MHD Power Generation Based on Pressure Gain Combustion Systems

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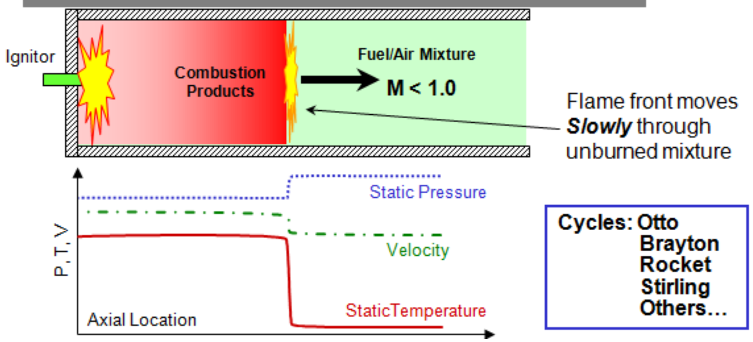
Outline

- Pressure Gain Combustion Background
- PDEs
- RDEs
- Benefits of PGC
- PDEs and MHD: Past research
- RDEs and MHD
- RDE Generator and Applications
- Transient Plasma Injection Experiments
- Research Opportunities
- Summary
- Supplementary Info and References

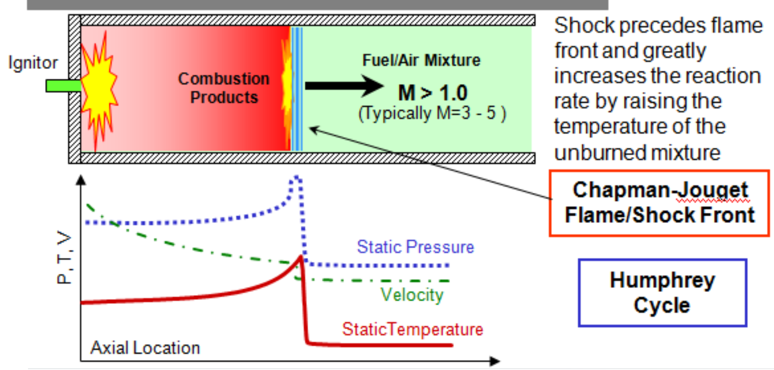
Pressure-Gain Combustion (PGC) Definition and Physics

- ***Pressure-Gain Combustion*:*** A process whereby the static pressure of a flammable mixture rises upon combustion
  - *Most combustion processes result in a static pressure reduction*
- The most prevalent mechanism for developing PGC is through **detonation**
  - *Essentially supersonic, shock-induced combustion (as opposed to subsonic deflagration)*
  - *The static temperature rise behind the shock wave initiates combustion kinetics*
  - *The detonation wave is often referred to as a **Chapman-Jouget (C-J)** wave front*
- Detonation results in a substantial **increase in static pressure and temperature**

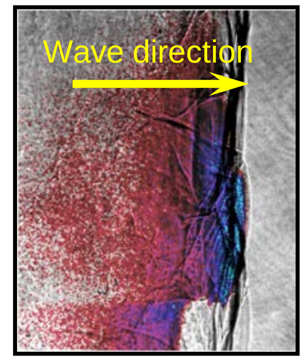
***Deflagration* – Typical Chemical Combustion**

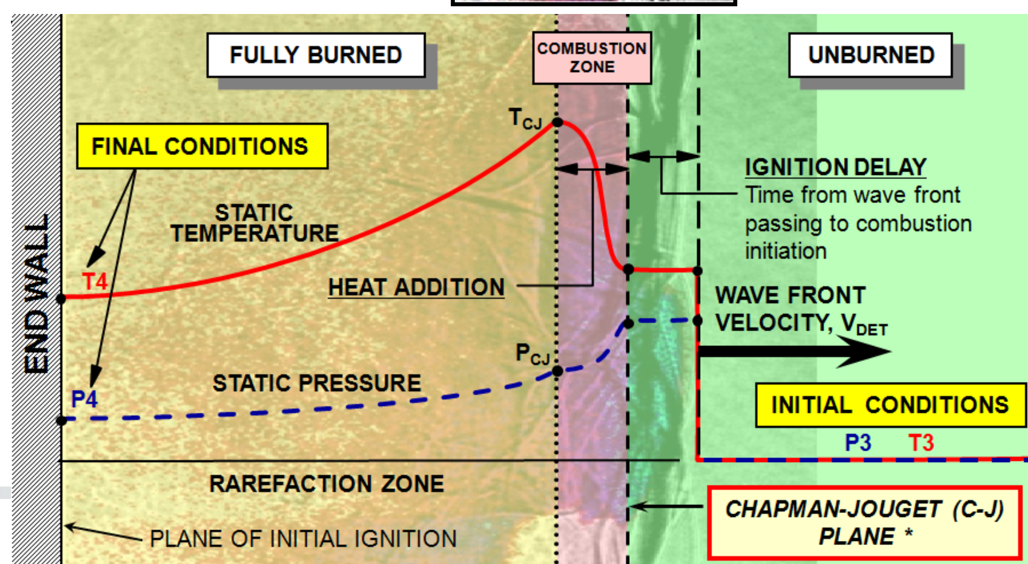


***Detonation* – Shock-Induced Combustion**



Color-enhanced Schlieren photograph of C-J wave

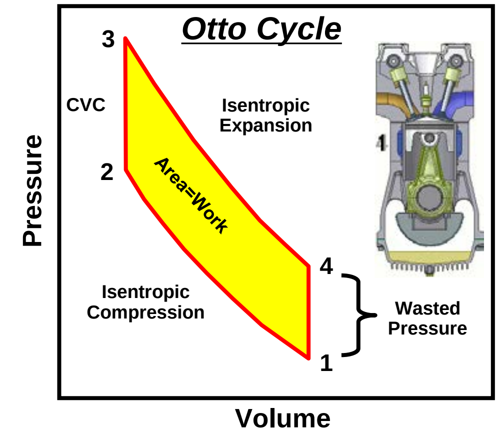


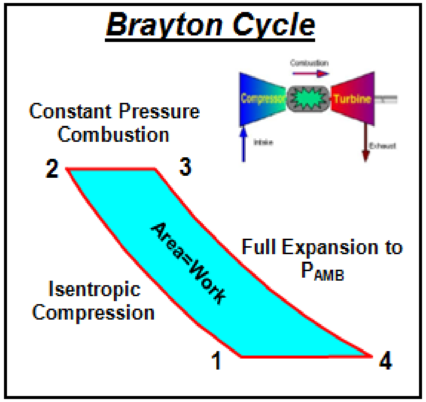


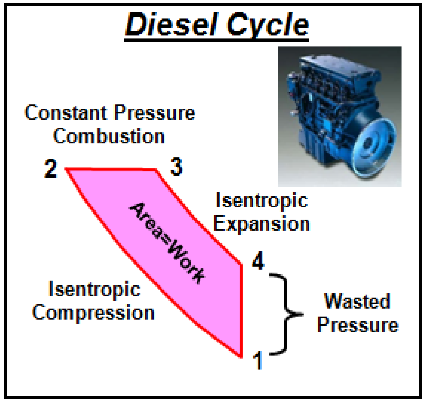
* This is MY modified version of the proposed definition of PGC as given by the AIAA PGC Program Committee formed in July of 2014

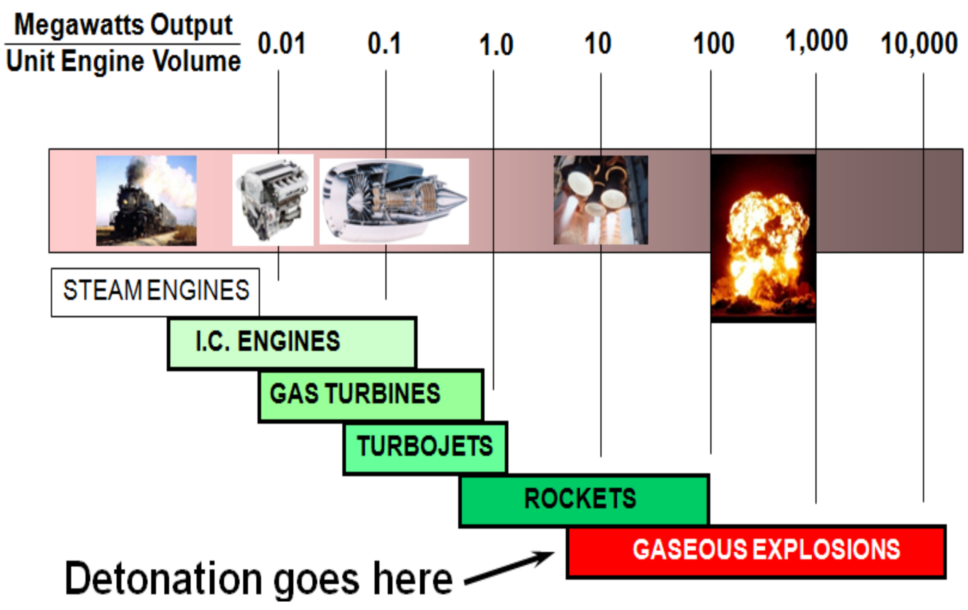
PGC Power Density and Cycle Comparison

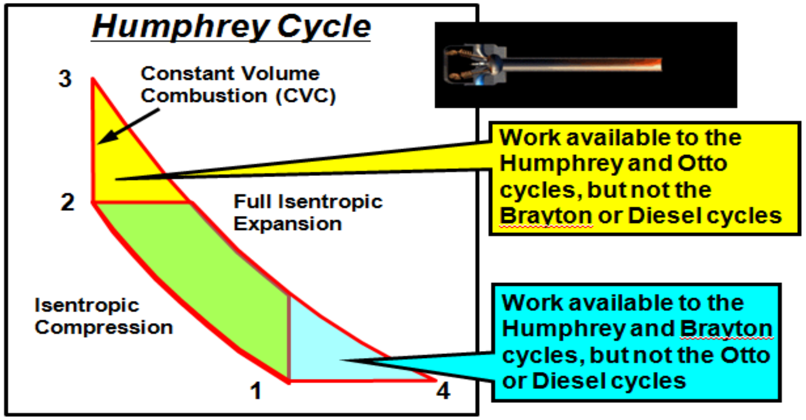
- Detonation processes can have nearly **two orders of magnitude** greater power density than rocket based systems
- A detonation-based, PGC power cycle can be approximated with a constant-volume combustion (CVC) thermodynamic process
  - *PGC can also occur through deflagration, but detonation processes are more energetic*
  - *PGC can be represented by the CVC **Humphrey cycle** and does not depend on detonation*
    - Combines the Otto and Brayton cycles







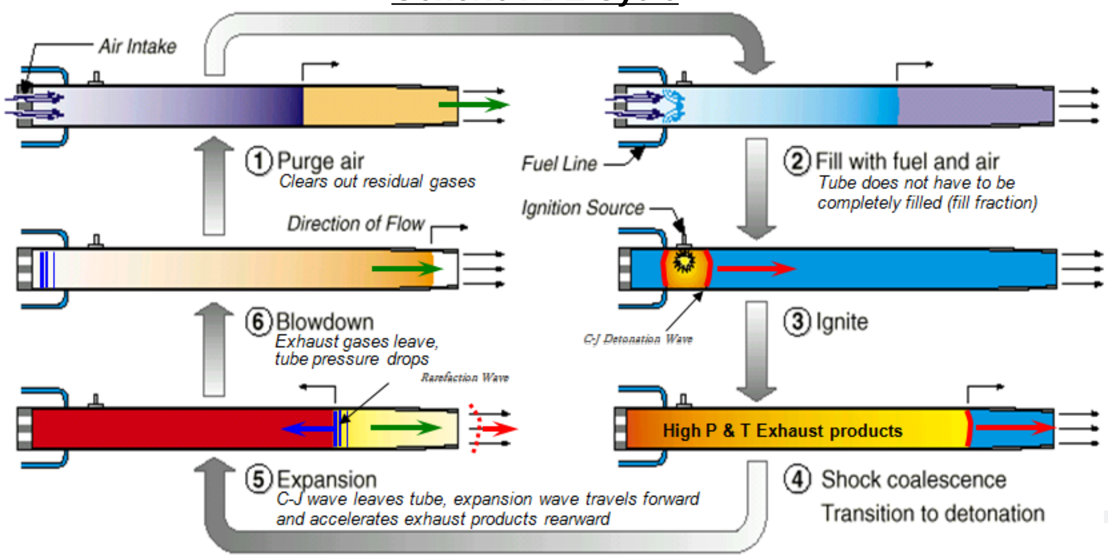




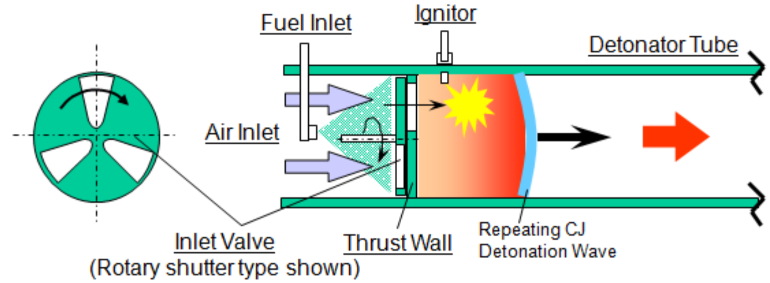
Pulse Detonation Engines (PDE) - 1

- A **single, axially-traveling detonation** wave is initiated at the closed end of a tube partially filled with combustible mixture. The hot, high-pressure products then accelerate out of the device (sometimes through a nozzle). The remaining gases are purged and the process repeats in a cyclic manner (typically between 15-80 Hz)
- PDEs are not self-aspirating, can not self-ignite and are not steady-state machines
- PDEs require complex, oscillatory subsystems (valves, plumbing, ignition) to sustain operation
- **Dozens of gov't, industry and academic experimental programs** have analyzed PDEs to:
  - *Explore the operational challenges of **various liquid and gaseous propellants***
  - *Validate complex thermodynamic models*
  - *Anchor unsteady detonation combustion chemistry codes*
  - *Examine the effects of inlet and exhaust nozzle geometry on performance*
  - *Identify and address the challenges with **downstream hardware integration** (i.e. turbines)*
  - *Explore mitigation techniques for **autoignition***

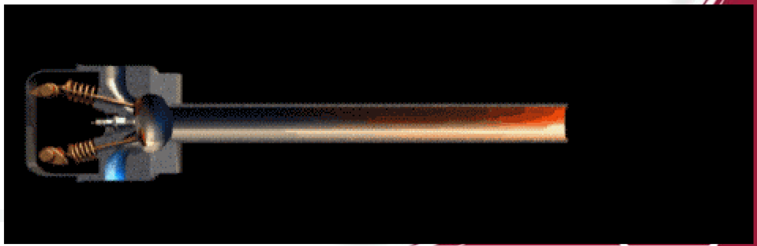
Generic PDE Cycle



Basic Parts of a PDE



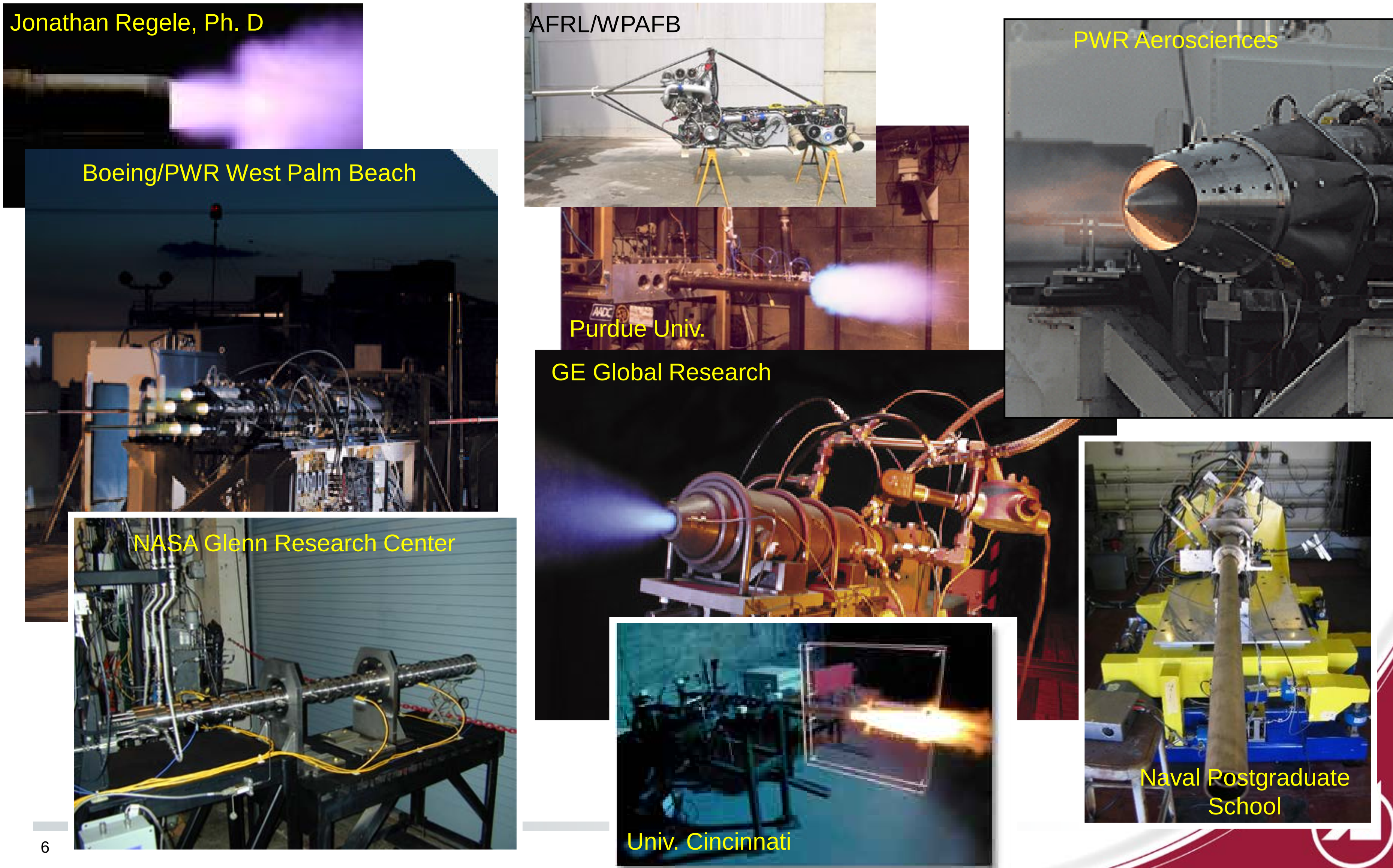
PDE Cycle Animation



Based on F. Schauer's PDE Test Rig at AFRL/WPAFB

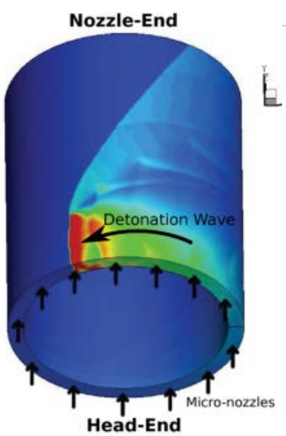
Pulse Detonation Engines - 2

- Below are (dated) photos of just a few of the **working** engines
- **PDEs were successfully flight tested** in January of 2008 (see Supplemental Information)

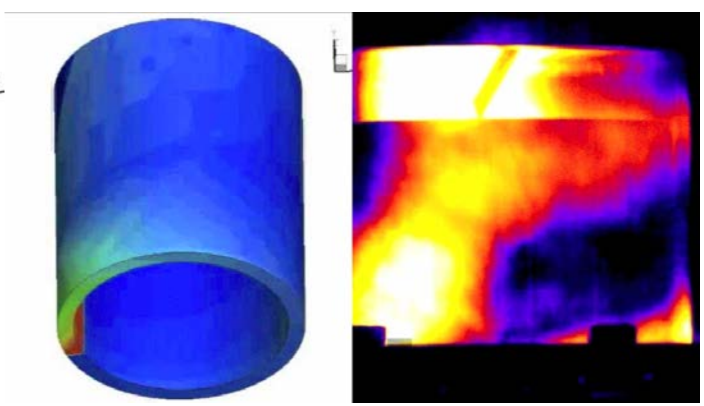


Rotating Detonation Engines (RDE) - 1

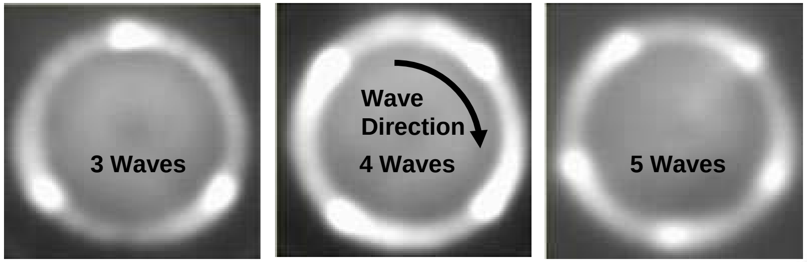
- **Single or multiple detonation waves tangentially travel** around an annulus that is continually filled with combustible mixture. After detonation, the hot, high-pressure gas then accelerates out of the device. Continuous injection of propellants around the annulus feeds and sustains the detonation waves. No purging is needed.
- RDEs are not self-aspirating and only require a single ignition event (to start)
- RDEs do not oscillate or pulse. Their subsystems can operate at a steady-state condition
- **Dozens of gov't, industry and academic experimental programs** have analyzed RDEs to:
  - ***Accomplish the same intents as for PDE research, and*** *(among many others)…*
  - *Explore low pressure loss* ***injection schemes***
  - *Determine RDE behavior with various liquid and gaseous propellants*
  - *Examine methods to mitigate detonation expansions traveling into the injector*
  - *Understand the influences on wave preferential direction, multiple wave creation and coalescence*
  - *Determine nozzle effects and basic performance*
  - *Characterize the operational parameters (equiv. ratios, flow rates, etc.) and sensitivities*

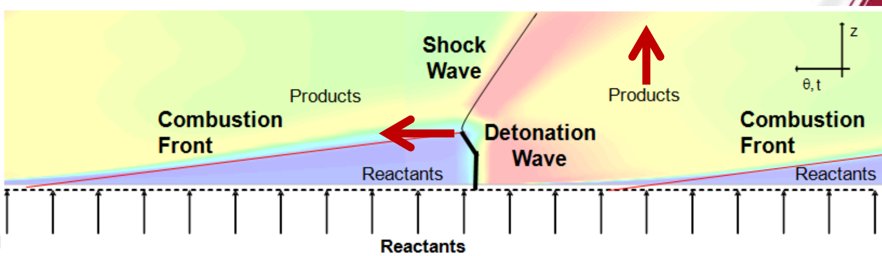


RDE Cycle Animation

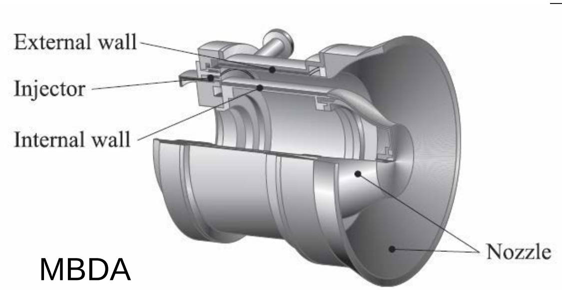


Wave Structure Inside an RDE

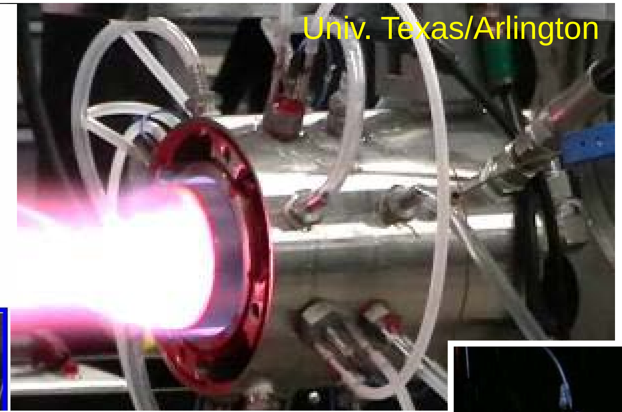




Rotating Detonation Engines - 2



MBDA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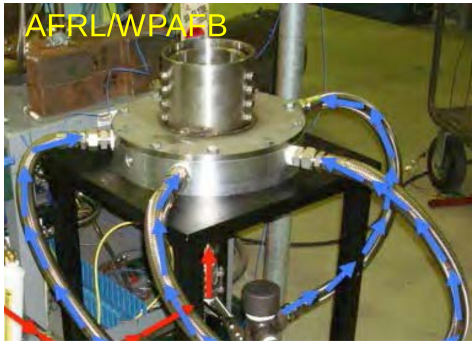
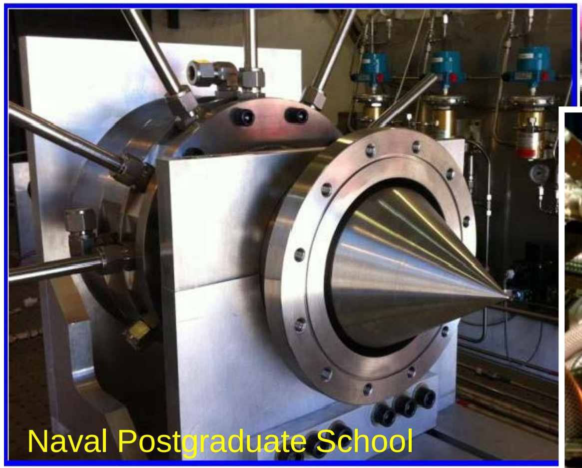
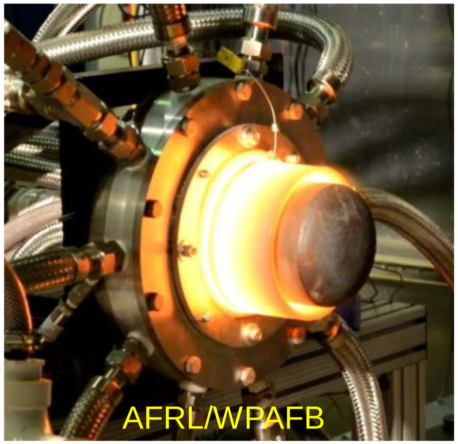

AFRL/WPAFB


Naval Postgraduate School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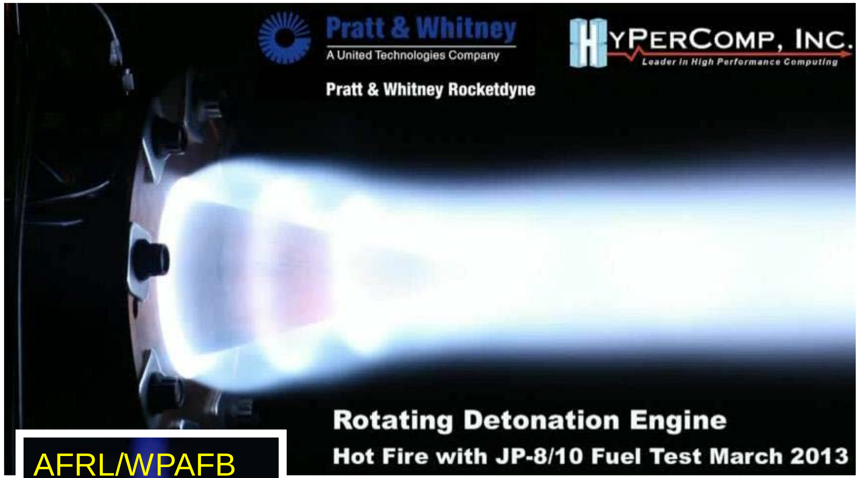
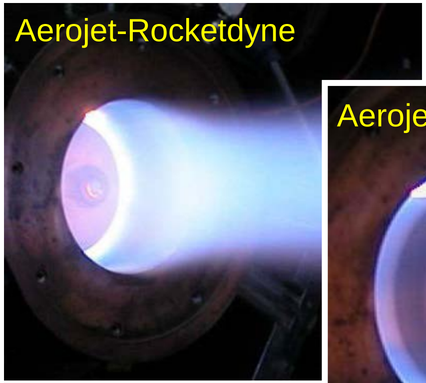
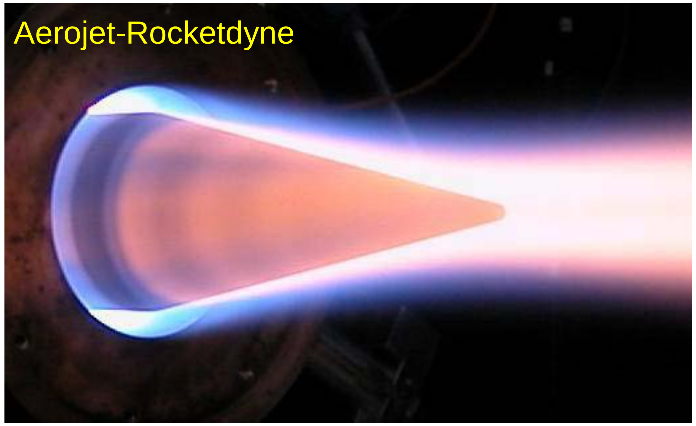
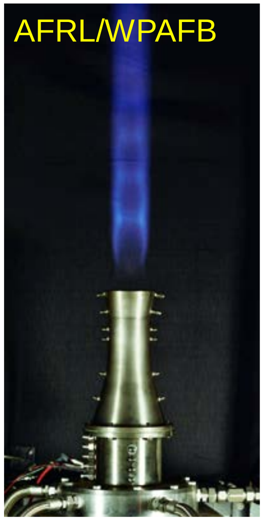



Aerojet-Rocketdyne


Aerojet-Rocketdyne


AFRL/WPAFB

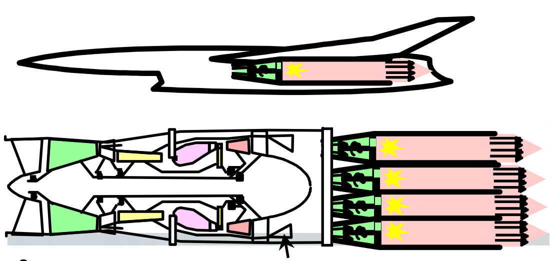
Why Do Detonation PGC?

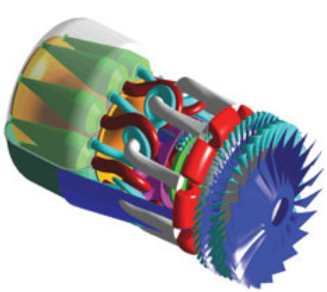
General:

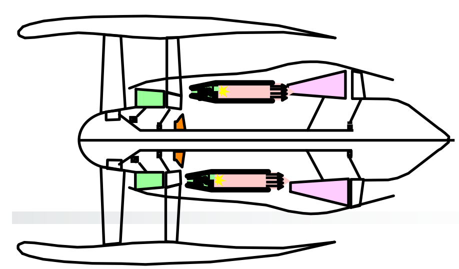
- **Operating pressures and temperatures** similar to those of modern gas turbine cores and rocket engines can be achieved with **~30% higher efficiencies** and **no turbomachinery**
  - *Outlet pressures of **300 psi or greater***
  - *Outlet temps of **3000K or greater***
  - *Exhaust velocities ranging between **M=3 and M=5** (typ. C-J velocity depending on propellants)*
- Detonation PGC can be configured to employ **very few or no moving parts** (RDE)
  - *Significant reduction in cost, weight and reliability risk*
- **Multiple fuel/oxidizer capability** can permit dual-mode operation (air-breather/rocket)
- **"Easy" to build and test** with COTS technology since no turbomachinery involved
  - *Commonly done and demonstrated even at the academic level*
- **"Simplified" cooling issues** due to periodic operation
  - *Peak temps reached only for fractions of a second as detonation wave passes*
- **Throttleable, restartable,** broad operational equivalence ratio range and tolerant to inlet condition dispersions (as long as they remain detonable)

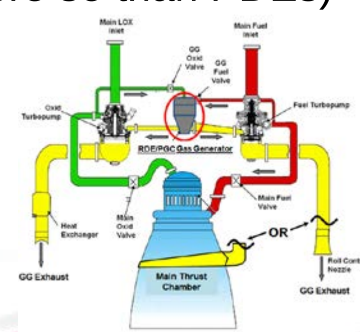
Application:

- Main applications are for **direct thrust production** or as a **gas generator** to drive a turbine
- **Potentially higher thrust-to-weight** than aircraft gas turbines (depending on reference)
- Theoretical **flight velocities of Mach 4+** are possible (for aircraft applications)
- Specific impulse, I_{SP}, **could exceed 500 seconds** (for rocket applications)
- **Versatile geometry** for packaging and vehicle integration (RDEs more so than PDEs)







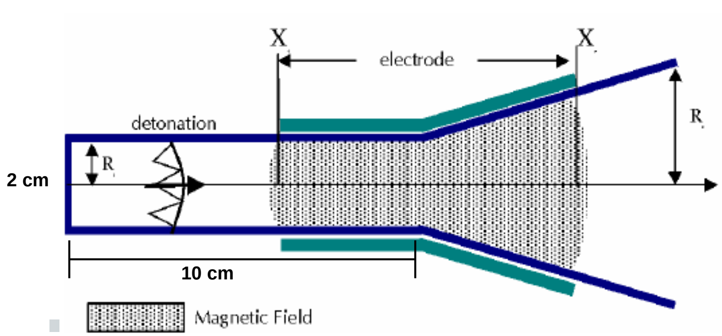


Merging PDEs with MHD Power Generation - 1

- Since PDEs are absent of shaft power or usable bleed flows, several past efforts explored using MHD to provide **power for PDE ignition or ancillary subsystems**
- The combustion kinetics following a detonation wave create a short-lived, structured plasma with **favorable electron density** and **high ionization potential** (seeding)
  - *Detonation combustion yields higher electron density than deflagration (good for plasma energy), but also higher pressures (bad for plasma residence time)*
- Detonation PCG yields **high thermal energies, detonation wave speeds and exhaust flow velocities**
- These provide favorable characteristics for incorporating MHD processes for flow control, **power generation** or performance enhancement

Cambier, J. -L., MSE Technologies, 1998 (AIAA 98-3876)

- *Numerical study of feasibility, energy output, scaling approximations, parametric analysis (field strength, nozzle geometry, etc.) and effects on PDE performance (thrust)*
- *Assumed H_2-air with 1% mole fraction cesium seed uniformly mixed in fully-filled tube*
- *Preliminary results were **highly encouraging**:*
- ***Suggested that sufficient energy can be extracted for direct initiation** in some mixtures*
- *Recommended further work on the optimization of the gas conductivity, seed injection, distribution and ionization kinetics*



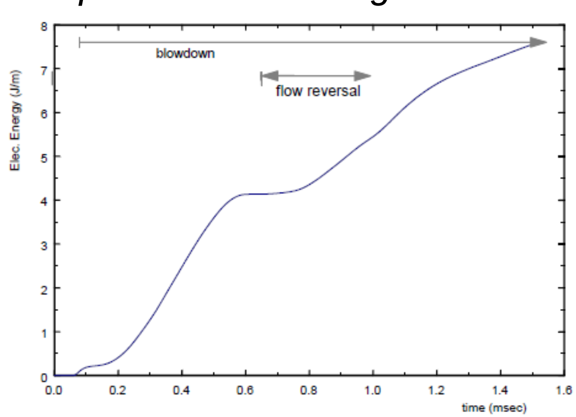


Figure 2: Electric energy versus time, for K=1/2.

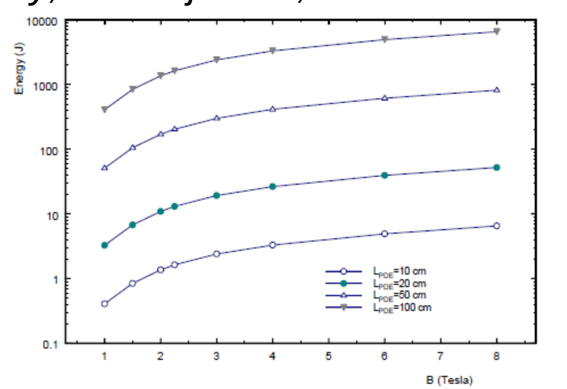


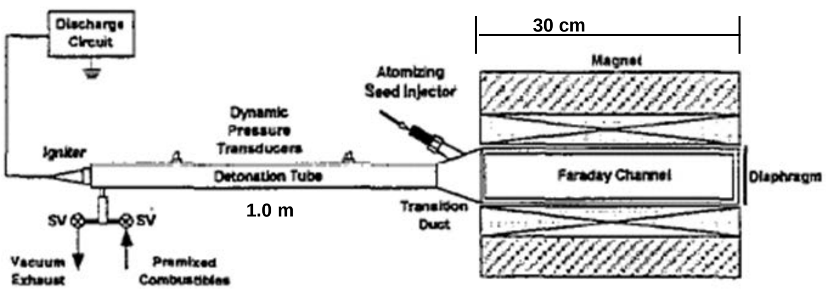
Figure 25: Energy extracted as function of magnetic field for various cases of PDE size. L_{PDE} is the length of the contant area tube section. For L_{PDE}=10 cm, the tube height and width are 2 cm. Both height and width scaled by same amount as L_{PDE}.

Merging PDEs with MHD Power Generation - 2

Litchford, R., ERC Inc. & NASA MFSC, 1998-2002 (AIAA 98-2918, 2002-2231)

- *<u>Empirical exploration</u> of ionization potential, charge density and plasma diagnostics of detonation flows enhanced with conductive species*
- *Oxy-acetylene (at stoich MR) seeded with cesium-hydroxide/methanol spray yielded:*
  p2 /p1 ~ 34; wave speed ~ 2400 m/s; plasma current density ~ 2 A/cm^2; elec. condct. ~ 6 mho/m
- *Faraday channel included an active loading circuit to characterize power-extraction dependence on load impedance while also simulating higher effective magnetic induction*
- *Measured peak electrical energy density ranged from 10 to 103 J/m3 when the effective magnetic induction was varied from 0.6 to 4.2 T*
- *Optimizing the potential drop across electrodes* ***predicts a 5-10x increase in power generation***
- *Continued work (2002) addresses this and further characterizes MHD power generation using H_2-oxygen and a segmented Faraday channel*
- *The* ***highly favorable*** *results support that* ***PDE ignition power can be produced via MHD***
- *Limitations from experiment size and B field strength prevented further work*

1998-1999
ERC Inc.



2001-2002
NASA/MFSC

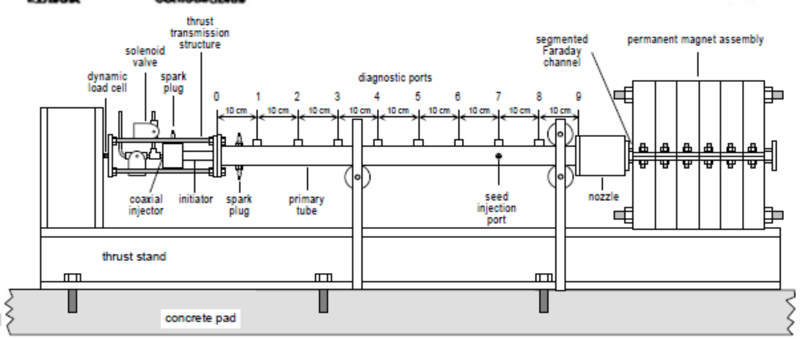
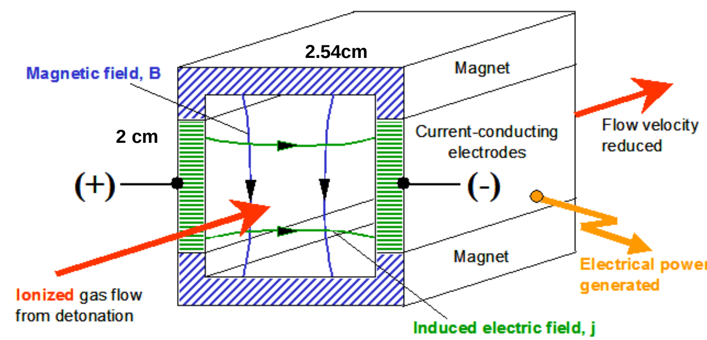


Figure 6: Schematic of fully assembled PDRE-G-2 research engine on the thrust stand with nozzle and MHD generator attached.

<u>Cutaway of Faraday Channel</u>



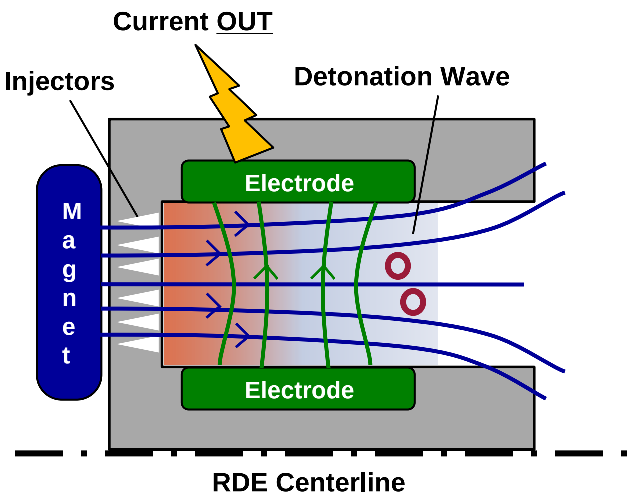
RDEs and MHD

- Experimental efforts have demonstrated that **significant MHD power can be generated via PGC** coupled with a PDE device
  - *Analysis techniques addressed, optimization considered*
- These were the only published projects located by the author that focus on using PGC and MHD power generation
  - *There are many, published, novel concepts that use MHD as a flow accelerator for* ***PDE*** *applications, but these will not be discussed*
- RDEs have become a popular focus of PGC research due to their simplicity, operation and integration potential compared to PDEs
- RDEs offer a high potential for MHD power production over PDEs
  - *Continuous, rotational operation*
  - *Single or multiple detonation/combustion plasma waves*
  - *Quasi-steady-state inlet and flows*
- The next pages will describe conceptual applications for **incorporating MHD into an RDE** for power generation: **RDE Generator**
  - *Electrical power could be generated by the same PGC mechanism that produces high-enthalpy exhaust*
  - *Power would be used for ancillary engine systems or vehicle needs instead of PGC ignition*
- Initially conceived for propulsion applications
- **No analysis has been done** to assess feasibility, power productivity, configuration/layout or impacts to RDE performance
- Two configurations are proposed:

Possible RDE Generator Configurations

Parallel B-Field

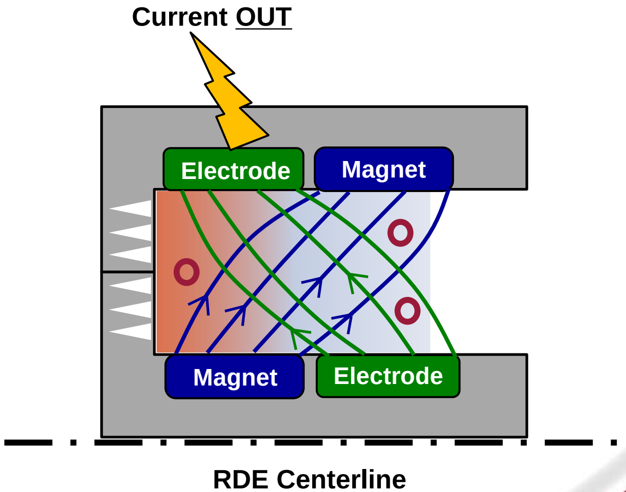
- Easiest to construct
- Magnet not exposed to extreme temps
- May need very strong (i.e. heavy) permanent magnet to produce required B field strength and axial alignment
- May complicate head-end injection/feed systems
- Strong B field could affect detonation wave & combustion dynamics at injector face
    - May positively influence upstream wave coupling
- Need robust electrode material (active cooling?)



<< Det. Wave traveling Normal to Page >>

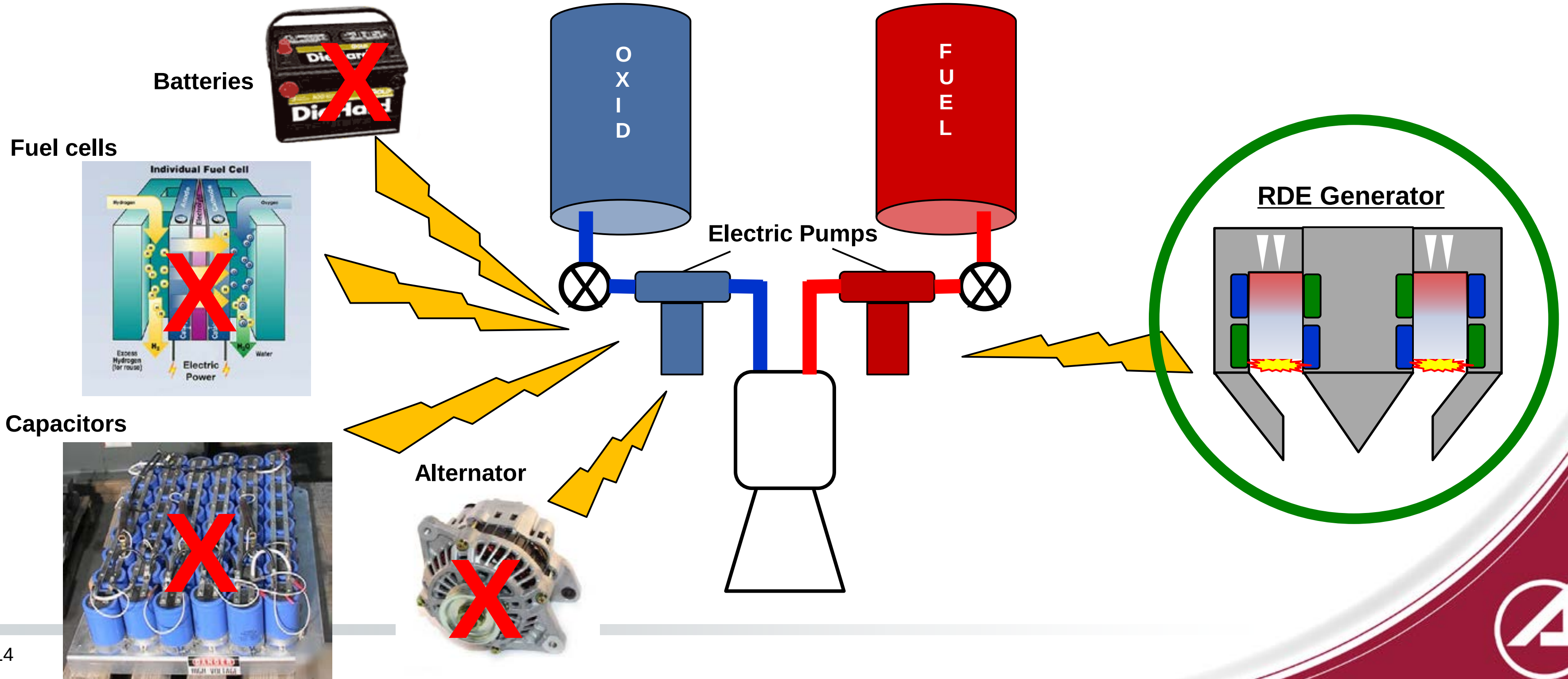
Cross-Flow B-Field

- More complicated to construct
- Uses unique, permanent magnet ring design that enables offset B field
- Head-end injectors/systems not affected
- Field gradients may induce losses along gas flow path
- B fields could be axially distanced from detonation/combustion dynamics at injector face
- Need robust magnet and electrode material (active cooling?)



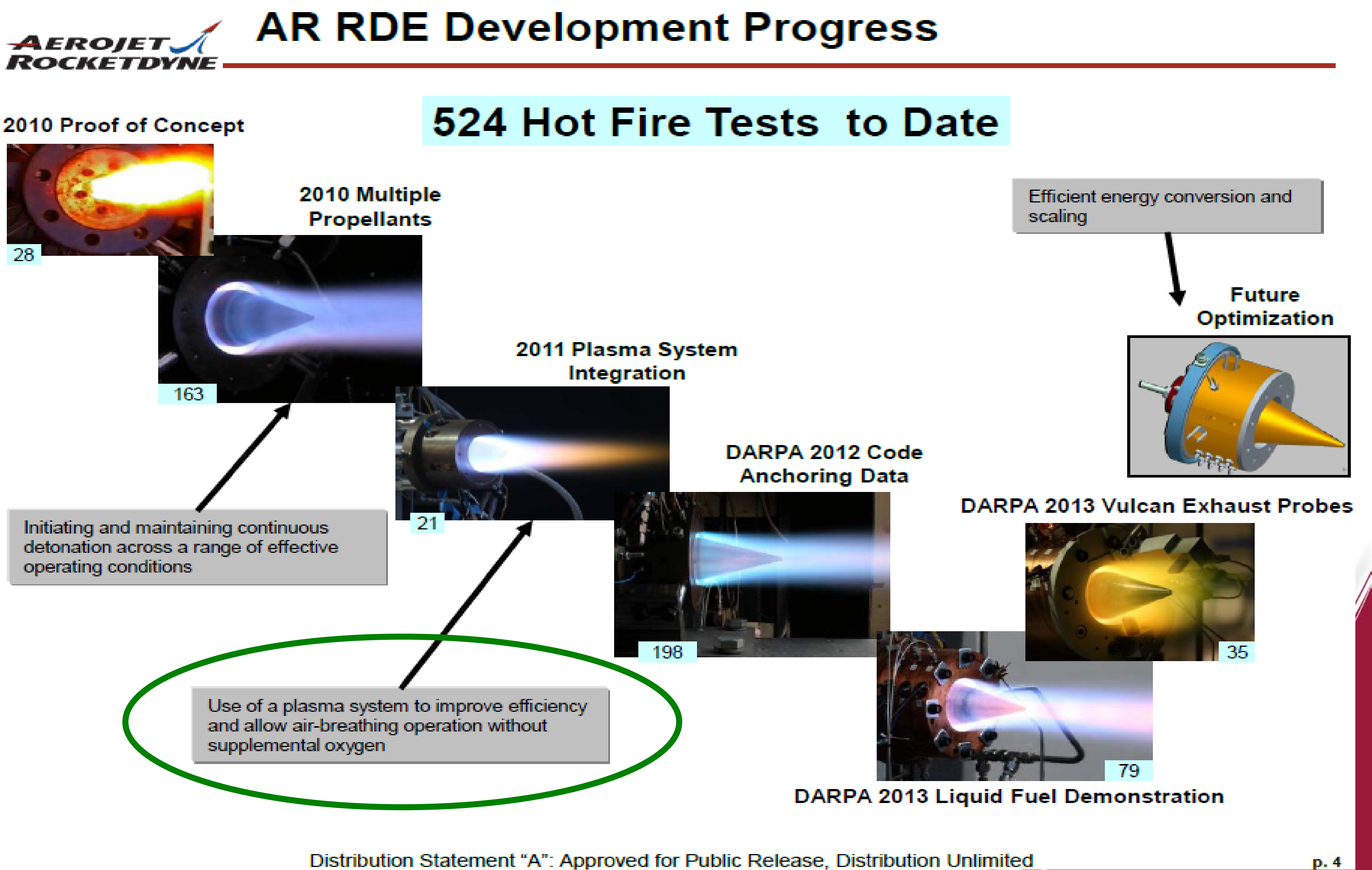
RDE Generator Applications

- When optimized, RDE generators may lend themselves to **compact size** and **relatively low weight** compared to generators of similar power class
  - *Could have many **industrial, transportation, energy or propulsion applications***
- Since this is a relatively new configuration for RDEs, potential applications **have yet to be explored**
- Example: Alternative power source for **all-electric rocket engine** concepts
  - *Use electrically-driven pumps to feed a conventional combustion chamber*
  - *The RDE generator could provide a **high-density, light-weight, continuous-duty, reliable** power source*
  - *High-velocity RDE effluent could also be used to augment engine thrust*



Transient Plasma Injection (TPI) - 1

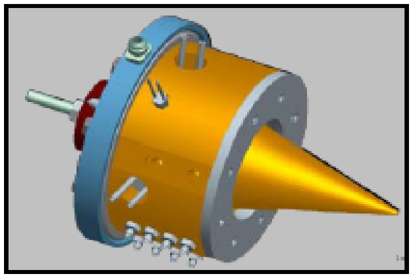
- Aerojet-Rocketdyne experimented with injecting plasma into an RDE to explore potential gains in combustion efficiency with certain propellants
  - *Called* ***Transient Plasma Injection***

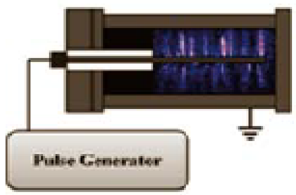


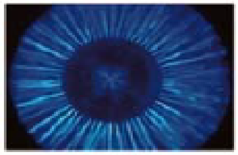
Transient Plasma Injection (TPI) - 2

2011 Plasma Augmentation Tests

- **In 2011, The Power Innovations group successfully conducted 20 tests of an RDE which incorporated a novel plasma augmentation system**
  - **Demonstrated an increase in detonation velocity (efficiency)**
  - **Demonstrated air-breathing operation with minimal supplemental oxygen.**







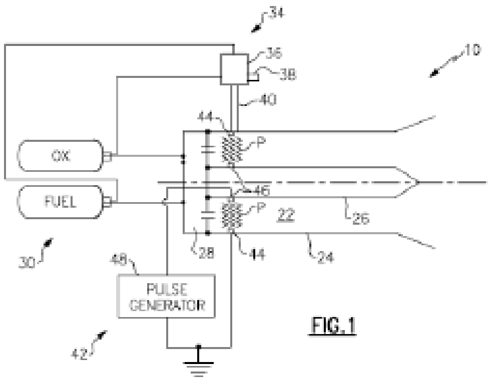
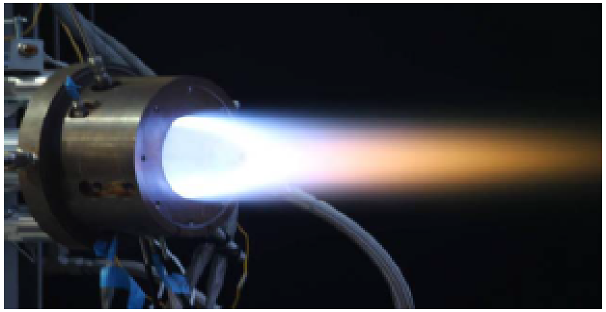
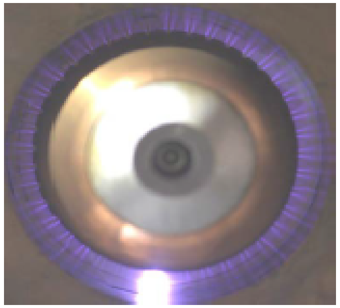


FIG.1





Research Opportunities for PGC-Based MHD Power Gen.

Just a partial list of questions that need to be examined:

- The Chapman-Jouget (C-J) wave speed will be reduced due to kinetic energy extraction via MHD. How does this affect RDE continuous operation, overall pressure rise, flow enthalpy, gas temps, etc.?
- Could the slower wave speed and/or exhaust velocity enable “easier” integration with a turbine?
- Can power be extracted from the C-J wave itself, and if so, what is the axial length/height of the detonation wave from which power could be extracted?
- Can MHD be used on the downstream shockwave to attenuate/augment its characteristics?
- What happens to the C-J wave and pressure wave during MHD power extraction?
  - Do they slow down together (velocity drops, temperature rise across the wave drops, combustion is halted)?
  - Do they decouple (the flame front slows down, ignition delay increases and combustion stops, but the pressure wave keeps going)?
- What power levels can be produced? How “clean” is it? How stable/consistent is it?
- Ionizing the flow enhances MHD effects. How might ionizing the flow affect detonation physics?
- Can the Aerojet-Rocketdyne TPI process be used to seed the flow and enhance plasma ion density?
- How do contra-rotating waves in and RDE affect the MHD system?
- What B field strengths are required? How “big” and heavy are the magnets? And how are they cooled?

Summary

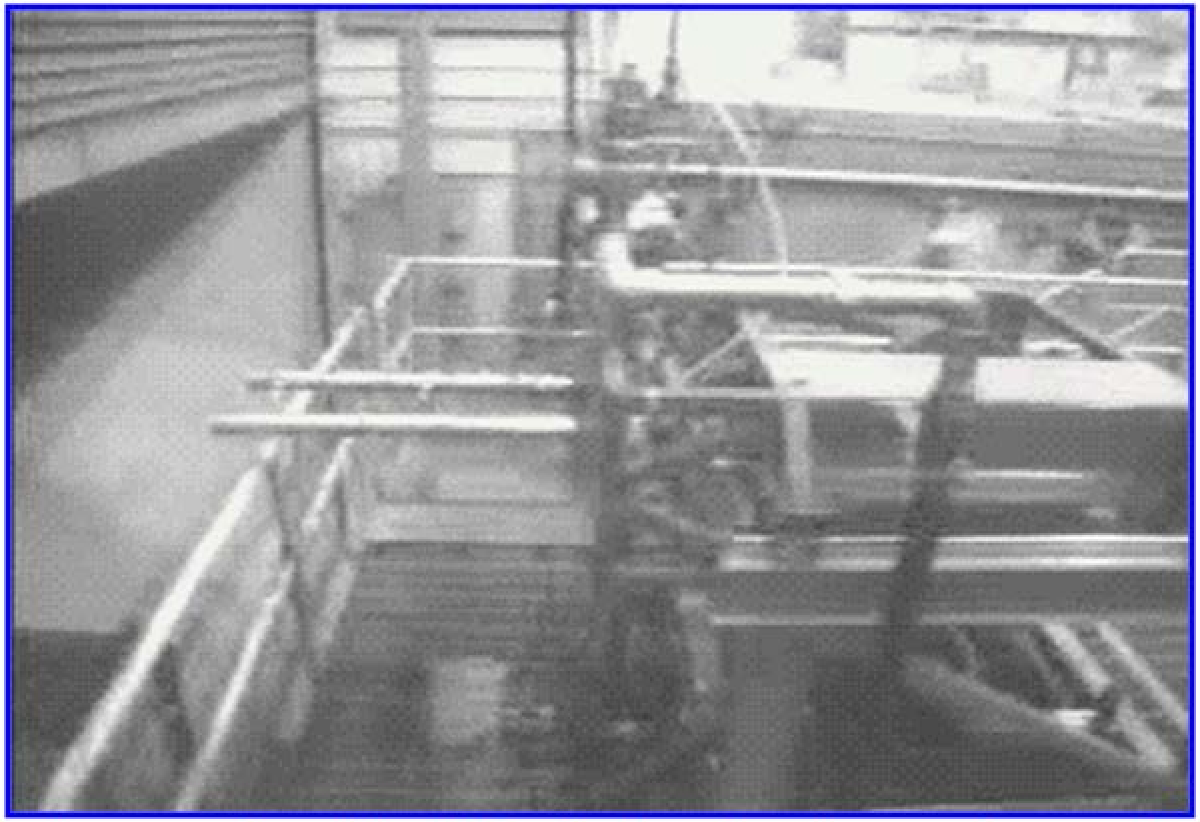
- **PGC yields several favorable characteristics** for coupling with MHD processes
  - *High temperatures, high gas velocities, moderate plasma densities*
  - *Cyclic (PDE) or continuous (RDE) operation*
- Experimental efforts for producing PGC-based MHD power have yielded **highly encouraging results**
  - *Demonstrated production of electrical power for ignition*
  - *Optimization strategies, system challenges and modeling approaches considered*
  - ***No technical or systematic "show-stoppers" have been identified*** *(yet?)*
- PGC power generation may **not be as reliant on performance optimization**
  - *Simplifies design requirements and expands tolerance to sensitivities*
- The RDE Generator concept may offer unique advantages in **energy density, simplicity and power-to-weight** over other power sources or PDE systems
  - *If viable, application studies would need to be performed*
  - *Could enable all-electric or hybrid-electric liquid rocket engine cycles*
  - *RDE Generator* ***may provide power for detonation enhancement*** *concepts (i.e. TPI)*
- **No analysis has been done** to assess feasibility, power productivity, configuration/layout or impacts to RDE performance
- Although not discussed here, concepts exist for **using MHD as a flow control mechanism for PDE systems**
  - *The same approaches may also address some issues unique to RDEs*
- **Plenty of research topics to explore** and questions to answer for power generation applications

If proven viable, detonation PGC in an RDE configuration could be a prime candidate for efficient, compact, reliable MHD power production

Supplemental Info and References

Development and Flight Test of a PDE

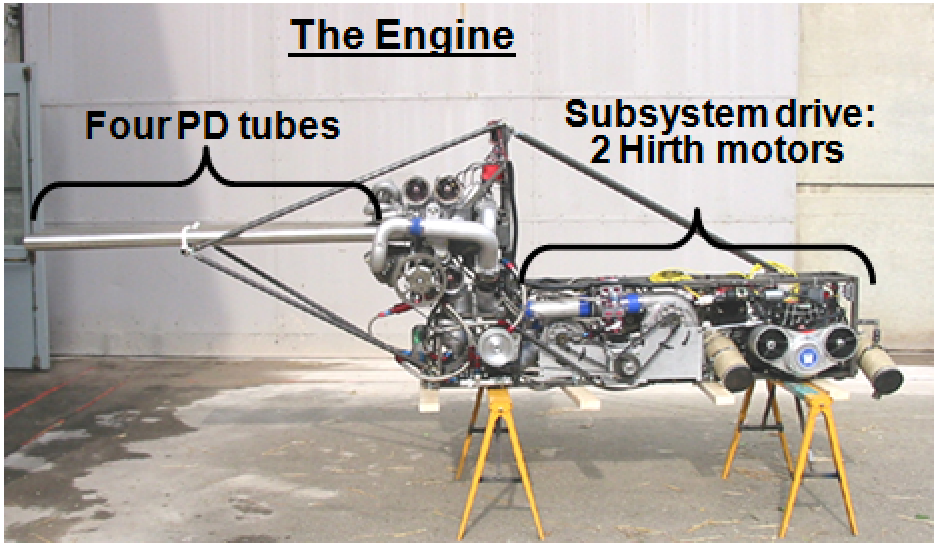
PDE Rig at Wright-Patterson AFB



Rig designed and built by Dr. Fred Schauer (circa 1999)

- Propellants: H_2/Air
- Tube Dimensions: 2 in. dia. x 36 in.
- Operating Frequency: 40 Hz
- Valve system: Cylinder head from a 4-cyl Pontiac engine and driven by an electric motor
- 2 Tubes, Complete fill
- Static Thrust: approx. 20 lbs. per tube
- Ignition: Weak initiation (auto spark) to DDT

Development and Flight Test of a PDE



Successful Flight Test – January 2008, Mojave CA

Successful flight test of PDE occurred in late January 2008. The Long-EZ built by Scaled Composites used a small gas turbine for takeoff, but then transitioned to the PDE once in flight. Flight time was only **tens of seconds**, over the runway and at **60-100 ft altitude**. The purpose was to see if the pilot (Pete Siebold) and airframe could withstand the PDE vibrations. Each of the 4 tubes was operating at **20 Hz** and developed a peak **thrust of 200 lb** to push the aircraft to just over **100 kts airspeed**.

References

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Pg. 5	Pics - Meholic, G., “An Overview of Detonation Propulsion and Applications,” presented at the Advanced Space Propulsion Workshop, CalTech, October 2000. PDE animation - http://www.flightglobal.com/blogs/graham-warwick/Quad4animResized.gif, May 19, 2009.
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Pgs. 13, 14	RDE Generator concepts - Meholic, G. “Potential Applications of RDE Technology in Liquid Rocket Engines,” presented at UCLA RDE Tech. Interchange Mtg., June 2014.
Pg. 15	TPI charts: Provided by Claflin, S., Aerojet-Rocketdyne, September 25, 2014.