Pulse Detonation Propulsion Systems
Introduction

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Outline

1. Introduction
   - ❑ Truths and myths
   - ❑ Who’s Who in PDEs
   - ❑ Overview: comparisons between PDEs, ramjets/scramjets, turbojets, rockets, pulsejets, combined cycles (pros and cons)
   - ❑ Advantages of PDEs
   - ❑ Types of PDEs/PDRs/hybrids
2. Basic Detonation Physics
   - ❑ Chapman-Jouguet, Zeldovich-Neumann-Doring models
   - ❑ Initiation and propagation, including techniques pertinent to pulsed detonation – initiator tube
   - ❑ Detonation enhancement
3. Thermodynamic Cycle Analysis
   - ❑ Ideal
   - ❑ Nonideal
   - ❑ Various other combinations
   - ❑ Single shot v. cyclic studies
4. Review of propulsion principles
5. Overview of experimental and numerical techniques
6. Pulse detonation propulsion systems, configurations, system studies, optimization strategies
   - ❑ System components (technology development) – valves, igniter, nozzles, intakes
   - ❑ Fuel types – gas, liquid, solid
   - ❑ Component integration
   - ❑ Airframe/propulsion integration
7. Conclusions and Outlook

Pulse Detonation Engines

Truths and Myths

In October 1990 Aviation Week & Space Technology published reports of

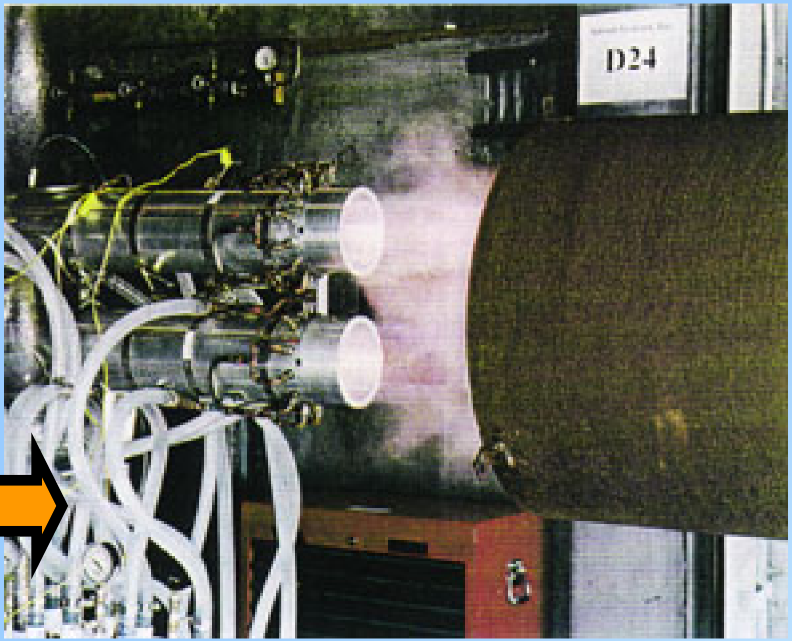
"A high altitude aircraft that crosses the night sky at extremely high speed.... The vehicle typically is observed as a single, bright light -- sometimes pulsating -- flying at speeds far exceeding other aircraft in the area, and at altitudes estimated to be above 50,000 ft.... Normally, no engine noise or sonic boom is heard."

POPULAR SCIENCE - MARCH 1993
OUT OF THE BLACK - SECRET MACH 6 SPY PLANE

An eyewitness description, a secret test site, and a new analysis of advanced aeronautics paint a portrait of Aurora

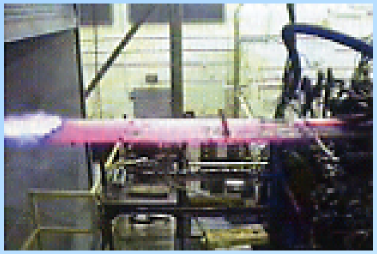
AVIATION WEEK & SPACE TECHNOLOGY

- October 28, 1991, Vol. 135, No. 17, Pg. 68
  PROPULSION TECHNOLOGY; Renewed Interest in Pulsed Engines May Be Linked to 'Black' Aircraft,
  WILLIAM B. SCOTT, LANCASTER, CALIF.
- May 11, 1992; Vol. 138, No. 19; Pg. 62, HEADLINE NEWS;, New Evidence Bolsters Reports Of Secret, High-Speed Aircraft,
  WILLIAM B. SCOTT, LANCASTER, CALIF.
- May 30, 1994, Vol. 140, No. 22; Pg. 17
  INDUSTRY OUTLOOK; PARALLEL PULSE DETONATION WORK, MICHAEL O. LAVITT
- July 4, 1994, Vol. 141, No. 1; Pg. 72,
  HEADLINE NEWS; SWEDE TESTS SUBSONIC PULSE DETONATION ENGINE, WILLIAM B. SCOTT, WASHINGTON
- December 5, 1994, Vol. 141, No. 23; Pg. 11
  INDUSTRY OUTLOOK; SHOTS HEARD 'ROUND THE WORLD, PAUL PROCTOR
- May 4, 1998, Vol. 148, No. 18; Pg. 48
  PROPULSION TECHNOLOGY; NASA Tests APRI Pulse Detonation Tube, Seattle
- May 4, 1998, Vol. 148, No. 18; Pg. 50
  PROPULSION TECHNOLOGY; Rocket PDE Tested, Bellevue, Wash
- May 4, 1998, Vol. 148, No. 18; Pg. 48
  PROPULSION TECHNOLOGY; Pulse Detonation Technologies Advance, PAUL PROCTOR, BELLEVUE, WASH.
- November 8, 1999, Vol. 151, No. 19; Pg. 17
  INDUSTRY OUTLOOK; HITCHING A RIDE, PAUL PROCTOR
- July 17, 2000, ; Vol. 153, No. 3; Pg. 70
  SPACE TECHNOLOGY; ASI Hot-Fires PDRE Powerplant, PAUL PROCTOR, BELLEVUE, WASH.
- November 13, 2000, Vol. 153, No. 20, Pg. 110
  TECHNOLOGY INNOVATION AWARDS; Pulse Detonation Advances on Two Fronts
- February 5, 2001, Vol. 154, No. 6, Pg. 15
  SMART MOVE, EDWARD H. PHILLIPS
- March 8, 2004, Vol. 160, No. 10; Pg. 30
  WORLD NEWS & ANALYSIS; Flights of Fancy, Stanley W. Kandebo, New York



ASI's two-tube pulse detonation engine is shown firing on a test stand. Flexible tubes supply cooling water and exhaust is directed into a noise-abating "safety" tank.

A LongEZ, fitted with a four-tube pulse detonation engine, is expected to make 3-10 flights. The engine will run on standard aviation gasoline during the trials.



Static thrust of the flight test-configured, four-tube pulse detonation engine was measured at Wright-Patterson AFB, Ohio.

- March 8, 2004, Vol. 160, No. 10; Pg. 32
  TECHNOLOGY INNOVATION AWARDS; Taking the Pulse, Stanley W. Kandebo, New York

FLIGHT INTERNATIONAL

AVIATION WEEK & SPACE TECHNOLOGY

Five-tube integrated test rig was run at the Navy's China Lake, Calif., facility. The PDE, reflecting a flight architecture configuration, was used to measure performance.

- September 8, 1999; NEWS; Pg. 7
  NASA SELECTS PROJECTS TO PAVE WAY TO FUTURE TECHNOLOGIES
- May 9, 2000; SPACE NEWS; Pg. 32
  NASA STUDIES PULSE DETONATION ENGINE
- August 22, 2000; NEWS; Pg. 8
  BOEING SECURES NASA PDE TECHNOLOGY CONTRACT
- March 5, 2002; OTHER NEWS; Pg. 39
  PULSE DETONATION USAF PLANS SELF-STARTING SYSTEM FOR HYBRID ENGINE
- March 5, 2002; DEFENCE: NEWS; Pg. 26
  PROPULSION GUY NORRIS / LOS ANGELES JAPANESE CONSIDER PULSE- DETONATION POWERED MISSILES
- April 16, 2002; Pg. 32
  FEELING THE PULSE/GUY NORRIS/LOS ANGELES
- June 18, 2002; News; Technology; Pg. 38
  GE fires up pulse detonation engine; Configuration for demonstrator to be decided by 2003 as air-breathing powerplant runs in laboratory environment
- July 23, 2002; News; Defence; Pg. 32
  Team push to extend PDE risk-reduction programme;
  Partners say work aimed at long-range missile could be switched to other applications
- August 20, 2002; News; Technology; Pg. 24-25
  More studies for pulse afterburner
- February 4, 2003; News; Technology; Pg. 32
  Mixed results for pulse detonation; US Air Force technology promises to improve efficiency for high-speed aircraft, but big hurdles remain
- March 25, 2003; News; Technology; Pg. 28
  Pulse detonation engine moves closer to reality; P&W-led team developing powerplant for possible use in supersonic strike missiles
- June 17, 2003; Features; Propulsion; Pg. 50
  Deep in the Californian desert, engineers are working on a project that could revolutionise the next generation of supersonic and subsonic craft.
- July 29, 2003; News; Headlines; Pg. 5
  Pulse detonation engine set to fly: Historic flight aims to prove PDE engines produce thrust
- September 9, 2003; Features; Future of Flight; Pg. 40
  Thrust forward; The next century of propulsion promises ground-breaking advances with steps towards cleaner engines rivalled only by the search for greater speed
- February 17, 2004; News; Technology; Pg. 42
  P&W makes hybrid pulse detonation test proposals; Powerplant is potentially ideal for missile and unmanned combat air vehicle applications
- July 26, 2005; News; Technology; Pulse detonation trials back on

FLIGHT INTERNATIONAL

Features; Propulsion; Pg. 50
Deep in the Californian desert, engineers are working on a project that could revolutionise the next generation of supersonic and subsonic craft.
June 17, 2003

Test firing of five tube PDE

Five tube PDE fitted with compound nozzle.

http://www.pratt-whitney.com/shock-system/flightinternationalmag.html

Features; Future of Flight; Pg. 40

Thrust forward; The next century of propulsion promises ground-breaking advances with steps towards cleaner engines rivalled only by the search for greater speed

September 9, 2003

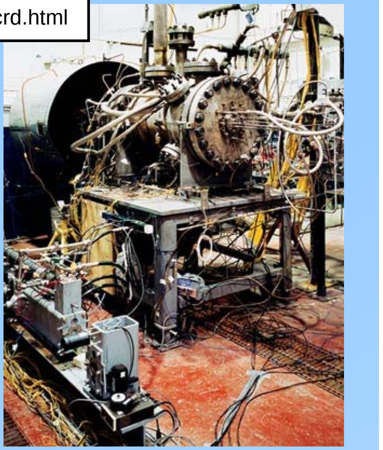
The first 100 years: Propulsion

Guy Norris

1900s
1903 Charles Taylor's four-cylinder lightweight piston engine powers the Wright brothers' first flight
1908 Gnome rotary
1910s
1917 Liberty V-12
1920s
1925 Pratt & Whitney runs first engine, the nine-cylinder Wasp radial
1926 Armstrong Siddeley Jaguar -- first use of supercharging
1930s
1936 Rolls-Royce Merlin -- more than 150,000 eventually built
1937 First runs of Whittle turbojet and Von Ohain He S1 turbojet
1938 Hamilton Standard constant-speed feathering propeller
1939 Jet-powered He 178 flies for first time
1940s
1940 Jendrassik Cs-1 -- first turboprop to go on test
1943 Argus propulsive pulsejet engine powers V-1
1944 Gloster Meteor 1 and Messerschmitt 262 twinjets enter service
1945 Rolls-Royce Trent -- first turboprop to fly
1950s
1952 Kuznetsov NK-12 -- most powerful turboprop of 20th century
1953 Rolls-Royce thrust measurement rig "Bedstead" -- first jet VTOL
1959 Pratt & Whitney Canada runs first PT6 free-turbine turboprop
1960s
1963 Pratt & Whitney J58 -- first sustainable Mach 3 engine
1964 Pratt & Whitney JT8 -- most produced commercial turbofan
1966 Pratt & Whitney JT9D -- first high bypass-ratio turbofan
1970s
1974 First GE/Snecma CFM56 demonstrator runs
1980s
1986 General Electric GE36 unducted fan flies
1990s
1990 Pratt & Whitney YF119-powered Lockheed YF-22 supercruises
1994 Progress D-27 propfan flies on An-70
1998 Tests start on STOVL F119 variant with lift fan for JSF
2000s
2002 Revolutionary Turbine Accelerator contracts issued
2003 Pratt & Whitney hypersonic scramjet reaches Mach 6.5 in ground tests
General Electric GE90-115B reaches record thrust level of 127,900lb
First Pulse Detonation Engine-powered aircraft flight attempted

POPULAR science

http://www.popsci.com/popsci/aviationspace/e46d5b4a1db84010vgnvcm1000004eecbccdrcrd.html



Photograph by C. Morlinghaus

SOUND & FURY
GE's pulse-detonation test rig, ready for firing. Is this the engine of the future?

After Combustion: Detonation!

The race heats up to replace the jet turbine with a more efficient source of Mach-breaking airpower: the pulse-detonation engine.

By Jim Kelly | August 2003

Image Gallery
August 4, 2003

Gentlemen, Start Your Engines ...

Those attending Experimental Aircraft Association's AirVenture air show held July 29-August 4 in Oshkosh, Wisconsin, got a look at a pulsed detonation engine. The engine is often tied to classified aircraft, particular the mysterious Aurora Project.

The engine was on review at the air show, displayed by the Air Force Research Laboratory (AFRL) from Wright-Patterson Air Force Base in Ohio. On hand to explain the pulsed-detonation engine being shown was its creator, AFRL's Fred Shauer.

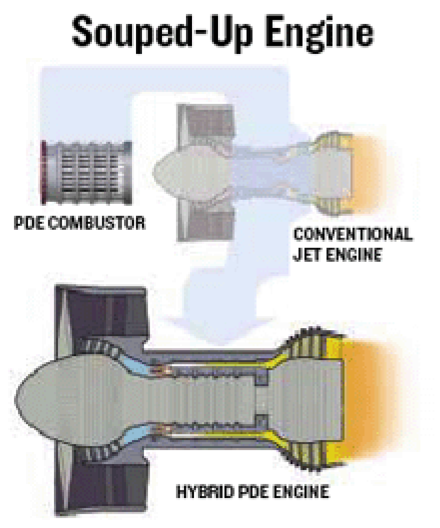
The engine on display -- built from mostly off-the-shelf automotive parts -- was touted as a test bed for future engines that will be capable of powering aircraft to speeds of up to Mach 4. In its final form, this type of detonation engine could make aircraft faster, lighter and more maneuverable.

A pulsed-detonation engine creates propulsion by using a string of controlled explosions of fuel and air in detonation tubes that look like long exhaust pipes. Shauer and his team have developed a method to burn the fuel and air in a way that increases the intensity of the explosions, providing increased thrust that could power future aircraft to speeds of up to Mach 4, or four times the speed of sound.

-- Leonard David

http://www.space.com/imageoftheday/image_of_day_030804.html

Forbes.com



Today's commercial aircraft engine will be replaced by Nazi-era technology in the next decade. We'll be f s.
The jet engine that powers an aircraft is a pretty distant cousin to the engine that powers a car. But someday thes ay become far more alike. Engineers are tinkering with jets that burn fuel in a sequence of miniature explosions muc engine's pistons.

General Electric and the Pratt & Whitney division of United Technologies, the two largest jet engine makers, have h traditional jet engine technology. Their replacement isthe pulse detonation engine, which propels an aircraft or m controlled detonations--100 per second (a car's V-8 does 33). Pratt and GE are racing to be first, but both say the engines will likely be out in 10 to 15 years.

Today's jet engines suck in air, compress it, combine it with fuel and then ignite the fuel. The air pushes out the b g the turbine blades that power the compressor. The pulse detonation engine dispenses with the compressor and t weight and maintenance. Existing jets can power a commercial aircraft at up to 500mph of airspeed at an altitude uld be able to go at four times the speed and as high as 40,000 feet.

"We'd like to do to the jet what the jet did to the propeller," says Sanjay Correa, who runs engine research for GE in Niskayuna, N.Y. Last year GE Chief Executive Jeffrey Immelt anointed pulse detonation engines as one of six "disruptive technologies," in GE's research pipeline.

Pulse propulsion technology has been around since the 1930s, when Nazi engineers developed it to power the infamous V-1 missiles that blitzed England in World War II. U.S. military engineers built knockoffs from captured parts, but the design received little attention outside the Air Force, where it was used to develop high-speed cruise missiles.

In the 1980s Boeing engineer Thomas Bussing decided to give pulse detonation another spin. "I was really fascinated with the V-1 technology,"he says. "I wanted to make a viable engine out of the idea." Bussing, who has a doctorate in aerospace engineering from MIT, started work on the concept in his Seattle garage. In 1992 he left Boeing to launch an aerospace research arm of the privately held military contractor Adroit Systems. He raised $24 million in private capital and government grants and built his first working pulse detonation engine in 1995.

Pratt & Whitney bought Bussing's business in 2001, invested another $16 million and began working out possible engine configurations. GE quickly followed P&W's lead. Both now have several working prototypes. Pulse engines will use the same materials as conventional jet engines and can be fitted onto the current aircraft fleets. But if they are to reach speeds beyond the sound barrier (761mph), Boeing and Airbus will have to redesign passenger planes completely. In the meantime the new engines will likely be used on cruise missiles and as afterburners to provide extra thrust for conventional supersonic fighter jets. This winter aviation maverick Burt Rutan of *SpaceShipOne* fame plans to fly his Long-EZ plane fitted with a pulse detonation engine built by the Air Force using elements of Bussing's design.

Says GE's Correa: "People need to go to Bangalore or Shanghai. There's this unmet need building up, much like when people first needed to cross the oceans and continents on a routine basis. If you could deliver five times the speed of sound at a reasonable price and without a disastrous effect on the environment, people would like to do this."

http://www.forbes.com/free_forbes/2005/1128/085.html

SPACEFLIGHT NOW breaking news

New millennium concept: Rockets like auto engines
NASA/MARSHALL TECHNOLOGY RELEASE
Posted: Feb. 28, 2000

Artist's drawing of Pulse Detonation Propulsion System. Photo: NASA

http://www.spaceflightnow.com/news/0002/28pulsedetonate/

HOLLYWOOD SCIENCE

http://www.sonypictures.com/movies/stealth/site/

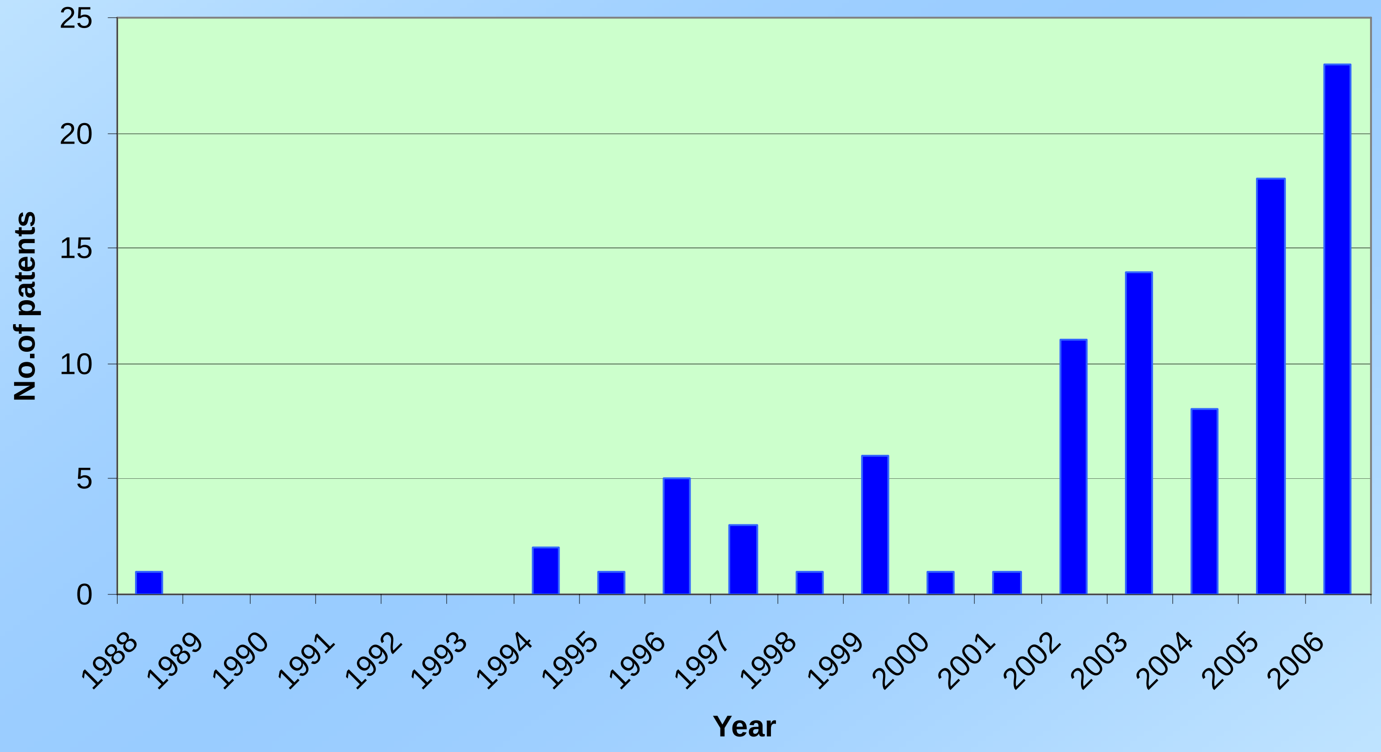
Pulse Detonation Engines

Who’s Who

- NASA, USAF, USN, other DoD
- GE, P+W, Allison (RR), LM, Boeing, small businesses
- Numerous universities

http://memory.loc.gov/cgi-bin/query/r?ammem/gmd:@field(NUMBER+@band(g3201f+ct001916))

U.S. Patents on Pulse Detonation Technologies



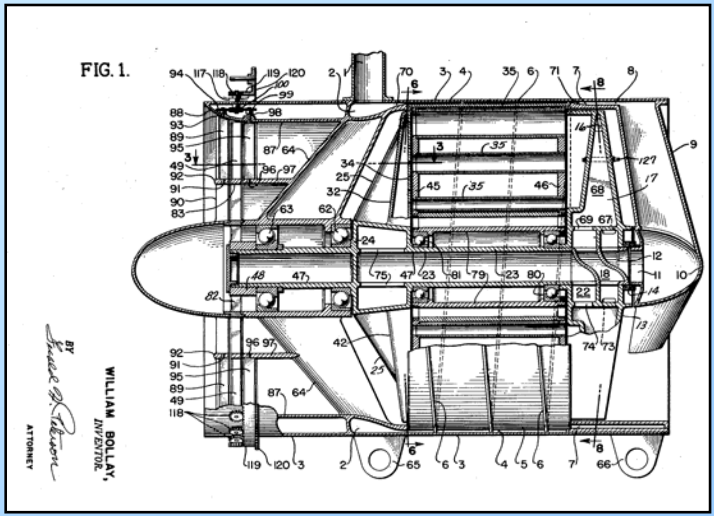
Quotable quotes

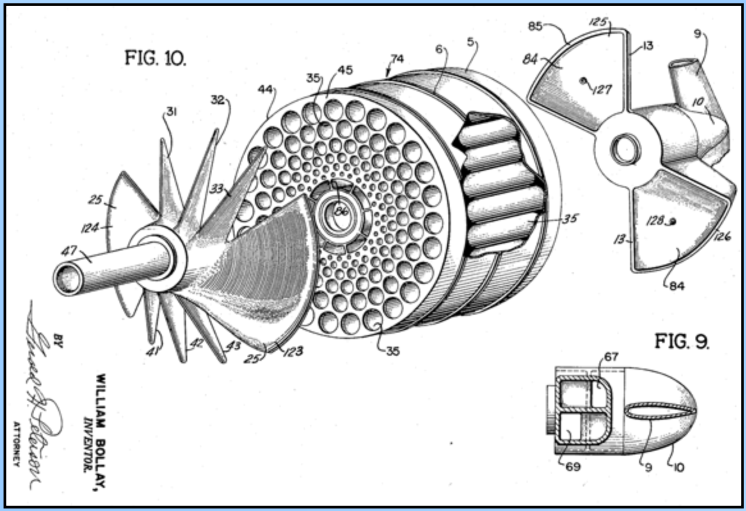
- Joe Doychak, project manager of PDE development technology at NASA Glenn Research Center (GRC) echoes these thoughts. "**The question still remains about if it is a viable propulsion system. There are various aspects that have been demonstrated, but an entire propulsion system itself has never been developed**. The fact is, that it is an unsteady device with gas-dynamic interactions through the inlet to the nozzle - or in other words the entire length of the engine. This means you don't know what you've got until you put the whole engine together."

- "We have one engine running and producing thrust in a lab environment," says GE advanced engine program's general manager Mike Benzakein. "It is going to take a lot of work, but **the potential is terrific**," he adds. The PDE concept, although rumored to have been developed for classified US defense programs, has yet to be proven as a viable propulsion option for applications such as missiles, manned and unmanned aircraft.

- "**Each step is critical**," says P&W Seattle Aerosciences Center division manager Tom Bussing. "It required us to demonstrate the appropriate level of performance and operability at each stage. So far we've worked out the performance of the rotary valve, initiator, combustion tubes and now the nozzle. We're working from left to right through the flow path."

US2942412, June 28, 1960 – Pulse detonation jet propulsion



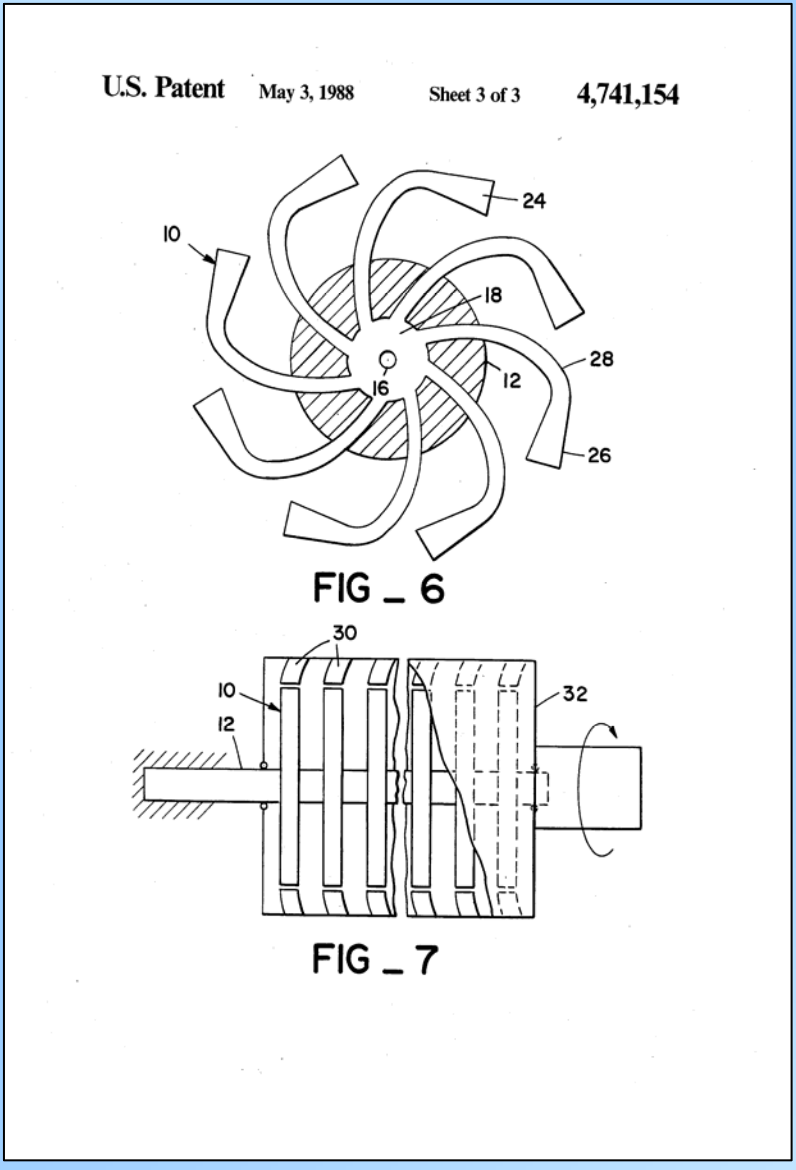


Reviews of “classic” work on PDE development

Bussing, T. and Pappas, G., “Pulse Detonation Engine Theory and Concepts,” in *Developments in High-Speed-Vehicle Propulsion Systems*, ed. S.N.B. Murthy and E.T. Curran, AIAA, 1996, pp. 421–472

Lynch, E.D. and Edelman, R.B., “Analysis of the Pulse Detonation Wave Engine,” in *Developments in High-Speed-Vehicle Propulsion Systems*, ed. S.N.B. Murthy and E.T. Curran, AIAA, 1996, pp. 473–516

US4741154, May 3, 1988 – Rotary detonation engine

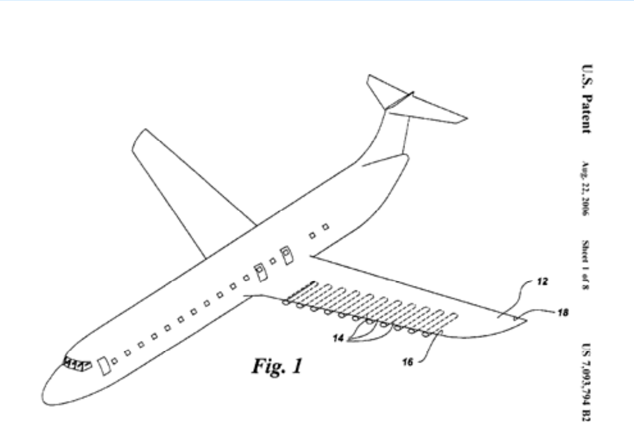


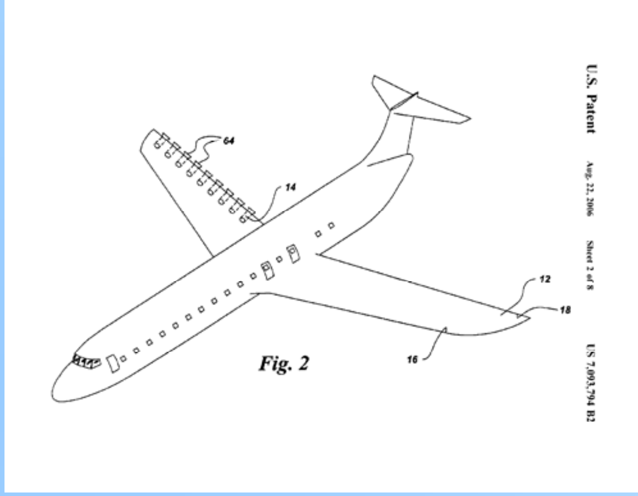
U.S. Patent May 3, 1988 Sheet 3 of 3 4,741,154

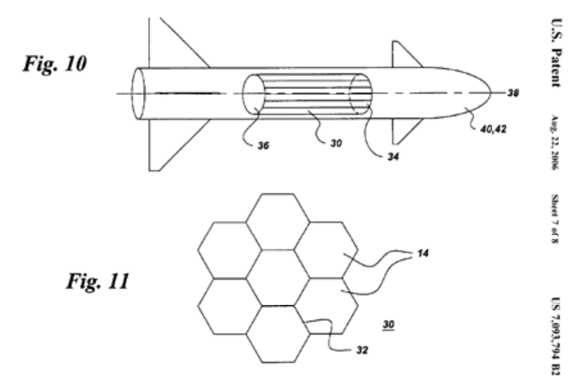
FIG _ 6

FIG _ 7

US7093794, August 22, 2006 – Aircraft and detonative engine incorporating pulse detonation engines







EP 1557356A1, July 27, 2005 – Aircraft, particularly small aircraft, having a propulsion system including a plurality of pulse detonation engines (PDEs)

FIG. 1

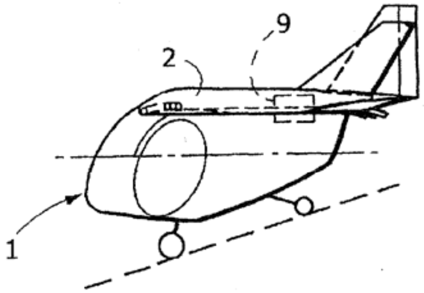


FIG. 2

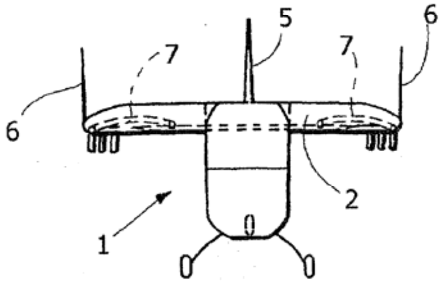
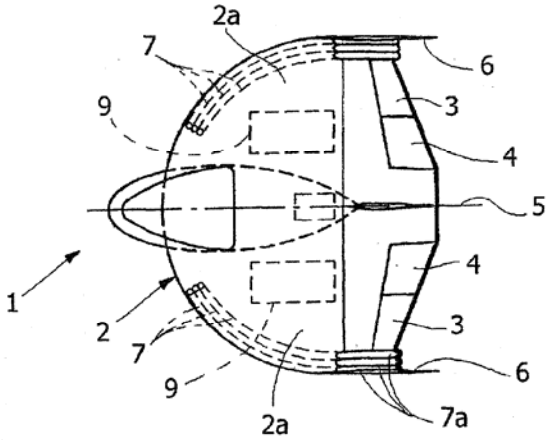
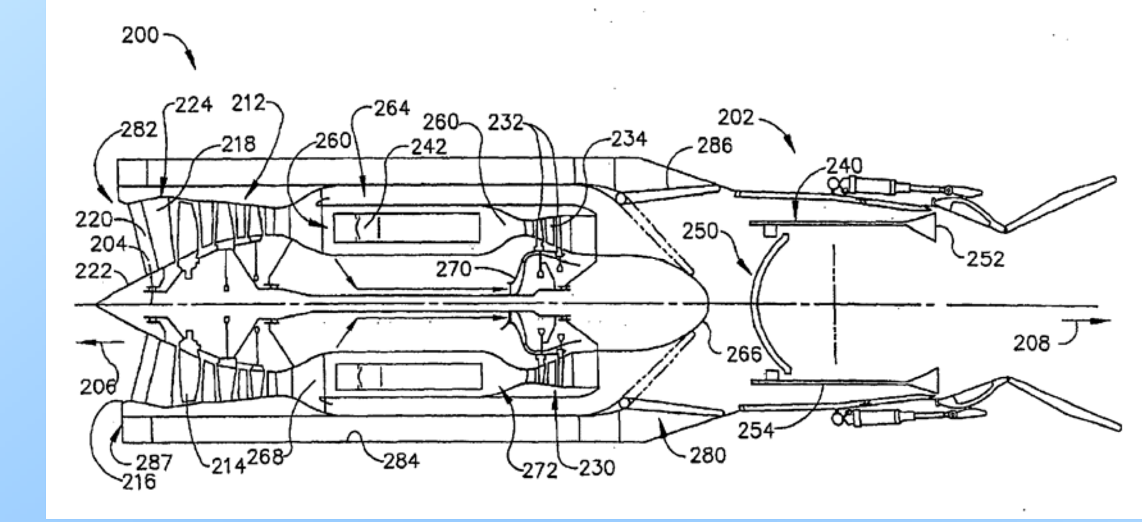


FIG. 3



EP1433946A1, June 30, 2004 – Combined cycle pulse detonation turbine engine



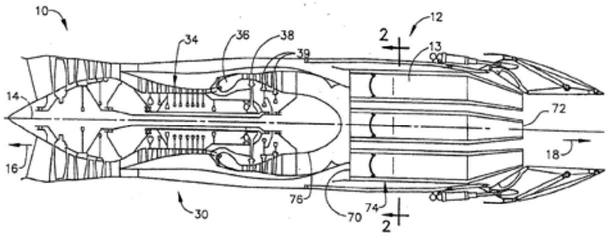


FIG. 1

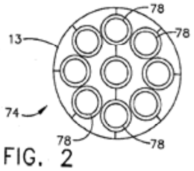


FIG. 2

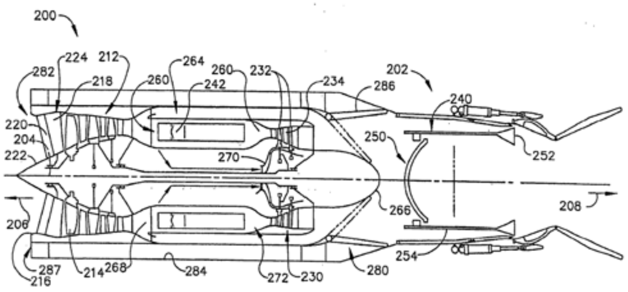
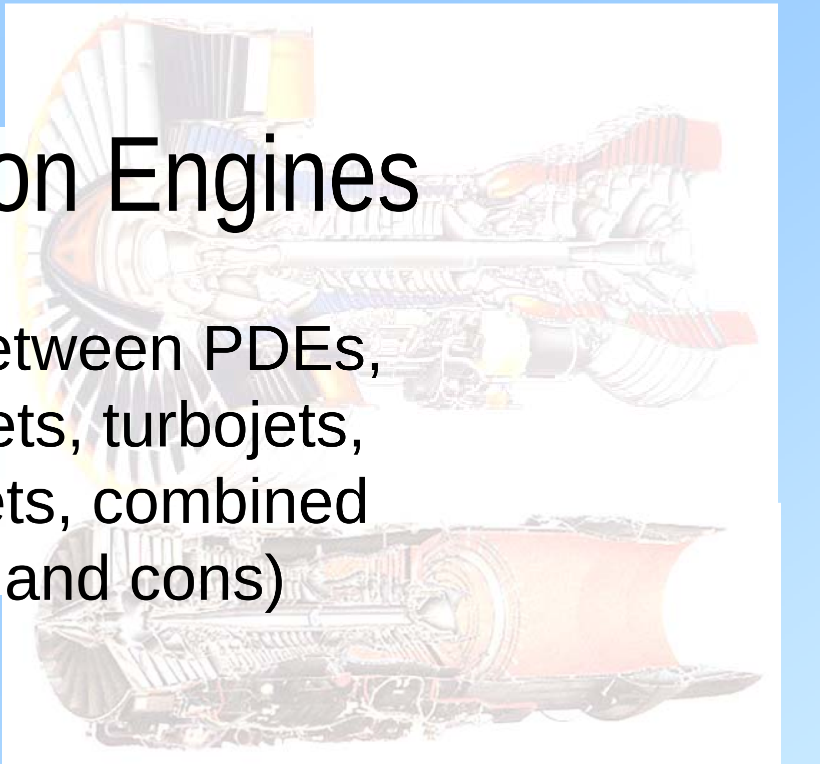


FIG. 4

UTA

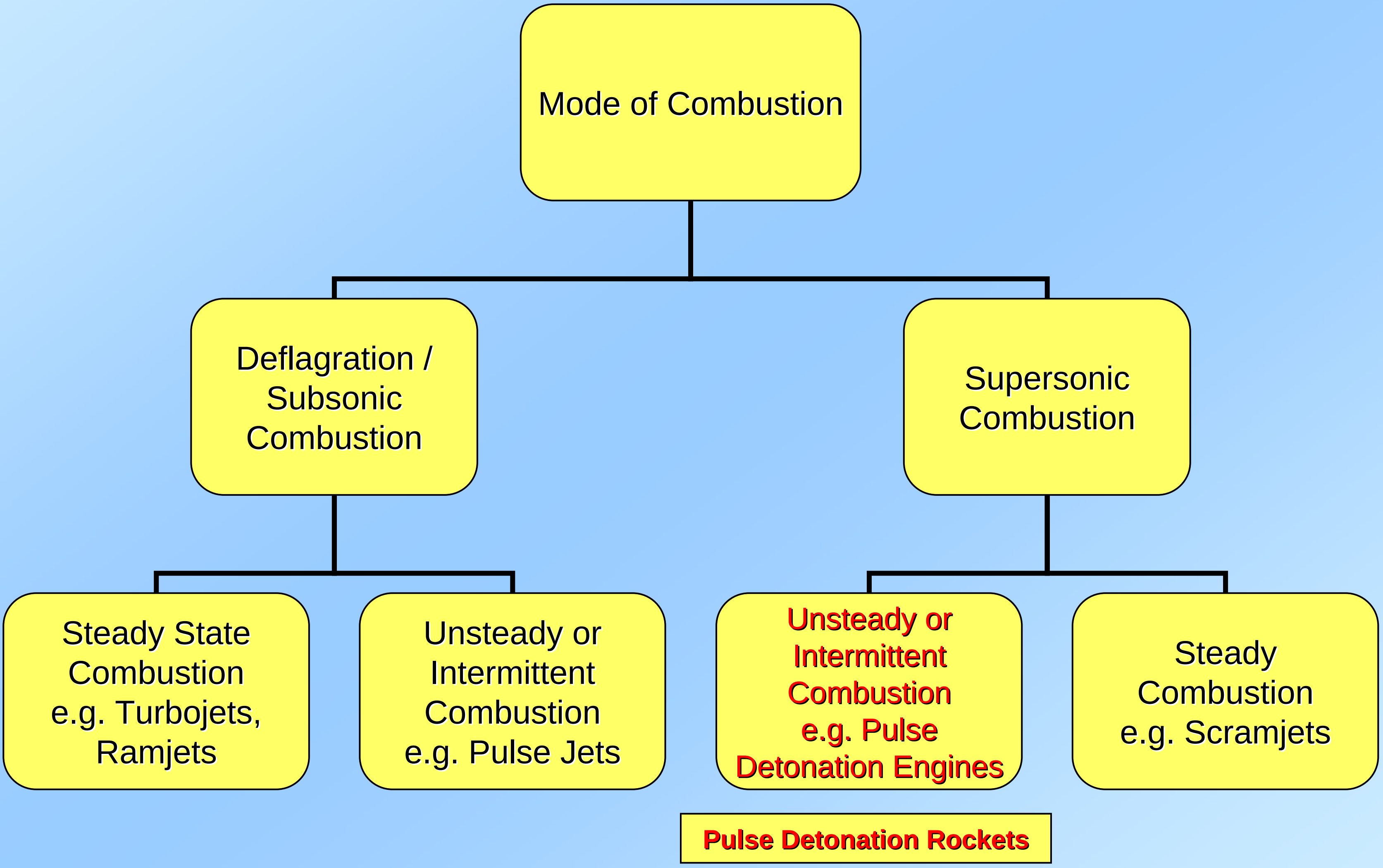
- US 6,857,261: Wilson, D.R. and Lu, F.K., “Multi-mode pulsed detonation propulsion system”
- US Patent Application 20050144959: Lu, F.K. and Wilson, D.R., “Scalable power generation using a pulsed detonation engine”
- IP disclosure 2006: Lu, F.K., Panicker, P.K., Lai, W.-H., Li, J.-M. and Wilson, D.R., “Power production using a hybrid helical detonation device”
- IP disclosures
  - 2006: Lu, F.K., Panicker, P.K., Lai, W.-H., Li, J.-M. and Wilson, D.R., “Power production using a hybrid helical detonation device,”
  - 2006: Lu, F.K., Wilson, D.R., Lai, W.-H. and Li, J.-M., “Detonation reciprocating engine”
  - 2007: Panicker, P.K., Lu, F.K. and Wilson, D.R., “Power production using a hybrid helical detonation device”
  - 2007: Lu, F.K., Panicker, P.K., Ortiz, A.A. and Wilson, D.R., “Aircraft with pulse detonation engine propulsion”

Pulse Detonation Engines

Comparisons between PDEs, ramjets/scramjets, turbojets, rockets, pulsejets, combined cycles (pros and cons)

Air Breathing Engines



Mode of Combustion

Deflagration / Subsonic Combustion

Supersonic Combustion

Steady State Combustion e.g. Turbojets, Ramjets

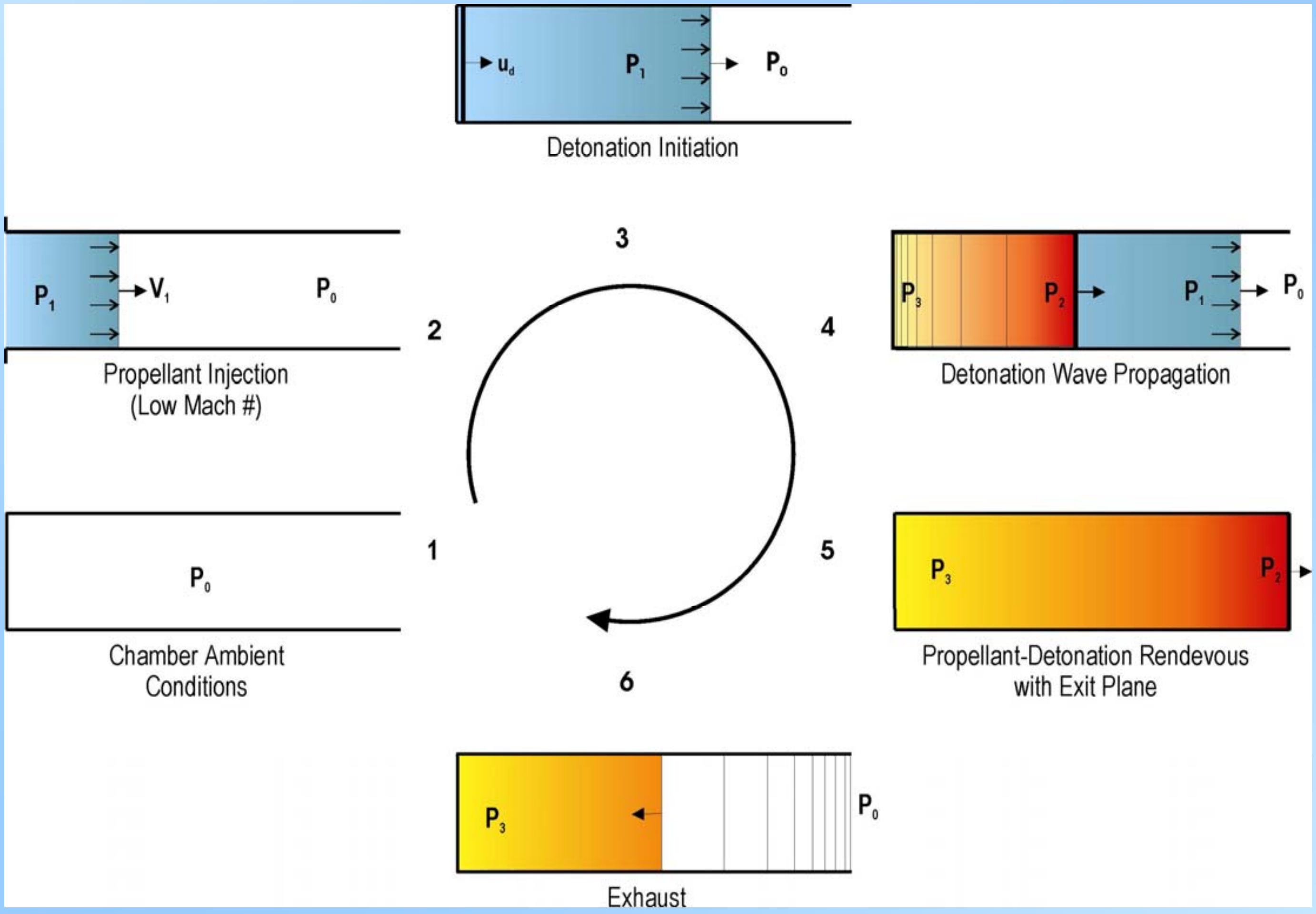
Unsteady or Intermittent Combustion e.g. Pulse Jets

Unsteady or Intermittent Combustion e.g. Pulse Detonation Engines

Steady Combustion e.g. Scramjets

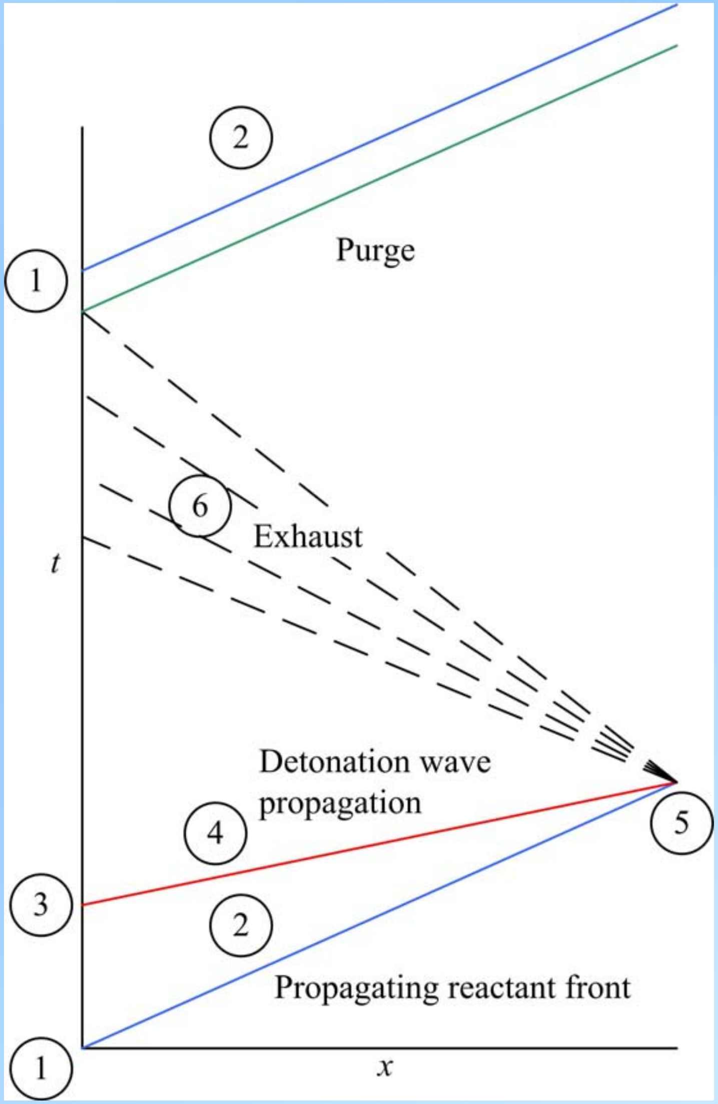
Pulse Detonation Rockets

Basic Pulse Detonation Cycle

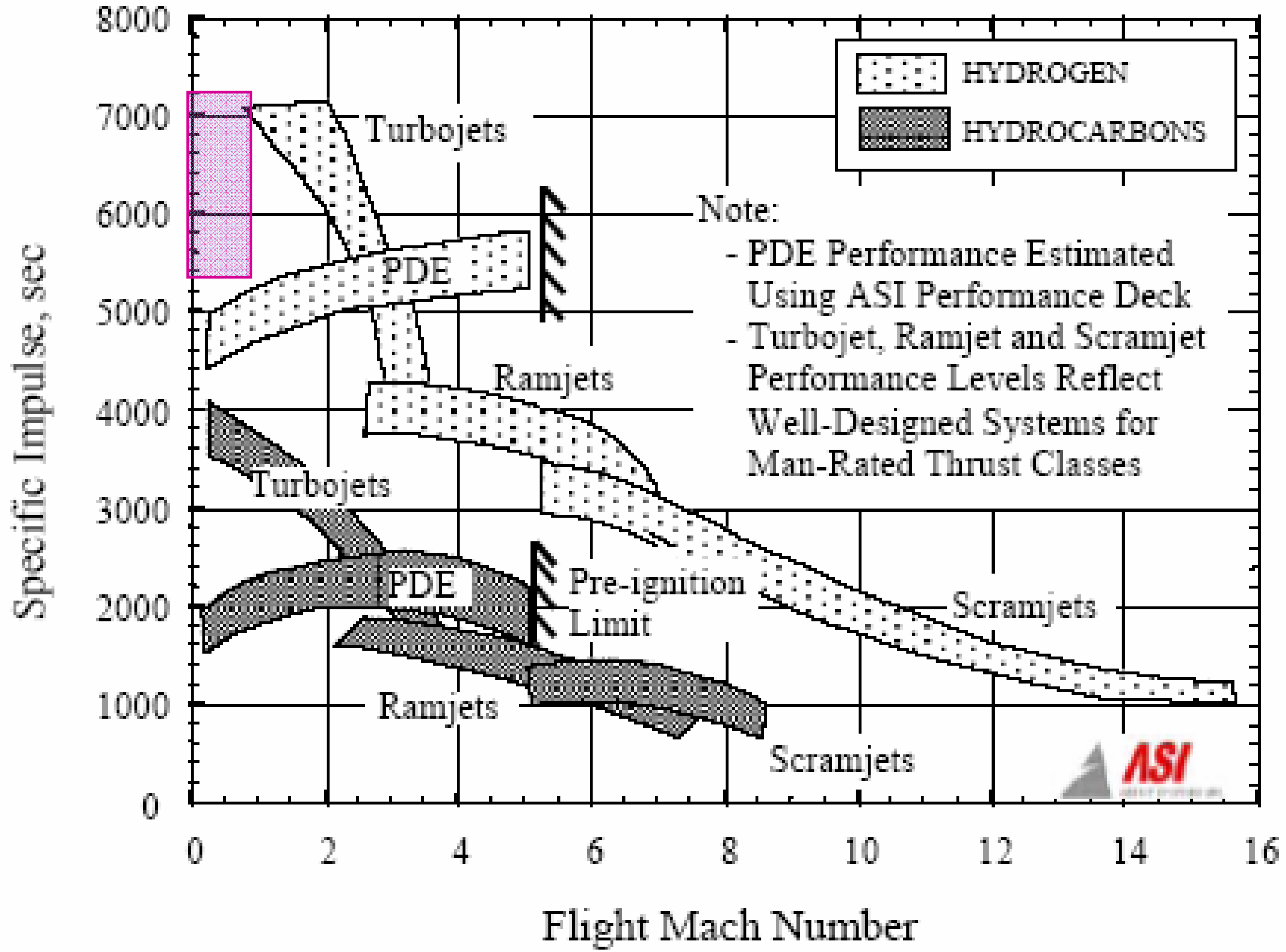


Basic PDE Cycle (Unit Cycle Process)

1. Initially, chamber at ambient conditions
2. Propellants injected from closed end
   - ❑ Variation – sidewall injection
3. Ignition from closed end
4. Wave propagation and transition in tube
5. Wave exits tube
   - ❑ Proper timing ensures wave reaches exit at the same time as propellants
6. Exhaust and purge



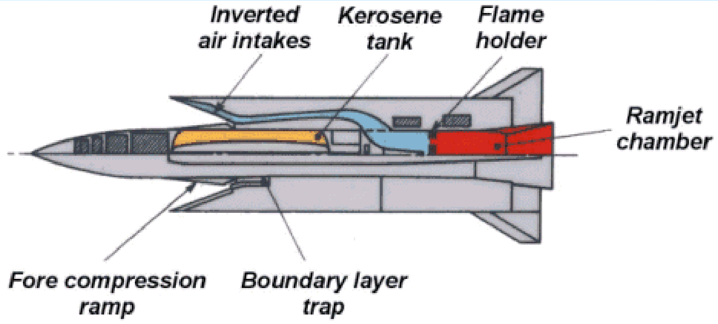
Specific Impulse of Propulsion Systems



Note:
- PDE Performance Estimated Using ASI Performance Deck
- Turbojet, Ramjet and Scramjet Performance Levels Reflect Well-Designed Systems for Man-Rated Thrust Classes

Pratt and Whitney
McDonnel Douglas

Pratt and Whitney
McDonnel Douglas



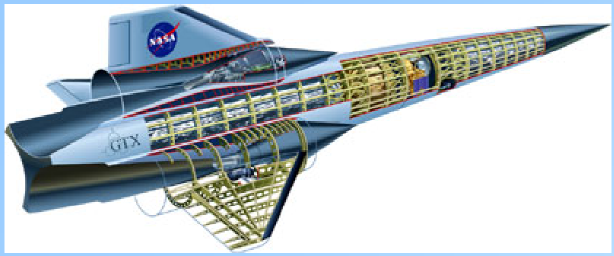
Ramjet – The ONERA SCORPION Project

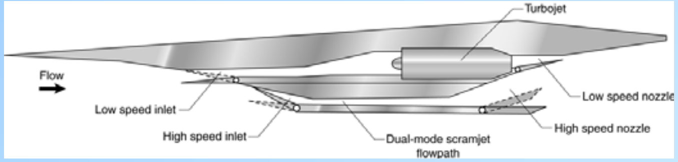

Turbojet – MQM-107 Streaker


Turbofan – Cessna CJ1+


Pulsejet – JB-2 LOON (V-1 BUZZ BOMB)


Solid Rocket – PAC3


RBCC – NASA GTX



TBCC

http://www.onera.fr/conferences-en/ramjet-scramjet-pde/
http://www.nationalmuseum.af.mil/shared/media/photodb/photos/060609-F-1234S-001.jpg
http://www.af.mil/news/airman/0105/targets2b.shtml
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http://www.lerc.nasa.gov/WWW/RT2001/7000/7740roche.html
AIAA-2006-8138

Alternatives Considered

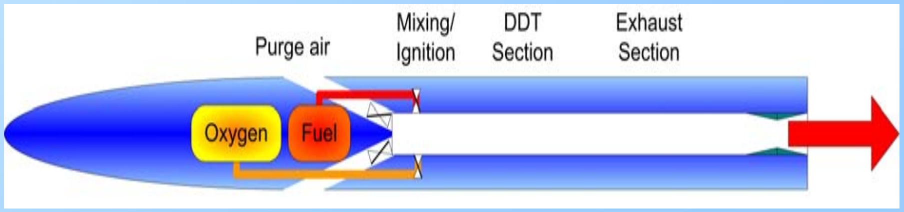
PDE	Pulsejets	Turbofans	Rockets
Detonation combustion (pressure rise)	Deflagration combustion (pressure loss)	Deflagration combustion (pressure loss)	Deflagration combustion (pressure loss)
Humphrey cycle (Higher cycle efficiency)	Brayton cycle (Lower cycle efficiency)	Brayton cycle (Lower cycle efficiency)	Brayton cycle (Lower cycle efficiency)
Potentially lower SFC	Very high SFC	Acceptable SFC	Very high SFC
Simple architecture	Simple architecture	Complex architecture	Simple to complex architecture
Lightweight, high T/W	Lightweight, low T/W	Heavy, high T/W	Heavy, high T/W
Compact	Compact	Bulky	Bulky
Low cost to acquire and operate - few moving parts	Low cost - Few moving parts	High cost - High-speed rotating parts	Low cost - Few moving parts
Broad operating range	Subsonic	Subsonic/low supersonic	Limited operating range
Scalable	Scalable	Scalable	Scalable
Easy integration to airframe	Easy integration to airframe	Easy integration to airframe	Easy integration to airframe
Reusable	Limited reusuability	Limited reusability, salt water corrosion	Limited reusability
New technology – higher risk	Not well developed	Mature technology - high reliability	Mature technology

Litke, et al. AIAA 2005-0228
Harris, et al. JPP 22(2):462–473, 2006

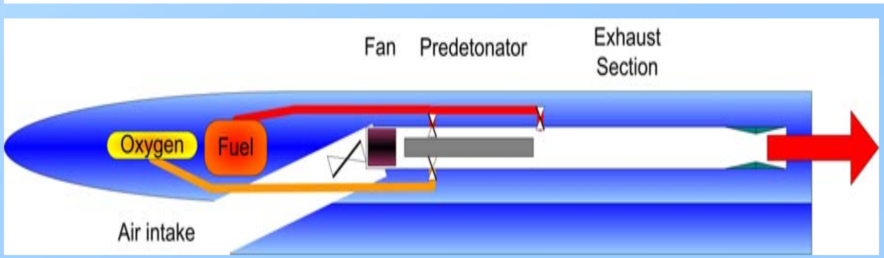
Some PDE Variants and Hybrids

Schematics (actual installation and details vary)

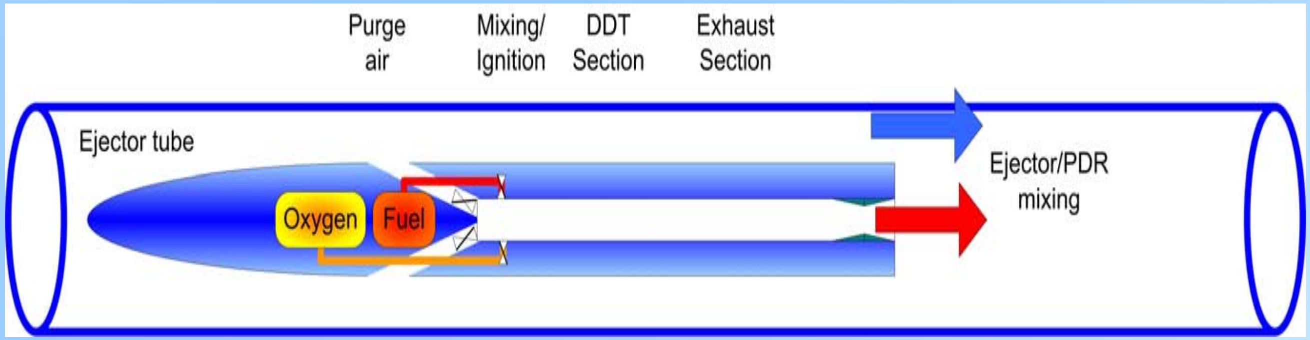
PDR



PDE



EAPDR



Some PDE Variants and Hybrids

PDR	PDE	Ejector-Augmented PDR
Static thrust capability	Likely requires auxiliary launch system	Static thrust capability
Highest purge air performance penalty	Lower purge air performance penalty	Lowest purge air performance penalty
Highest SFC	Lower SFC	Lowest SFC
Highest on-board oxygen requirement	Lowest on-board oxygen requirement for initiator	Lower on-board oxygen requirement
Comparable thrust/weight ratio	Comparable thrust/weight ratio	Comparable thrust/weight ratio
Highest exhaust temperature	Lower exhaust temperature	Lowest exhaust temperature
Highest noise	Lower noise	Lowest noise
Most mature technology	Less mature technology	Least mature technology
Lowest risk	Higher risk	Highest risk
Comparable thrust/weight ratio	Comparable thrust/weight ratio	Comparable thrust/weight ratio

Applications

- Tactical missiles
- Manned and unmanned tactical aircraft
- Decoys
- Subsonic/supersonic propulsion for hypersonic cruise
- Space launchers
- Space propulsion

Eidelman, et al., JPP 7(7):857–865, 1991
Pegg, et al., AIAA 96–2918
Kailasanath, K., AIAA J 38(9):1698–1708, 2000; AIAA 2001–0474
Falempin, et al., AIAA 2000–3473, 2001–3815

Critical Issues

- Potentially high-payoff aerospace propulsion system
- Still considered high risk
- “Revolutionary,” “breakthrough,” “disruptive”

Critical technologies must be developed

- ☛ **Detonation initiation (PDE/PDR)**
- Air induction (PDE)
- Fuel/air injection and mixing (PDE/PDR)
- Coupling with external flow (PDE)
- Design optimization (PDE/PDRE)
- Quick detonation after ignition
- Multi-tube and high-frequency operation
- Liquid fuels
- High altitude/space applications
- Engine/vehicle integration

Research Issues

- Gaseous detonation physics
  - Structure; hot-spot reaction zones; homogeneity effects; cell size and structure; ignition requirements; effects of pressure, fuel temperature, oxidizer/air temperature, equivalence ratio, wall temperature, diameter
- Two-phase detonation physics
  - Liquids and solids; droplet size; droplet shattering models; atomization; partial vaporization; subcritical and supercritical states; effects of pressure, fuel temperature, oxidizer/air temperature, equivalence ratio, wall temperature, diameter
- Fuel management
  - Atomization and distribution, mixing, turbulence generators, high frequency operation
- Inlet/combustor/nozzle integration – from start to high Mach number
- Thermodynamic cycle analysis
  - Performance assessment of design configurations, thermal and propulsion efficiencies, SFC
- Structural design
  - Thrust transfer, flight-weight structure
- Experimental techniques
  - Flow visualization, non-intrusive measurements, thrust, pressure, heat transfer
- Numerical techniques
  - Multi-cycle simulation, reduced chemical kinetics, unsteady flow, 1-3D, geometric optimizations, internal/external combined flows, effects of boundary conditions, integration with experiment
- Heating
- Fuels
  - Thermochemistry, transport properties, kinetics, detonability, auto-ignition
- Engine concepts
  - Hybrids, combined cycle, valveless and valved concepts, power production, scaling laws
- Noise