Hypersonic Airbreathing Propulsion

Nishant Agarwal
Dept. Of Aerospace Engineering Sciences, University of Colorado Boulder

Hypersonic airbreathing, horizontal takeoff and landing (HTOL), vehicles are highly integrated systems involving many advanced technologies. The design environment is variable rich, intricately networked, and sensitivity intensive; as such, it represents a tremendous challenge. Creating a viable design requires addressing three main elements: (1) an understanding of the "figures of merit" and their relationship, (2) the development of sophisticated configuration discipline prediction methods and a synthesis procedure, and (3) the synergistic integration of advanced technologies across the discipline spectrum. This paper is a literature review that looks at different aspects related to Hypersonic airbreathing propulsion and tries to analyse the current state of technology.

I. Introduction

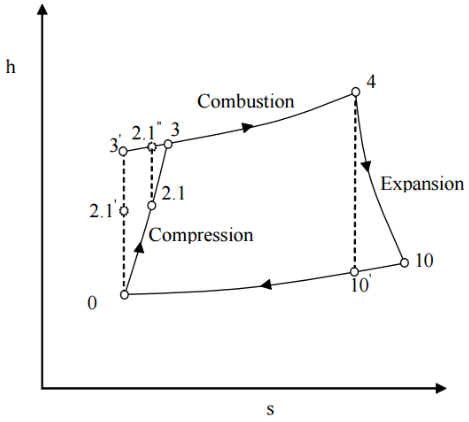
To travel at velocities greater than the speed of sound the traditional jet engines cannot be used to provide propulsion. This is because of the shock waves generated at the inlet which the engine have to overcome. These shock waves on the compressor blades would make the engine unusable both because of the very large pressure fluctuations that would cause fatigue and failure of blades, and because of the high level of drag. For this purpose a ramp is used in front of the engine to create a shock wave just enough to slow down the flow to subsonic speed for efficient operation of the jet engine. This however is effective only till around Mach 1.5 after which a Ramjet is to be used to produce thrust. Ramjet engines have no moving parts, instead operating on compression to slow freestream supersonic air to subsonic speeds, thereby increasing temperature and pressure, and then combusting the compressed air with fuel. Lastly, a nozzle accelerates the exhaust to supersonic speeds, resulting in thrust. At around Mach 4 the pressures and temperatures become so high in supersonic flight that it is no longer efficient to slow the oncoming flow to subsonic speeds for combustion. Then a scramjet (supersonic combustion ramjet) is used in place of a ramjet. Scramjet engines are a type of jet engine, and rely on the combustion of fuel and an oxidizer to produce thrust. Similar to conventional jet engines, scramjet-powered aircraft carry the fuel on board, and obtain the oxidizer by the ingestion of atmospheric oxygen (as compared to rockets which carry both fuel and an oxidizing agent). This requirement limits scramjets to suborbital atmospheric propulsion, where the oxygen content of the air is sufficient to maintain combustion.

The scramjet is composed of three basic components: a converging inlet, where incoming air is compressed; a combustor, where gaseous fuel is burned with atmospheric oxygen to produce heat; and a diverging nozzle, where the heated air is accelerated to produce thrust. Similar to ramjet a scramjet does not use rotating, fan-like components to compress the air; rather, the achievable speed of the aircraft moving through the atmosphere causes the air to compress within the inlet.

Due to the nature of their design, scramjet operation is limited to near-hypersonic velocities. As they lack mechanical compressors, scramjets require the high Kinetic Energy of a hypersonic flow to compress the incoming air to operational conditions. Thus, a scramjet-powered vehicle must be accelerated to the required velocity (usually about Mach 4-5) by some other means of propulsion, such as turbojet, railgun, or rocket engines.

II. Ideal Scramjet Cycle

The scramjet engine belongs to the family of Brayton cycles which consists of two adiabatic and two constant pressure processes. A simplified schematic of a scramjet engine is shown in Figure 2 describing a lifting body with the vehicle's fore-body contributing to a large extent to the inlet compression and the after-body constituting part of the engine nozzle. The engine, therefore, occupies essentially the entire lower surface of the vehicle. The standard engine designation, derives from the standard station designation of gas turbine engines and is used to emphasize the separation between the major engine components. (Using Heiser and Pratt's designations)



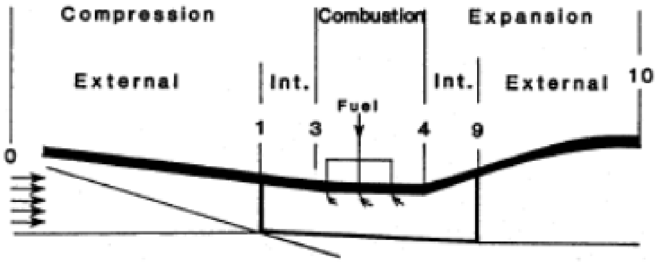


Fig. 1 Brayton Cycle

Fig. 2 Scramjet Stages

- station 0 represents the freestream condition,
- station 1 represents the beginning of the compression process. Hypersonic shock waves angles are small resulting in long compression ramps (or spikes for an axisymmetric configuration) which, in many suggested configurations, begin at the leading edge of the vehicle. Additional compression takes place inside the inlet duct.
- station 2.1 represents the entrance into the isolator section. The role of the isolator is to separate the inlet from the adverse effects of pressure rise due to combustion in the combustion chamber. The presence of a shock train in the isolator contributes to further compress the air before entering the combustion chamber. Thermodynamically the isolator is not a desirable component, since it is a source of additional pressure losses, increases the engine cooling loads and it adds to the engine weight. However, operationally it is needed to include a shock train that adjusts such that it fulfills the role described above.
- station 3 is the combustion chamber entrance. Unlike the turbojet engine cycle, where the air compression ratio is controlled by the compressor settings, in a fixed geometry scramjet the pressure at the combustion chamber entrance varies over a large range depending on the flight regime.
- station 4 is the combustion chamber exit and beginning of the expansion.
- station 10 is the exit from the nozzle and due to the large expansion ratios the entire aft part of the vehicle may be part of the engine nozzle.

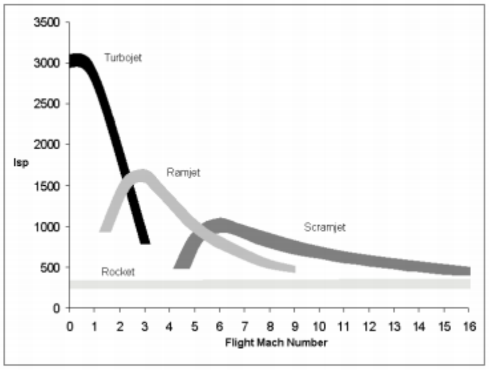


Fig. 3 Isp for various flight regimes

Fig. 4 Computerized version of X-51

III. Design Challenge

While scramjets are conceptually simple, actual implementation is limited by extreme technical challenges. Hypersonic flight within the atmosphere generates immense drag, and temperatures found on the aircraft and within the engine can be much greater than that of the surrounding air. Maintaining combustion in the supersonic flow presents additional challenges, as the fuel must be injected, mixed, ignited, and burned within milliseconds. While scramjet technology has been under development since the 1950s, only very recently have scramjets successfully achieved powered flight.

There are three main areas that these problems lay in, namely Air Inlet, Combustor, and Structures and Materials. Problems within these areas vary from inlet starting problems to the inherent difficulty of the ignition of the fuel in a supersonic flow, as the possibility of failure exists anywhere from the fuel not igniting to the possibility that the ignition could take place outside of the combustor due to the extraordinary velocity of the air in the engine. Additionally, structures that can withstand the extreme temperatures experienced during hypersonic flight combined with the additional temperatures experienced during combustion are necessary.

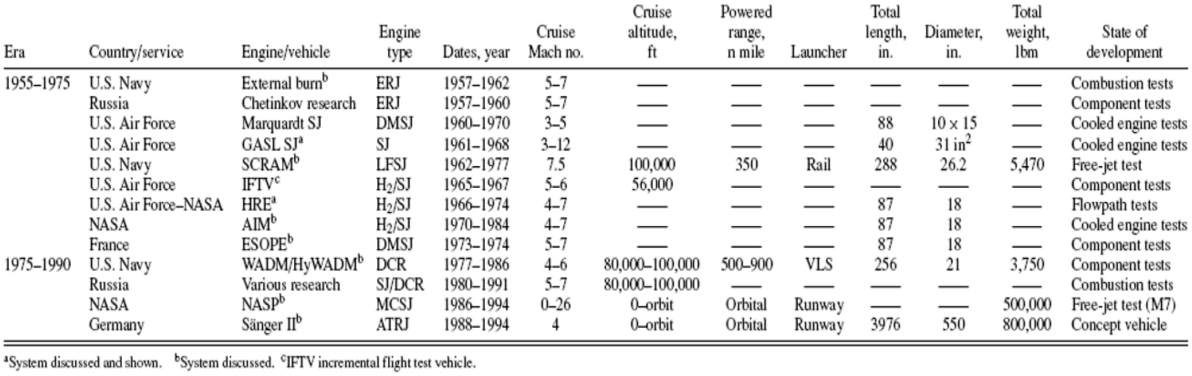
In addition to the current technical challenges of scramjet development, there is another area of scramjet development which deserves attention. Despite the wide range of applications possible with scramjet technology, the vehicle must first be propelled to a high enough Mach number for the scramjet to start. This requires, depending on the needed application, one or two additional propulsion systems to propel the vehicle to the needed scramjet start velocity. Current scramjet designs target the start of supersonic combustion to be between Mach 5 and 6. [1][6] In order to minimize the weight and complexity of having multiple propulsion systems, a dual-mode ramjet/scramjet is often proposed. This will be discussed in the following sections. [19]

IV. History

[1, 2, 3] As mentioned previously, the scramjet is a direct descendent of the ramjet. Therefore, in an attempt to provide a brief historical timeline of the modern-day scramjet, we must first begin with the invention of the ramjet. The first patent for a subsonic ramjet device, specifically for what is now known as an ejector ramjet, was issued to Lake in the United States in 1909 [3]. Simultaneously, René Lorin of France was working on ejector ramjets, publishing the first treatise on subsonic ramjets in 1913 [1,3]. According to Fry [3], the ramjet engine reached a relative peak of interest during the 1950s in terms of the number of operational systems being deployed, with a subsequent international resurgence of attention beginning in the 1980s.

Development on the scramjet, on the other hand, did not begin until the mid-1950s through early 1960s [1,3,4]. The basis for its development came about due to an interest in "burning fuels in external streams to either reduce the base drag of supersonic projectiles or to produce lift and/or thrust on supersonic and hypersonic airfoils in the early 1950s" [3]. Additionally, the findings of the 1960 study by Dugger on the relative performance of a kerosene-fueled conventional ramjet engine (CRJ) and a scramjet engine showed that the scramjet's performance would exceed the performance of the CRJ in the speed range of Mach 6 to 8 [2]. The first scramjet demonstration also took place in 1960 by Ferri [3]. Following this demonstration, many major scramjet development programs were started in the United States, the most extensive of these being the NASA Hypersonic Research Engine [3] or Hypersonic Ramjet Experiment [1, 4, 3] (HRE) program in 1964. The core goal for the HRE project was to test a "complete, regenerative cooled, flight weight scramjet on the X-15A-2 rocket research airplane" [1, 2, 3]. Unfortunately, this program was not able to be flight tested as the cost to repair the X-15 A-2 was too high and the entire X-15 program was cancelled in 1968 [1]. (Note: The damage referred to here occurred during the first non-burning test flight when the shock wave from the inlet spike impinged on the lower ventral fin, causing extensive damage—one of the first incidents of shock-shock interaction heating, which became a major research area in itself [1].) However, many other projects continued towards developing the scramjet. Fry [3] has compiled an impressive summary of the scramjet's evolution beginning with its conception in 1955 through 2004 and can be found below in Tables 1.1 and 1.2.

Table 1.1: Worldwide Scramjet Evolution, 1955-1990 [3]



Era	Country/service	Engine/vehicle	Engine type	Dates, year	Cruise Mach no.	Cruise altitude, ft	Powered range, n mile	Launcher	Total length, in.	Diameter, in.	Total weight, lbm	State of development
1955–1975	U.S. Navy	External burn[b]	ERJ	1957–1962	5–7	—	—	—	—	—	—	Combustion tests
	Russia	Chetinkov research	ERJ	1957–1960	5–7	—	—	—	—	—	—	Component tests
	U.S. Air Force	Marquardt SJ	DMSJ	1960–1970	3–5	—	—	—	88	10 × 15	—	Cooled engine tests
	U.S. Air Force	GASL SJ[a]	SJ	1961–1968	3–12	—	—	—	40	31 in^2	—	Cooled engine tests
	U.S. Navy	SCRAM[b]	LFSJ	1962–1977	7.5	100,000	350	Rail	288	26.2	5,470	Free-jet test
	U.S. Air Force	IFTV[c]	H_2/SJ	1965–1967	5–6	56,000	—	—	—	—	—	Component tests
	U.S. Air Force–NASA	HRE[a]	H_2/SJ	1966–1974	4–7	—	—	—	87	18	—	Flowpath tests
	NASA	AIM[b]	H_2/SJ	1970–1984	4–7	—	—	—	87	18	—	Cooled engine tests
	France	ESOPE[b]	DMSJ	1973–1974	5–7	—	—	—	87	18	—	Component tests
1975–1990	U.S. Navy	WADM/HyWADM[b]	DCR	1977–1986	4–6	80,000–100,000	500–900	VLS	256	21	3,750	Component tests
	Russia	Various research	SJ/DCR	1980–1991	5–7	80,000–100,000	—	—	—	—	—	Combustion tests
	NASA	NASP[b]	MCSJ	1986–1994	0–26	0–orbit	Orbital	Runway	—	—	500,000	Free-jet test (M7)
	Germany	Sänger II[b]	ATRJ	1988–1994	4	0–orbit	Orbital	Runway	3976	550	800,000	Concept vehicle

[a] System discussed and shown. [b] System discussed. [c] IFTV incremental flight test vehicle.

Fry [3] has a useful system—for which he cites McClinton et al. [10]—for dividing up the generations of scramjet development, namely: Beginnings (1960-1973), Airframe Integration (1973-1986), NASP (1986-1994), and Resurgence (1995-Today) [3]. Table 1.1 displays the Beginnings generation through the NASP generation; Table 1.2 displays mainly what Fry describes as the Resurgence generation.

Table 1.2 leaves off in 2004, just prior to the X-43A setting the Guinness World Record for a jet-powered aircraft with a Mach number of 9.6 in November of that year [5]. Though the X-43A set a new speed record, it was not the first flight test of a scramjet. That title is occupied by the University of Queensland in Australia for the HyShot program in July 2002 [6].

In summary, the major propulsion systems of the modern era have a direct correlation between the year of their first flight and their current prevalence of application: Turbojet-1939, Ramjet-1940, High-Performance Large Liquid-Fueled Rocket Engine-1943, Practical Man-Rated Reusable Throttle Rocket Engine-1960, and the Scramjet-2002 [3]. However, despite the fact that no operational and readily available scramjet engine currently exists, this is not due to a lack of potential applications which would benefit greatly from the use of the scramjet.

US efforts are probably the best funded, and the Hyper-X team claimed the first flight of a thrust-producing scramjet-powered vehicle with full aerodynamic maneuvering surfaces in 2004 with the X-43A.

In 2007, the US Defense Advanced Research Project Agency (DARPA), in cooperation with the Australian Defense Science and Technology Organization (DSTO), announced a successful scramjet flight at Mach 10 using rocket engines to boost the test vehicle to hypersonic speeds.

A series of scramjet ground tests was completed at NASA Langley Arc-Heated Scramjet Test Facility (AHSTF) at simulated Mach 8 flight conditions. These experiments were used to support HIFiRE flight 2. [13]

In 2009, Woomera (Australia) hosted the first successful test flight of a hypersonic aircraft in HIFiRE. The launch was one of 10 planned test flights. The series of up to 10 planned hypersonic flight experiments is part of a joint research program between the Defense Science and Technology Organization and the US Air Force, designated as the Hypersonic International Flight Research Experimentation (HIFiRE). [13] HIFiRE is investigating hypersonic technology and its application to advanced scramjet-powered space launch vehicles — the objective is to support the new Boeing X-51 scramjet demonstrator while also building a strong base of flight test data for quick-reaction space launch development and hypersonic "quick-strike" weapons.[13] In 2010, scientists successfully tested a (HIFiRE) hypersonic rocket. It reached an atmospheric velocity of "more than 5,000 kms per hour" after taking off from the Woomera Test Range. [14] [15]

NASA and the USAF successfully flew the X-51A Waverider for approximately 200 seconds at Mach 5, setting a new world record hypersonic airspeed, in 2010. The Waverider flew autonomously before losing acceleration for an unknown reason and destroying itself as planned. The X-51A was carried aboard a B-52, accelerated to Mach 4.5 via a solid rocket booster, and then ignited the Pratt & Whitney Rocketdyne scramjet engine to reach Mach 5 at 70,000 feet. However, a second flight in 2011 was ended prematurely when the engine lit briefly on ethylene but failed to transition to its primary JP-7 fuel, failing to reach full power.

Same year Australian scientists successfully demonstrated that the high-speed flow in a naturally non-burning scramjet engine can be ignited using a pulsed laser source.

A further X-51A Waverider test failed in 2012. The attempt to fly the Scramjet, carried by a B-52 for a prolonged period at Mach 6 was cut short when, only 15 seconds into the unmanned flight, the craft lost control and broke apart, falling into the Pacific Ocean north-west of Los Angeles. The cause of the failure was blamed on a faulty control fin.

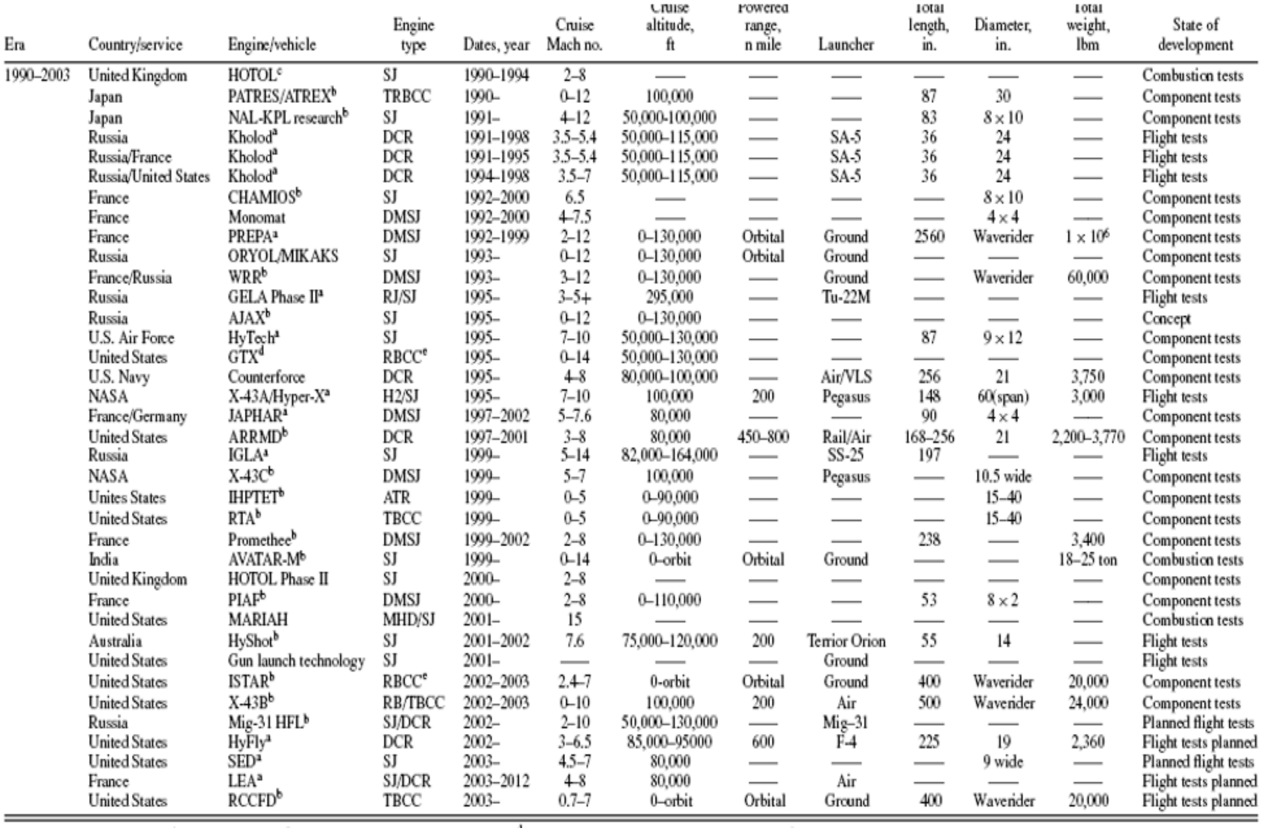
In May 2013 an unmanned X-51A WaveRider reached 4828 km/h (Mach 5.1) during a three-minute flight under scramjet power. The WaveRider was dropped at 50,000 feet from a B-52 bomber, and then accelerated to Mach 4.8 by a solid rocket booster which then separated before the WaveRider's scramjet engine came into effect.

Announced in 2013 by Lockheed Martin, SR-72 is the next-generation plane, (successor of SR-71) which should be able to travel at six times the speed of sound will use state-of-the-art computer technology with hypersonic missiles to make super-fast stealth strikes on targets. It is planned for release by 2030. It’s planned for release by 2030.

British company Reaction Engines is working on a new type of engine called SABRE that would allow for the development of an unmanned spaceplane (not a spy plane) that could take off and land like a conventional aircraft. It would initially use air-breathing engines to take off and fly at Mach 5.5 before switching to a rocket engine at high altitude to ascend into the Earth’s orbit, where it could travel at a speed of Mach 25 (25 times the speed of sound).

In June,2015 The Chinese Defense Ministry confirmed the fourth test of a hypersonic nuclear delivery vehicle, which the US called an “extreme maneuver,” amid rising tensions between the two powers in the South China Sea. The WU-14 is a strategic strike weapon and can travel at 10 times the speed of sound, or 12,231.01kph. [20] [21]

Table 1.2: Worldwide Scramjet Evolution, 1990-2004 [3]



Era	Country/service	Engine/vehicle	Engine type	Dates, year	Cruise Mach no.	Cruise altitude, ft	Powered range, n mile	Launcher	Total length, in.	Diameter, in.	Total weight, lbm	State of development
1990–2003	United Kingdom	HOTOL[c]	SJ	1990–1994	2–8	—	—	—	—	—	—	Combustion tests
	Japan	PATRES/ATREX[b]	TRBCC	1990–	0–12	100,000	—	—	87	30	—	Component tests
	Japan	NAL-KPL research[b]	SJ	1991–	4–12	50,000-100,000	—	—	83	8 × 10	—	Component tests
	Russia	Kholod[a]	DCR	1991–1998	3.5–5.4	50,000–115,000	—	SA-5	36	24	—	Flight tests
	Russia/France	Kholod[a]	DCR	1991–1995	3.5–5.4	50,000–115,000	—	SA-5	36	24	—	Flight tests
	Russia/United States	Kholod[a]	DCR	1994–1998	3.5–7	50,000–115,000	—	SA-5	36	24	—	Flight tests
	France	CHAMIOS[b]	SJ	1992–2000	6.5	—	—	—	—	8 × 10	—	Component tests
	France	Monomat	DMSJ	1992–2000	4–7.5	—	—	—	—	4 × 4	—	Component tests
	France	PREPA[a]	DMSJ	1992–1999	2–12	0–130,000	Orbital	Ground	2560	Waverider	1 × 10[6]	Component tests
	Russia	ORYOL/MIKAKS	SJ	1993–	0–12	0–130,000	Orbital	Ground	—	—	—	Component tests
	France/Russia	WRR[b]	DMSJ	1993–	3–12	0–130,000	—	Ground	—	Waverider	60,000	Component tests
	Russia	GELA Phase II[a]	RJ/SJ	1995–	3–5+	295,000	—	Tu-22M	—	—	—	Flight tests
	Russia	AJAX[b]	SJ	1995–	0–12	0–130,000	—	—	—	—	—	Concept
	U.S. Air Force	HyTech[a]	SJ	1995–	7–10	50,000–130,000	—	—	87	9 × 12	—	Component tests
	United States	GTX[d]	RBCC[e]	1995–	0–14	50,000–130,000	—	—	—	—	—	Component tests
	U.S. Navy	Counterforce	DCR	1995–	4–8	80,000–100,000	—	Air/VLS	256	21	3,750	Component tests
	NASA	X-43A/Hyper-X[a]	H2/SJ	1995–	7–10	100,000	200	Pegasus	148	60(span)	3,000	Flight tests
	France/Germany	JAPHAR[a]	DMSJ	1997–2002	5–7.6	80,000	—	—	90	4 × 4	—	Component tests
	United States	ARRMD[b]	DCR	1997–2001	3–8	80,000	450–800	Rail/Air	168–256	21	2,200–3,770	Component tests
	Russia	IGLA[a]	SJ	1999–	5–14	82,000–164,000	—	SS-25	197	—	—	Flight tests
	NASA	X-43C[b]	DMSJ	1999–	5–7	100,000	—	Pegasus	—	10.5 wide	—	Component tests
	Unites States	IHPTET[b]	ATR	1999–	0–5	0–90,000	—	—	—	15–40	—	Component tests
	United States	RTA[b]	TBCC	1999–	0–5	0–90,000	—	—	—	15–40	—	Component tests
	France	Promethee[b]	DMSJ	1999–2002	2–8	0–130,000	—	—	238	—	3,400	Component tests
	India	AVATAR-M[b]	SJ	1999–	0–14	0–orbit	Orbital	Ground	—	—	18–25 ton	Combustion tests
	United Kingdom	HOTOL Phase II	SJ	2000–	2–8	—	—	—	—	—	—	Component tests
	France	PIAF[b]	DMSJ	2000–	2–8	0–110,000	—	—	53	8 × 2	—	Component tests
	United States	MARIAH	MHD/SJ	2001–	15	—	—	—	—	—	—	Combustion tests
	Australia	HyShot[b]	SJ	2001–2002	7.6	75,000–120,000	200	Terrior Orion	55	14	—	Flight tests
	United States	Gun launch technology	SJ	2001–	—	—	—	Ground	—	—	—	Flight tests
	United States	ISTAR[b]	RBCC[e]	2002–2003	2.4–7	0-orbit	Orbital	Ground	400	Waverider	20,000	Component tests
	United States	X-43B[b]	RB/TBCC	2002–2003	0–10	100,000	200	Air	500	Waverider	24,000	Component tests
	Russia	Mig-31 HFL[b]	SJ/DCR	2002–	2–10	50,000–130,000	—	Mig–31	—	—	—	Planned flight tests
	United States	HyFly[a]	DCR	2002–	3–6.5	85,000–95000	600	F-4	225	19	2,360	Flight tests planned
	United States	SED[a]	SJ	2003–	4.5–7	80,000	—	—	—	9 wide	—	Planned flight tests
	France	LEA[a]	SJ/DCR	2003–2012	4–8	80,000	—	Air	—	—	—	Flight tests planned
	United States	RCCFD[b]	TBCC	2003–	0.7–7	0–orbit	Orbital	Ground	400	Waverider	20,000	Flight tests planned

V. Applications

There are a number of future potential missions and applications for Hypersonic Vehicles propelled by high-speed propulsion systems. High-speed propulsion systems include the more conventional ramjet and scramjet propulsion systems as well as less developed concepts such as shock-initiated combustion and detonation devices and even more revolutionary engine cycles.

Candidates for future research and development include the following concepts.

Hypervelocity flight propulsion systems

- Hypervelocity scramjet development
- Shock-initiated combustion engine concepts utilizing strong shocks for ignition and flame holding
- Pulsed detonation engines
- Oblique unsteady engine flow cycles
- Air-augmented rockets

Revolutionary engines cycles

- MHD energy extraction and addition to scramjet cycle
- Ground-based injection energy sources
- Matter-antimatter energy sources
- Micro-fusion/fission engines that use anti-matter and deuterium or hydrogen to achieve high specific impulse
- Plasma enhanced scramjet cycles

There are a number of potential mission to which conventional and advanced propulsion systems can be applied. Earlier efforts as well as current activities have concentrated on the evolution of hypersonic cruise vehicles using scramjet propulsion systems.

Some of the applications of military interest are -

- Hypersonic cruise missiles
- Hypersonic reconnaissance vehicles
- Ground-to-air-defensive systems
- Mach 6 to 8 vehicles with excursive ability to go suborbital and return.
- A scramjet as a specific impulse enhancer. Rockets would be packed with the scramjet allowing the package to operate in the intermediate range of Mach 6 to 10

Space Launch

- SSTO

Civil Application

VI. Scramjet Engine Systems

A. Propulsion Systems

- *Dual-Mode Scramjet*

The term “dual-mode” refers the ability of the engine to operate with flow regions in the combustor that are subsonic, supersonic, or a mixture of the two. The sizes of these regions change as the vehicle speed changes. This means that fuel injection, fuel–air mixing, ignition, flame holding and combustion can occur over a broad range of conditions.

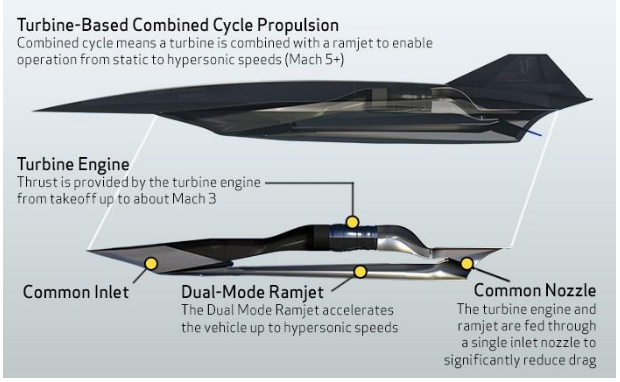


Fig. 5 Dual Cycle System: SR-72

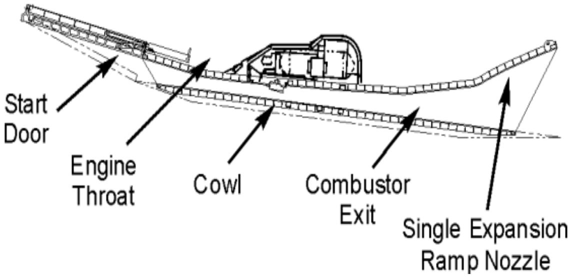


Fig. 6 Hydrocarbon Scramjet

- *Dual-Mode Variable Geometry Scramjet*

In a variable geometry scramjet, the flowpath is changed according to the freestream Mach number to ensure high performance values throughout a wide range of Mach numbers. An example of a program which employed this technique is the HRE program which developed a flight-weight hydrogen-fueled scramjet designed to operate from Mach 4 to 7 using variable geometry [3]. This hardware requires remote actuators, articulating top wall, fixed cowl, replaceable/parametric seal.

- *Hydrocarbon Scramjet Technology*

HySET is necessary to demonstrate the operability, performance and structural durability of a liquid hydrocarbon fueled scramjet propulsion system that operates from Mach 4 to 8. Successful tests have been done at NASA Glenn Research Center for evaluating the combustion efficiency, mixing efficiency and heat flux in various parts of the scramjet.

Pratt & Whitney (P&W) tested engine in 2004, known as the Ground Demonstration Engine (GDE-1), used standard JP-7 fuel in an "endothermic/regeneratively cooled cycle" during which the fuel cooled the engine's interior walls before being introduced to the combustion chamber to produce trust. The engine injects, mixes and burns fuel to make thrust in a time span of less than 0.001 seconds.

- *MHD Ramjet*

Magnetohydrodynamic (MHD) energy extraction with later addition to supersonic flows offers possible benefits in the area of propulsion flow path flow control that are not available in conventional supersonic reaction flows, where high pressure and temperature are continually present. MHD flow control can in principle be used to minimize flow losses and increase engine efficiency. It can be used for drag reduction, shock attenuation and to enhance fuel-air mixing in scramjets.

- *Combined Cycle Engine Optimization*

  Many ideas have been suggested to combine scramjets with other conventional propulsion systems to increase the mission range. Although the use of CPS avoids propulsion systems integration issues, it requires carrying at all times at least one propulsion system that is not actively contributing to thrust generation and, thus, leads to inefficient use of weight, volume and increases the heating load.
  - The Turbine Based Combined Cycle – TBCC
  - The Rocket Based Combined Cycle – RBCC

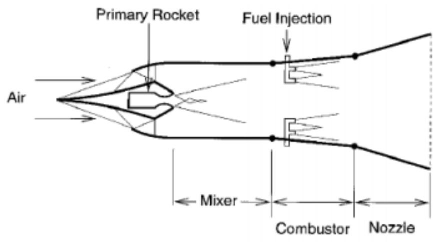


Fig. 7 **RBCC** with a rocket acting as an ejector to augment the airflow into the ramjet/scramjet segment.

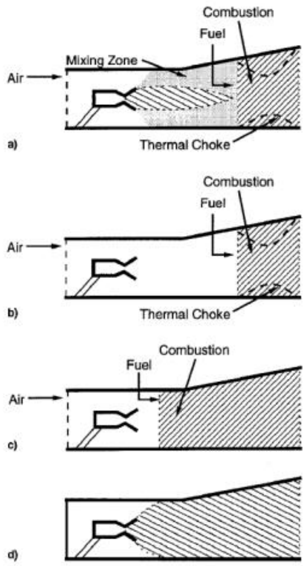


Fig. 8 Operation of an ejector scramjet RBCC:
a) rocket-ejector, b)ramjet, c)scramjet and, d) rocket-only

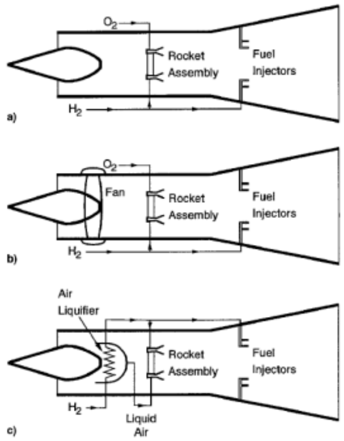


Fig. 9 Subsystems that could be added to an ejector scramjet engine*: a) basic ejector scramjet, b) ejector scramjet with turbofan and c) ejector scramjet with air liquefaction system.*

- *Detonation/Pulse Detonation Engine*: Detonative combustion produces high pressure which is converted to thrust. After all mixture is consumed by detonation, combustion products have to be evacuated from the tube and fresh mixture must be quickly resupplied, and the cycle is repeated. It is almost a constant volume process that is more efficient than a constant pressure Brayton cycle. The detonation speed is characterized by C-J velocity, which is many magnitudes greater than the deflagration speeds. Hence, the pressure produced are extremely high which can be converted directly into thrust. [12] [13]

B. Fuels

In this section the following have been considered as candidate fuels: hydrogen, hydrocarbons, exotic high-energy-density fuels, Endothermic Hydrocarbons.

Hydrocarbons: All hydrocarbon fuels decompose at high temperature, and generally absorb heat in the process. Methane and JP-7 are hydrocarbon compounds, and characteristically exhibit thermal instability at some elevated temperature, resulting in decomposition of the fuel and deposition of carbon and varnish on surfaces in the fuel system. The process, commonly called coking, results in plugging of passages, and ultimate failure of engine systems. The rate of deposition depends on several factors, such as fuel temperature and pressure, surface temperature, fuel velocity, and surface characteristics. The sensitivity to the different variables, and the resulting maximum temperature and environmental conditions in which a fuel can be satisfactorily used is a characteristic of each specific fuel. Methane, although not yet well characterized, is thought to be usable at temperatures up to about 1200F. JP-7, on the other hand, is well characterized and is considered usable up to 550F for long term operation, and up to 600F for short term use, on the order of fifteen minutes or less. [11]

Endothermic Fuels: Endothermic fuels exhibit the desirable characteristic of clean decomposition without forming surface deposits, and absorb large quantities of heat in the process. Endothermic decomposition can occur thermally due to exposure to high temperature, but is more useful when promoted with a catalyst under controlled conditions. In this process, fuel which has been heated by prior use as a coolant is decomposed by catalytic dehydrogenation, yielding hydrogen and new hydrocarbon compounds, while significantly decreasing in temperatures. The resulting decomposed products can then be further used as a coolant. Several hydrocarbon fuels have been demonstrated to exhibit significant endothermic characteristics, notably decalin and methylcyclohexane (MCH).

Hydrogen: Hydrogen, being an element rather than a compound, is stable at temperatures below about 3000F, and exhibits dissociation to the monatomic form only at very high temperatures. Thus, hydrogen is not thermally limited in application, except by the thermal limitation of the surrounding structure. Also, liquid Hydrogen is very effective for active cooling of vehicle structures, which is an important requirement for high speed flights. A comparison of the heat sink capability of these fuels is shown in Figure 10. Hydrogen ignition and combustion occurs in moderate-heated air under very lean conditions, and is rapid enough that scramjet combustion is possible over a reasonable length. Further, Hydrogen ignition and combustion is possible at rates 10 to 30 times higher than flames using gaseous light-hydrocarbons (HCs) at typical temperatures, it is preferred fuel for air-breathing scramjets based on reactivity alone. Hydrogen on a mass basis is the preferred choice, however, on a volumetric basis, it is not any better than methane. Also unfortunately, liquid hydrogen is difficult to store and handle on routine basis. [11]

Another fundamental difference in these fuels is their storage temperatures. Hydrogen and methane are cryogenic, with ambient pressure boiling temperatures of 36R and 200R respectively, whereas JP-7 is storable as a liquid at ambient temperature. This characteristic increases the available heat sink of the cryogenic fuels over their usable temperature range, but makes their storage more difficult because of heat leakage from the surrounding environment resulting in fuel boil-off.

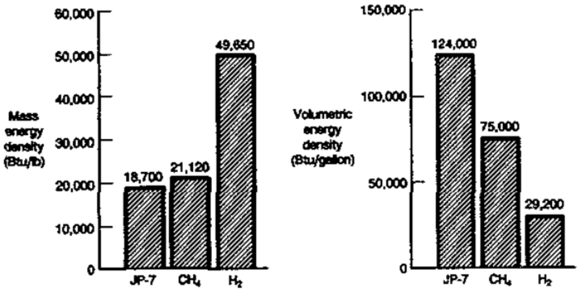


Fig. 10 Enegry Density Comparison

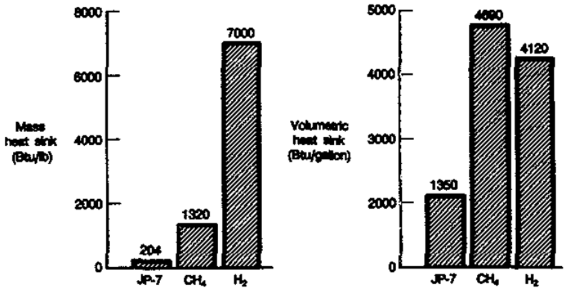
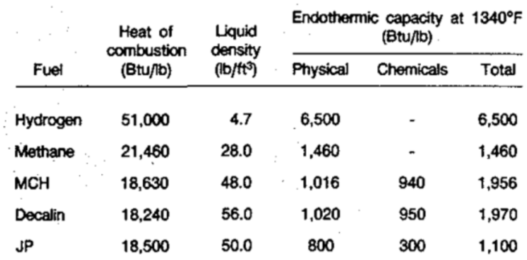


Fig. 11 Fuels as Heat sink



Fuel	Heat of combustion (Btu/lb)	Liquid density (lb/ft³)	Endothermic capacity at 1340°F (Btu/lb) Physical	Chemicals	Total
Hydrogen	51,000	4.7	6,500	-	6,500
Methane	21,460	28.0	1,460	-	1,460
MCH	18,630	48.0	1,016	940	1,956
Decalin	18,240	56.0	1,020	950	1,970
JP	18,500	50.0	800	300	1,100

Fig. 12 Characteristic Properties of Fuels

High-Energy-Density Fuels : Various fuels have been developed with improved reactivity and energy release like Cubane, polymeric BxNyHz, liquid Hydrogen gelled with HCs and other organic additives like nitrates, nitrites, ethers and peroxides. These have typical problems of stability, storage, toxicity and increased cost.

C. Inlet

The performance of scramjet inlets can be described by two key parameters: 1) capability, or how much compression is performed, and 2) efficiency, or what level of flow losses does the forebody/inlet generate during the compression process.

Design Objectives:

- Minimum weight geometry
- Low external drag
- Produce nearly uniform flow into combustor
- Operate over a specified range of Mach number and angle-of-attack

Classes of Hypersonic Inlets:

- ***External Compression:*** all the compression is performed by flow turning in one direction by shock waves that are external to the engine. These inlet configurations have large cowl drag, as the flow entering the combustor is at a large angle relative to the freestream flow, however, external compression inlets are self-starting and spill flow when operated below the design Mach number (this is a desirable feature for inlets that must operate over a large Mach number range).
- ***Internal Compression:*** Here all the compression is performed by shock waves that are internal to the engine. This type of inlet can be shorter than a mixed compression inlet, but it does not allow easy integration with a vehicle. It maintains full capture at Mach numbers lower than the design point, but its most significant limitation is that extensive variable geometry is always required for it to start.
- ***Mixed Compression:*** Here the compression is performed by shocks both external and internal to the engine, and the angle of the external cowl relative to the freestream can be made very small to minimize external drag. These inlets are typically longer than external compression configurations, but also spill flow when operated below the design Mach number. Depending on the amount of internal compression, however, mixed compression inlets may need variable geometry in order to start
- ***3D Sidewall Compression:*** The sidewall compression inlet configuration was designed to integrate smoothly with a hypersonic vehicle as a series of modular ducts. It had a fixed geometry (self-starting), mixed compression inlet.
- ***Streamline Traced:*** Streamline-traced inlets are typically used in a modular arrangement to meet a given mass capture requirement
- ***Combined Cycle Inlet:*** This design is necessary for the engine to operate in different flight regimes.

Inlet Operability:

- ***Inlet Starting:*** Due to choked flow at the inlet, the boundary layer separation takes place upstream of cowl lip. This results in large peak pressure at cowl lip and large unsteady pressure components. An estimate of internal contraction ratio is obtained assuming a normal shock at the lip and sonic flow at the throat. The resulting area ratio is given by Kantrowitz limit.

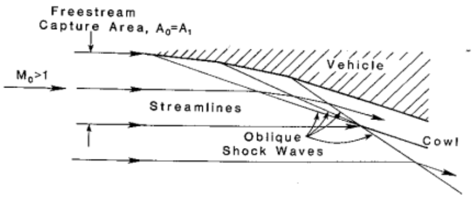


Fig. 13 External Combustion Inlet

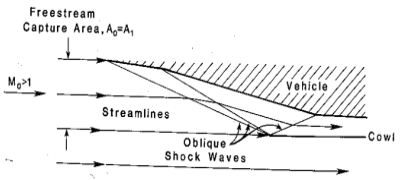


Fig. 14 Mixed Combustion Inlet

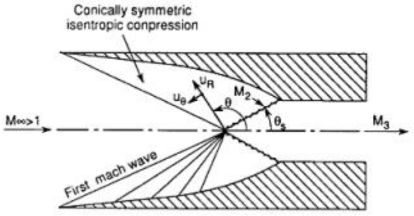


Fig. 15 Internal Combustion Inlet

- ***Maximum Contraction Ratio**:* It is the ratio of inlet area to the throat area. Maximum CR occurs at minimum throat Mach number.

- ***Shock-Wave/Boundary Layer Interaction:*** When a shock wave interacts with a boundary layer, its main effect is to cause a sudden retardation of the flow, with subsequent thickening and, in many cases, separation of the boundary layer. These phenomena have a significant (typically negative) impact on the aerodynamic performance of aircraft through their effect on the global force coefficients. The low-frequency unsteadiness associated with intermittent flow separation can cause strong buffeting of the aircraft structures, which may lead to failure by structural fatigue or to payload damage. [14]

- ***Maximum Back-Pressure:*** When the combustor intel pressure crosses the critical value the spillage becomes unstable resulting in loss in efficiency.

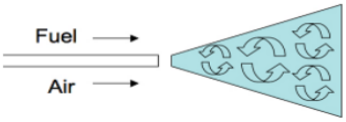


Fig. 16 Paraller Injection

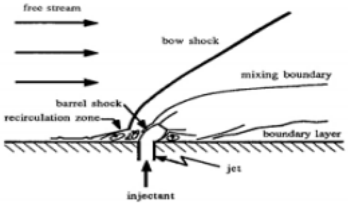


Fig. 17 Normal Injection

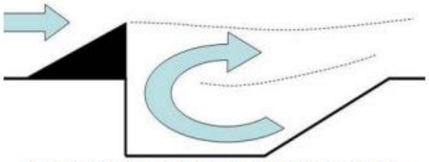


Figure 13. Cavity flame holder with inclined downstream ramp and leading edge pylon (on centerline)

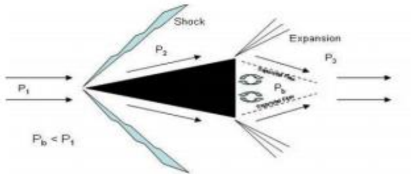


Fig. 18 Cavity Flame Holder

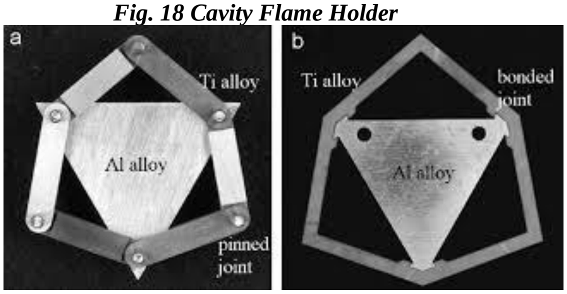


Fig. 19 Lattice Structure of Metal combination with low coefficient of thermal expansion

D. Combustor - Ignition and Flame Holding

Fuel injection techniques into scramjet engines are a field that is still developing today. The fuel that is used by scramjets is usually either a liquid or a gas. The fuel and air need to be mixed to approximately stoichiometric proportions for efficient combustion to take place. The main problem of scramjet fuel injection is that the airflow is quite fast, meaning that there is minimal time for the fuel to mix with the air and ignite to produce thrust (essentially milliseconds). Hydrogen is the main fuel used for combustion. Hydrocarbons present more of a challenge compared to hydrogen due to the longer ignition delay and the requirement for more advanced mixing techniques. Enhancing the mixing, and thus reducing the combustor length, is an important aspect in designing scramjet engines. There are number of techniques used today for fuel injection into scramjet engines. [15]

1) Parallel, Normal and Transverse Injection
2) Ramp Injectors
3) Strut injector
4) Plasma Ignitor
5) Pylon Injection
6) Upstream Injector
7) Barbotage Injection System
8) Pulsed Injector
9) Cavity Flame holders
10) Cavity-Pylon Flame holder
11) Conventional-scale bluff-body flame holders
12) Micro-flame holder
13) Cantilever Fuel Injectors

E. Materials

The extreme conditions present in hypersonic vehicles lead to unprecedented design challenges. The most critical regions include the scramjet engine, acreage surfaces, and leading edges.

The compression contour that is designed for optimal operation at one Mach number may be inefficient at other Mach numbers. Surfaces that can dynamically change shape would greatly impact engine performance. Active cooling is required for that purpose. Experimental results for a Mach 7 vehicle under steady-state flight conditions and stoichiometric fuel combustion reveal that, while C-SiC satisfies the design requirements at minimum weight, the Nb alloy Cb752 and the Ni alloy Inconel X-750 are also viable candidates, albeit at about twice the weight. Under the most severe heat loads (arising from heat spikes in the combustor), only Cb752 remains viable.

While metallic systems are desirable for durability and manufacturability, they often lack sufficient strength and oxidation resistance for the combustion environment. One technique used for this is Vapor Phase Strengthening of Actively-Cooled Structures. The approach consists of initial fabrication of requisite panel shape with formable, alloy-lean Ni or Nb sheet materials. Once shaped, the high-temperature strength and/or oxidation resistance are enhanced by incorporation of desirable elements, e.g. Al in Ni, using vapor phase processes, followed by high temperature homogenization. The diffusional homogenization of the deposited layer results in precipitation of strengthening phases uniformly through the wall thickness. Another technique is designing Low Thermal Expansion Lattices for Thermal Protection Systems. To ensure durability at elevated temperatures, a new coating approach was developed. Coating with submicron alumina particles incorporated into Si-20Cr-20Fe. Thermal gravimetric analysis results indicate that the addition of submicron alumina particles reduces the oxidative mass gain by a factor of four during thermal cycling, thereby increasing lifetime. The result is a structure with a thermal expansion coefficient as low as 10^-6 / K at 1000°C. [16]

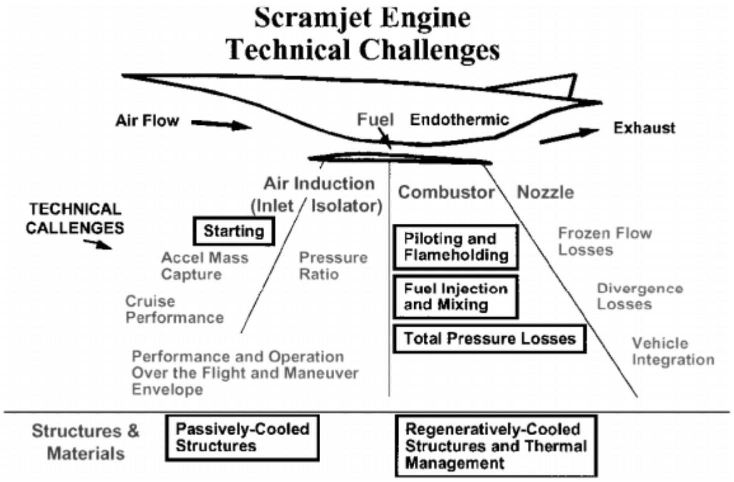


Fig. 20 Design Challenges for Scramjet Engines

VII. Conclusion

There are a number of potential missions and applications for hypersonic vehicles utilizing both conventional and non conventional airbreathing propulsion. Past and current work has included vehicles that have served mainly as test beds for development of propulsion systems. Future work should continue to develop and improve propulsion systems, but more effort should be expended on vehicle class that captures interest of potential users.

Acknowledgments

I would like to thank Dr Lakshmi Kantha of University of Colorado at Boulder Department of Aerospace Engineering for his assistance with this report. Also, I would like to acknowledge the authors of various Research Papers, Thesis, whose reports were refered for this paper.

References

[1] Heiser, William H., David T. Pratt, Daniel H. Daley, and Unmeel B. Mehta. Hypersonic Airbreathing Propulsion. Washington, D.C.: American Institute of Aeronautics and Astronautics, 1994

[2] Curran, Edward T., "Scramjet Engines: The First Forty Years." Journal of Propulsion and Power, Volume 17, No. 6, November-December 2001.

[3] Fry, Ronald S. "A Century of Ramjet Propulsion Technology Evolution." Journal of Propulsion and Power, Volume 20, No. 1, January-February 2004: 27-58.

[4] Waltrup, Paul J., Michael E. White, Frederick Zarlingo, and Edward S. Gravlin. "History of Ramjet and Scramjet Propulsion Development for U.S. Navy Missiles." Johns Hopkins APL Technical Digest, Volume 18, 1997: 234-243

[5] Disruptive Technology: Hypersonic Propulsion; Dr. William U. Borger Director Propulsion Directorate Air Force Research Laboratory

[6] "HyShot Program Secures Place in Flight History." The University of Queensland in Australia. 16 Aug. 2002

[9] Dr. Phillip T. Harsha; Lowell C. Keel; Dr. Anthony Castrogiovanni; Robert T. Sherrill, "X-43A Vehicle Design and Manufacture"

[10] C. McClinton. "X-43–Scramjet Power Breaks the Hypersonic Barrier"

[11] AIAA-86-2620, L.L. Coons, Pratt & Whitney - West Palm Beach, FL, PROPULSION CHALLENGES FOR HYPERSONIC FLIGHT

[12] AIAA 2002-0470, RECENT DEVELOPMENTS IN THE RESEARCH ON PULSE DETONATION ENGINES; K. Kailasanath Laboratory for Computational Physics and Fluid Dynamics Naval Research Laboratory

[13] Journal of KONES Powertrain and Transport, Vol. 18, No. 3 2011 : DETONATION ENGINES; Piotr Wolanski, Institute of Aviation Al. Krakowska and Institute of Heat Engineering, Warsaw University of Technology

[14] Analysis of unsteady effects in shock/boundary layer interactions; S. Pirozzoli, J. Larsson, J. W. Nichols, M. Bernardini, B. E. Morgan AND S. K. Lele

[15] Recent Advances in Scramjet Fuel Injection - A Review K.M.Pandey, Member IACSIT and T.Sivasakthivel

[16] Revolutionary Materials for Hypersonic Flight; Tresa M. Pollock, Office of Naval Research

[17] Hypersonic Airbreathing Propulsion: An Aerodynamics, Aerothermodynamics, and Acoustics Competency White Paper; NASA/TM-2002-211951

[18] ANALYSIS AND DESIGN OF A HYPERSONIC SCRAMJET ENGINE WITH A STARTING MACH NUMBER OF 4.00; KRISTEN NICOLE ROBERTS, University of Texas at Arlington

[19] Current State of High Speed Propulsion: Gaps, Obstacles, and Technological Challenges in Hypersonic Applications; Timothy A. Barber, Brian A. Maicke, and Joseph Majdalani University of Tennessee Space Institute

[20] https://www.rt.com/news/267115-china-tests-hypersonic-missile/

[21] http://www.theguardian.com/science/2014/jan/16/china-tests-hypersonic-missile-vehicle