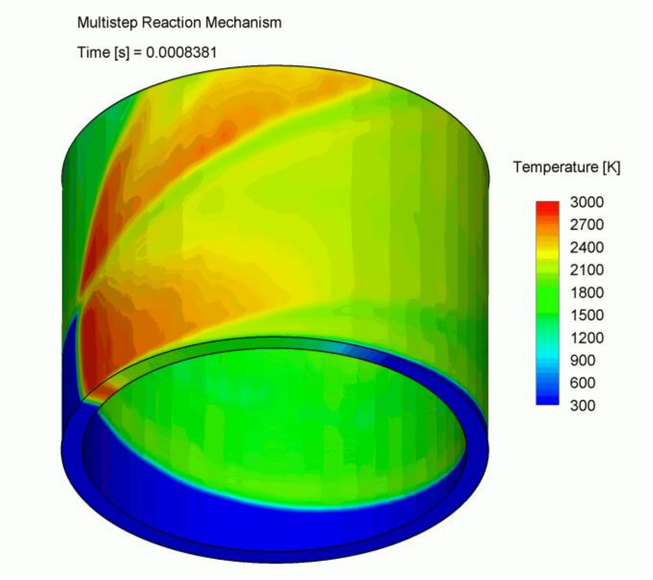
NATIONAL ENERGY TECHNOLOGY LABORATORY



New Developments in Combustion Technology

Part II: Step change in efficiency

Geo. A. Richards, Ph.D.
National Energy Technology Laboratory - U. S. Department of Energy

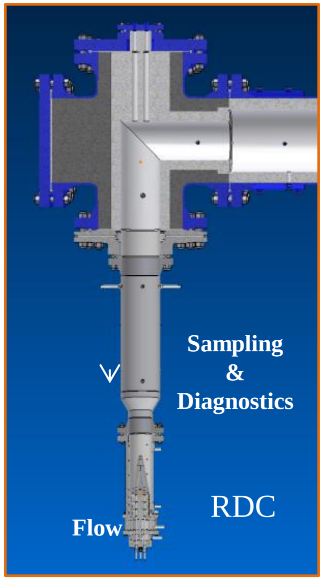
2014 Princeton-CEFRC Summer School On Combustion
Course Length: 6 hrs
June 23-24, 2014

U.S. DEPARTMENT OF ENERGY

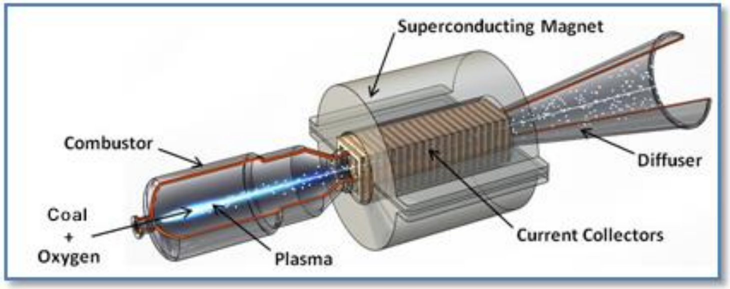
This presentation

Updated, expanded from 2012 CEFRC lecture:

- Inherent carbon capture: chemical looping combustion (Day 1)
- Step-change in generator efficiency: pressure gain combustion (Day 2)
- Frontier approach (?!): making oxy-fuel an efficiency advantage (Day 2)



P-gain rig @ NETL

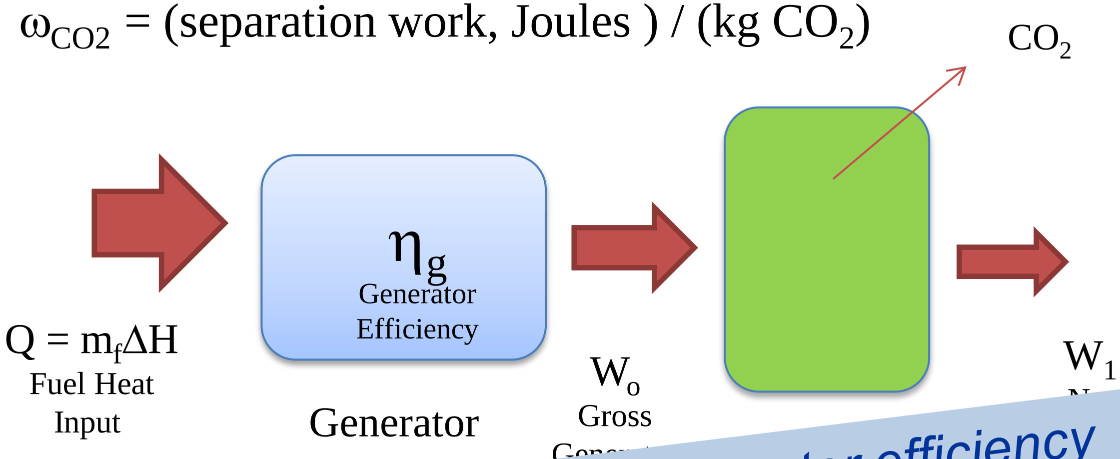


The role of capture AND generator efficiency

Define:

α = (kg CO_2 produced) / (kg fuel burned)

ω_{CO2} = (separation work, Joules) / (kg CO_2)



Can we make a big jump in generator efficiency to offset the capture penalty?

$$\eta_{ov} = \frac{W_1}{Q} = \eta_g - \frac{\omega_{CO2}\,\alpha}{\Delta H}$$

Approx Ranges: (30 – 60%) (6-10%)

- A simple heat/energy balance defines the overall efficiency η_{ov} with a carbon separation unit.
- Reducing the penalty from carbon capture comes from BOTH:
  - Decreasing ω_{CO2}
  - Increasing η_g

Turbines for propulsion and power

Almost any fuel – even coal, via integrated gasification combined cycle (IGCC).

Shale gas revolution = more turbines!

"…The research firm (Forecast international) anticipates that 12,054 turbines with a value of $218 billion will be sold world-wide in the coming decade…" ***Siemens Moves Fueled by U.S. Gas*, Wall Street Journal, May 8, 2014, pp. B2**

IGCC plant under construction, Kemper County, Mississippi, USA

History and Turbine Efficiency

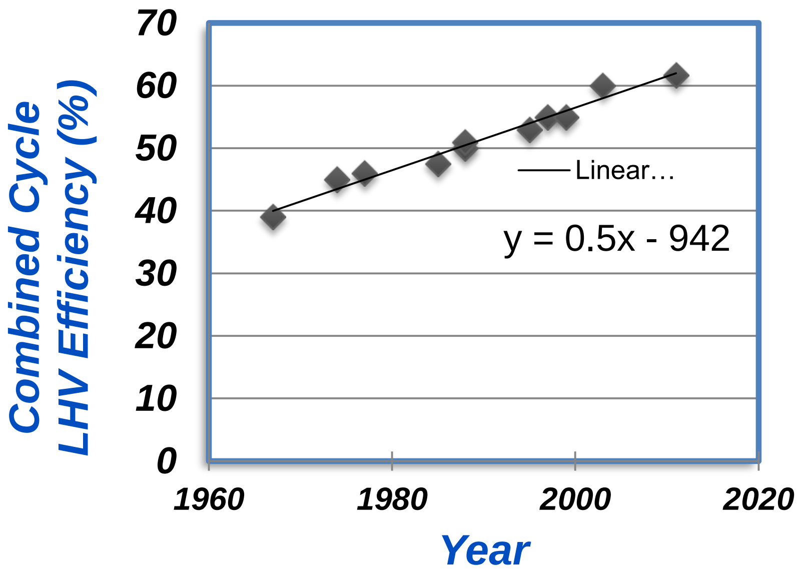
- **Combined Cycle Gas Turbine Efficiency is today + 61% (LHV).**
- **Efficiency gains have occurred with steady progress in materials, heat transfer, and system design.**
  - About +0.5 % per year (right).
- **Impressive performance is still well-below potential:**

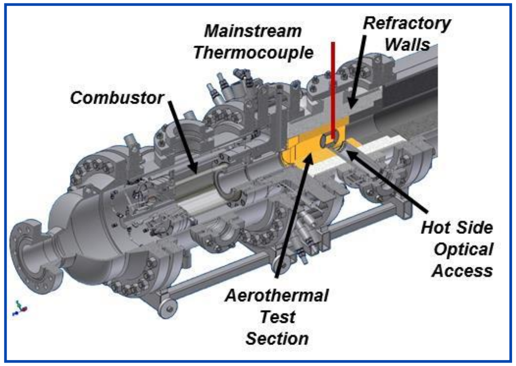
$$\eta_{\text{Carnot @ 1600C}} = 1\text{-}293/(1873) = 84\%$$

~ State of the art turbine inlet temperature

- **What can be done to "jump above" the line?**

*Gas turbine efficiency trend**



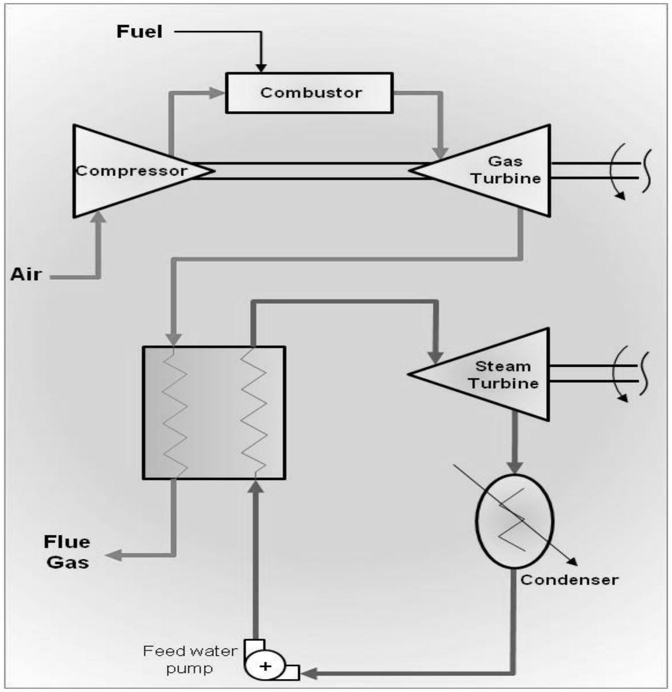


Test rig for advanced aerothermal cooling development

** Sources: (1) Herzog, H., Unger, D. (1998) Comparative Study on Energy R&D Perfrmance: Gas Turbine Case Study, Final Report for Central Research Institute of Electric Power Industry (CRIEPI), Figure B, pp. iii. , http://web.mit.edu/energylab/www/pubs/el98-003a.pdf (2) Gas Turbine World 2012 Performance Specs, 28th ed Vol 42, No1, pp 31.*

A step-change in efficiency

- **Turbine pressure-ratio and firing temperature influence the combined cycle efficiency.**
- **A *combined cycle* exploits the heat rejected by the "hotter" turbine cycle to the "colder" steam cycle.**
- **If you want a "step-change" in efficiency, it is logical to identify the biggest losses and work on those.**
  - Where is the biggest loss of *thermodynamic availability* (or exergy)?
  - An interesting example for a *cogen* system (e.g. no steam "bottom", but steam heat) is presented by Bejan et al. in the table.



Component	Exergy Destruction (% of fuel input)
Combustion Chamber	30.0
Steam generator	7.3
Turbomachinery	3.5
Gas turbine recuperator	3.1
Compressor	2.5
Overall	46.4

Bejan, A., Tsatsaronis, Moran, M. (1996) Thermal Design and Optimization, John Wiley publishing, Table 3.2, page 140.

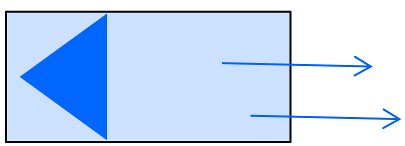
Pressure Gain Combustion

A different cycle

Constant-volume combustion products are at a significantly greater thermodynamic availability than constant-pressure.

30 bar, 600 K

30 bar, 1600 K



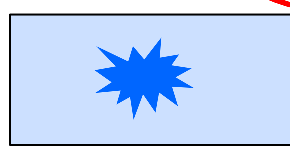
Conventional steady combustion (~constant pressure)

$$\Delta H = Q$$

$$C_p \, \Delta T_{cons\ P} = Q$$

30 bar, 600 K

100 bar, 2000 K



Pressure -gain combustion (~constant volume)

$$\Delta U = Q$$

$$C_v \, \Delta T_{cons\ V} = Q$$

Pressure Gain Combustion

A different cycle

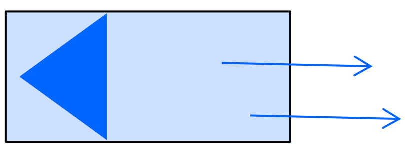
Constant-volume combustion products are at a significantly greater thermodynamic availability than constant-pressure…..but what happens if the pressure is bled off to the ambient - unrestrained?

Unrestrained expansion

Returns to constant pressure availability –must capture the pressure gain to have a benefit.

30 bar, 600 K

30 bar, 1600 K



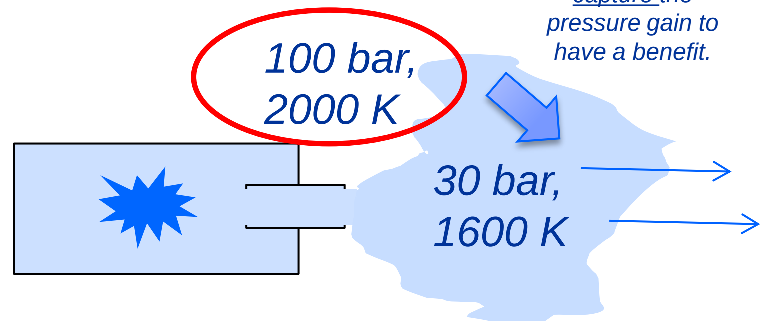
Conventional steady combustion (~constant pressure)

$$\Delta H = Q$$

$$C_p \, \Delta T_{cons\ P} = Q$$

30 bar, 600 K

100 bar, 2000 K



Pressure -gain combustion (~constant volume)

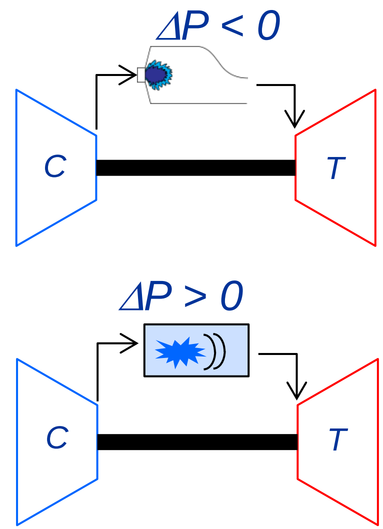
$$\Delta U = Q$$

$$C_v \, \Delta T_{cons\ V} = Q$$

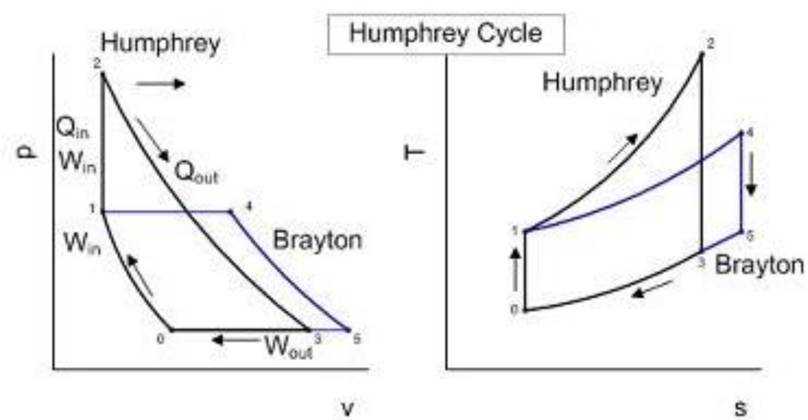
Noisy, but no benefit

Pressure Gain Combustion Cycle

- **Convention gas turbines combustion results in a pressure loss across the combustor (Brayton cycle)**



- **Pressure gain with *constant volume combustion (Humphrey cycle)***
  - *Deflagration or detonation pressure wave* increases pressure and peak temperatures at turbine inlet - reduced entropy production during combustion.



History

- **The idea of capturing the available energy from confined combustion (versus constant pressure) is well recognized.**
  - Piston engines do this already.
  - Early gas turbines used the concept (Holzwarth “explosion” turbine).
  - Compound piston-turbines have been built and flown.
  - Constant-volume combustion eclipsed by easier improvements

THYSSEN-HOLZWARTH OIL AND GAS TURBINES, *Journal of the American Society for Naval Engineers Volume 34, Issue 3, pages 453–457, August 1922. .*

From the article:
“……Holzwarth-turbine working with a compression of 2.2 atmospheres and an explosion pressure of 17.3 atmospheres absolute….”

Photo used with permission from Naval Engineers Journal

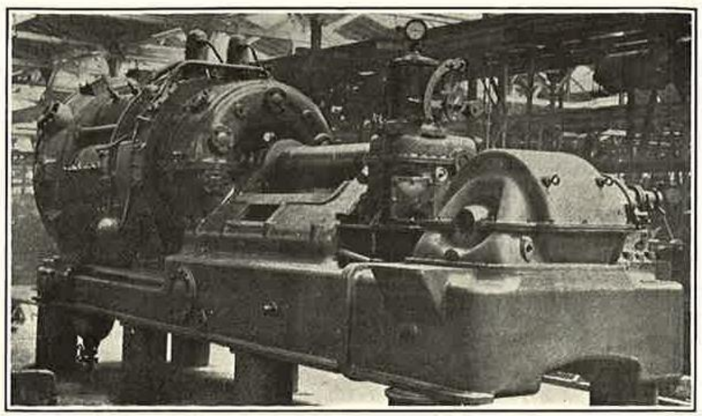
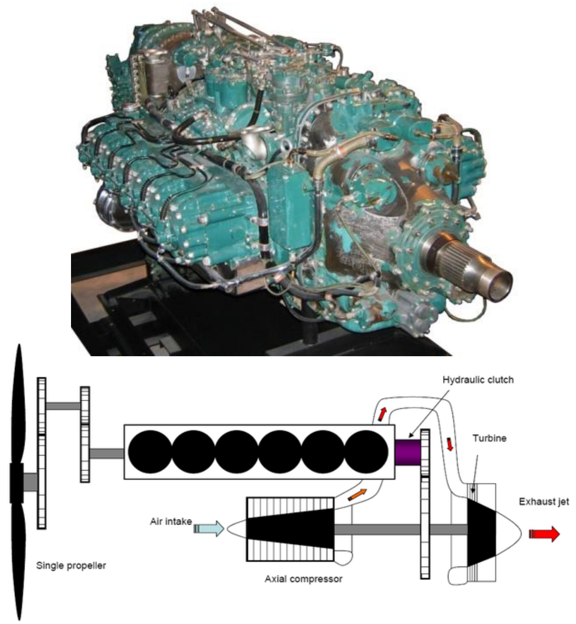


FIG. 8. – THE 500B.H.P. THYSSEN-HOLZWARTH OIL TURBINE, WHICH MAY BE THE POWER OF THE FUTURE FOR MERCHANT SHIPS.



Napier Nomad Engine (~1950)

Nomad photo credit: Kimble D. McCutcheon via the Aircraft Engine Historical Society. http://www.enginehistory.org/napier.htm

Why is pressure-gain appealing *now*?

Pressure-Gain Combustion for Power Generation

Michael Idelchik, Vice President of Advanced Technologies at GE Research… *Research…Sept 2009 interview on Pulse Detonation for Technology Review published by MIT.*

"An existing turbine burns at constant pressure. With detonation, pressure is rising, and the total energy available for the turbine increases. We see the potential of ***30 percent fuel-efficiency improvement***. Of course realization, including all the hardware around this process, would reduce this.

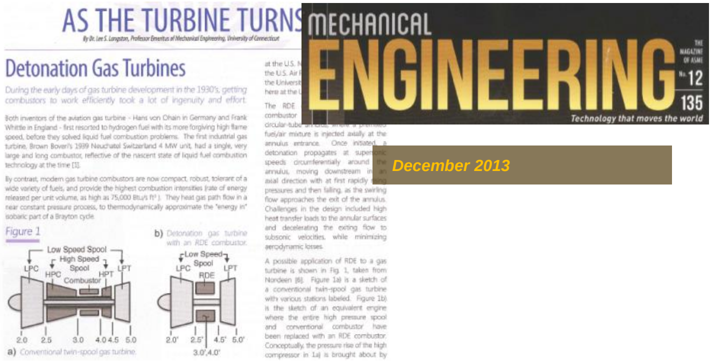
I think it (efficiency gains) will be anywhere from 5 percent to 10 percent. That's percentage points--say from ***59 to 60 percent efficient to 65 percent efficient***. We have other technology that will get us close [to that] but **no other technology that can get so much at once.** It's very revolutionary technology.

The first application will definitely be land-based--it will be power generation at a natural-gas power plant. "

> **"If we can turn 5% pressure loss in a turbine into 5% pressure gain, it has the same impact as doubling the compression ratio" – Dr. Sam Mason, Rolls-Royce (2008)***

** Quotation courtesy Fred Schauer AFRL*

2012 lecture


AS THE TURBINE TURNS
By Dr. Lee S. Langston, Professor Emeritus of Mechanical Engineering, University of Connecticut

Detonation Gas Turbines

During the early days of gas turbine development in the 1930's, getting combustors to work efficiently took a lot of ingenuity and effort.

Both inventors of the aviation gas turbine - Hans von Ohain in Germany and Frank Whittle in England - first resorted to hydrogen fuel with its more forgiving high flame speed, before they solved liquid fuel combustion problems. The first industrial gas turbine, Brown Boveri's 1939 Neuchatel Switzerland 4 MW unit, had a single, very large and long combustor, reflective of the nascent state of liquid fuel combustion technology at the time [1].

By contrast, modern gas turbine combustors are now compact, robust, tolerant of a wide variety of fuels, and provide the highest combustion intensities (rate of energy released per unit volume, as high as 75,000 Btu/s ft³). They heat gas path flow in a near constant pressure process, to thermodynamically approximate the "energy in" isobaric part of a Brayton cycle.

at the U.S. N… the U.S. Air F… the Universit… here at the U…

The RDE … combustor … circular-tube … fuel/air mixture is injected axially at the annulus entrance. Once initiated, a detonation propagates at supersonic speeds circumferentially around the annulus, moving downstream in an axial direction with at first rapidly rising pressures and then falling, as the swirling flow approaches the exit of the annulus. Challenges in the design included high heat transfer loads to the annular surfaces and decelerating the exiting flow to subsonic velocities, while minimizing aerodynamic losses.

A possible application of RDE to a gas turbine is shown in Fig. 1, taken from Nordeen [6]. Figure 1a) is a sketch of a conventional twin-spool gas turbine with various stations labeled. Figure 1b) is the sketch of an equivalent engine where the entire high pressure spool and conventional combustor have been replaced with an RDE combustor. Conceptually, the pressure rise of the high compressor in 1a) is brought about by

ASME Mechanical Engineering Magazine, Image used with permission

Gas Turbine World

Pequot Publishing

Nov – Dec 2013 issue

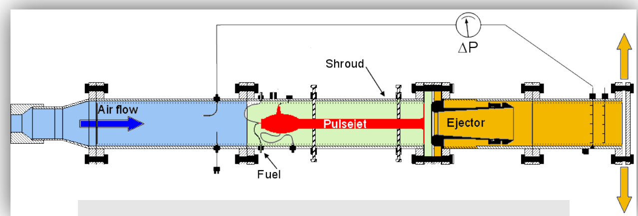
Pulse detonation for 65% plant efficiency

Page 20

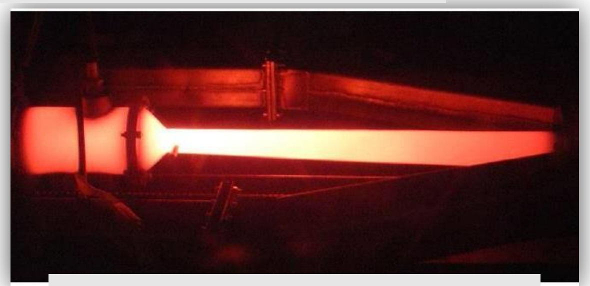
Image used with permission of Gas Turbine World

Current Technology Approaches

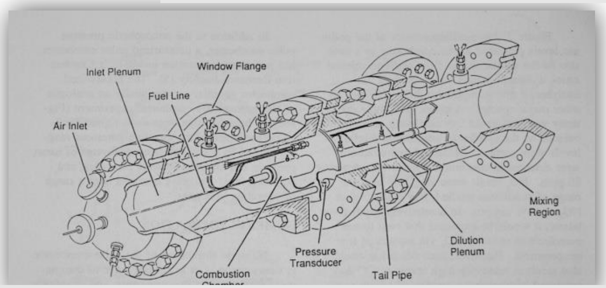
Resonant Pulsed Combustion
(deflagration)†
†Envisioned as a canular arrangement



NASA Glenn, 2005



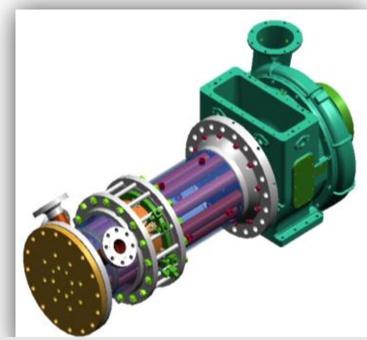
University of Cambridge, 2008



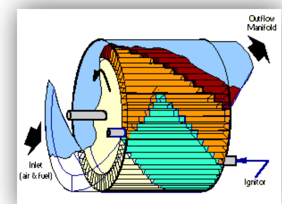
DOE National Energy Technology Laboratory, 1993

Slide provide by Dan Paxson, NASA Glenn

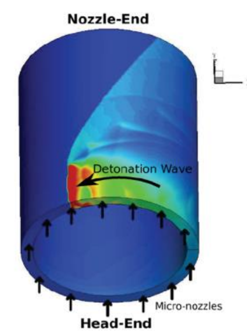
Detonation
or
'Fast' Deflagration



G.E. Global Research Center 2005



IUPUI/Purdue/LibertyWorks, 2009



Rotating Detonation Engine (NRL)

Pulse deflagration combustion

Current R&D at NASA, Cambridge-Whittle
Past Work at NETL

Aerovalved Pressure Gain Combustor

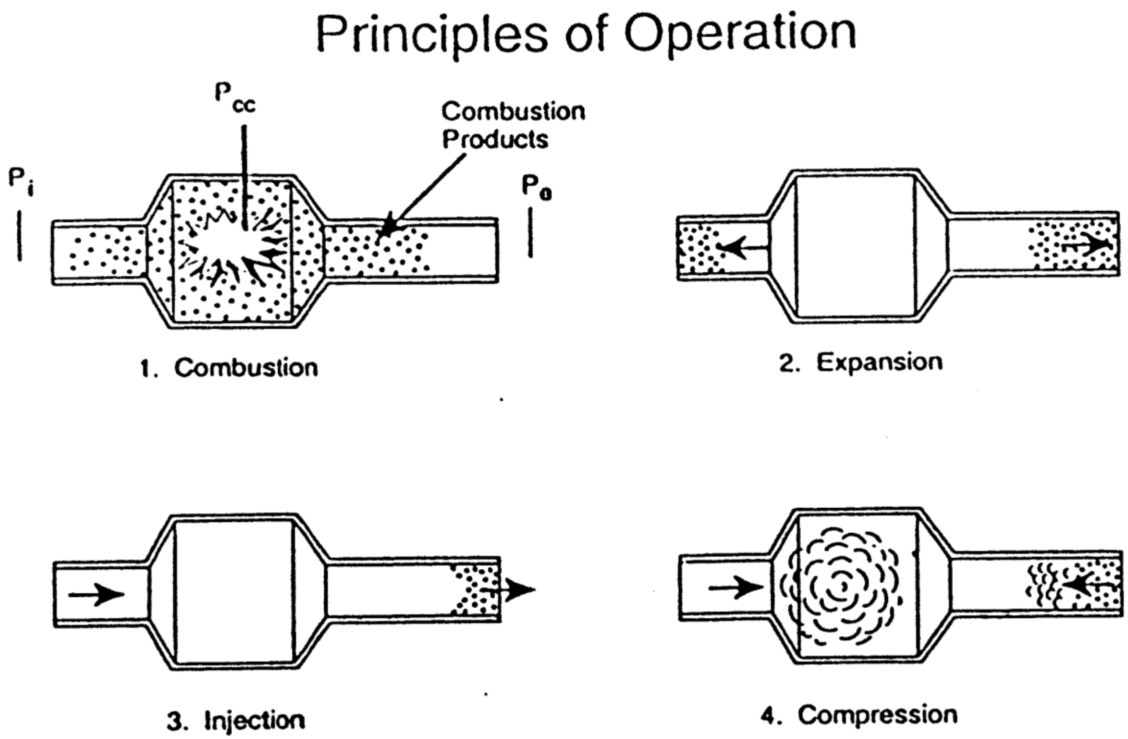
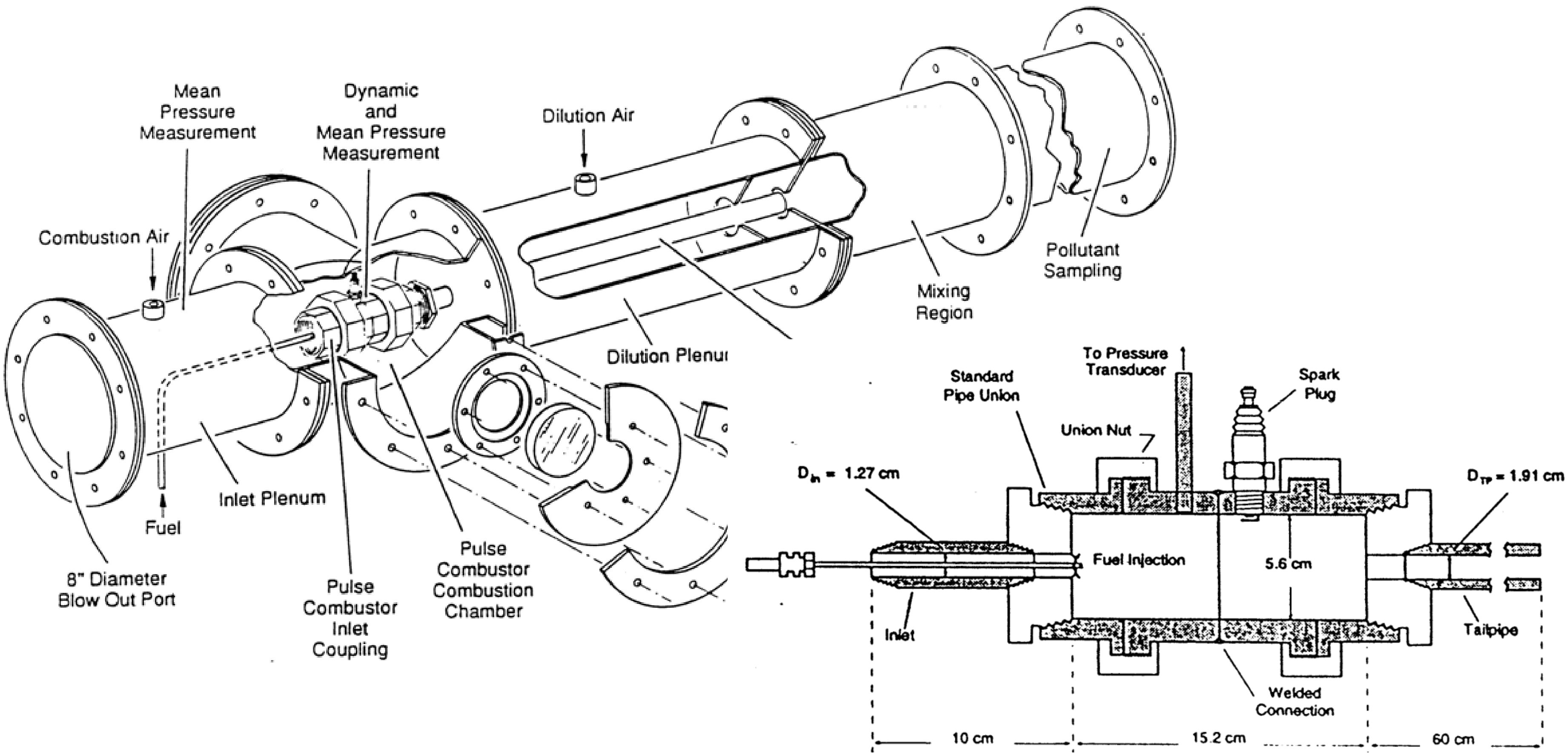


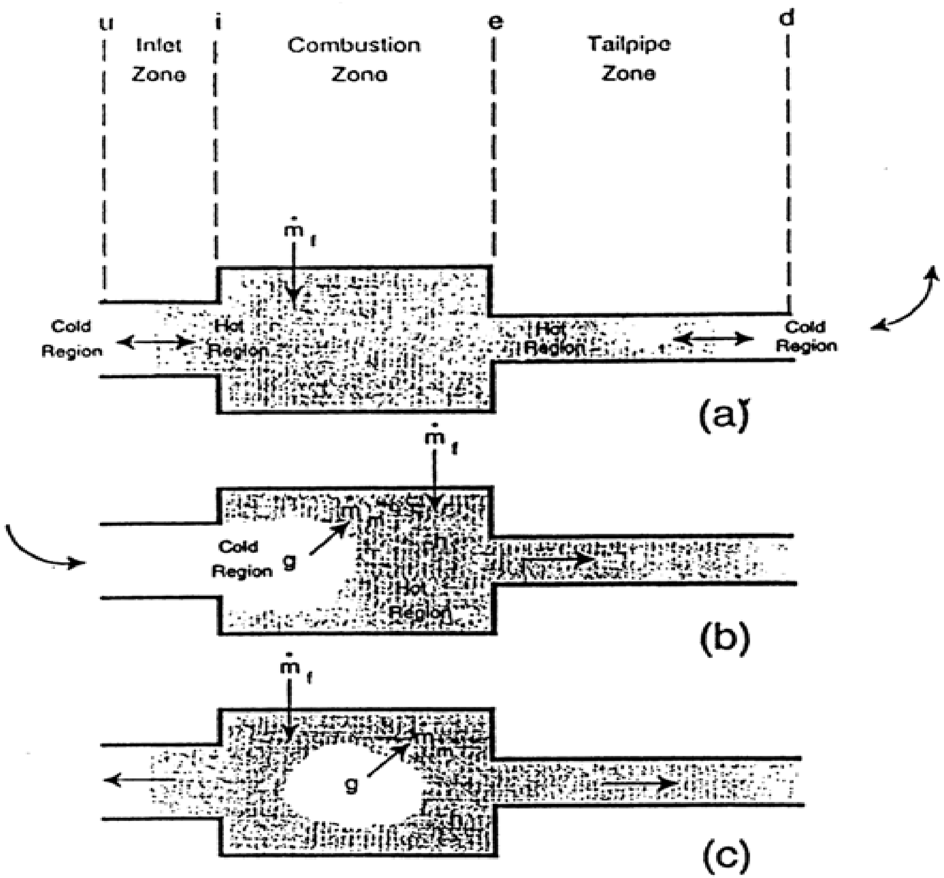
Fig. 1 Operation of an aerodynamically valved pulse combustor. The combustion event (1) raises the pressure in the combustion chamber (P_{cc}), forcing gas out of the inlet pipe and tailpipe (2), the momentum of fluid in the tailpipe draws fresh air through the inlet (3), with a subsequent compression of gases in the combustion chamber (4). On a time average, the flow is from left to right.

NETL Atmospheric Pressure Rig (1991)



- **Combustor constructed with standard pipe fittings.**
- **Allows simple changes in inlet and tailpipe geometry.**

One-Dimensional Modeling



Characteristic Timescales

$$\tau_i = \frac{\rho_A V_c}{\dot{m}_i} \quad \text{(inlet flow time)}$$

$$\tau_f = \frac{\rho_A V_c}{\dot{m}_f} \quad \text{(fuel flow time)}$$

$$\tau_e = \frac{\rho_A V_c}{\dot{m}_e} \quad \text{(exit flow time)}$$

$$\tau_c = \frac{P_A}{\dot{Q}(\gamma - 1)} \quad \text{(combustion time)}$$

$$\tau_{HT} = \frac{\rho_A R V_c}{h A_s} \quad \text{(heat transfer time)}$$

$$\tau_m = \frac{\rho_A V_c}{\dot{m}_m} \quad \text{(mixing time)}$$

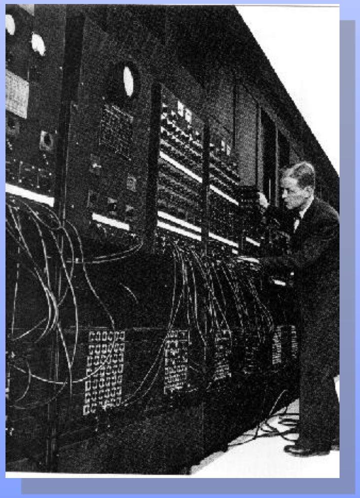
- **Divide combustor into three distinct zones.**
- **Solve conservation equations of mass, momentum and energy.**
- **Provides estimation of frequency and amplitude.**

One-Dimensional Modeling

Why not CFD?

1) Hint: this was 1990.

2) No theory for initial design & scaling.



Nice Computer!

<u>*Characteristic Timescales*</u>

$$\tau_i = \frac{\rho_A V_c}{\dot{m}_i} \quad \text{(inlet flow time)}$$

$$\tau_f = \frac{\rho_A V_c}{\dot{m}_f} \quad \text{(fuel flow time)}$$

$$\tau_e = \frac{\rho_A V_c}{\dot{m}_e} \quad \text{(exit flow time)}$$

$$\tau_c = \frac{P_A}{\dot{Q}(\gamma - 1)} \quad \text{(combustion time)}$$

$$\tau_{HT} = \frac{\rho_A R V_c}{h A_s} \quad \text{(heat transfer time)}$$

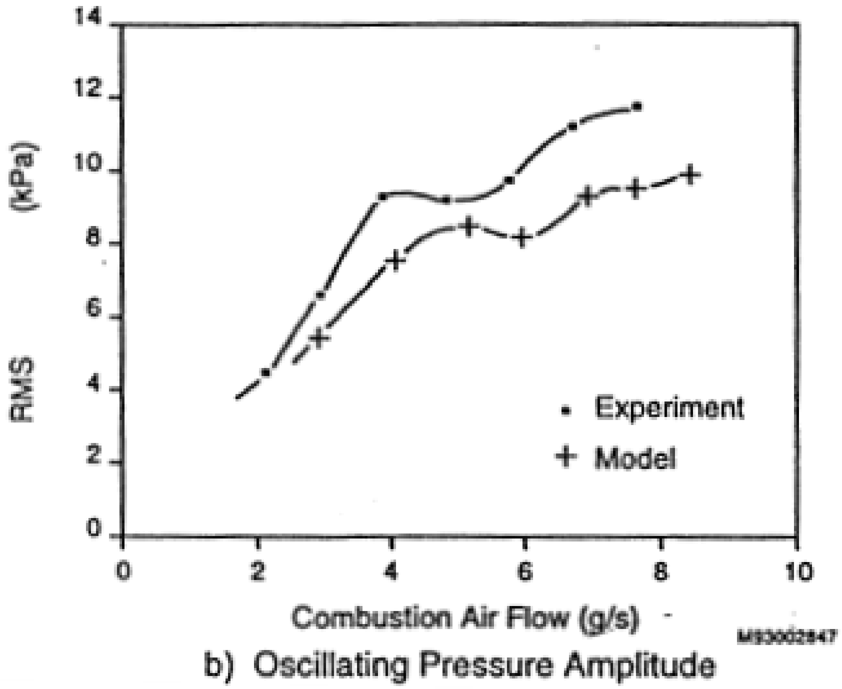
$$\tau_m = \frac{\rho_A V_c}{\dot{m}_m} \quad \text{(mixing time)}$$

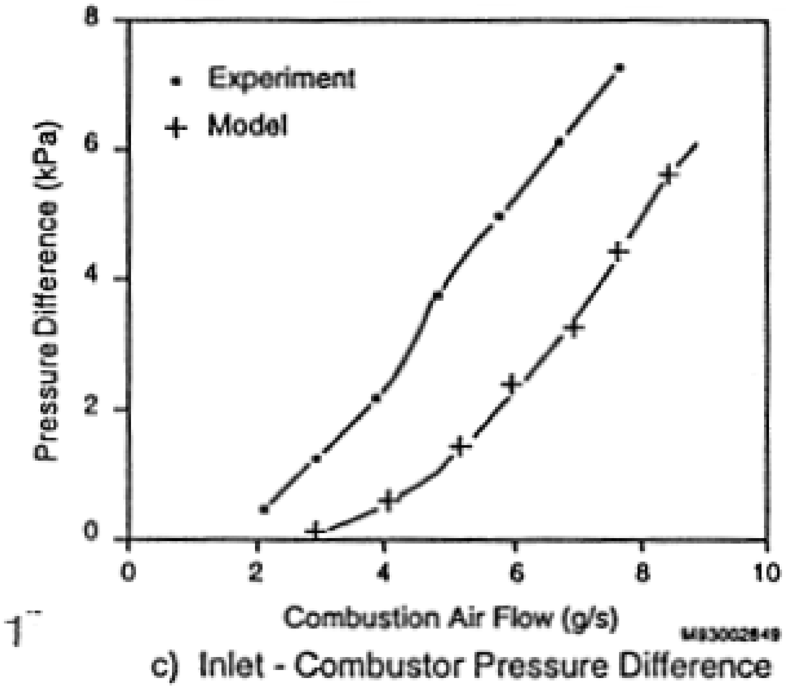
ct zones.

- **Solve conservation equations of mass, momentum and energy.**
- **Provides estimation of frequency and amplitude.**

Atmospheric Pressure Rig Data

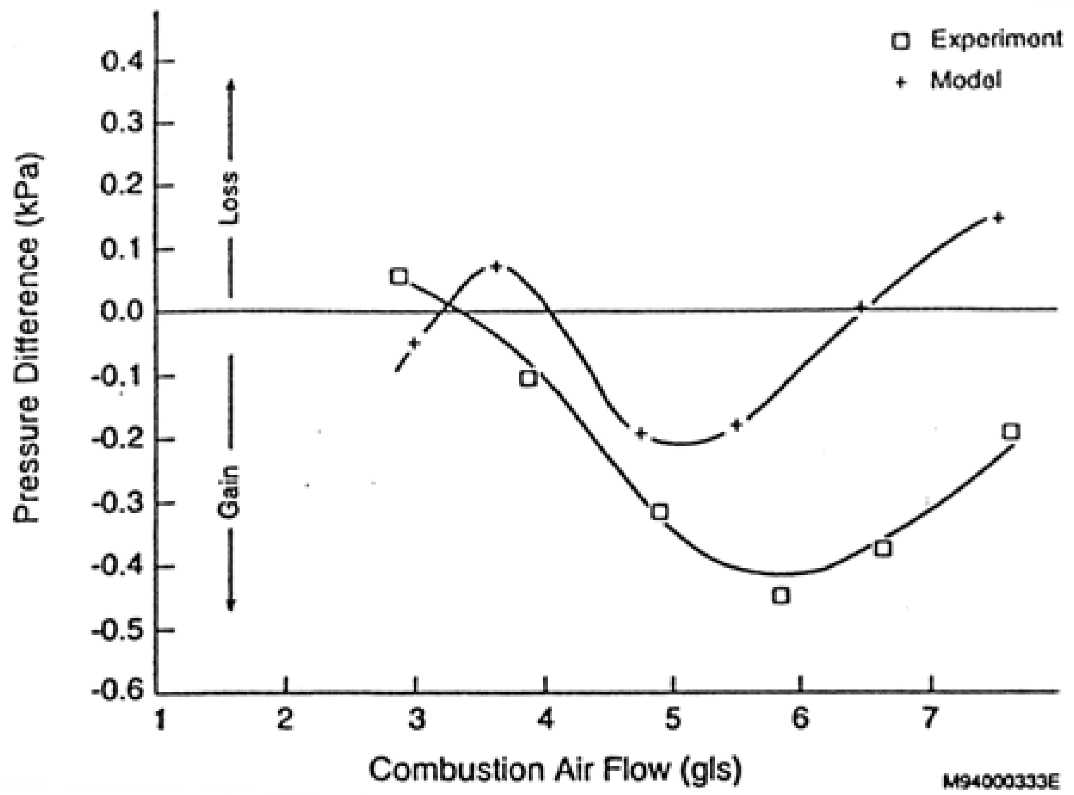
NG/Air ϕ=0.82





- **Baseline geometry (L_{in}=10 cm, L_{ex}=60 cm).**
- **Resonant frequency ~ 160 Hz**

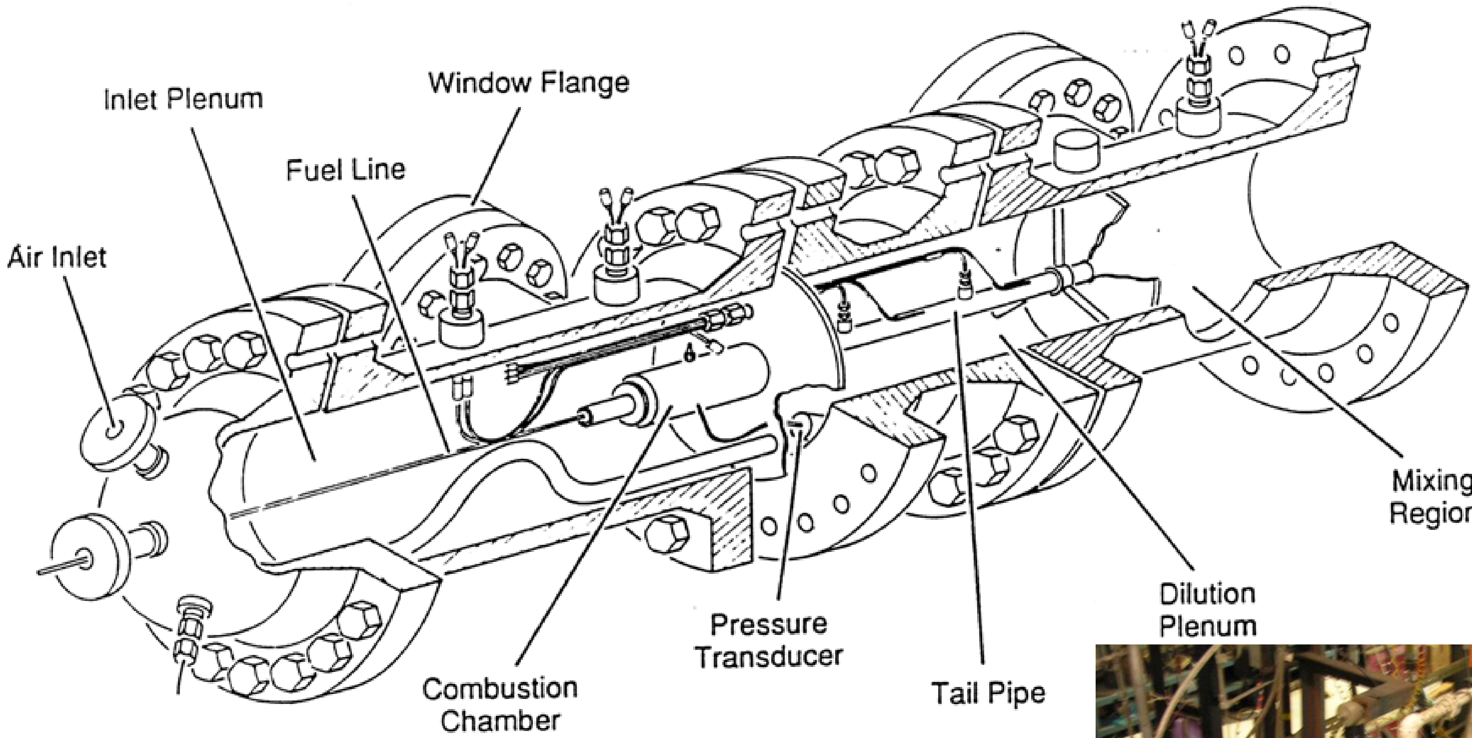
Optimized Geometry

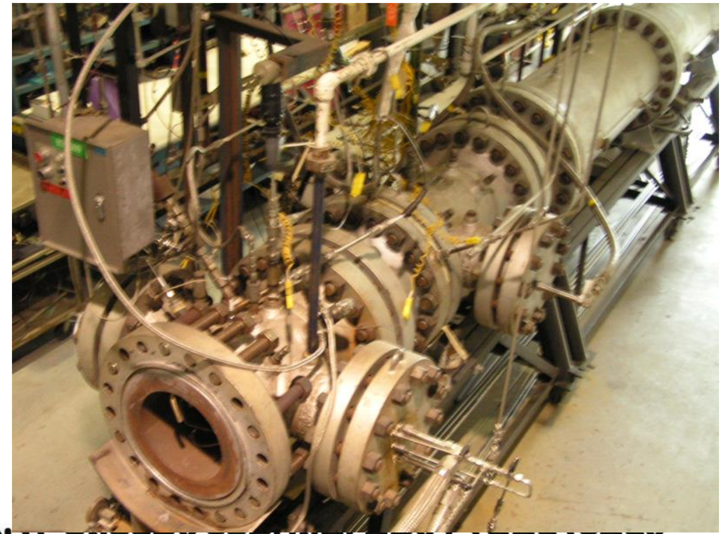


Lengths (m)			Diameters (m)		
Inlet	L_i	0.152	Inlet	D_i	0.0222
Tailpipe	L_{tp}	0.900	Tailpipe	D_{tp}	0.0191
Combustor	L_{comb}	0.152	Combustor	D_{comb}	0.0556

- **Maximum of 0.45% pressure gain achieved.**

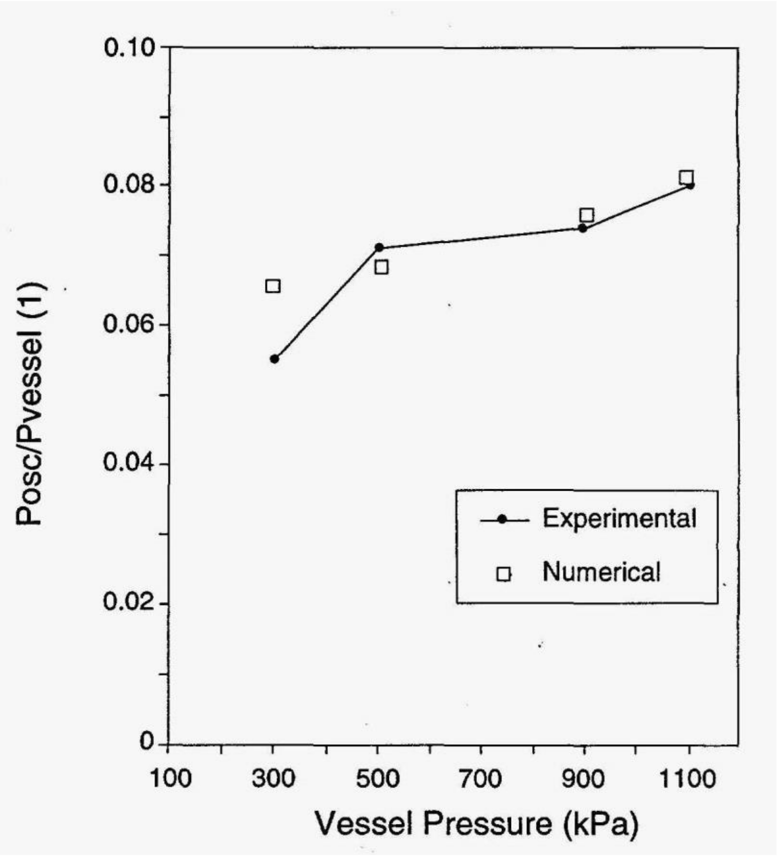
NETL High Pressure Rig (1994)





- **NG/Air up to 11 atm.**
- **Simple non-rectified design.**

High Pressure Results



- ***Pressure controlled with a control valve on chamber exhaust.***
- ***Flow rates increased linearly with pressure.***

- **Little effect of pressure when flow-rates are scaled linearly with pressure.**
- **Slight gain likely due to reduced frictional and heat losses.**

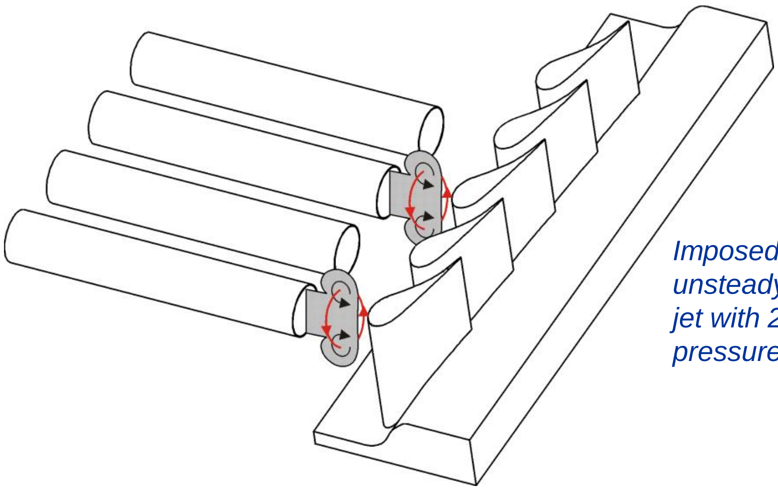
Some challenging problems

- **Predicting a design that will produce oscillations.**
  – Progress in eliminating oscillations in premixed gas turbines makes this (relatively) easy.
  – But, at what operating condition?
- **Developing an oscillating design that will also have a pressure gain.**
  – Qualitative understanding, but no fundamental criterion, theory.
  – Modern CFD may be the enabler!
- **Capturing the energy of the unsteady flow**

Capturing the pressure-gain

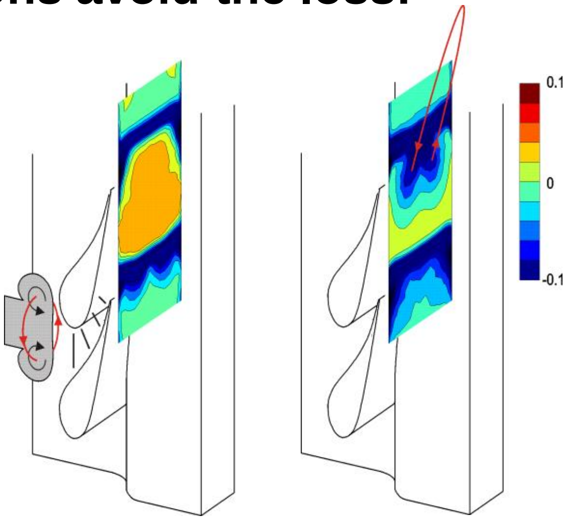
Courtesy R.J.Miller, Whittle Lab, Cambridge University

- **Time resolved experimental data.**
- **Vortex-induced separation leads to loss in Phase II.**
- **Work in progress: some configurations avoid the loss!**



Transonic test facility

Imposed unsteady jet with 2-3% pressure gain



Color corresponds to pressure gain fraction (0.1 = 10% pressure gain)

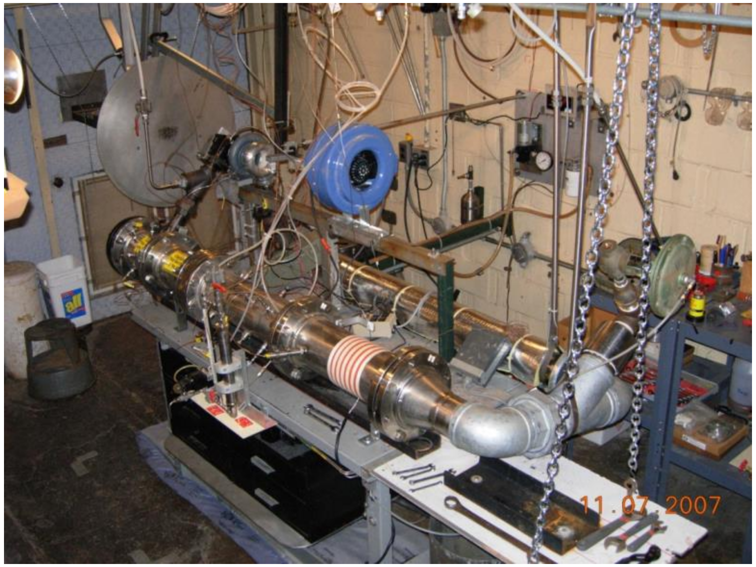
Phase I
Pressure gain in free stream

Phase II
Large rise in loss as vortex exits

Cause of loss : Vortex interacting with vane suction surface.

Work at NASA

- **Demonstrated pressure-gain and small turbine operation.**
- **Simulations of pulse jet using commercial CFD.**

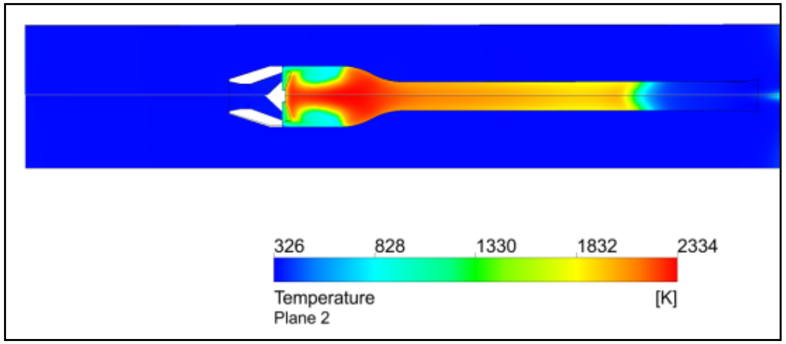


Liquid fueled.

Automotive turbocharger "turbine"

Reed-valve pulse combustor.

Experimental results:*
Combustor pressure ratio 1.035 at temperature ratio 2.2



Simulation of pulse-jet behavior –with NOx emissions and experimental validation.

Graphics courtesy Dan Paxson, NASA Glenn

** Paxson, D. , Dougherty, K. (2008). Operability of an Ejector Enhanced Pulse Combustor in a Gas Turbine Environment NASA/TM—2008-215169*

Movie of pulse jet ejector (courtesy Dan Paxson, NASA)

pulsejet_ejector_shroud.mov

Pulse Detonation (Tubes)

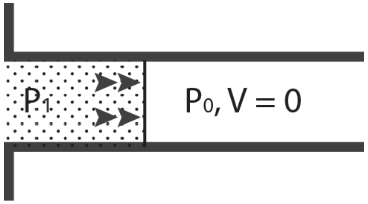
The detonation essentially "traps" the combustion behind the shock.

Compared to pulse deflagration, much higher pressure gains are possible.

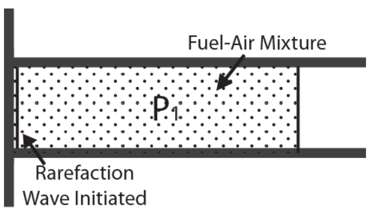
This may be the only _*constructive*_ applications of detonations?

Typical Pulse Detonation Cycle

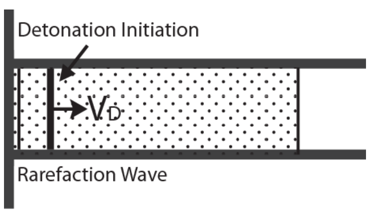
1. Fill



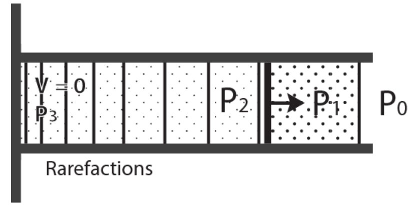
2. Upstream end closes



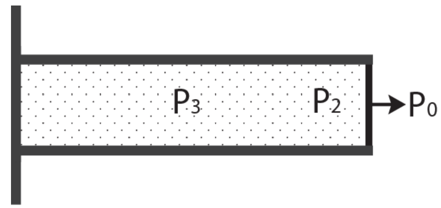
3. Detonation initiated (DDT)



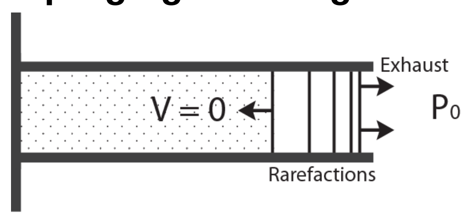
4. Detonation wave propagates at CJ velocity with coupled combustion wave



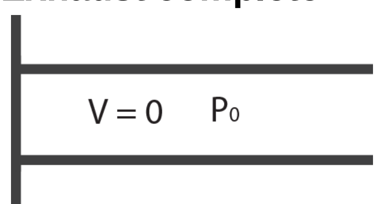
5. Detonation wave exits tube. Remaining gas at elevated T and P.



6. Rarefaction wave propagate upstream to assist with purging burned gases



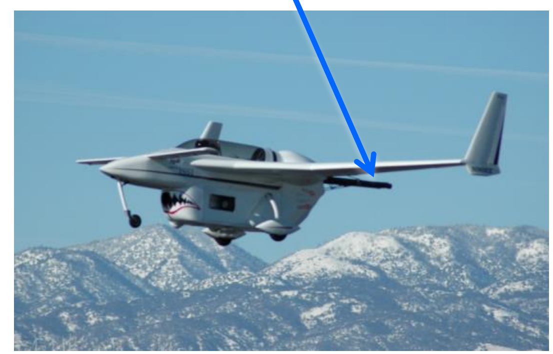
7. Exhaust complete



Pulse Detonation for Propulsion

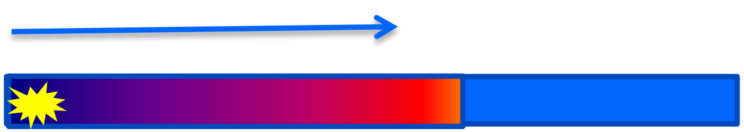
- **Pulse detonation tube concept has been extensively studied.**
- **"Direct" propulsion: simple!**
  - No turbomachinery.
  - Conventional recip. engine valve assembly for inlet.
  - Progressed to flight demonstration.
- **A key scientific issue:**
  - Optimizing deflagration/detonation transition (DDT).

Lab test



Flight Demonstration

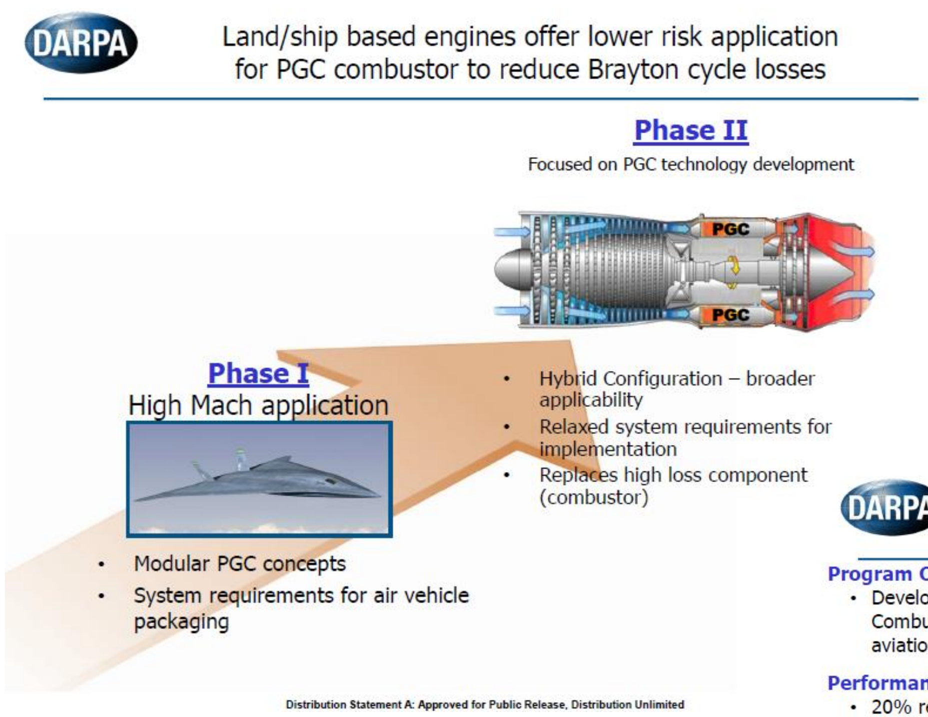
Photos courtesy Fred Schauer, AFRL



The run-up to detonation sets the length.
***Obstacles** can accelerate – but add losses.*

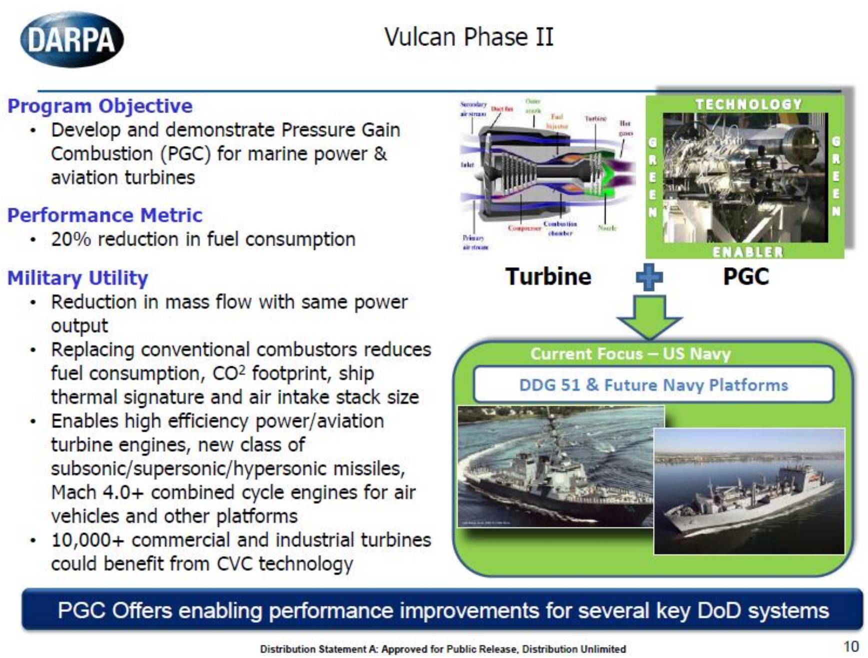
"…The applicability of a single combustion model to cover all the regimes of turbulent flames, which are encountered in confined high-speed flame transitioning to a detonation…..is yet to be established" Tangirala et al, Proc. Combustion Institute 30 (2005) 2817-2842

DARPA Vulcan Project



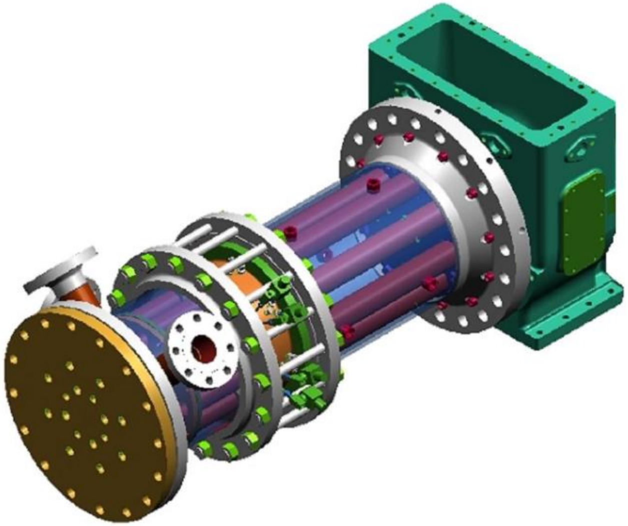
- **Integration in a turbine – humphrey cycle.**

- **Combines the PDE with turbomachinery**



Multitube PDC-Turbine Hybrid System

- **Eight tubes arranged in a can-annular configuration coupled to a single stage axial turbine**
- **Accumulated 144 minutes of PDC fired operation**
- **Turbine performance was indistinguishable between steady flow operation and pulsed flow at 20 Hz per tube**



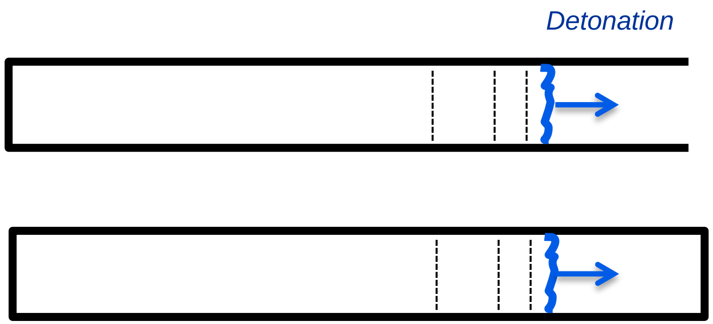
GE Global Research

Some work supported from:
NASA Constant Volume Combustion Cycle Engine Program

Tangirala, V., Rasheed, A. and Dean, A.J., "Performance of a Pulse Detonation Combustor-Based Hybrid Engine", GT2007-28056, ASME Turbo Expo, Montreal, Canada, May 14-17, 2007.

An instructive question

A detonation is started in tubes filled with fuel/air mixture, and travel left to right. One tube is open, and one is closed at the right end.



The lower sketch shows what <u>will become</u> constant volume combustion.

Both devices will release the same heat, burn the same fuel.

The top device has significant mechanical energy as the detonation gets to the end.

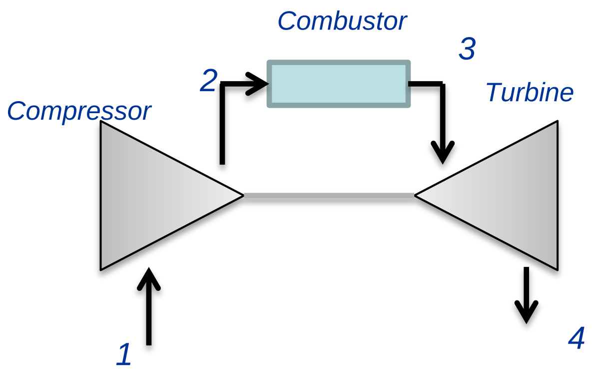
The bottom device has significant mechanical energy as the detonation gets to the end.

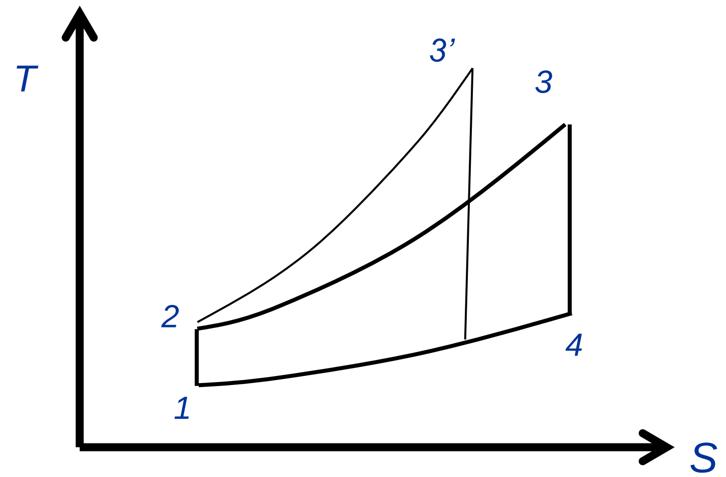
What happens to that <u>mechanical energy (with high availability)</u>   in both devices?

Brayton and Humphrey thermodynamic cycles

The ideal Brayton cycle (e.g., gas turbine) compresses the mixture (1-2), adds combustion heat at ~ constant pressure (2-3), extracts work from isentropic expansion (3-4) and then rejects heat from the working fluid at constant volume (4-1).

For the Humphrey cycle, the heat addition occurs at constant volume, (2 – 3').





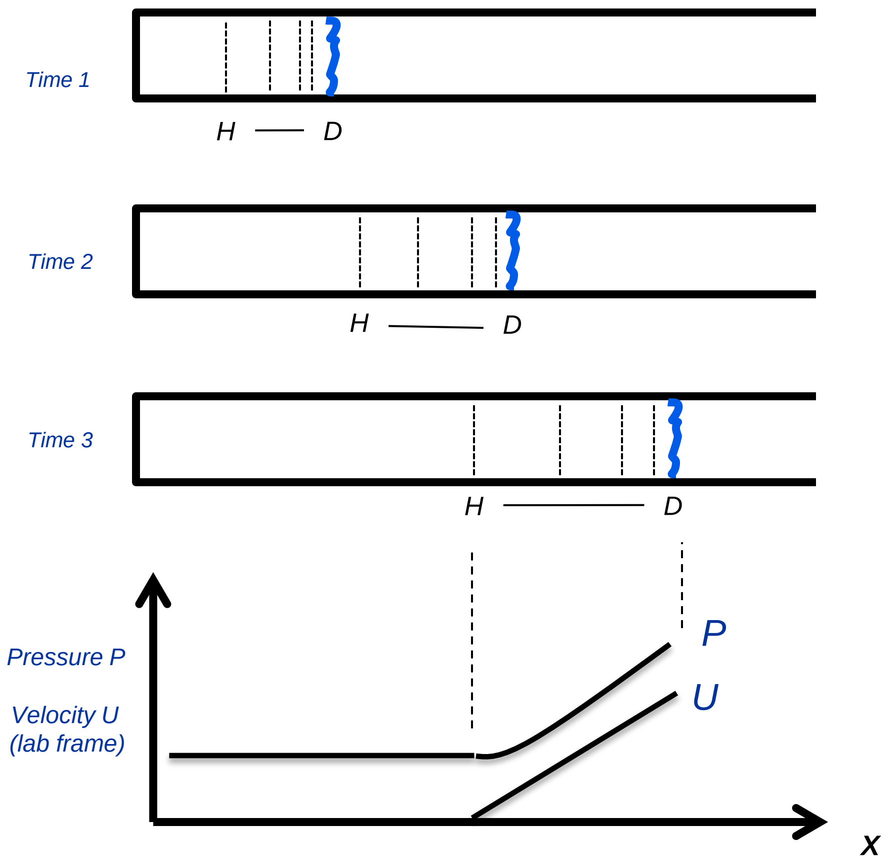
Assume you add the same quantity of heat for both cases.
2-3 Conventional constant pressure heat addition
2-3' Constant volume heat addition
*Note that **how** you add the heat determines state 3.*

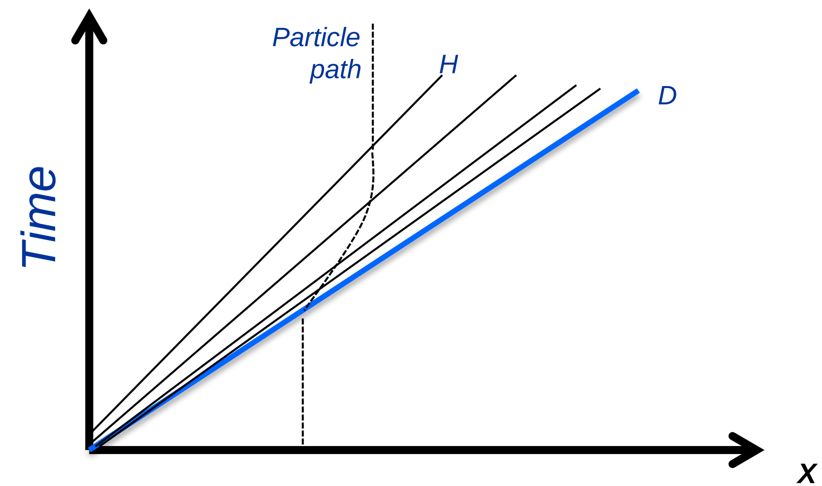
How does a detonation add the heat?

Particle history behind a detonation

For more details: Law, C.K. (2006) Combustion Physics, Cambridge University Press, pp. 656 ff provides derivation of the flow field.

H = head of expansion wave, D = detonation



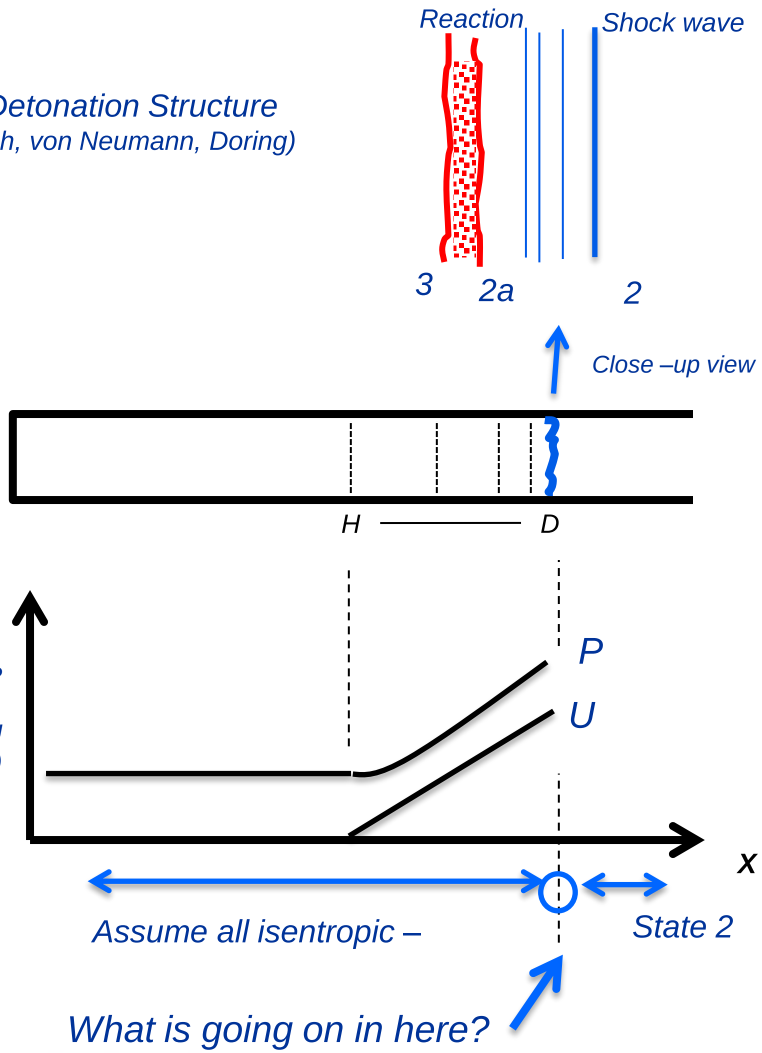


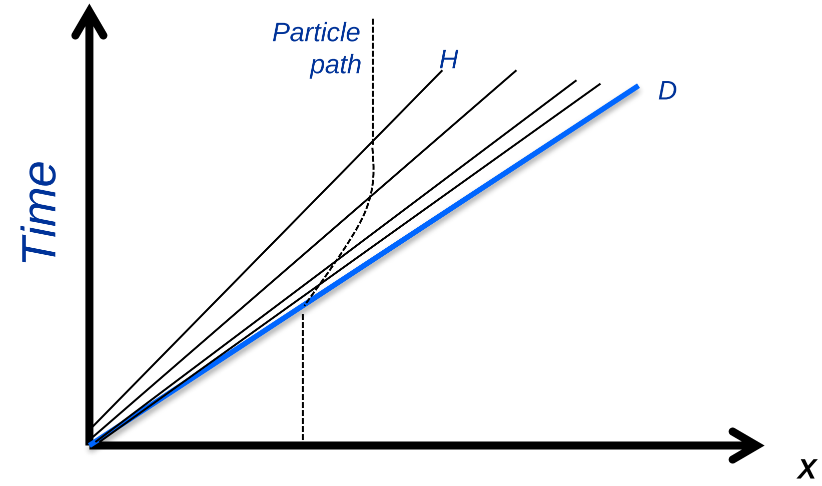
What does the T-s diagram look like for the particle of gas?

Particle history behind a detonation

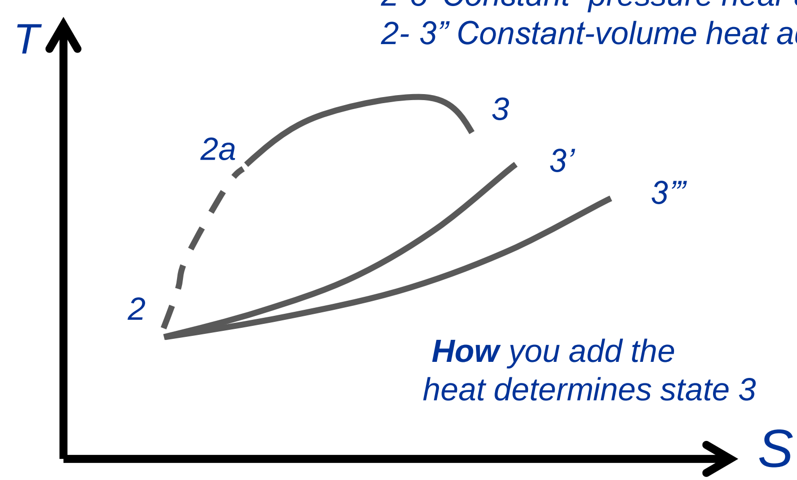
For more details: Law, C.K. (2006) Combustion Physics, Cambridge University Press, pp. 656 ff provides derivation of the flow field.

ZND Detonation Structure
(Zeldovich, von Neumann, Doring)





2-2a-3 Detonation
2-3’ Constant -pressure hear addition
2- 3” Constant-volume heat addition

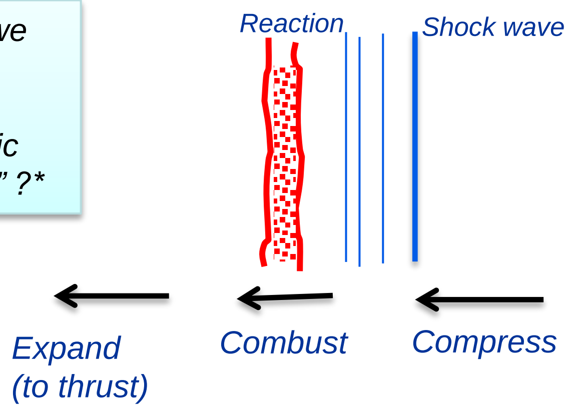


Note: 2-2a is shock compression. 2a-3: T can indeed have a maximum with heat addition for (gamma)^(-1/2) < Mach < 1; subsonic Rayleigh curve.

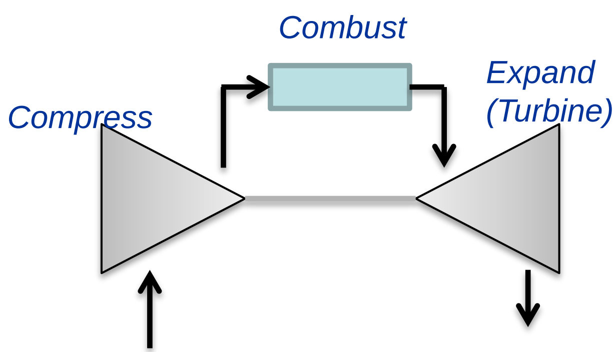
A few comments – and more details

Interesting analogues

*Could we call it a "Gas Dynamic Engine" ?**



*This phrase is not used in the open literature



Note that the "gas dynamic engine" does not have constant pressure combustion as in a turbine; the analogy is not perfect!

- **Pressure gain combustion turbine- two ways:**
  - Constant volume combustion: Humphrey cycle
  - Replace the conventional constant pressure combustor with a "gas dynamic engine" – a new *combined* cycle.
- **It is useful to treat the "gas dynamic engine" as a thermodynamic cycle (why?).**
  - Literature citations, next slide.
  - Definitions:
    - Fickett-Jacobs cycle: ignores the shock structure; does not account for compression before heat addition.
    - ZND cycle: described here.
  - Be very careful with cycles:
    - Stagnation versus static properties.
    - Unsteady, adiabatic flow: total enthalpy is NOT constant**.

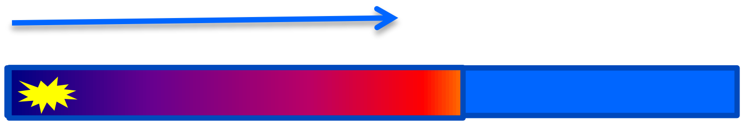
$$\rho \frac{Dh_o}{Dt} = \frac{\partial p}{\partial t} + \rho \dot{q} + \rho(\boldsymbol{f} \cdot \boldsymbol{U})$$

***Anderson, J.D., Modern Compressible Flow, McGraw Hill, (1982). pp. 161 eq. 6.43 & also pp. 179*

References for thermodynamic cycle analysis of detonation

- **These references do show a modest theoretical efficiency advantage (+ 1 ~ 3% <u>points</u>) to the detonation heat addition versus pure constant volume heat addition.**

- **What practical issues may limit the actual advantage?**

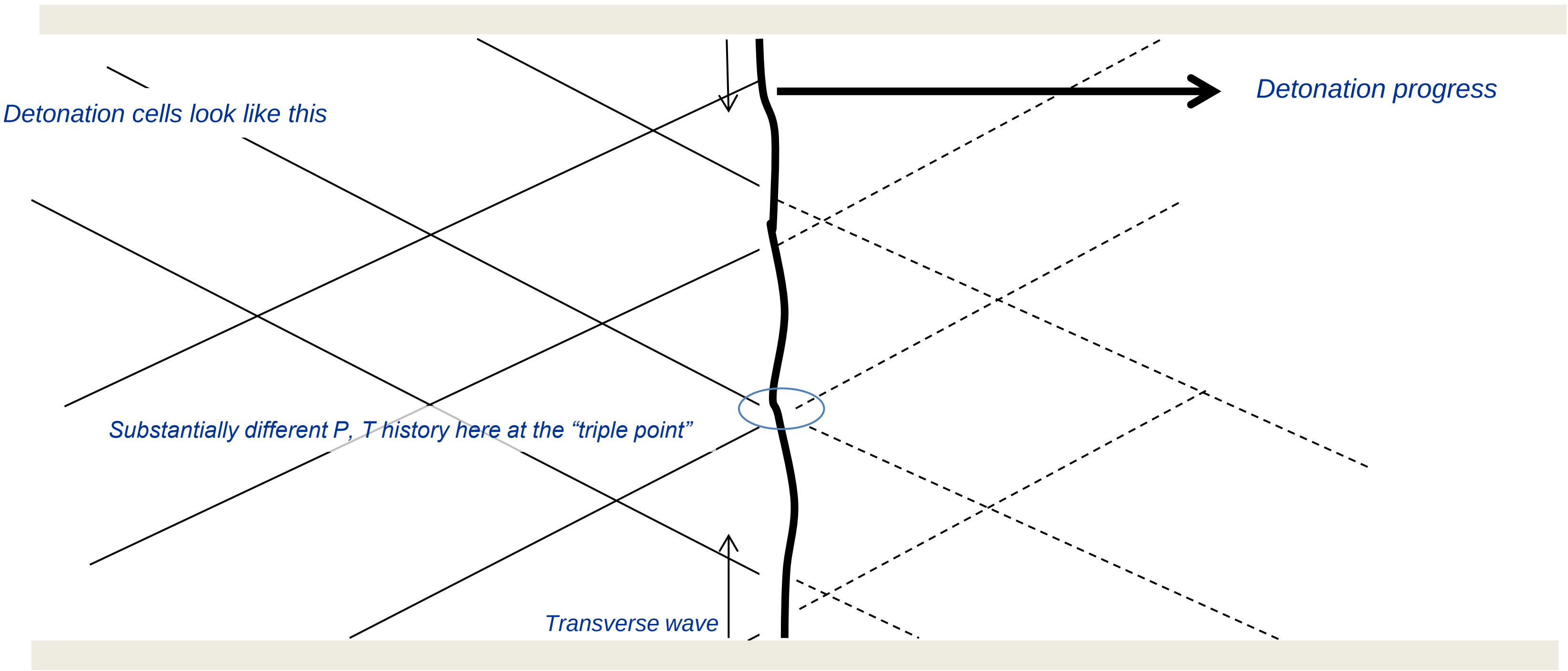


The gas at the left starts as a deflagration; there is a deflagration/detonation transition

(1) Heiser, W. H., Pratt, D. T. (2002) Thermodynamic Cycle Analysis of Pulse Detonation Engines, AIAA J. Prop. & Power Vol. 18, No.1, pp. 68-76.
(2) Kentfield, J. A. C. (2002) Fundamentals of Idealized Airbreathing Pulse Detonation Engines, AIAA J. Prop. & Power Vol. 18, No.1, pp. 77-83.
(3) Winterberger, E., Shepherd, J. E., (2006). Thermodynamic Cycle Analysis for Propagating Detonations, AIAA J. Prop. & Power, Vol. 22, No. 3. pp. 694- 697.
(4) Vutthivithayarak, R., Braun, E. M. Lu, F. K., (2012). On Thermodynamic Cycles for Detonation Engines, 28th Int. Symp. on Shock Waves, Kontis, K., [ed] Springer Berlin Heidelberg pp. 287-292.
(5) Wu, Y., Ma, F., Yang, V. (2003). System Performance and Thermodynamic Cycle Analysis of Airbreathing Pulse Detonation Engines, AIAA J. Prop & Power, Vol. 19, No. 4, pp. 556- 567
(6) Nalim, M. R. (2002). Thermodynamic Limits of Work and Pressure Gain in Combustion and Evaporation Processes, AIAA Journal of Propulsion and Power, *Vol. 18, No. 6 pp. 1176-1182.*

There are more details….

- **Actual detonations don't travel as plane waves.**
- **Detonation progress is affected by transverse waves reflected from the tube walls…and other factors.**
- **Thermodynamic model? Use a computer!**



Good background & images – see Austin, J.M. (2003) The Role of Instability in Gaseous Detonation, Ph.D. thesis, California Institute of Technology, Pasadena, CA.

A different approach

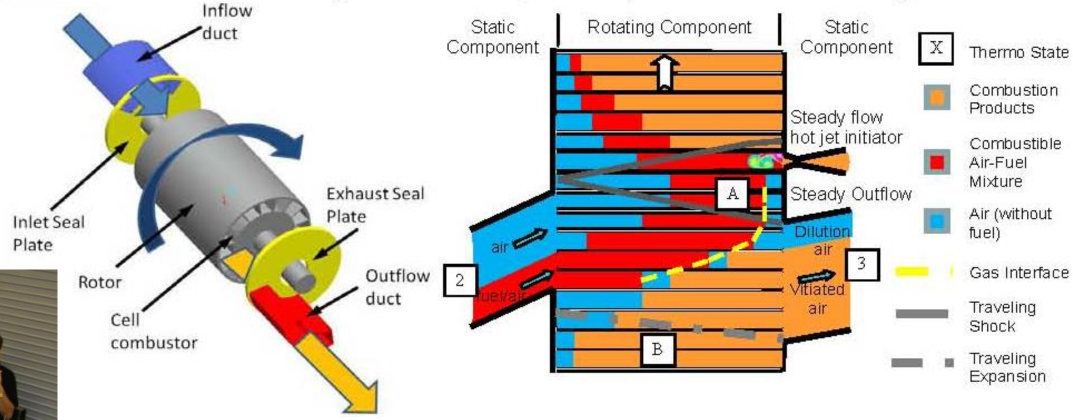
- **Wave Rotor Pressure Gain Combustor.**
- **Developed by Rolls-Royce Liberty Works, IUPUI*, and Purdue Zucrow Lab**
- **Tubes on a rotor spin past inlet and exit ports – containing combustion.**
- **Does not require detonation – just rapid flame propagation.**

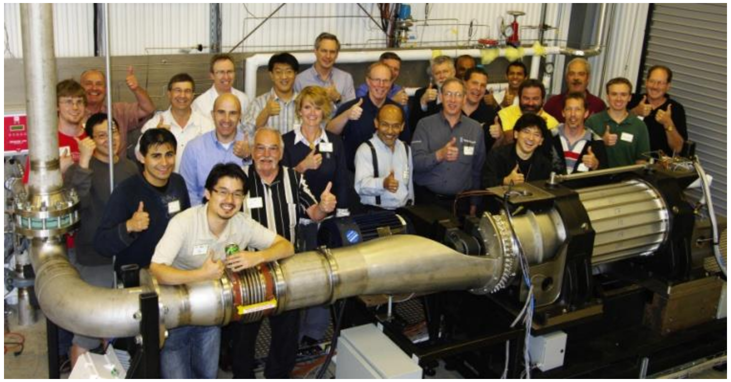
** Indiana University - Purdue University at Indianapolis*

Benefits:
Almost steady air flow
Steady torch ignition
Balanced thrust load

Challenges:
Sealing
Weight (for flight applications)

Figure 1.Wave-rotor pressure-gain combustor (WRPGC) schematic and internal processes





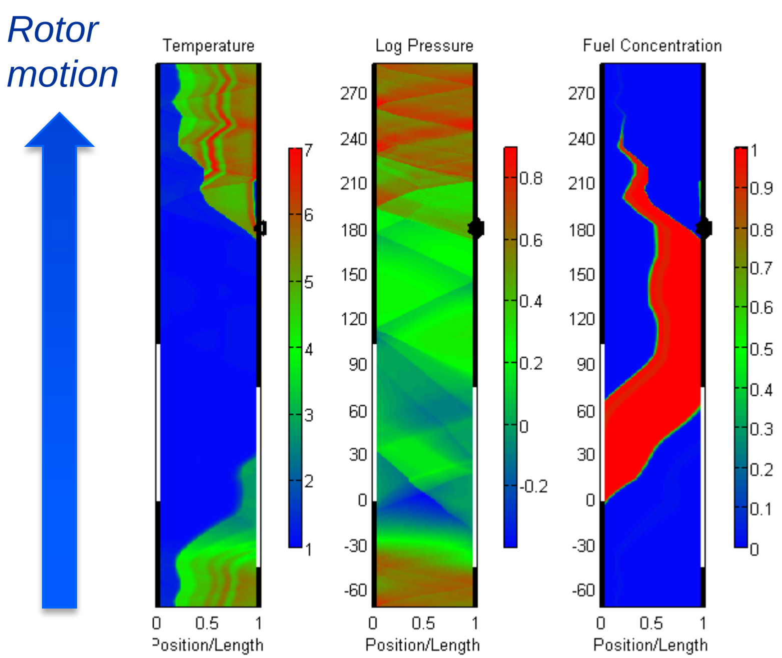
Successful test of wave rotor pressure gain combustor (2009)

The channels in the sketch at the right represent the tubes in the rotor at the left - but "unwrapped" at a moment in time. The rotor revolution is driven by a motor at a speed selected to allow the flame to complete the channel combustion within a rotation.

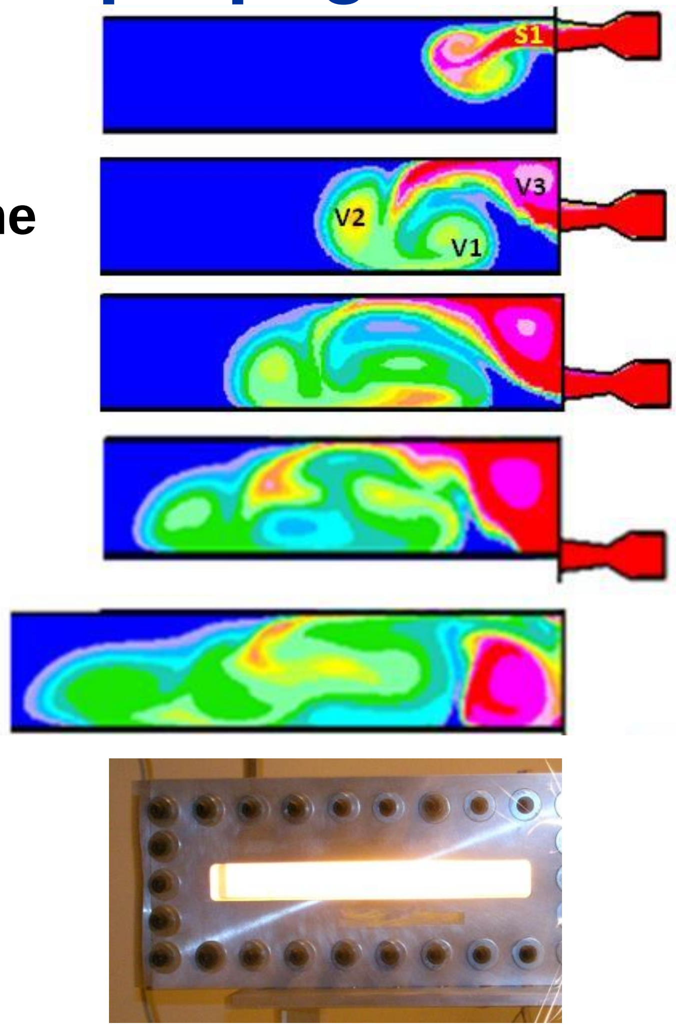
All photos and graphics: courtesy Dr. Phil Snyder (R-R)and Professor Razi Nalim (Purdue)

Understanding the flame propagation

- **Simulation development from basic studies (right) leads diagnosis of experiments for pressure rise and flame propagation.**



Snapshot of rotor tubes "unwrapped" (simulation).
Experiments and simulations used to establish design rotor speed and flow rate for fuel conversion and pressure rise.



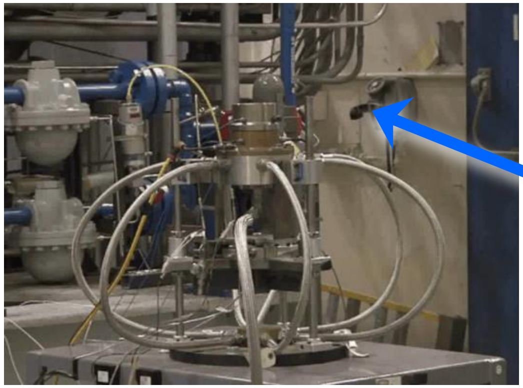
Study of flame propagation in a channel experiment with a moving entrance.

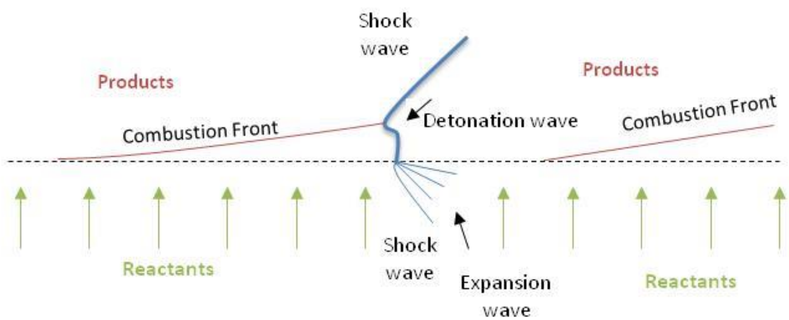
All photos and graphics: courtesy Dr. Phil Snyder (R-R) and Professor Razi Nalim (Purdue)

Rotating Detonation Wave Engine

- Objective: detonation pressure rise with ~ steady output.
- Rotating detonation idea has been in the literature since 1950s.*
- Recent studies have demonstrated new potential for the concept.

Experiment at AFRL
Courtesy Fred Schauer



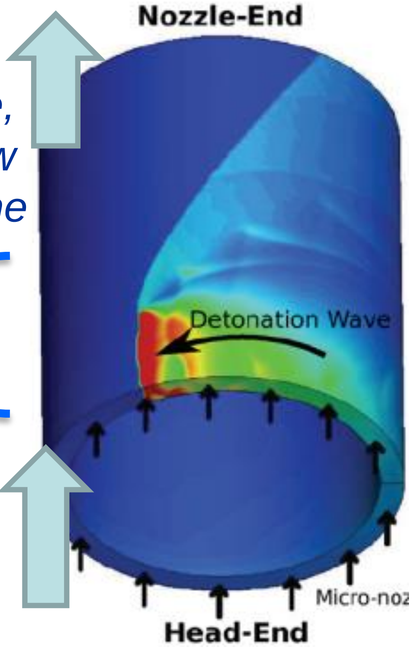


Combustion annulus unrolled. Reactant flow from the bottom.
Detonation moving right to left

Higher pressure, ~ steady flow to turbine

Rotating Detonation

Inlet from compressor



Simulation results courtesy K. Kailasanath, U. S.. Naval Research Laboratory

**see Kailasanath, K. (2011). The Rotating-Detonation –Wave Engine Concept: A Brief Status Report ,AIAA 2011-580.*

RDE photo

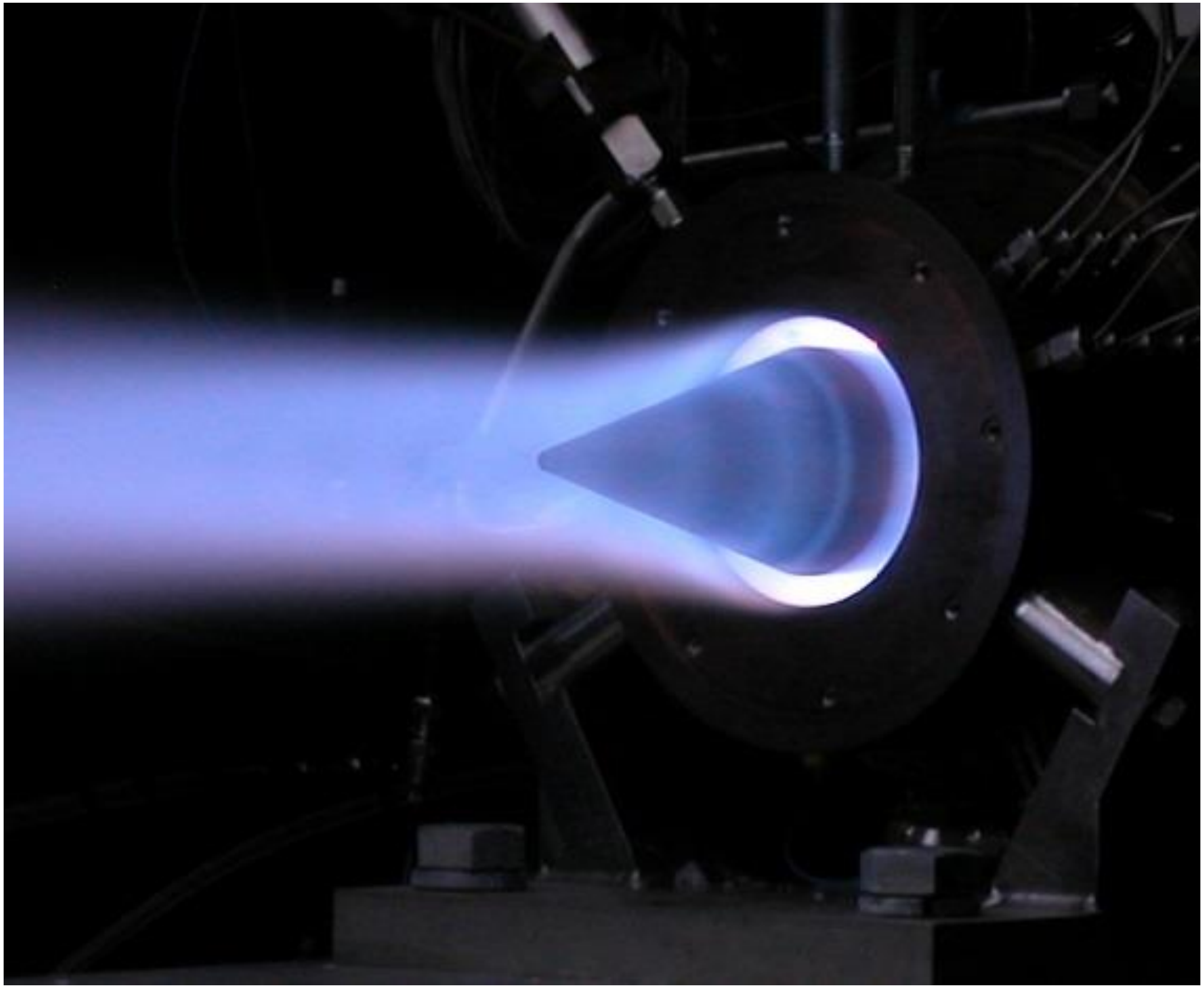
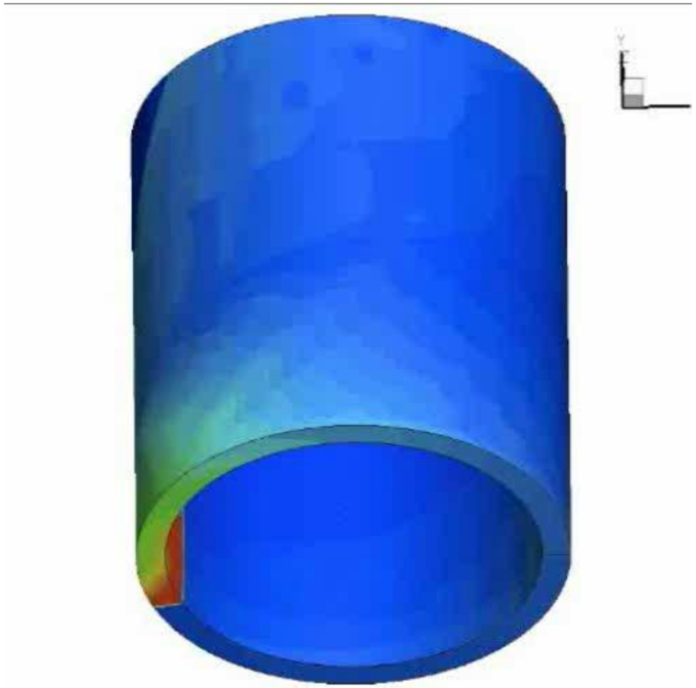


Photo courtesy
Scott Claflin
Aerojet Rocketdyne

End view

Side View



Rotation rate ~ 5000 Hz

Simulation results courtesy K. Kailasanath, U. S.. Naval Research Laboratory

From tests at AFRL

Side

Movie

Experiment at AFRL
Courtesy Fred Schauer

End

Movie

What is the thermodynamic history of gas particles ?

How does energy transfer go into pressure-gain?

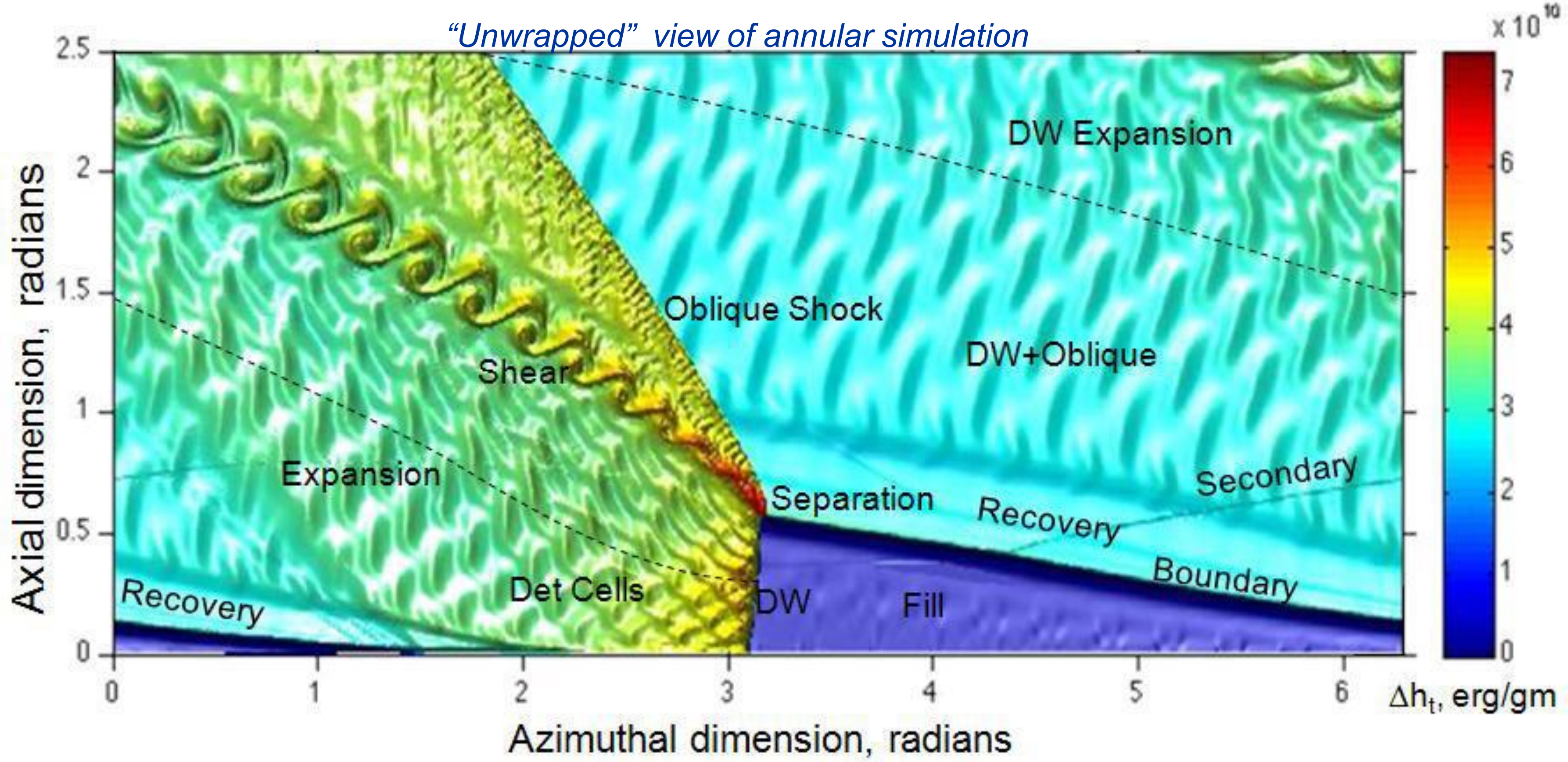
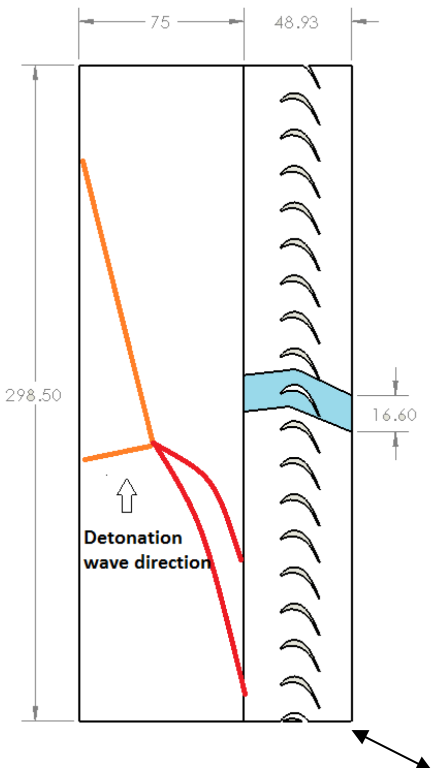


Image from Karnesky, J. and Schauer, F. (2013). Flowfield Characterization of a Rotating Detonation Engine, AIAA 2013-0278, courtesy Fred Schauer.

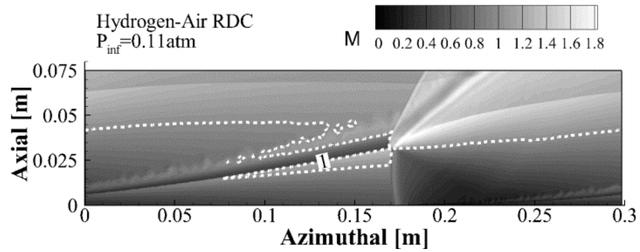
See also Nordeen, C. A., Schwer, D., Schauer, F., Hoke, J., Cetegen, B., Barber, T. (2011). Thermodynamic Modeling of a Rotating Detonation Engine, AIAA 2011-803

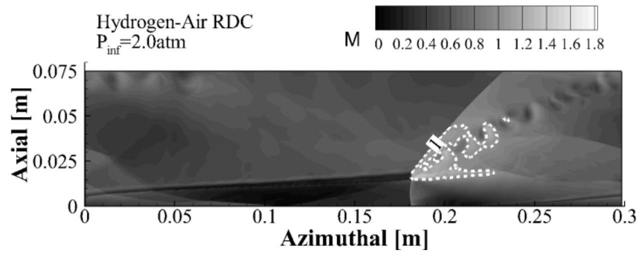
Some work in progress at NETL

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

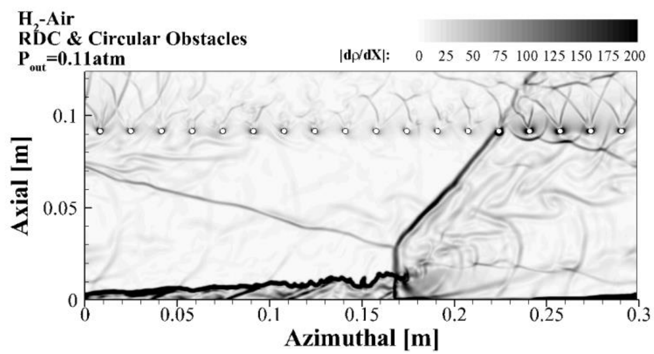


Schematic of simulation of interaction of RDE and integrated turbine exit.

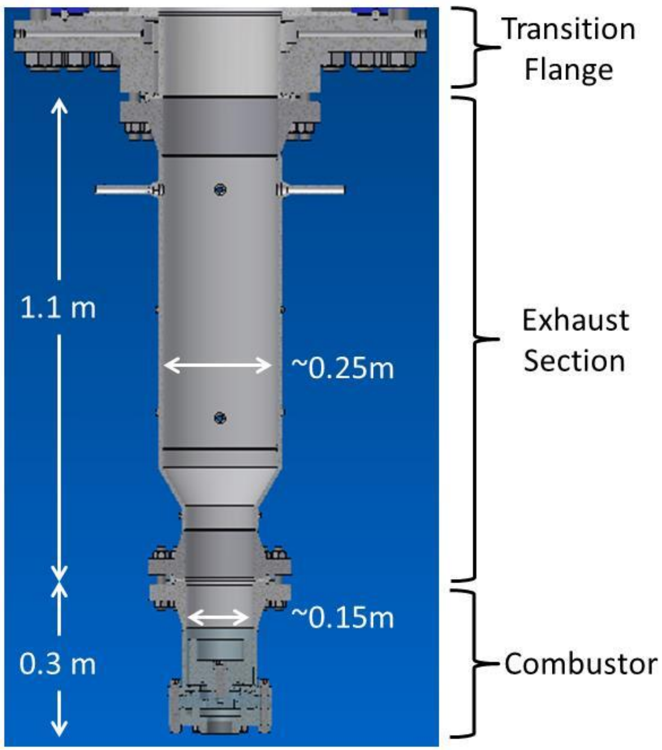




Mach number contours for Pout=0.11atm (top) and Pout=2atm (bottom)



Pressurized test rig for stationary turbine applications *– emissions and integration with coal syngas (H2) , natural gas fuels.*



Graphic courtesy Todd Sidwell - NETL

Discussion/Thinking Questions: Pressure-gain Combustion

- **What are the *combustion* research issues associated with different types of pressure-gain?**

- **In your opinion, what is the greatest challenge to development of the pressure gain technology for power production combustor inside a gas turbine (i.e., not a simple cycle thrust device) ?**

Left blank to write notes from question slide

Summary of Pressure-gain combustion

- **Potential for an efficiency breakthrough.**
- **Similar past concepts recognized; eclipsed by "conventional" improvements.**
- **Successful demonstrations for direct propulsion tubes.**
- **Promising work on turbine applications:**
  - Pulse deflagration
  - Detonation tubes integrated with engine
  - Constant volume combustion wave-rotor
  - Rotating detonation wave combustor
- **Combustion and thermal science research needs discussed.**