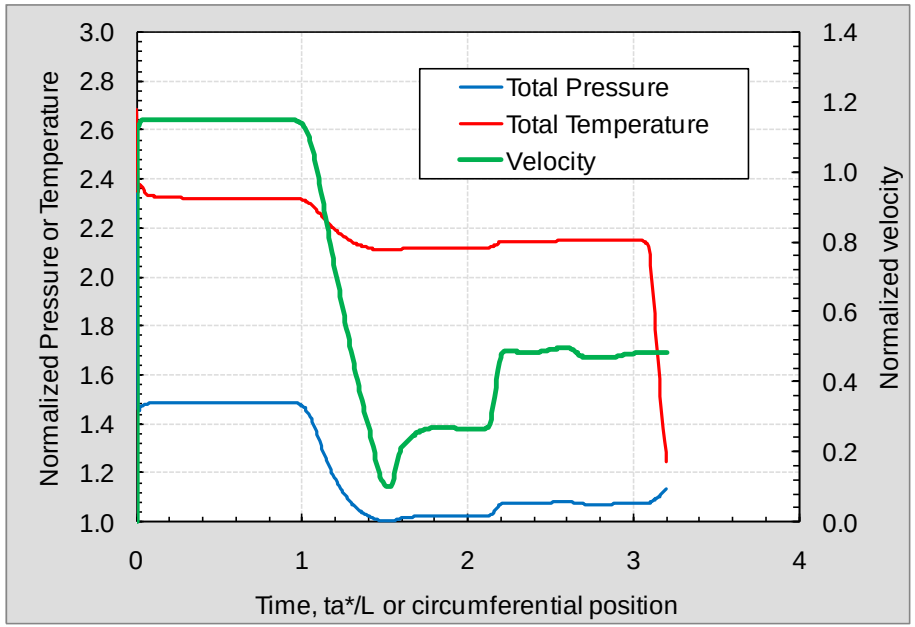
- Fundamentally limited pressure ratio (PR=1.01-1.08 @ relevant TR)
- Interaction and synchronization of multiple combustor segments

- Substantial pressure ratios are possible (PR>1.2)
- Synchronization is straightforward

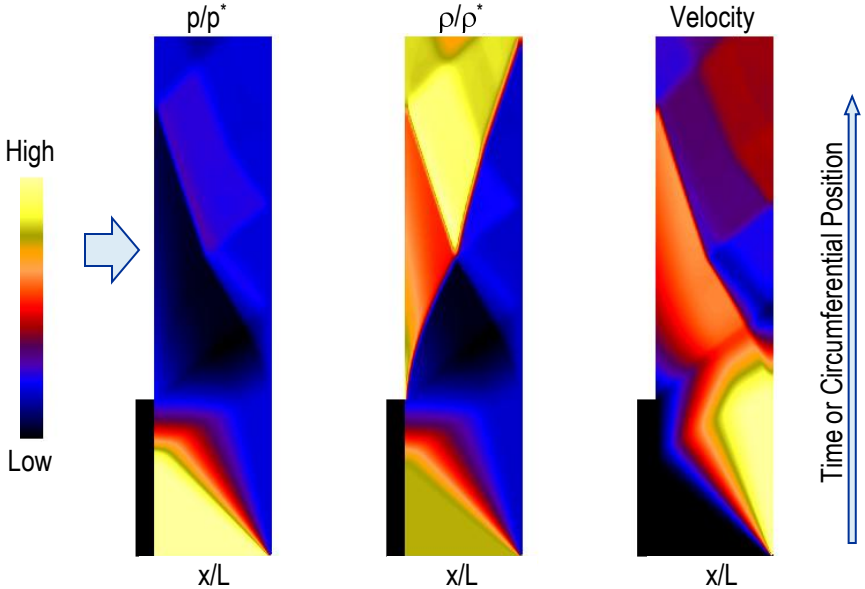
- Higher risk and complexity
- Few published in-situ pressure rise demonstrations

PGC-How?
Cycle Details-Expansion or Blowdown

- To assess cycle benefits, what total conditions are assigned to the profile?
  - *Some sort of average or mixing calculation must be applied*
- How will the turbine respond to the profile?



Computed normalized total pressure, total temperature, and velocity in the exit plane of one tube of a notional pressure gain combustor, over the course of one ideal constant volume combustion (Lenoir) cycle. The mass-averaged temperature ratio is 2.24. The tube is open at one end, and ideally valved at the other. The cross-sectional area is constant over the length.

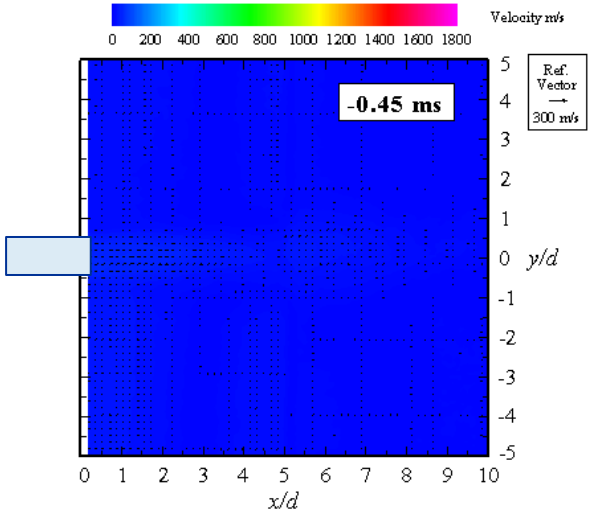


Computed contours of normalized pressure, density, and velocity in one tube of a notional pressure gain combustor, over the course of one ideal constant volume combustion (Lenoir) cycle. The mass-averaged temperature ratio is 2.24. The tube is open at one end, and ideally valved at the other. The cross-sectional area is constant over the length.

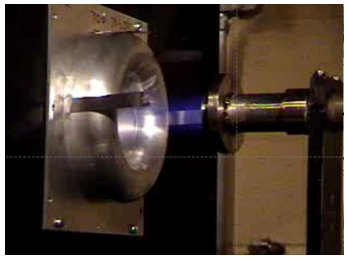
Challenges

Aerodynamic

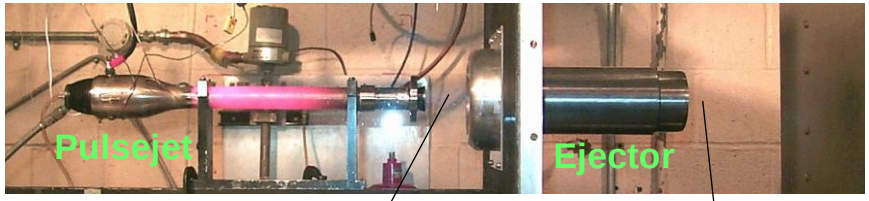
- *How can the impulsive PGC outflow be put to good use?*
  - *Mix and diffuse (minimizing the entropy and duct length)*
  - *Accelerate and turn with an advanced nozzle ring*
  - *Redesign the turbine*
  - *Etc.*
- *How do we assess its impact on turbine performance?*

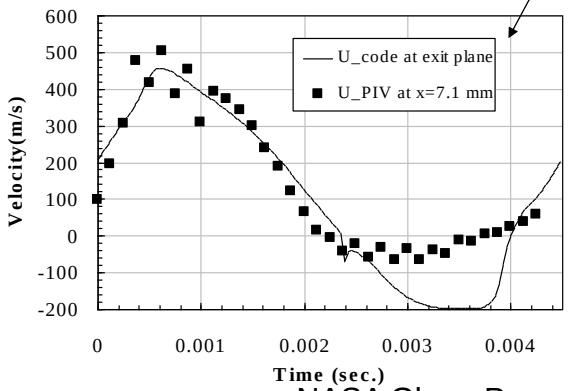


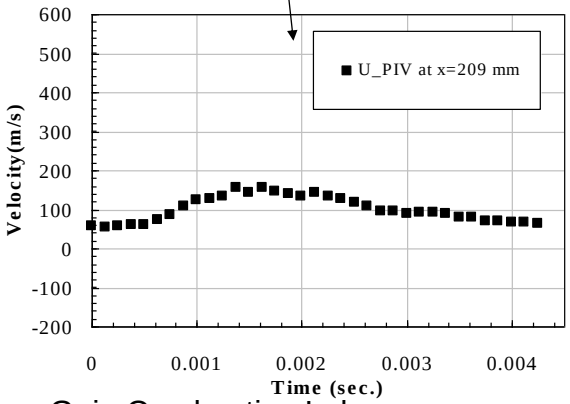
Measured velocity behind a detonation tube operated at 20 Hz.



Mix and Diffuse

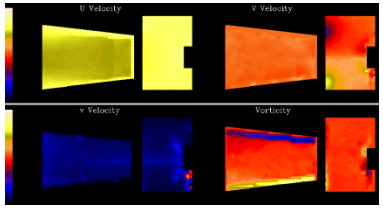






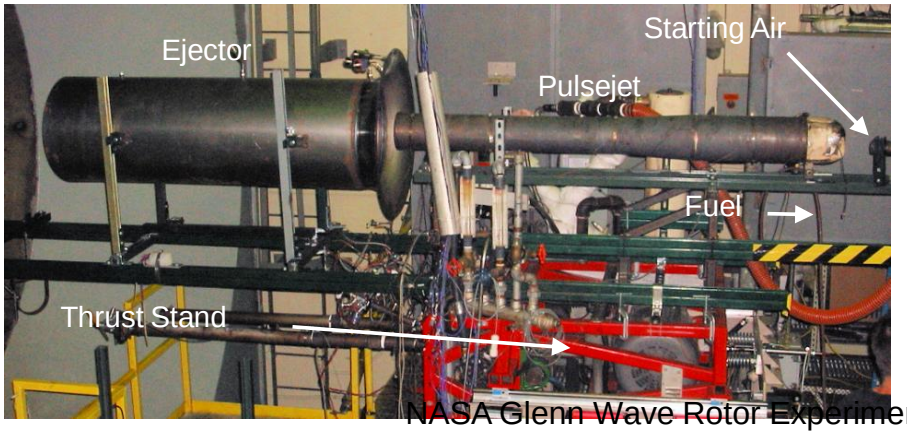
NASA Glenn Pressure Gain Combustion Lab

Fixed Tube Strategies



Large Scale Ejector Performance

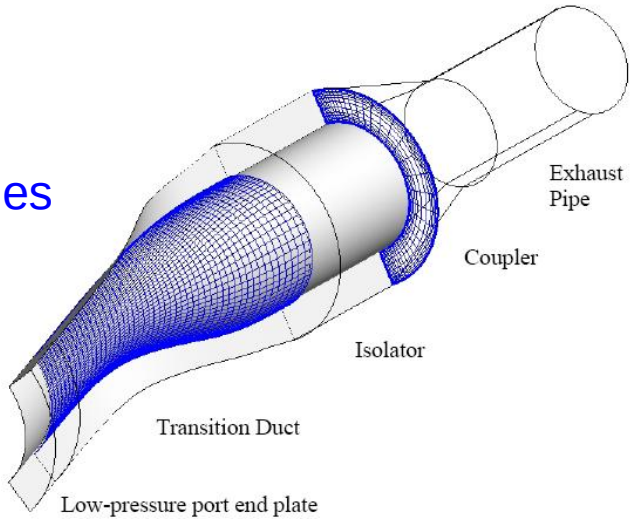
AFRL/NASA- 2005

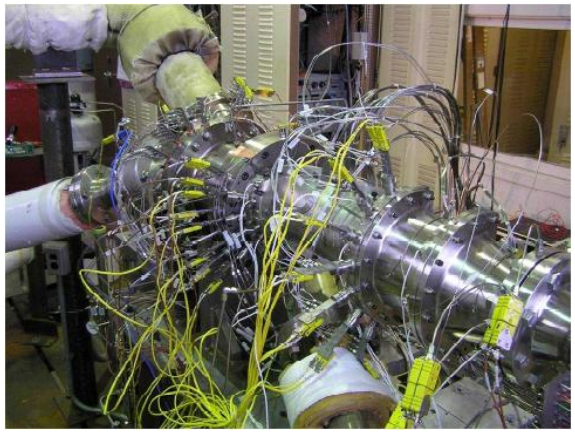


NASA Glenn Wave Rotor Experiment

Mix and Diffuse

Wave Rotor Strategies





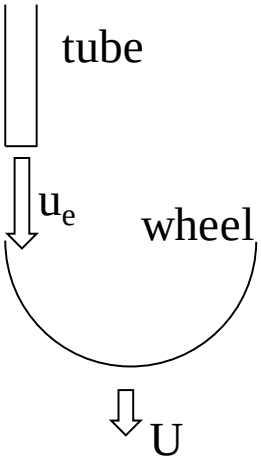
Impact on Turbine Performance

- *What is the Aerodynamic Price of Non-Uniformity?*
- *Does it Outweigh the Thermodynamic Benefit?*

Overbars indicate mass averaging

$$\frac{\overline{u_e^2}}{2} = \frac{\overline{u}_e^2}{2} + \frac{\overline{u_e'^2}}{2}$$

K.E. Avg. deviation



Turbine specific work

$$\overline{W} = 2U\left(\overline{u}_e - U\right)$$

has a maximum when

$$U = \frac{\overline{u}_e}{2}$$

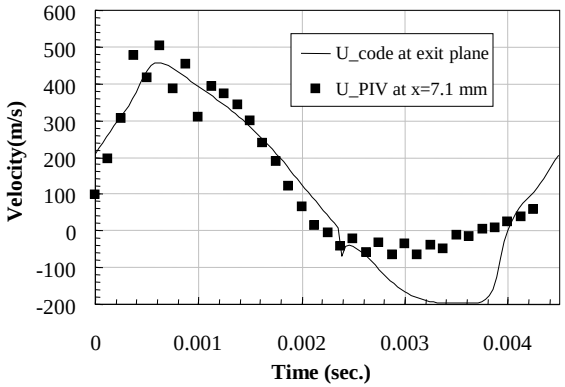
so that

$$\overline{W}_{max} = \frac{\overline{u}_e^2}{2}$$

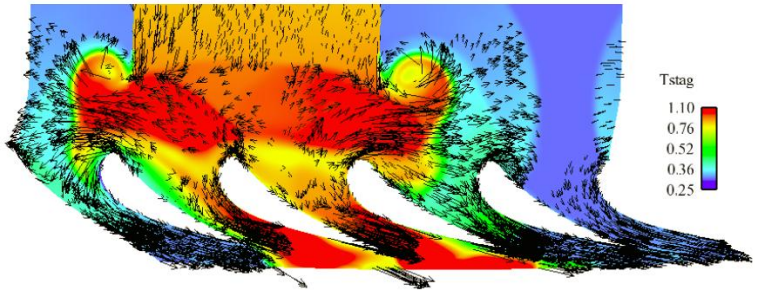
Turbine Efficiency = $\frac{\text{Work extracted}}{\text{Available K.E.}}$

$$\eta_t = \frac{\overline{u}_e^2}{\overline{u_e^2}}$$

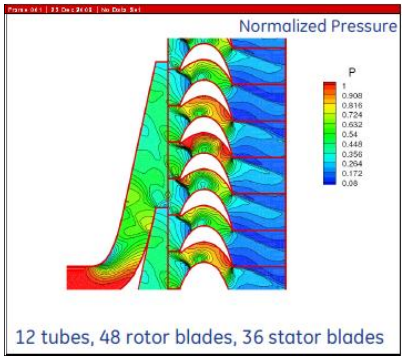
ALWAYS < 1.0 FOR NON-UNIFORM FLOWS



Impact on Turbine Performance

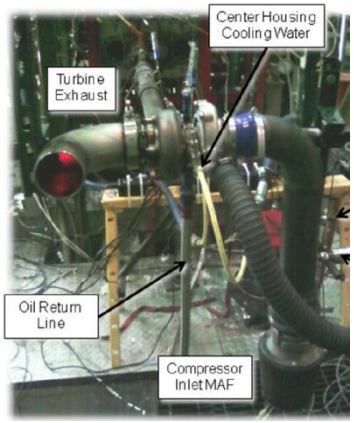


Van Zante, Envia, and Turner, "The Attenuation of a Detonation Wave by an Aircraft Engine Axial Turbine Stage," ISABE–2007–1260, also NASA/TM—2007-214972

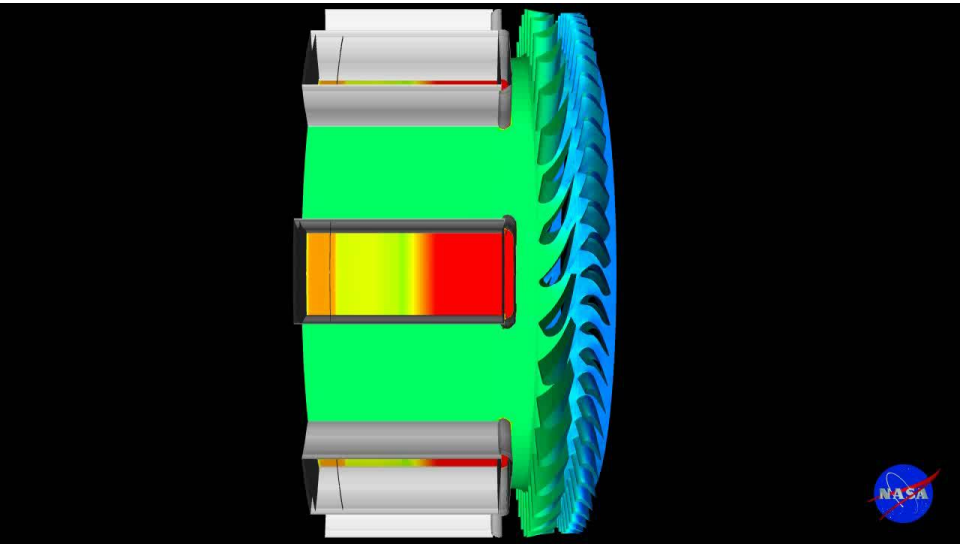


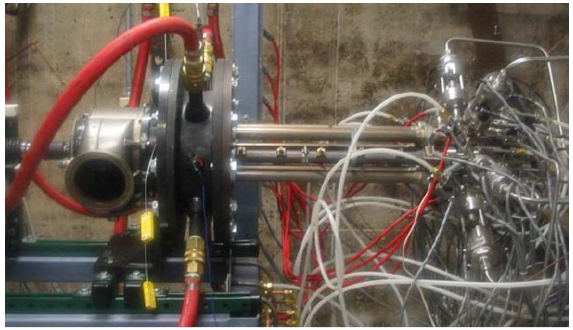
Suresh, "Turbine Efficiency for Unsteady Periodic Flows ," AIAA 2009-0504

Rasheed, Furman, and Dean AIAA 2005-4209



Rouser et. al., AIAA 2010-1116



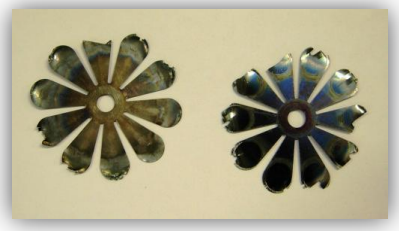


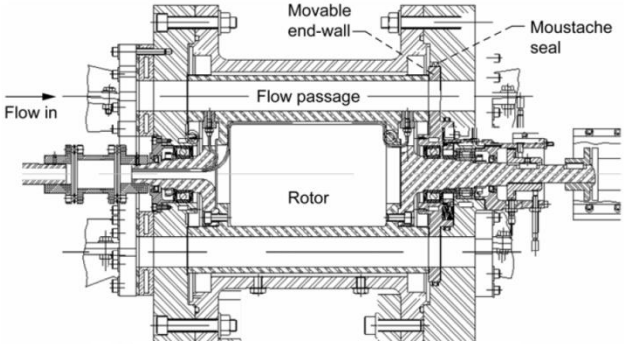
Caldwell, et. al. AIAA-2008-121

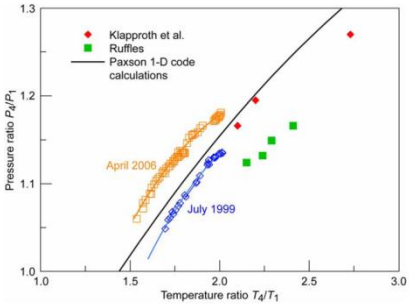
Challenges

Mechanical

- *Valves*
  - *–Long life*
  - *–Low loss*
  - *–High frequency*
- *Seals*
  - *–Long life*
  - *–No premature ignition*
- *Thermal Management*
  - *–Cooling for combustor*
  - *–Cooling for downstream turbomachinery*
- *Integration*
  - *–How does this actually fit into a gas turbine?*
  - *–How does the weight/size affect a mission?*







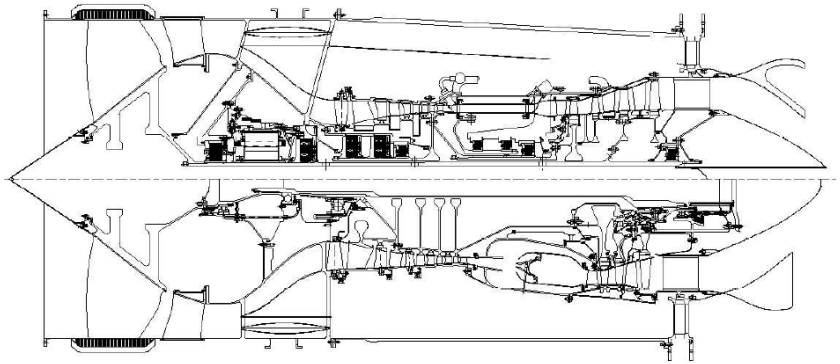
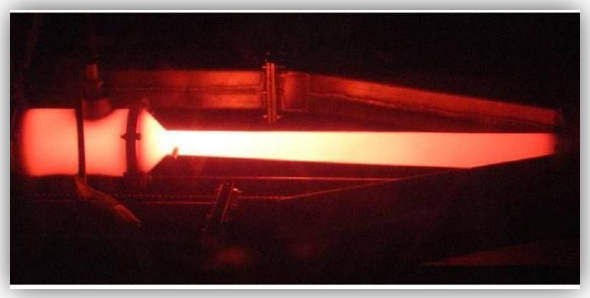


Figure 8. Conventional versus CVC engine

Smith, et. al., "Impact of the Constant Volume Combustor On A Supersonic Turbofan Engine," AIAA 2002-3916



Further Consideration

Emissions

No PGC System is Viable Unless Emissions (NOX, CO, UHC) Meet or Beat Current Levels

- *NASA complimentary SFW Goals: Noise, Fuel Burn, Emissions*
- *A Major focus for NASA's Constant Volume Combustion Cycle Engine Project (CVCCE)*
- *Must be a part of any proposal for commercial sector application*

Some PGC Concepts Show Great Promise

- *Pekkan, Nalim, 2003*
- *Keller, J. O, et. al., 1993*
- *Gemmen, R. S., et. al., 1995*
- *Kentfield, 1993*
- *Paxson?*

Convincing Demonstrations Are Needed.

- *Relevent Conditions*
- *Relevant Fuels*

CORNERS OF THE TRADE SPACE	N+1 Generation Conventional Tube & Wing (relative to B737/CFM56) (EIS 2015)	N+2 Generation Unconventional Hybrid Wing Body (relative to B777/GE90) (IOC 2020)	N+3 Generation (relative to B737/CFM56) (EIS 2030-2035)
Noise (cum below Stage 3)	- 42 dB	- 52 dB	better than - 81 dB (55 LDN at average boundary)
LTO NOx Emissions (below CAEP 2)	-70%	-80%	better than -80% plus mitigate formation of contrails
Performance: Aircraft Fuel Burn	-33%	-50%*	better than -70% plus non-fossil fuel sources
Performance: Field Length	-33%	-50%	exploit metro-plex concepts

Government Participants

- DARPA
- Air Force Research Laboratory
- NASA GRC (Until 2005)

The Future Lies In Collaboration

- DOE?

Industry Participants

- GE
- UTRC
- Rolls/Royce
- LibertyWorks

University Participants

- Purdue
- IUPUI
- U. Cincinnati
- Penn. State
- Cambridge
- North Carolina State

Broad Agency Announcement (BAA)

Vulcan Phase II

Turbine/Constant Volume Combustion Engine Demonstration Program

Defense Advanced Research Projects Agency
DARPA/TACTICAL TECHNOLOGY OFFICE (TTO)
3701 N. Fairfax Drive
Arlington, VA 22203-1714

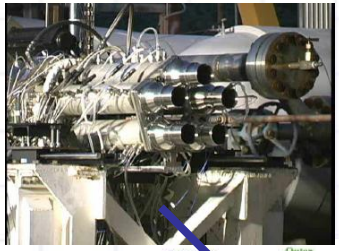
DARPA-BAA-10-11

DATE: January 11, 2010

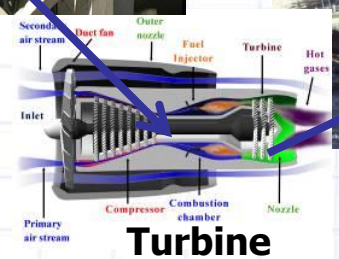
Vulcan Program

Program Objectives

- **Demonstrate a new and innovative combustion technology, constant volume combustion (CVC), which will enable a 20% reduction in fuel consumption when incorporated into existing and future Navy ship power turbine engines**



CVC



Turbine

DDGs and CGs

Performance Metrics

- **Allison 501k or equivalent replacement**
- **Operate on logistical fuel**
- **Maintain operability**
- **Reduced SFC (see table)**

Power Setting	Reduction in SFC
25%	25%
50%	20%
100%	20%

Military Utility

Successful implementation of this technology will allow the Navy to meet it's 20% fuel burn reduction goals

Phase II: CVC Demonstration
Phase III: Turbine Engine Demonstration

Vulcan maximizes transition to the Navy and Air Force

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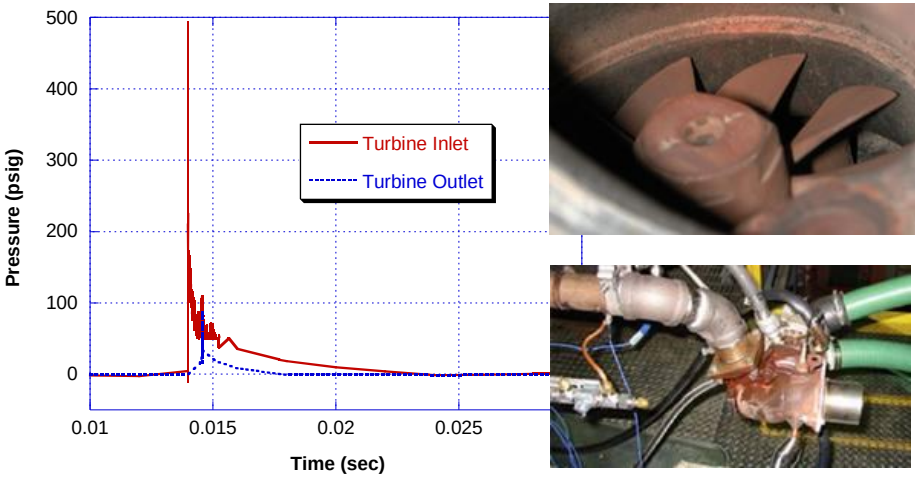
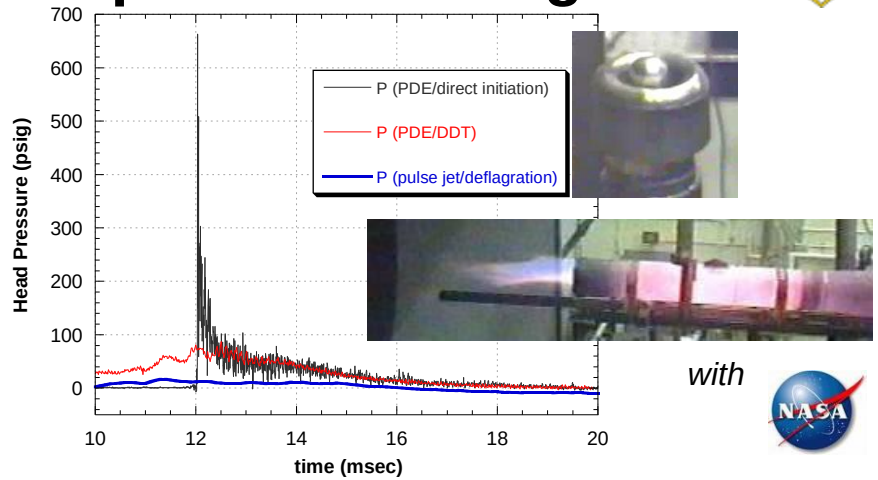
Distribution Statement "A" (Approved for Public Release, Distribution Unlimited). DISTAR case 15120.

Pressure Gain Combustion at AFRL

Currently part of RZT, High Impact Technologies

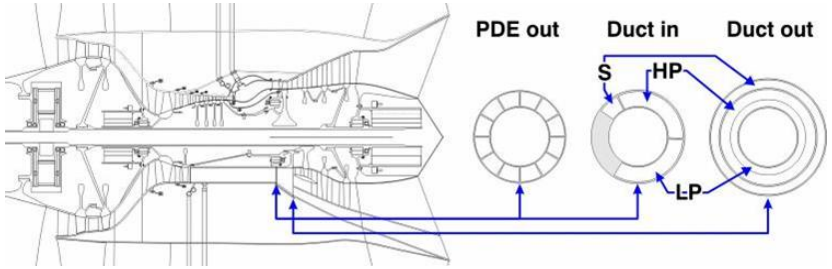


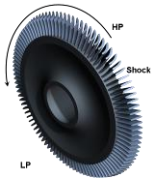
Detonation Combustion Driven Turbine



with

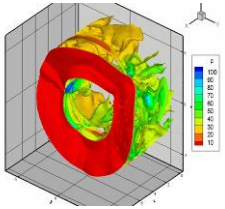
Low Cost Pressure Gain Pulsejets





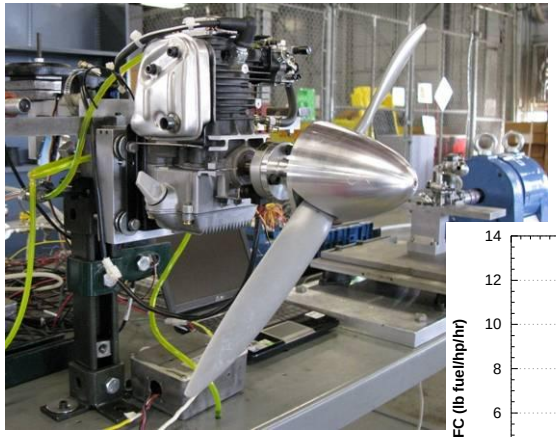
Unsteady Combustors/ Steady Turbine Concepts

Rotary Detonation Engines (RDE)

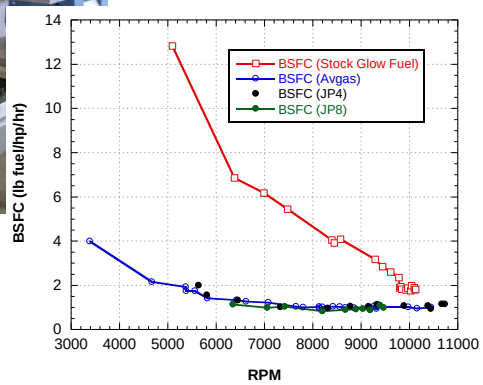


RDE CFD from

Advanced Combustion Concepts



AFRL Small Engine Research Stand

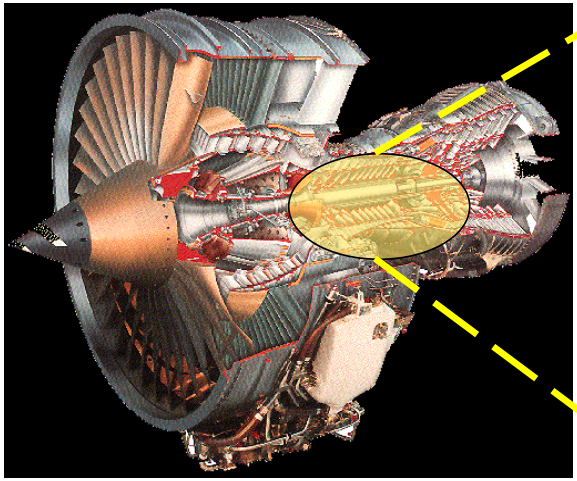


Otto Cycle Optimization

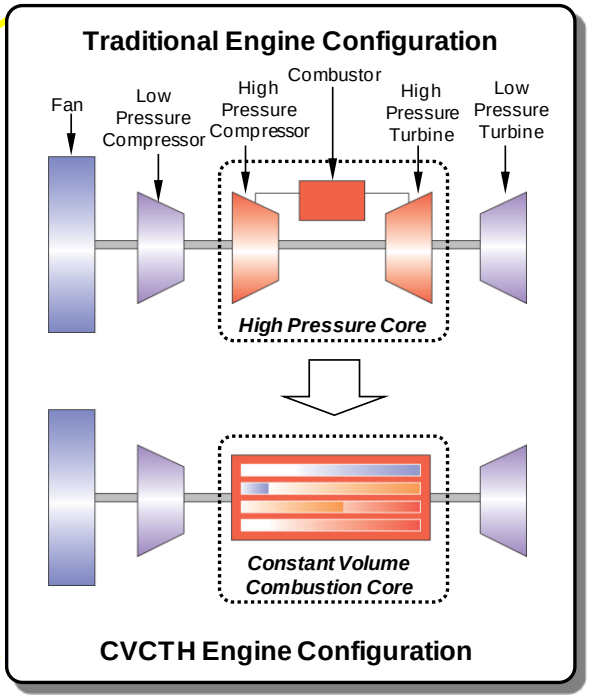
Long Endurance, Heavy Fuel Engines

CVCCE Subproject Objective

Develop Constant Volume Combustion Turbine Hybrid (CVCTH) component and system technology



Courtesy of General Electric

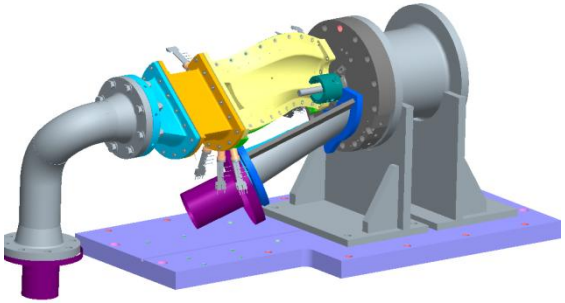


Courtesy of General Electric

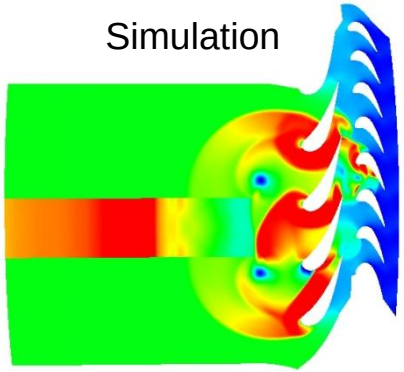
Source:
Leo A. Burkardt, CVCCE Manager
NASA Glenn Research Center
41st AIAA/ASME/SAE/ASSE
Joint Propulsion Conference and Exhibit
Tucson, AZ
July 11, 2005
Invited

CVCCE

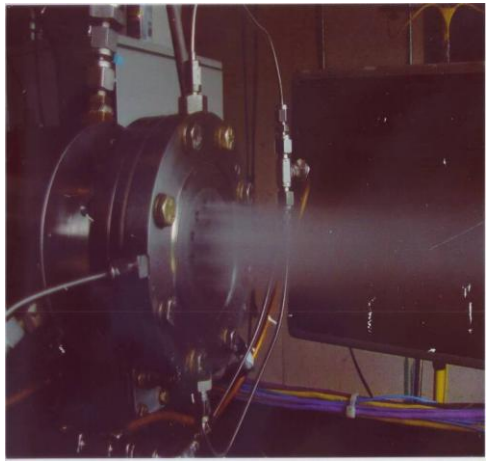
NASA four-port wave-rotor component test facility



Simulation



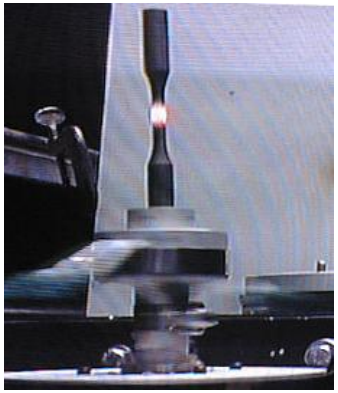
Jet Fueled Pulsed Detonation Tube



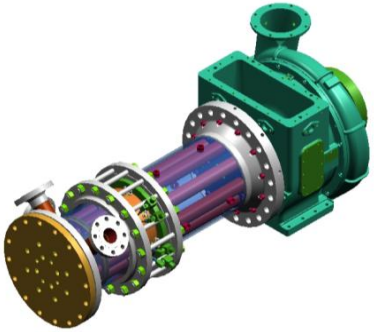
NASA/PW Detonative Initiator/Combustor Operation with JP fuel w/o Supplemental Oxygen

Build I Combustor/Initiator Hardware

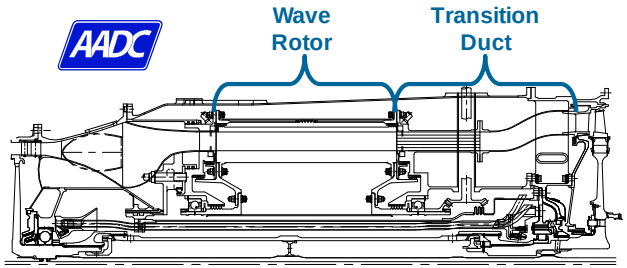
Materials Testing



NASA/GE Turbine Interactions



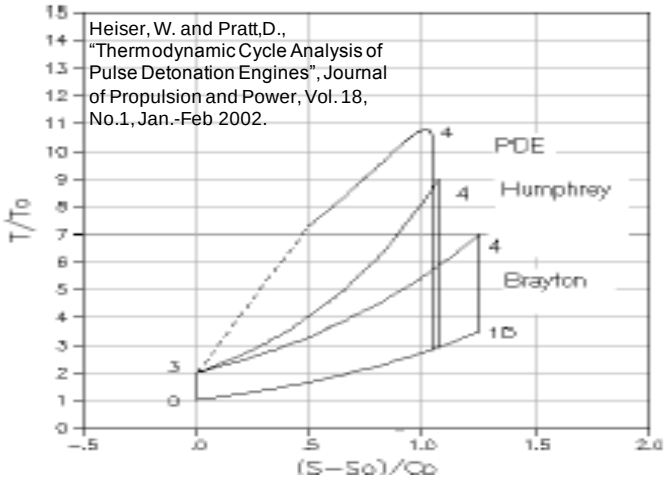
NASA/AADC Seal and Ducts

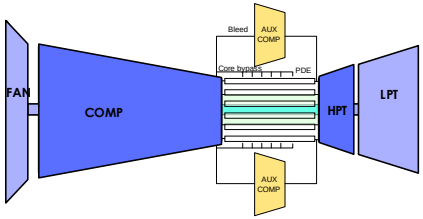


CVCCE

CVCTH System Performance Benefits

- **Potential for significant reduction in CVCTH mission fuel burn is the primary motivation for pursuing Constant Volume Combustion (CVC) technology for use in gas turbine engines**
- **NASA GRC-sponsored estimates of CVCTH SFC reduction range from 5% to 22%**
- **Develop robust CVCTH engine cycle modeling capability**
- **Incorporate CVCTH component performance models based on <u>experimental</u> data**





<u>NASA GRC Initial Internal Analysis</u>

- **OPR ~21**
- **Replace Combustor with CVC**
- **CVC combustor resulted in 8% to 11% reduction in sfc depending on component/flowpath loss assumptions**

Source:
Leo A. Burkardt, CVCCE Manager
NASA Glenn Research Center
41st AIAA/ASME/SAE/ASSE
Joint Propulsion Conference and Exhibit
Tucson, AZ
July 11, 2005
Invited

Concluding Remarks

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

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

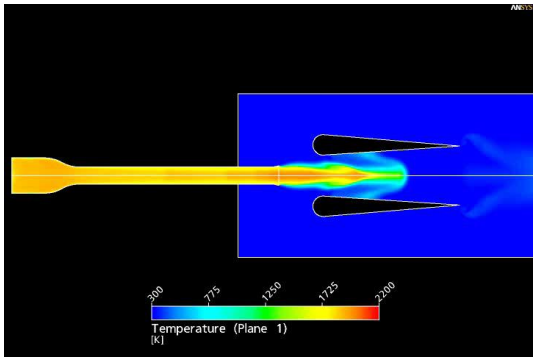
There are numerous implementation strategies under investigation

- *Wave rotor*
- *Resonant Pulsed Combustion*
- *Detonation/Deflagration*
- *Aero or mechanical valves*
- *Valves fore and aft, or just fore*
- *Mixing, bypass, lean, etc. operational modes to achieve acceptable TR*

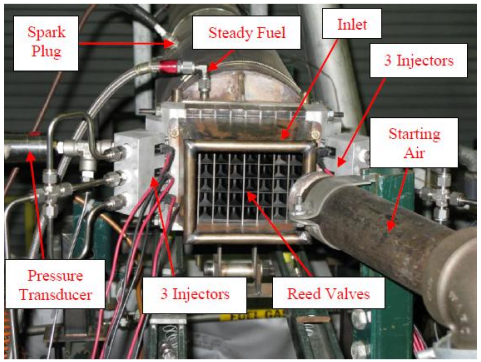
There are numerous challenges however:

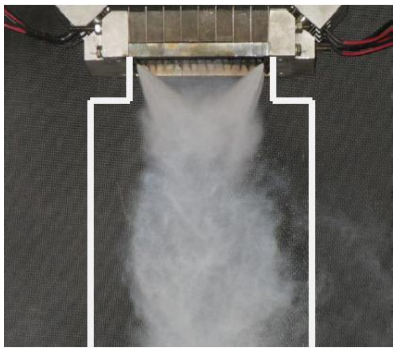
- *No 'Show Stoppers' have yet been identified*
- *Analysis tools have advanced significantly*
- *Understanding has increased dramatically*

Modeling and Simulation
North Carolina State/NASA- 2009



Active Liquid Fuel Modulation
AFRL/NASA- 2009





"It is common sense to take a method and try it. If it fails, admit it frankly and try another. But above all, try something"

Franklin D. Roosevelt

END
(extra slides follow)