Ramjet, Scramjet & PDE

an Introduction

par Paul Kuentzmann et François Falempin

Cet exposé a été donné à l'occasion du colloque "Chimie et Propulsions" organisé par la Fondation de la Maison de la Chimie à Paris le 20 mars 2002.

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Ramjet ou statoréacteur
Scramjet ou superstatoréacteur
PDE = Pulse(d) Detonation Engine ou moteur à onde de détonation pulsée

Les autres interventions du colloque "Chimie et Propusions" sont disponible sur le site du colloque.

Outline

The Ramjet Pioneers (1913-1947)

- René LORIN, FR (patent, 1913)
- Albert FONO, GE (patent, 1928)
- M. STECHKIN, SSSR (ramjet theory, 1929)
- René LEDUC, FR (patent, 1933)
- Other contributions :
  - FR : Marcel WANNER, Maurice ROY, Georges BRUN
  - GE : Eugen SÄNGER, Alexander LIPPISCH, O. PABST, M.

TROMMSDORFF, H. WALTER
- SSSR : MM. BONDARYUK, DUDAKOV, MERKULOV, POBEDONOSTSEV, TSANDER, ZOUYEV
- UK : BRISTOL
- USA : Roy MARQUARDT, APL/JHU

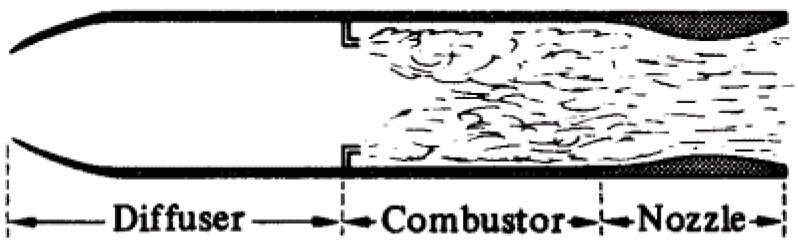
The French word "statoréacteur" has been created in 1945 by Maurice ROY (before : "trompes ou tuyères thermopropulsives"). The British adopted "Athodyd" (AeroTHermODYnamic Duct) before using ramjet. In Germany ramjet has been called "Lorinflugrohr" or "Staustrahltriebwerke". In SSSR, ramjet was named PVRD.

Some References Relating to Ramjet/Scramjet

- Books :
  - Aircraft and Missile Propulsion, Vols I and II, M.J. Zucrow, John Wiley, C. Son, Inc., 1958
  - Aircraft Propulsion, P.J. Mc Mahon, Harpert Row, 1971
  - The Rocket Ramjet Reader, CSD/UTC, ~ 1980
  - Hypersonic Airbreathing Propulsion, W.H. Heiser, D.T. Pratt, AIAA Education Series, 1994
  - Some Fundamentals on the Performance of Ramjets with Subsonic and Supersonic Combustion, TNO Prints Maurits Laboratory, 2000

- Recent French Articles :
  - Statoréacteurs et superstatoréacteurs, A. Chevalier, Science et Défense, 1993
  - Statoréacteurs et superstatoréacteurs, des moteurs pour demain, A. Chevalier, Science et Défense, 1995
  - Le statoréacteur, technologie d'avenir, F. Falempin, Colloque AAAF Aérodynamique et Propulsion des Véhicules à Grande Vitesse, 28-30 mars 2001
  - Ramjets et Scramjets, B. Petit, Encyclopedia of Physical Science and Technology, Vol. 13, 2002
  - Les statoréacteurs en France (1913-1992), l'Aéronautique et l'Astronautique n° 153, 1999/2

Main Principle of the Ramjet



Basic design

- The air inlet/diffuser admits air to the engine, reduces air velocity and develops ram pressure.

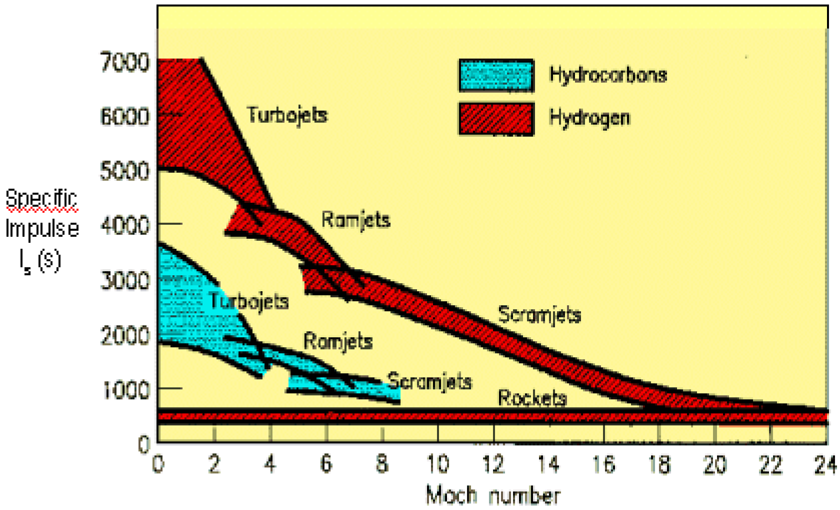
- The combustor adds heat and mass to the compressed air by burning a fuel. The nozzle converts some of the thermal energy of the hot combustion products to kinetic energy to produce thrust.

- Compression is given by the vehicle speed (bad performance at low speed, auxiliaryësster needed to reach interesting performances).

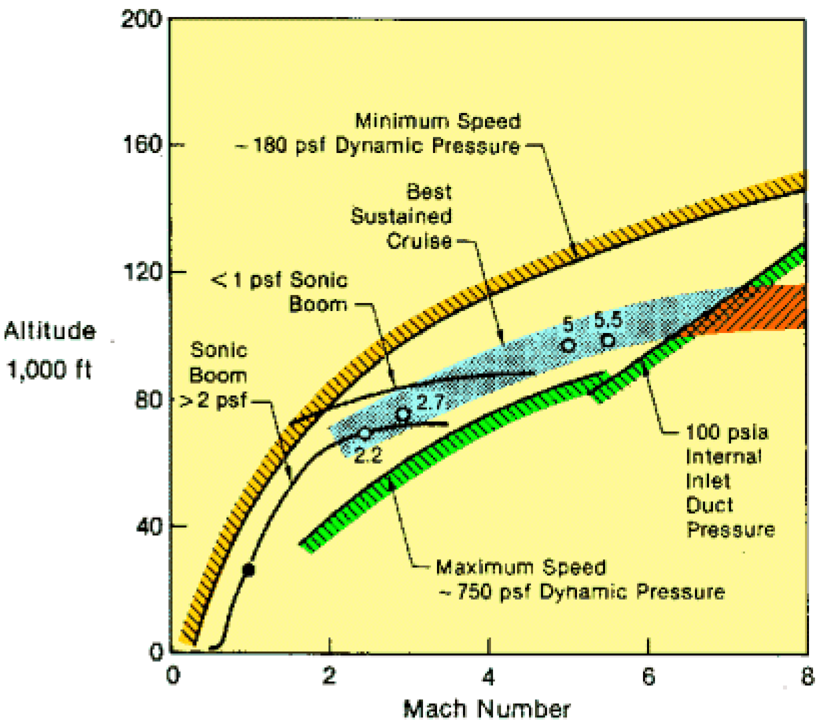
- No moving parts, flexibility in geometrical design.

- High thrust per unit frontal area.

Flight Range of Ramjet Propelled Vehicles



Consumption of air-breathing engines (Pratt & Whitney)



The hypersonic funnel (Mc Donnell Douglas)

The First Developments and Applications (1945 to 1970)

- Experimental vehicles and missiles (mainly with front air intake and jettisoned boosters)

- French achievements (more than 200 flight tests) :
  - ONERA Stataltex : M=5 at 25000 m (1965), M=3,8 at 39000 m
  - Arsenal (>> SFECMAS >> Nord Aviation >> Aerospatiale >> EADS) and SNCASE (>> Sud Aviation >> Aerospatiale >> EADS)
    - SE 4400 : M=3,7 at 22000 m (1957)
    - CT41, M=3 at 23000 m
    - VEGA, M=4,2 at 25000 m (1961)
  - MATRA, Snecma (ST 401, ST 402, ST 407)
  - Leduc and Griffon 2 (turboramjet)

- SSSR : SA4 Ganef - SA6 Gainful (SAN3 Goblet) ; Ramjets developed by NIITP ?

- Sweden : RR2, RRX-1, RRX-5

- UK : Bristol Siddeley Thor (Bloodhound) and Odin (Sea Dart)

- USA :
  -
  - RJ30, 31, 34, 37, 43, 57, 59 (Marquardt)
  - RJ55 (Curtiss Wright)
  - CIM10A/B : Bomarc/Super Bomarc

Some Poorly Known Achievements

- FR :
  - SE X 422 (the first french cruise missile)
  - ONERA SCORPION project (M6 missile)

- SSSR : Burya 2 (intercontinental strategic missile)

- USA : D21 (reconnaissance drone

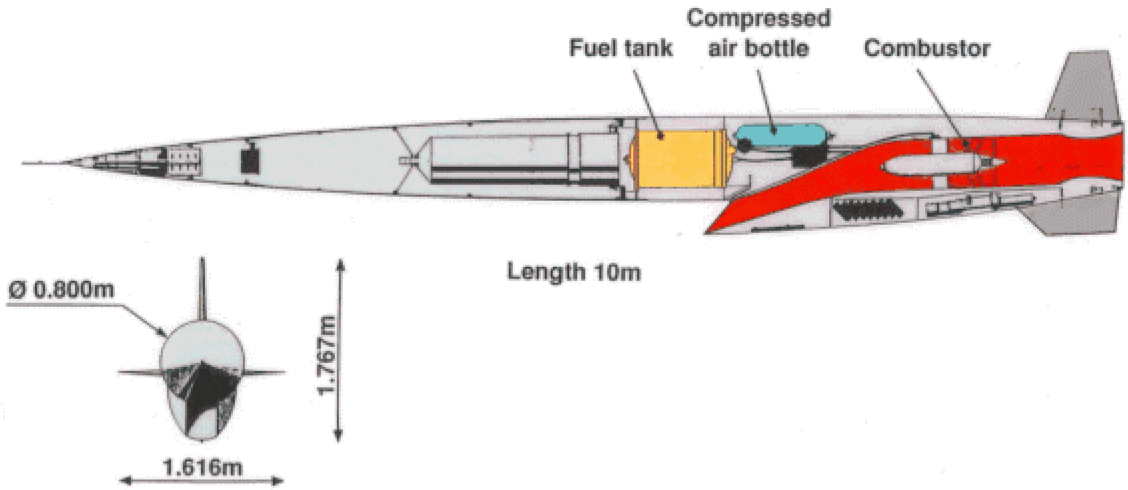
The SE X 422 Demonstrator

- Prototype of a long range cruise missile

- m_T = 1900 kg ; Ø 500 mm liquid fueled ramjet

- M = 2 during 70 km

- 3 successful tests in 1967 (Hammaguir and Levant Island)



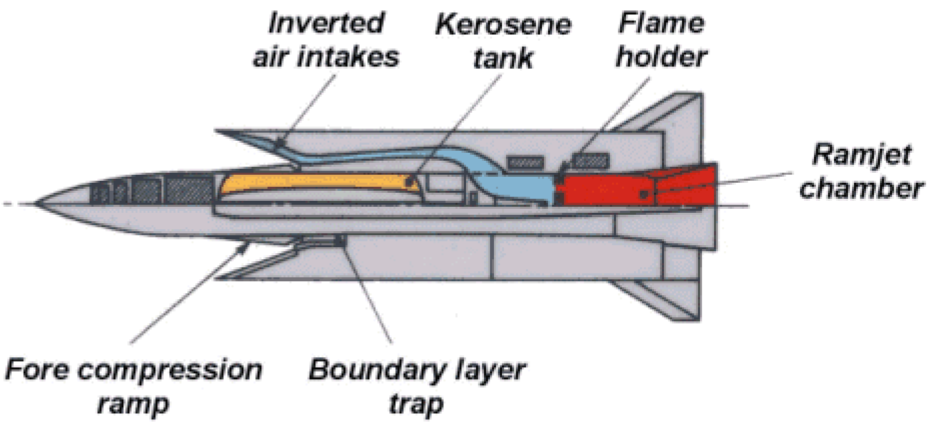
Ref : Les engins à statoréacteur du Groupe Technique de Cannes,
L. Trousse, L'Aéronautique et l'Astronautique, n° 153, 1999/2

The ONERA SCORPION Project

- SCORPION : Statoréacteur Cruciforme comme ORgane Portant Intégré à Orifices Nasaux

- Prototype of a long range ground to air missile (M = 6, 600 km) ; Ø 220 mm liquid fueled ramjet (demonstrator)

- Successful ground tests of the fully integrated vehicle in the S4 MA wind tunnel (1973-1974)

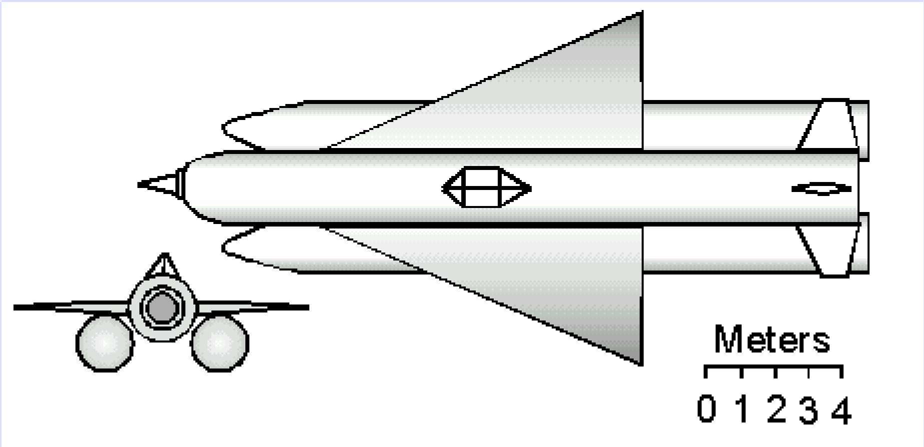


Operational lay-out

Model for S4 wind-tunnel testing

The Russian Burya (storm) Missile

- Development of an intercontinental strategic missile, similar to the US XSM64 Navaho (Lavotchkin, parallel development Buran by Miassischev)
- m_T = 216 t (including the two kerosene/nitric acid fueled boosters) - Bondyaruk's ramjet RD012U, Ø 1700 mm
- MMAX = 3,15 ; 8000 km expected range
- 5 successful tests ; project cancelled in 1958



Ref : Aviation Week and Space Technology, November 2, 1992, p. 50

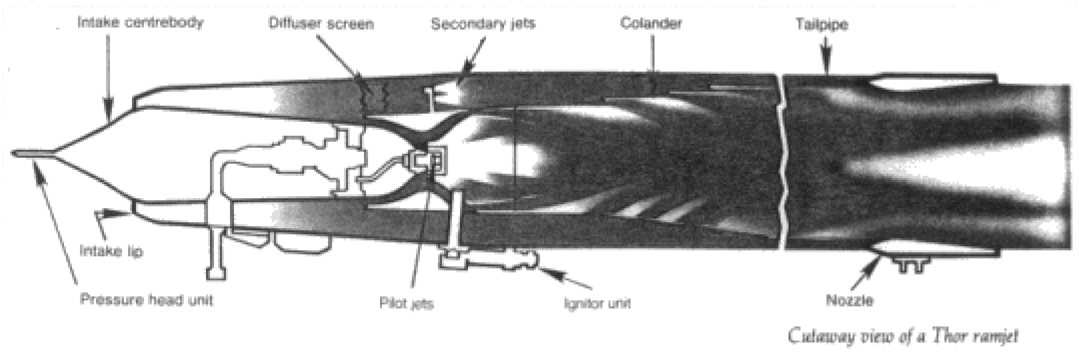
The Supersonic Reconnaissance Drone Lockheed D21 Tagboard

- Black program ($2B) disclosed around 1990
- m_T = 5 t ; Marquardt RJ43MA11 JP7 fueled ramjet, Ø 711 mm
  - D21 : launched from a Lockheed M12 aircraft at high supersonic speed (programme cancelled in 1966 after a collision during separation)
  - D21B : launched from a Boeing B52 bomber with a booster
- M_{MAX} = 4 at 30000 m ; endurance 4 h at M = 3,8 and 24000 m
- No recovery device

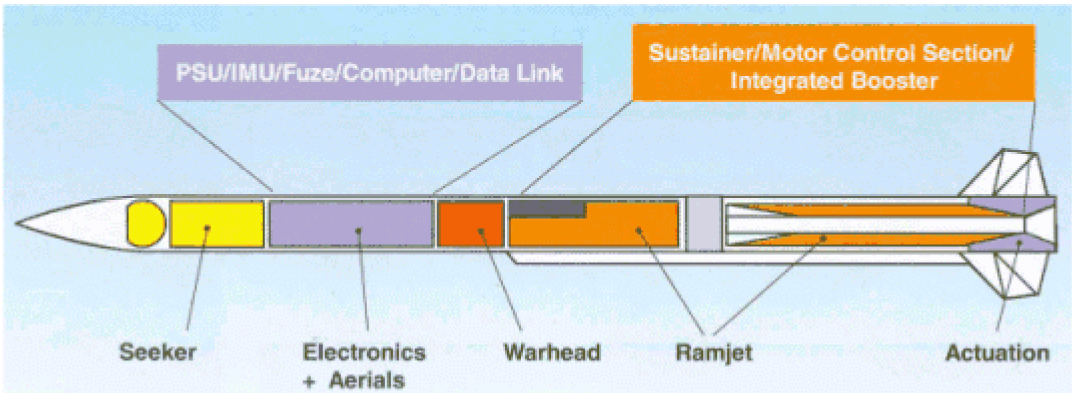

Ladies in waiting, a pictorial review of Davis Monthan AFB, S. Wonderly, C.R. Dunham, Squadron/Signal Publications, 1991

The Modern Ramjet for Missile Applications

- Integrated booster: ejectable booster nozzle or nozzleless booster
- Lateral air intake(s)
- Flame stabilization by recirculation zones



Thor ramjet (Bloodhound)



Integrated rocket ramjet (S225XR project)

Modern Ramjet Propelled Missiles

- Air to air missiles
  - MBDA Meteor (development)
  - Vympel RVV-AE-PD R77M (AA12 Adder, development)
  - Kentron ?
- Air to surface missiles
  - EADS/AMM
    - ASMP
    - ASMP-A (development)
  - Radouga Kh41 Moskit
  - Zvezda Kh31P (AS17 Krypton)
- Antiship missiles
  - Machinostroenie 3K55 Yakhont (SSN26)
  - Radouga 3M80/82 Moskit (SSN22 Sunburn)
  - CPMEC C301 (coast to ship)

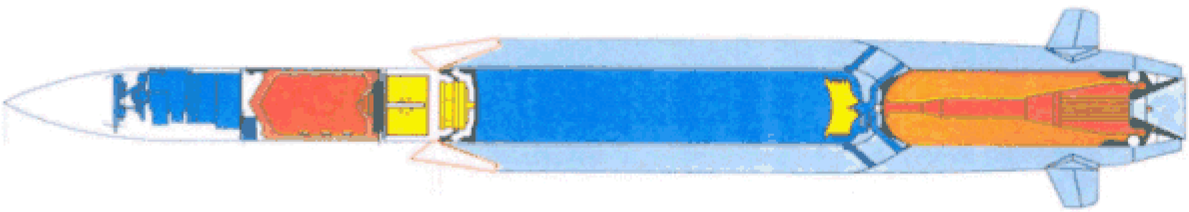
- Hsiung Feng 3

- Surface to air missiles
  - MBDA
    - Bloodhound Mk2
    - Sea Dart

A Classification of Ramjets According to the Fuel

- Pure fuel
  - gas (hydrogen : stored liquid but injected gaseous after wall cooling)
  - liquid or slurry
    - LFRJ (Liquid Fuel Ramjet)
  - solid
    - in bulk: SFRJ (Solid Fuel Ramjet)
    - powdery

- Solid propellant gas generator ? Ducted rocket (DR) or Ram rocket
  - Unchocked Flow
    - UFDR
  - Chocked or Variable Flow
    - VFDR



ANNG Project

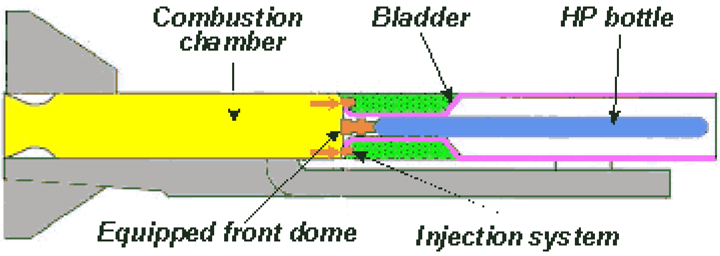
The LFRJ

- Liquid fuels
  - kerosenes or synthetic hydrocarbon fuels

    Examples :
    - USA :

        - RJ1, RJ4 (tetrahydrodi (methycyclopentadiene)), RJ5 (perhydrodi (norbornadiene)), RJ6 (blend RJ5-JP10), RJ9
        - - boranes (abandoned) .
    - FR :
        - CSD07T, CSD15T (developed and produced by IFP, derivatives of norbornadiene)
- endothermal fuels
  Example
    - MCH

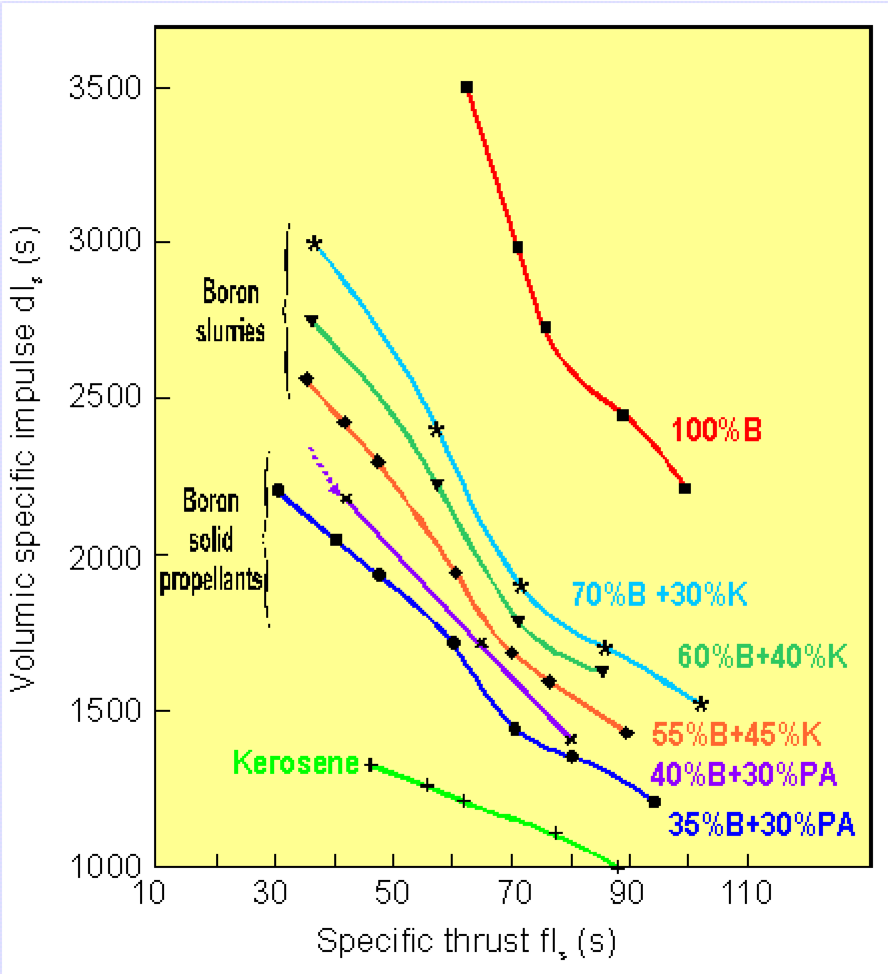
Choice of the fuel is a compromise between specific impulse Is, density/volumic specific impulse (dIs), mixture ratio and possibly cooling capability and cracking properties.
Combustion mechanisms : spray combustion



RASCAL : RAmjet Small CALibre

Use of a Slurry in the LFRJ

- Kerosene + boron particles (50 to 70 % mass content)
- FR : CHEOPS program ; US programs ; Russian programs ?



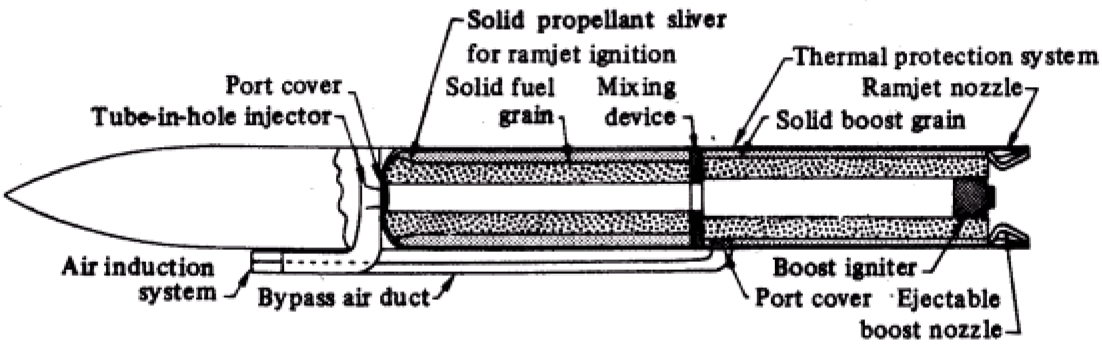
The SFRJ

- Solid fuels
  - Polymer possibly loaded with metal particles (Mg, Al or B)

- Combustion mechanisms : pyrolysis and diffusion flame

- Good performance for high Mach number cruise but moderate variability of the fuel regression rate, having an effect on the combustion chamber design ; self modulation of the fuel mass flow rate and of the mixture ratio

- Limited number of applications



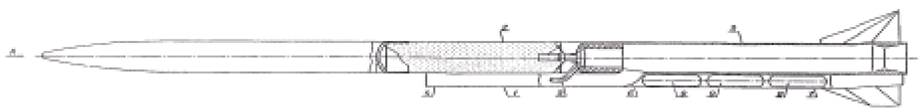
The Ramjet Burning a Metal Powder

- A concept born in Russia

- A technology imported in France (ONERA) and successfully demonstrated at middle scale (Ø 200 mm)

- Advantages : high performance, high density, management of a cool fuel, high modulation rate, relative insensivity of the loading

- Drawbacks: a secondary gaseous source (gas generator and cooler) is needed to fluidize the powder, preparation of the loading and control of the flow rate are critical



The Ducted Rocket (DR)

- Principle :
    - A "gas" generator is providing the fuel species which are injected in the ramjet combustion chamber (GFRJ)
    - The "gas" generator is working like a solid propellant rocket, except that the solid propellant has a low oxidizer content
    - The "gas" generator products can contain a high fraction of fuel particles (Mg, Al, B, C) to enhance the performances

- The first operational missile using such a concept has been the Russian SA6 Gainful (Mg). Work began in France at ONERA around 1972 (A. Moutet) and related propellant activity was shared quickly with SNPE ("aerogols")

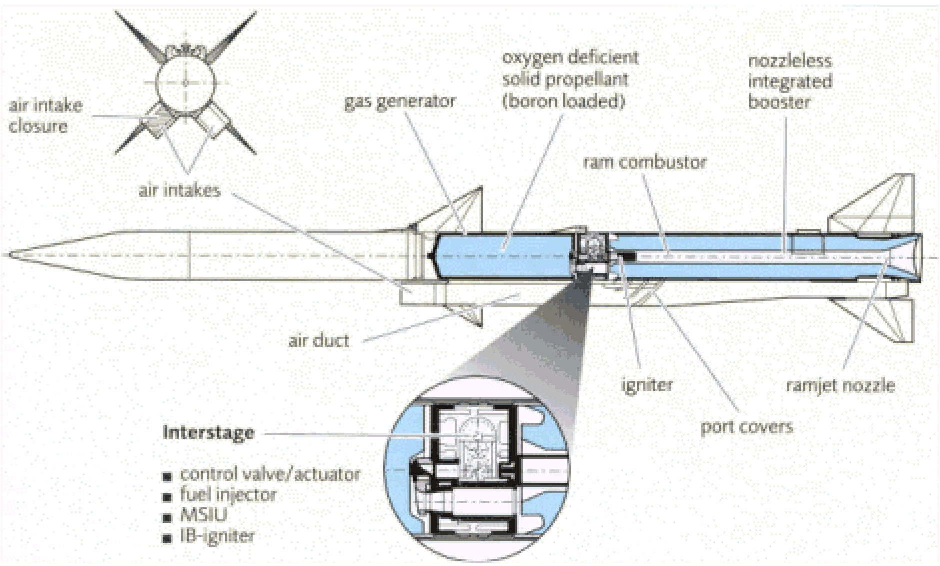
- A large variety of composite propellants for DR is now available for missiles applications, for instance :
    - propellants for "low" IR signature missiles ("aérolite")
    - high density, high performance propellants ("aérofluolèbe")
    - propellants for VFDR and UFDR C

- ombustion mechanisms are conventional one-phase or two-phase ones

The VFDR

- Throttling of the gas generator mass flow rate by variation of its throat, that gives a thrust modulation capability to the ramjet. But throttling of hot gases, possibly containing solid particles, is technically difficult

- Solution adopted on the Meteor (BVRAAM) ramjet



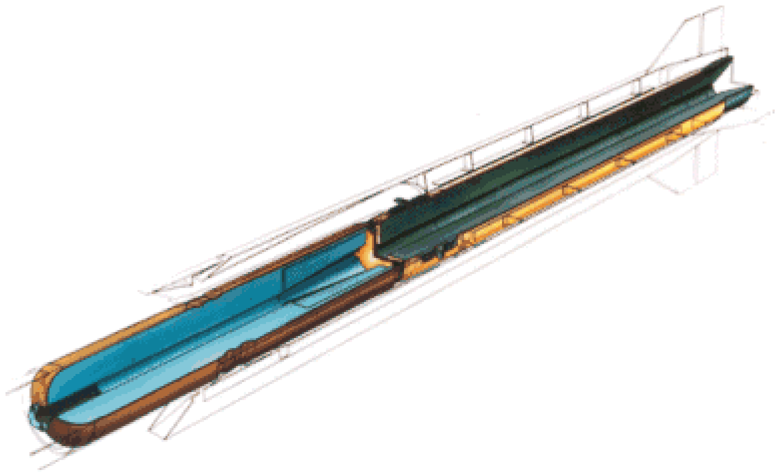
Source : PROTAC S.A.

The UFDR
- The French "Rustique" Concept

- No chocked throat between the gas generator and the ramjet combustion chamber ; the gas generator solid propellant burning rate depends on the combustion chamber pressure ; self-modulation of the mixture ratio can be obtained by giving a right value to the solid propellant pressure exponent

- Whole ramjet operation starting from the nozzleless booster ignition order (munition style)

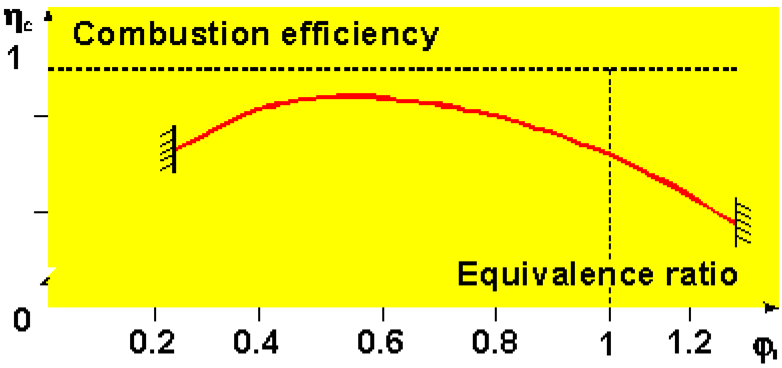
- Concept successfully demonstrated in flight through the MPSR and MPSR2 programs (MATRA, ONERA, SNPE) ; no current applications



Scientific Issues of Ramjet

- Air intakes : the design is critical (efficiency on the whole flight range, sensitivity to flow distorsions, participation to instabilities)

- Combustion chamber
  - combustion efficiency
  - lean and rich stability limits
  - wall cooling
  - operating instabilities



Combustion Efficiency and Stability Limits

- Combustion efficiency and stability limits are depending on several parameters : fuel, equivalence ratio, air stagnation pressure and temperature

- Experimental approach through tests : expensive

- The ONERA's approach, the research ramjet :
  - a modular design reproducing the main features of an actual ramjet
  - the capability to get a detailed characterization of the reactive flow by using the most advanced optical diagnostics (LDV, LIF, PLIF…)
  - a tool for validation the 3D turbulent reactive two phase flow codes (MBDA-ONERA)

Combustion Chamber Wall Cooling ▲

- Passive thermal protections
  - different materials (silicone based) are available

- Active thermal protection
  - a portion of the air flow entering is bypassed to protect the case and is reinjected in the combustion chamber through perforations
  - compatibility with booster integration demonstrated ; concept rather interesting for combustion stability
  - solution limited to flight Mach number less than 4

- Some successful developments of all composite cases, application to ASMP-A

Operating Instabilities ▲

- Different types of instability :
  - overall instability involving the air intake(s) : low/medium frequency (100 to

300 Hz) ; generally cured by improving the air intake(s)
  - combustion chamber acoustical instability : from medium to high frequency ; the highest frequencies (tangential modes) are the most dangerous, inducing an accelerated consumption of the thermal protections

- Mainly faced on LFRJ ; some instabilities on DR connected to specific solid propellant combustion phenomena

- Numerical prediction of ramjet instabilities is not yet achieved. Different solutions are however known to reduce or suppress the instability levels, like :
  - geometrical devices : baffles, local caps
  - modification of the injection devices or controlled distribution of the fuel

- A compromise between performance and instability level is generally sought

Some Unconventional Applications of Ramjet ▲

- Ramjet propelled rotor

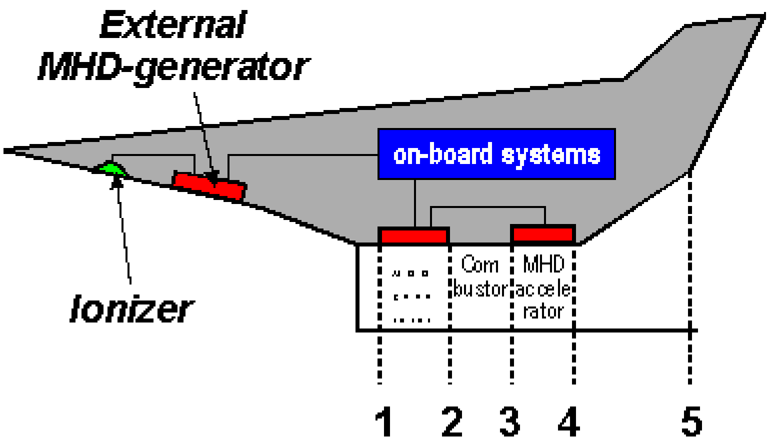
- Integrated ramjet in wing

- RAMAC (RAM ACcelerator) : launching of a small mass at a very high speed from a tube (NASA, NLR, ISL)

- Ramjet propelled shell

- Nuclear ramjet : PLUTO US program (nuclear reactor TORY II C), cancelled in 1965 ; concept revisited in the USA ?

- MHD ramjet : AJAX/NEVA project (Leninetz)
  - a fascinating concept, but beyond the present technical possibilities



Simplified scheme of scramjet
with MHD control under « AJAX » concept

From Ramjet to Scramjet (Supersonic Combustion Ramjet or SCRJ) ▲

- Beyond Mach = 5 (hypersonic domain), ramjet is less and less efficient. Increasing of air stagnation temperature and pressure tends to limit the performance and to increase the thermal and mechanical loads on the combustion chamber walls

- To bypass these issues, the solution is to maintain the flow supersonic from the air inlet to the engine exit and to achieve the combustion in the supersonic flow

- A geometrical throat is therefore no longer needed to accelerate the flow and produce the thrust ; transition from subsonic to supersonic flow can also be achieved, without geometry variation, by heat addition

- Two variants of scramjet :
  - pure scramjet
  - dual mode ramjet allowing transition from subsonic to supersonic combustion

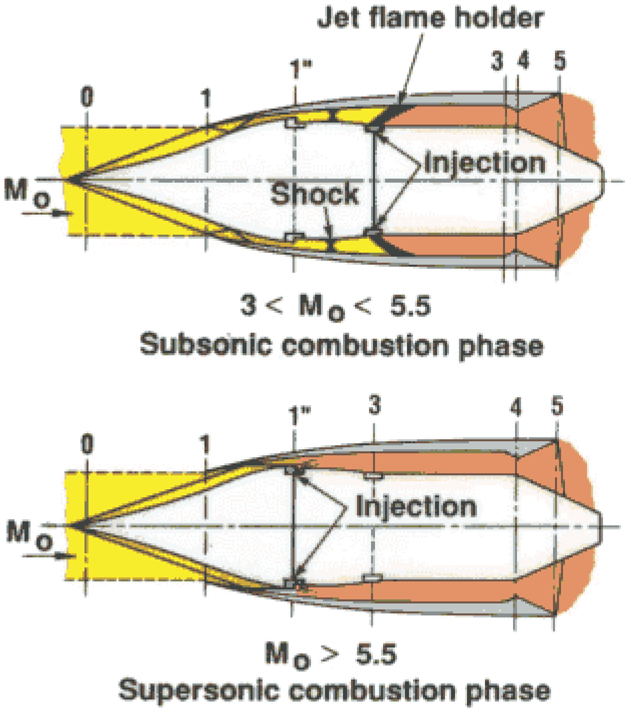
The First Scramjet Developments (1965-1975) ▲

- USA :
  - Marquardt
  - Garret Air Research HRE (Hypersonic Research Engine)
    - scheduled to be tested on the X15-A2 aircraft
    - finally only tested at ground around 1971

- SSSR :
  - TsIAM since 1957 (E.S. Chetinkov)
  - TsAGI, ITAM, MAI
  - no flight tests recorded

- France (ONERA) :
  - ESOPE (Etude de Statoréacteur comme Organe de Propulseur Evolué) program
  - ground tests around 1972 at S4MA wind tunnel

- Common features between HRE and ESOPE :
  - Hydrogen-fueled scramjets
  - axisymmetric combustion chamber, frontal central body
  - ground tests at simulated Mach number 5,5 to 7,4



Dual mode ramjet operation

The Renewal of Scramjet (1988-?) ▲

- Two trends for the applications :
  - hypersonic missiles (see AGARD Aerospace 2020 report)
  - reusable airbreathing launchers (NASP project for instance

- A lot of new developments :
  - USA (NASA, Air Force) : the HyXXX programs : HyStep, Hyper X/X43A (one attempt of flight), HyTech (X43C), HySet...
  - SSSR then Russia : the Kholod test flights (1991-1998), Igla project…
- France : PREPHA program, joint ONERA-DLR JAPHAR program, DGA PROMETHEE program, developments MBDA/MAI
- Germany : MTU, DLR/TsAGI
- Japan : NAL
- China : Institute of Mechanics, Chinese Academy of Sciences

- Australia (University of Queensland and International cooperation) : HyShot program (one attempt of flight)

Up to now, no scramjet propelled vehicle had a free flight allowing a drag-thrust balance estimation

The Fuel Issues

- Hydrogen has been selected for the first ground or flight demonstrations from energy considerations : high energy content, high capability of cooling, fast combustion after mixing with air. However hydrogen has two drawbacks for the applications : it should be stored liquid at very low temperature (~ 20 K) and its density is very low (~ 0,07)
    - rejected for military applications
    - design of a SSTO reusable space launcher seems difficult

- Hydrocarbons have a lower energy content than hydrogen and should face other issues related to injection, combustion… They can also be used to cool the structure through their endothermal properties

- Other concepts :
    - dual fuel scramjet
    - solid fuel scramjet
    - methane reforming (AJAX concept, Leninetz, Russia)

The "best" fuel will depend on the considered application and its selection will be the result of heavy system studies

The Ground Test Facilities

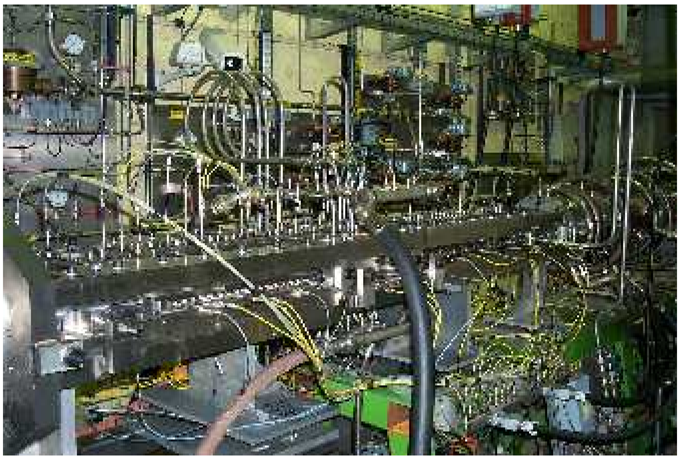
- Simulation of the high Mach number flight conditions (stagnation pressure and temperature) requires powerful and expensive facilities. The world operational facilities are limited to Mach = 8

- Three solutions to heat air, which can be combined :
    - pebble bed heater hydrogen-air
    - combustion and oxygen addition (air viciated by water vapor)
    - production of synthetic air

- Other solutions can be considered from hypersonic wind tunnels, but only for very short test time

- The most powerful facilities (high mass flow rates) are located in the USA and in Russia

- Some recent and high performance facilities developed in :
    - Germany : MTU, DLR
    - Japan : NAL Kakuda
    - France : MBDA line 4 (Subdray), ONERA LAERTE and ATD5 facilities



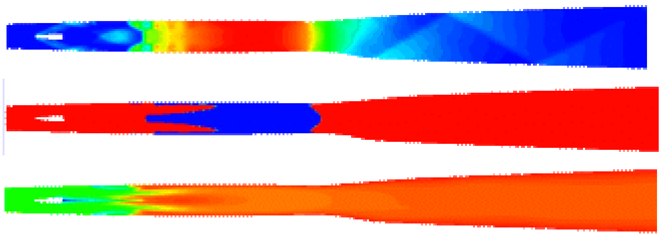
- An impressive US project : MARIAH (Magnetohydrodynamic Accelerator Research Into Advanced Hypersonics) : Princeton, Sandia, Livermore, MSE Technology Application, M = 15, 10 s !

Recent French Achievements and Projects

- Ground test of a dual mode H2 fueled ramjet with a fixed geometry (ONERA, JAPHAR program, M = 4 to 8)

- Development of the WRR (Wide Range Ramjet), a dual fuel dual mode ramjet, with a variable geometry, first ground tests on the demonstrator PIAF in May 2002 (MBDA and MAI, M = 3 to 12)

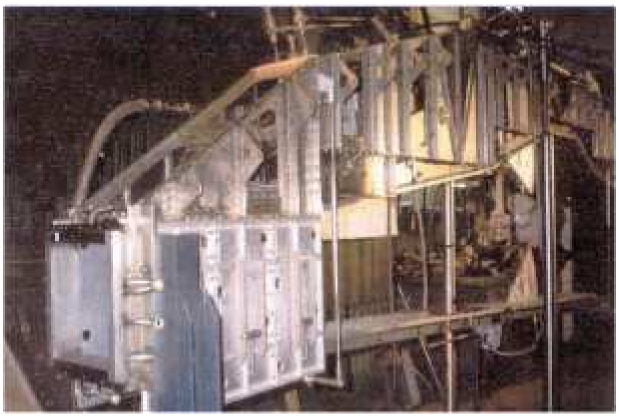
- MBDA and ONERA are working on the scramjet of the PROMETHEE program : dual mode, endothermal hydrocarbon-fueled scramjet, M = 2 to 8 (tests in 2002)

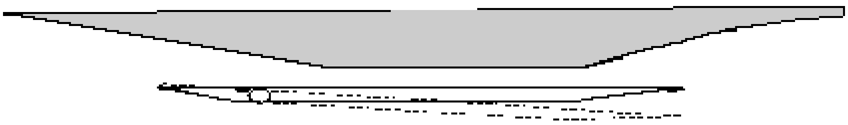


Pressure

Mach number

H_2O





From Ramjet to PDE

- Scramjet using a detonation wave (ODWE)
  - concept considered by several teams (Canada, France) for M > 10, no experimental demonstration

- Pulsed combustion already considered :
  - operational on pulsed jet (acoustically tuned chamber) :
    - Argus (Fieseler V1), mechanically valved type
    - Escopette (Snecma, 50's), valveless type
    - OKB Sokol and ENICS (Kazan, Russia)
  - considered for turbojet combustion chamber (Snecma, 50's)
  - considered for ramjet :
    - DSI resonating ramjet : one flight test ? (USA, 1976)
    - Technion project : ISABE 93-7038 (Israël, 1993)

- PDE :
  - combines pulsed combustion and detonation
  - is not a conventional pulsed jet : ignition is controlled

A Family of Concepts

- PDE = PDWE (Pulsed Detonation Wave Engine)

- PDRE = Pulsed Detonation Rocket Engine

- RVSPDE = Rotary Valved Single PDE (ASI's concept)

- RVMPDE = Rotary Valved Multiported PDE (ASI's concept)

Airbreathing PDE is known as PDE

Some References Relating to PDE
Reports and papers

- Bussing, Pappas : Pulse Detonation Engine theory and concepts, AIAA Progress in Aeronautics and Astronautics, 1995
- NPGS reports (experiments and theoretical analysis)
- NASA CR 187137 and AIAA 92-3174 (ISTAR Inc., CSTU Fullerton, NASA Lewis) : Detonation Duct Gas Generator Demonstration Program
- SAIC : AIAA 89-2446, AIAA 90-0460, AIAA 90-2420, AIAA 92-0392, AIAA 92-3168 (Eidelmann et al., computational analysis, PDE located in a wing section)
- ASI : AIAA 97-2742, AIAA 97-2743 (Bussing, Bratkovich et al., experiments and

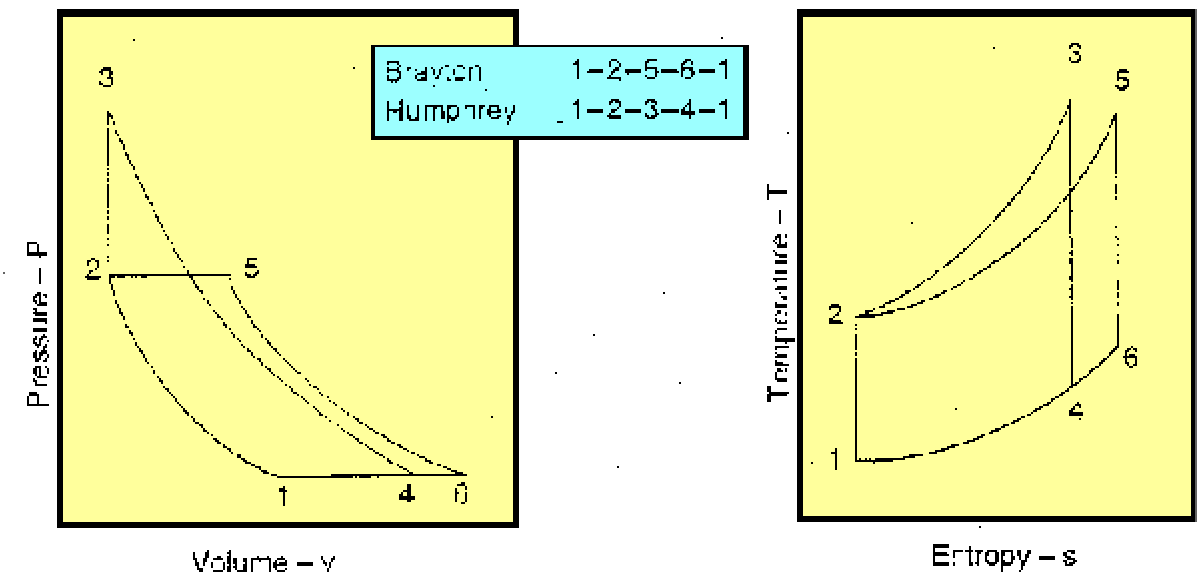
technologies)
- LCD/CNRS Poitiers : 21th ISSW 1997, CST 1999 (Zitoun, Desbordes, experiments on CnHm-O2 mixtures and theoretical analysis)
- CELERG internal reports (experiments and technologies)
- ONERA internal reports (computational analysis)
- MBDA : AIAA 00-3341, AIAA 01-3815

Recent programs

- USAF SBIR (Small Business Innovation Research)
- NASA REVCON (REVolutionary CONcept)
- DGA PEA POD

Main Principle of PDE

Constant volume combustion is more efficient than constant pressure combustion, as demonstrated by a cycle analysis



Constant pressure (Brayton cycle : 1-2-5-6-1)

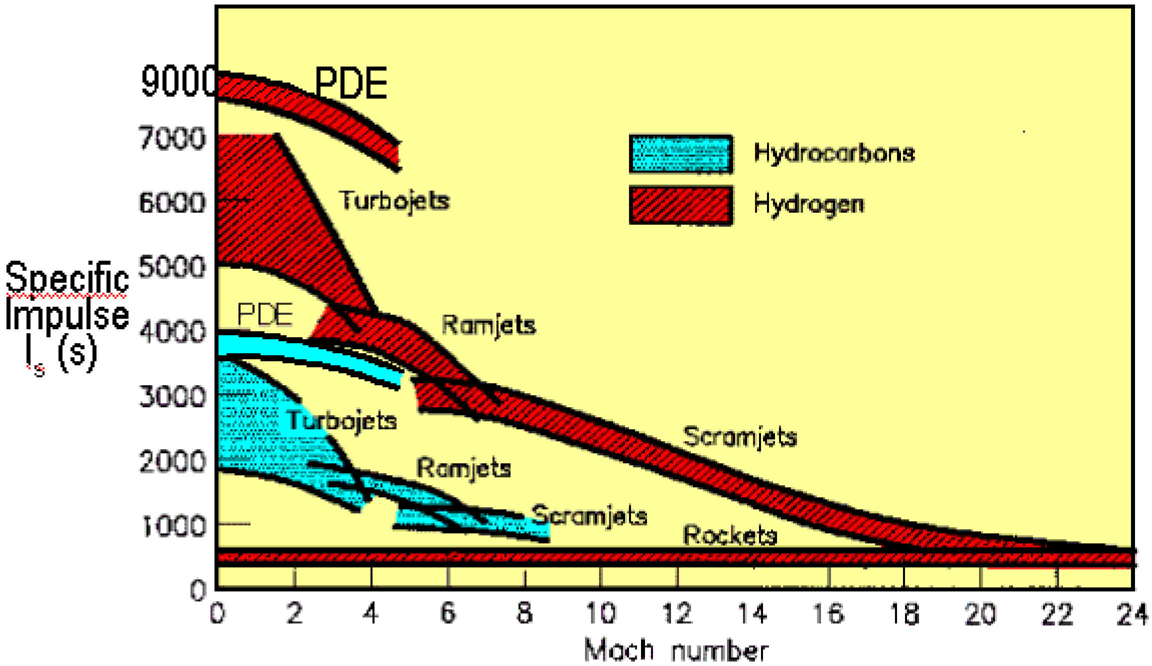
$$\eta_B = 1 - \frac{T_1}{T_2}$$

Constant volume (Humphrey cycle : 1-2-3-4-1)

$$\eta_H = 1 - \gamma \frac{T_1}{T_2} \times \frac{\left(\frac{T_3}{T_2}\right)^{\frac{1}{\gamma}} - 1}{\frac{T_3}{T_2} - 1}$$

η_H depends on γ and on the pressure ratio $\frac{P_2}{P_1}$

A performance gain is expected beside the conventional engines

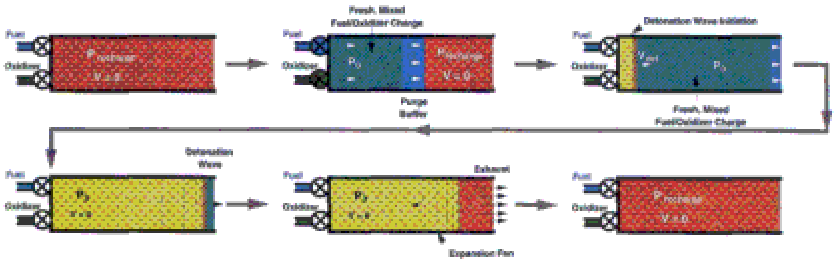


Theoretical gain for the rocket version : 5 to 10 % i.e.

$$I_s^{(v)} \geq 490\ s$$

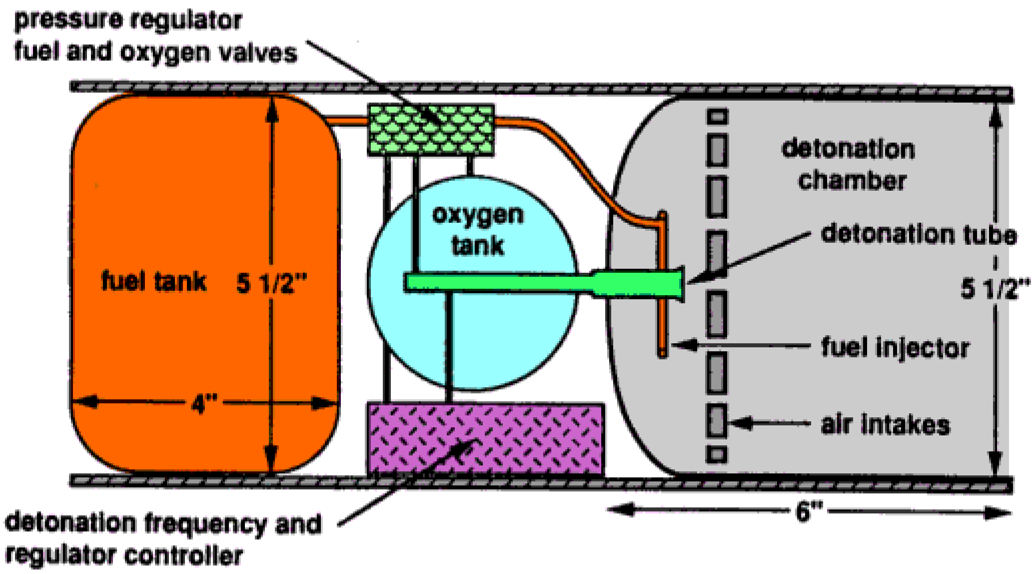
Operation possible at rest

Sequential View of the PDRE Operating Cycle



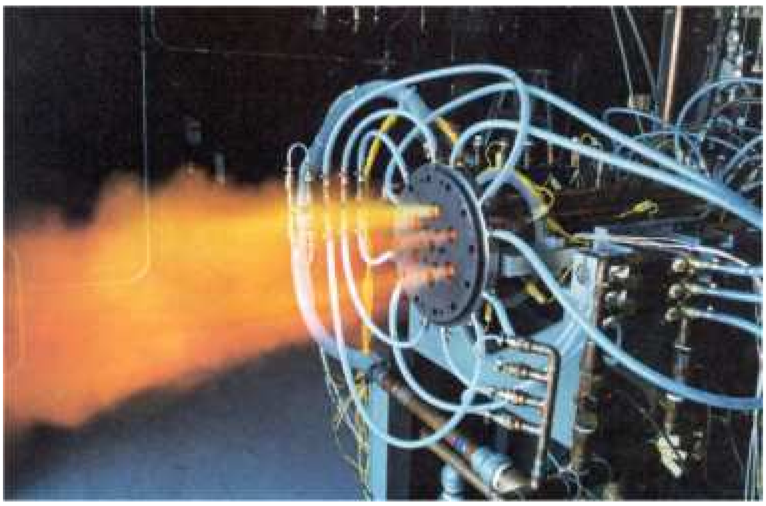
Ref : Aviation Week and Space Technology, July 17, 2000
Bigger : 104 Ko

The Airbreathing PDE



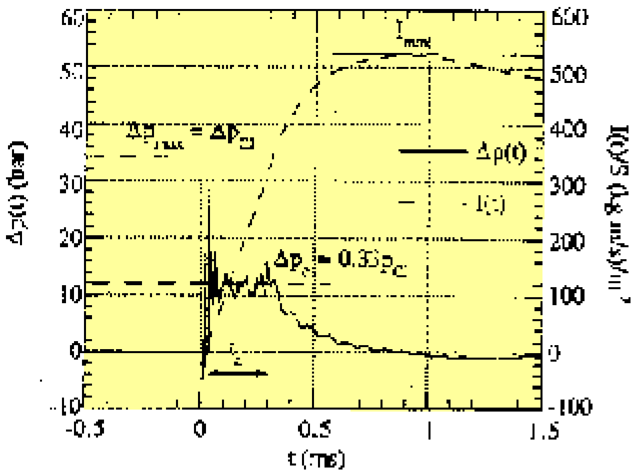
Remark : O2 is added to facilitate the detonation

ASI's Six Combustor PDRE on the Test Stand

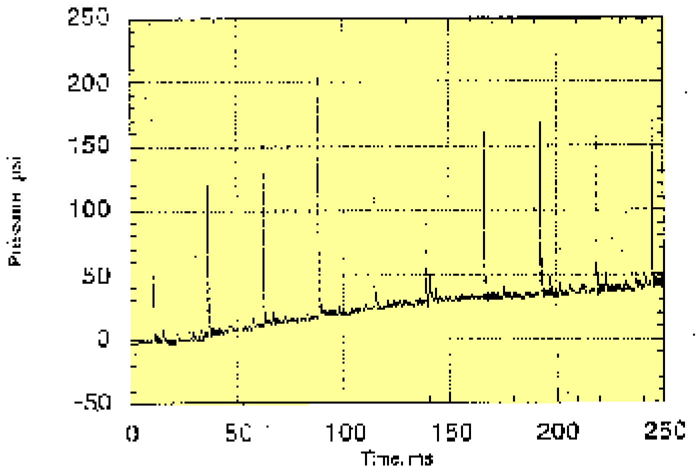


Ref : Aviation Week and Space Technology, July 17, 2000

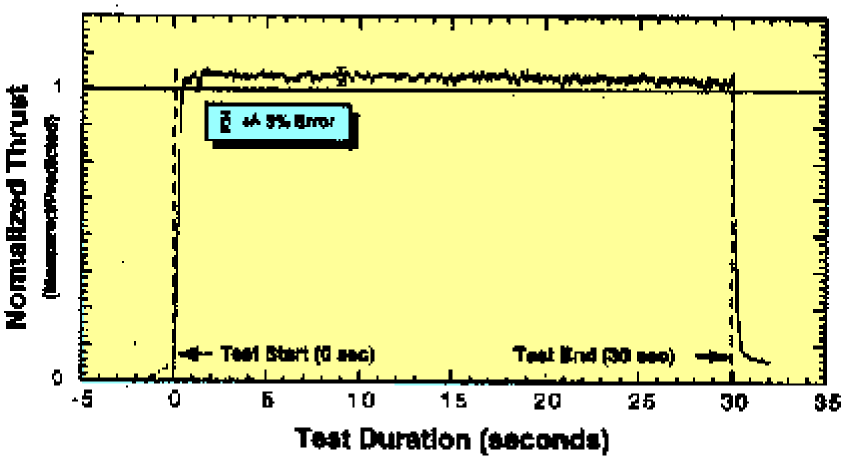
Experimental Results



Elementary cycle LCD/CNRS Poitiers



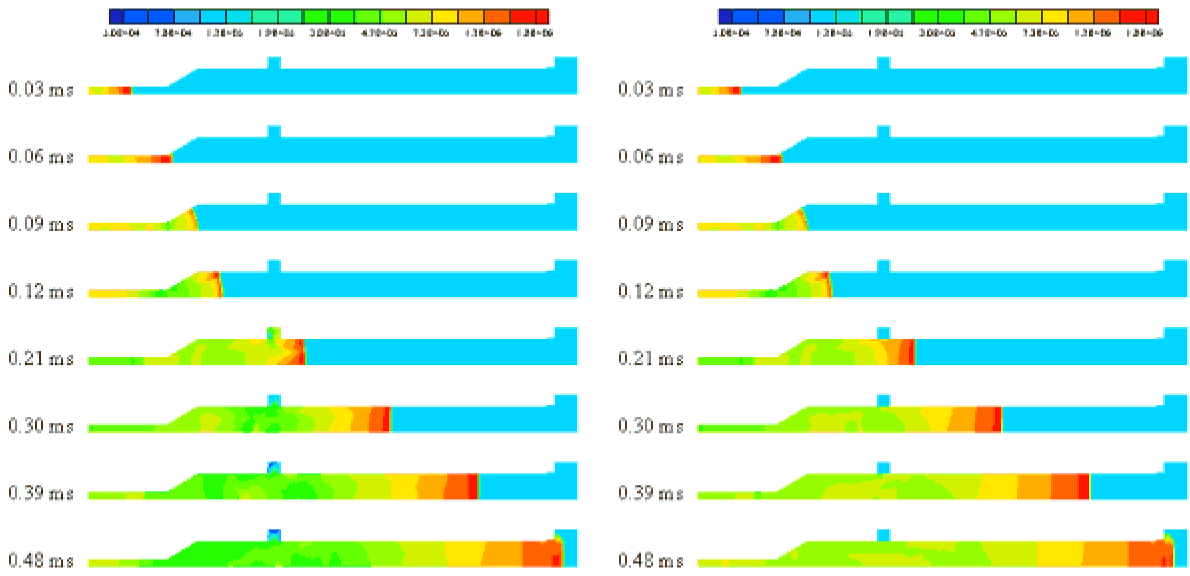
ASI PDRE



ASI RVMPDE

Computational Results

Comparison between PDE and PDRE (preliminary results)



Open air intake Pressure (Pa) Closed air intake

- CELERG configuration, hydrogen/oxygen/air, one cycle
- ONERA computation, MSD code, axisymmetrical flow description

Claimed PDE/PDRE Advantages and Key Issues

Claimed advantages

- No moving parts
- High thermodynamic efficiency
- Operating in a potential large Mach number range (from 0 to 4-5)
- Simplicity and flexibility of geometrical configuration
- Easy integration to the vehicle
- Low cost

Key issues

- Detonation initiation (PDE/PDRE)
- Air inlet design (PDE)
- Fuel/air injection and mixing (PDE/PDRE)
- Coupling with external flow (PDE)
- Design optimization (PDE/PDRE)

Potential PDE Applications

- Low cost and efficient vehicles for military applications
  - target and research drones
  - penetration aids devices
  - "smart" missiles

- Acceleration engines (for ramjet) ?

- Main engine for high supersonic aircraft ("Aurora" controversy) ??

- Stages of space launcher (PRDE) ?

Conclusions

- Ramjet technology is now mature
  - the main applications are military
  - turboramjet has a potential for high supersonic or hypersonic transportation

- Scramjet technology still needs heavy developments
  - military applications are considered
  - a potential for future RLV

- PDE looks attractive for special missions but is not yet totally mastered

- Future of ramjet/scramjet technology implies coupling of different thermodynamic cycles (hybrid powerplant systems)

Hypersonic flight requires a multi-disciplinary approach

Chemical sciences remain essential for fuel optimization and combustion process control

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ONERA

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