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SCRAMJET ENGINES ENABLING THE SEAMLESS INTEGRATION OF AIR & SPACE OPERATIONS

The desire to fly, to fly faster, and fly higher has shaped history over the last 100 years. With the Wright brother's flight in 1903, Yeager's breaking the sound barrier in 1947, and Gagarin's ride into space in 1961, the pages of aerospace history are written with "firsts". As this century unfolds, revolutionary engine technology is being developed with the potential to fly at high Mach numbers and seamlessly integrate air to space operations. Known as a supersonic combustion ramjet (scramjet), this engine, which uses no rotating parts, will power vehicles hundreds of miles in minutes, making rapid, global travel and affordable access to space a reality.

Historical Overview

Scramjets have a long development history in the United States. In the 1940s, fundamental theoretical studies provided an understanding of high-velocity flow in ducts with heat addition. In the late 1950s, the first efforts to develop and demonstrate scramjet engines took place with Air Force, Navy and NASA laboratory experiments, which provided a foundation for the many development programs that followed. From the 1960s through today, many programs have had the objective of developing and demonstrating hydrogen and hydrocarbon-fueled scramjet engines. McClinton[1] explored these developments and examined each generation along with its unique contributions to the understanding of supersonic combustion. Fry[2] provided a comprehensive look into advances in ramjet propulsion technology from subsonic to hypersonic flight speeds since the early 1900s. The following references provide insight into some of the key programs that have helped to evolve scramjet technology to its current state.

The most influential program in modern scramjet development was **N**ational **A**ero-**S**pace **P**lane (NASP) program, which was established in 1986 to develop and fly a synergistically integrated low speed accelerator, ramjet and scramjet propulsion system. Designed to operate on hydrogen fuel, the X-30 (shown in Figure 1[3,4]), was developed intensively over the years of the NASP program.

Figure 1. X-30 NASP National Aero-Space Plane

The original engine design from the NASP program, while significantly modified by NASA, was used as the foundation for power plant of the successful X-43A vehicle that flew at Mach 7 (5,000 miles/hour) in March 2004[5] as part of the Hyper-X program. The data collected during the flight of X-43A (Figure 2) is an important step in the validation of hypersonic air-breathing vehicle and engine design methods.

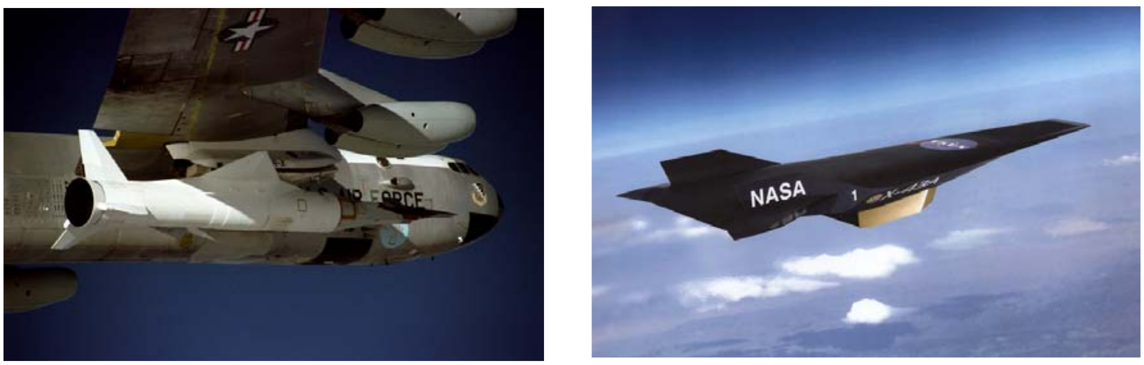

Figure 2. Captive Carry-to-Launch Conditions and X-43A First Free Flight Scramjet

The United States Government has been furthering the development of hydrogen and hydrocarbon scramjets. The U.S. Air Force/NASA and Pratt & Whitney ground tested the first uncooled hydrocarbon-fueled scramjet engine at simulated flight Mach numbers of 4.5 and 6.5, as reported in Aviation Week & Space Technology/March 2001[6]. Further development of this engine led to the ground demonstration of liquid JP7 hydrocarbon-fueled scramjet constructed from flight-weight (nickel-based alloys) fuel-cooled structures with the potential for satisfying requirements of future operational engines capable of powering missiles, aircraft, and access to space vehicles at sustained hypersonic speeds, as reported in Aviation Week & Space Technology/June 2003[7]. This program was marked by the first successful test of a flight-weight scramjet operating on storable JP-7 fuel. The Defense Advanced Research Projects (DARPA)/U.S. Navy and Boeing/Aerojet/JHU have also ground demonstrated a JP10 hydrocarbon-fueled dual combustion ramjet, which was constructed from non-flight weight materials (primarily nickel alloys) and intended exclusively for hypersonic missiles, as reported in Aviation Week & Space Technology/September 2003[8].

What is a Scramjet

A scramjet propulsion system is a hypersonic air-breathing engine in which heat addition, due to combustion of fuel and air, occurs in the flow that is supersonic relative to the engine[9,10]. In a conventional ramjet, engine the incoming supersonic airflow is decelerated to subsonic speeds by means of a multi-shock intake system and diffusion process. Fuel is added to the subsonic airflow, the mixture combusts and then re-accelerates through a mechanical choke to supersonic speeds. By contrast, the airflow in a pure scramjet remains supersonic throughout the combustion process and does not require a choking mechanism. Modern scramjet engines are able to seamlessly make the transition between ramjet and scramjet operation.

Why supersonic combustion

As flight Mach numbers increase beyond Mach 5, the use of supersonic combustion can provides higher performance (i.e. specific impulse) due to inlet efficiency offset by higher Rayleigh losses associated with combustion (Figure 3). Crossover points between ramjet and scramjet operation indicate the benefits of operating in ramjet until Mach 5-6. The process of decelerating airflow at flight Mach 6 to subsonic speeds for combustion results in near-stagnation conditions, with attendant high pressures and heat transfer rates. The engine structural integrity dictates supersonic combustion past Mach 6. Somewhere between Mach 5 and 6, the combination of these factors indicates a switch to scramjet operation. The physics beyond Mach 8 dictates supersonic combustion.

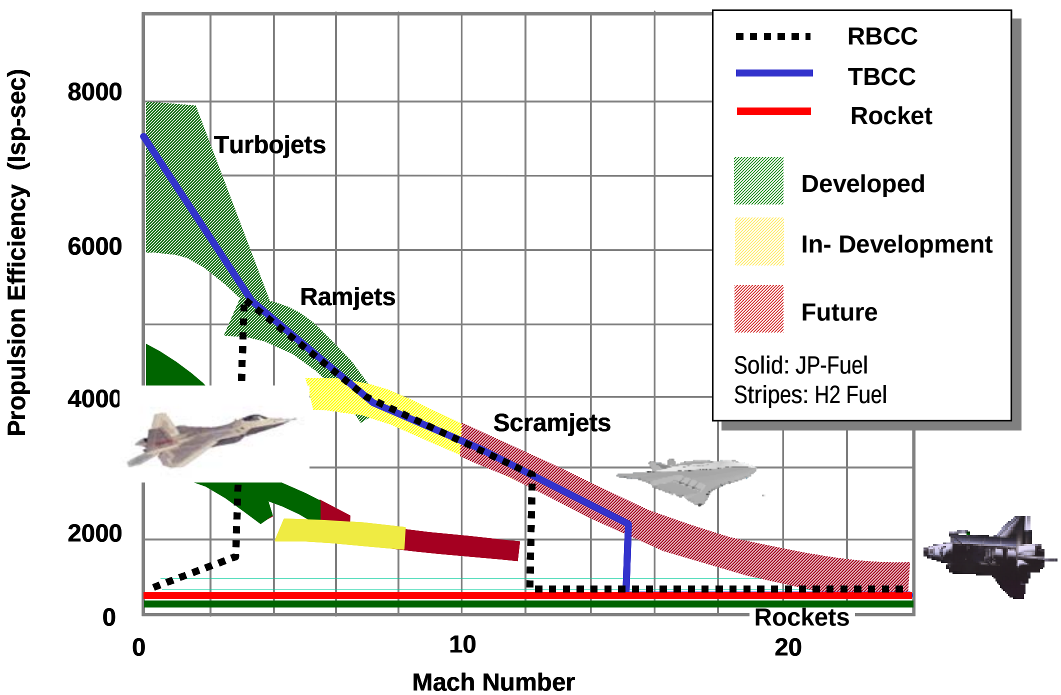

Figure 3. Propulsion Efficiency and Operating Regimes for Variety of Flight Systems

Aerophysics

The description of geometrical configuration and design consideration are the most important requirements for understanding the aerophysics of hypersonic air-breathing engines. The most closely integrated engine/vehicle integration is observed in the case of a propulsion system with a scramjet engine. The scramjet engine occupies the entire lower surface of the vehicle body. Scramjet propulsion system consists of five major engine and two vehicle components: internal inlet, isolator, combustor, internal nozzle and the fuel supply subsystem. The vehicle forebody is an essential part of the air induction system while the vehicle aftbody is a critical part of the nozzle component. These are described schematically in Figure 4.

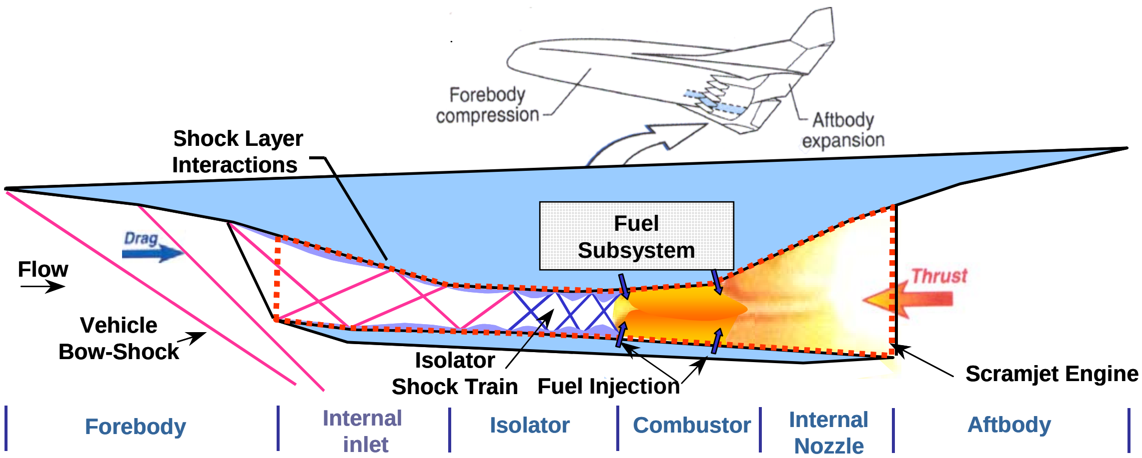

Figure 4. Representative Scramjet Engine

The primary purpose of the high-speed air induction system, comprised of the vehicle forebody and internal inlet, is to capture and compress air for processing by the remaining components of the engine. In a conventional jet engine, the inlet works in combination with the mechanical compressor to provide the necessary high pressure for the entire engine. For vehicles flying at high supersonic or hypersonic speeds, adequate compression can be achieved without a mechanical compressor. The forebody provides the initial external compression and contributes to the drag and moments of the vehicle. The internal inlet compression provides the final compression of the propulsion cycle. The forebody along with the internal inlet is designed to provide the required mass capture and aerodynamic contraction ratio at maximum inlet efficiency. The air in the captured stream tube undergoes a reduction in Mach number with an attendant increase in pressure and temperature as it passes through the system of shock waves in the forebody and internal inlet. It typically contains non-uniformities, due to oblique reflecting shock waves, which can influence the combustion process (Figure 5). Scramjet air induction phenomena includes vehicle bow shock and isentropic turning Mach waves, shock-boundary layer interaction, non-uniform flow conditions, and three-dimensional effects.

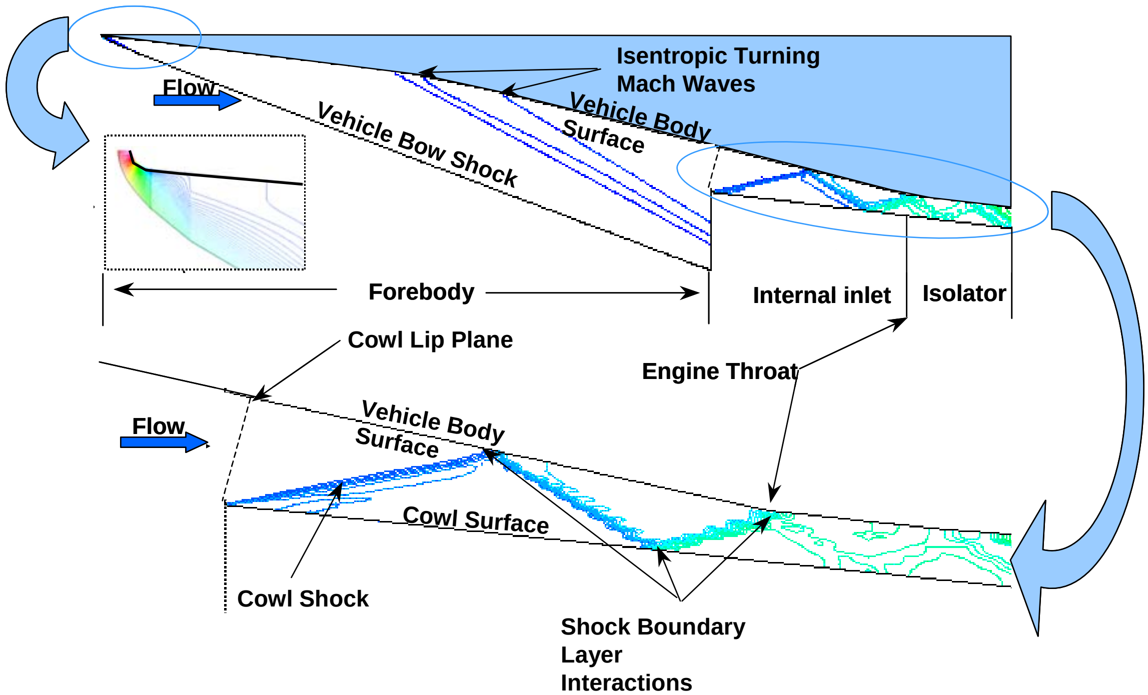

Figure 5. Summary of Important Forebody and Internal Inlet Physics

The isolator allows supersonic flow to adjust to a static backpressure higher than its inlet static pressure. The isolator cross-sectional area may be constant or slightly divergent to accommodate boundary layer separation. When the combustion process begins to separate the boundary layer, a pre-combustion shock forms (Figure 6). The shock structure or shock train allows the required pressure rise to occur over a finite distance, isolating the combustion process from the inlet compression process, thus acting to prevent inlet surge or unstart. The required length to capture the pressure rise is defined as the isolator length. The isolator in a dual mode (mixed flow supersonic and subsonic) ramjet and scramjet is a critical component that enables the combustor to achieve the required heat release profile and capture the induced combustor pressure rise without inlet unstart and ultimately facilitate the engine to complete transition to scramjet operation.

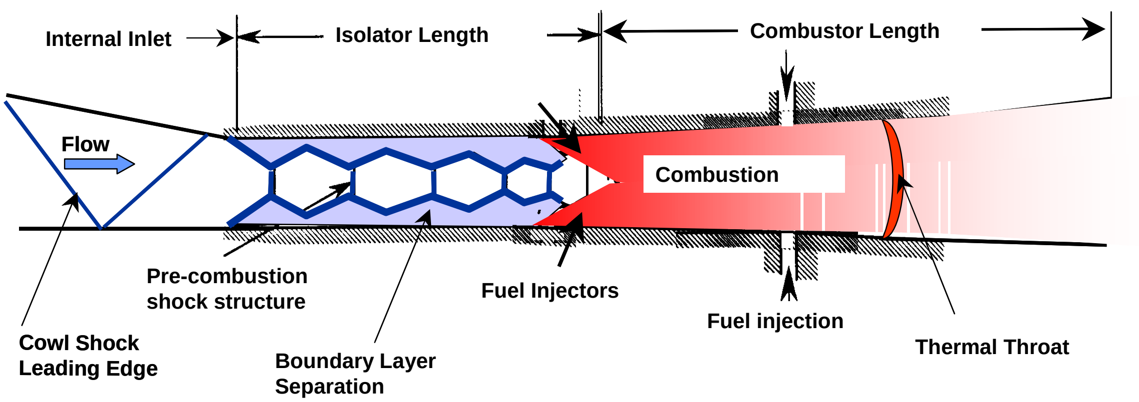

Figure 6. Summary of isolator and combustor physics

The combustor accepts the inlet/isolator airflow with variations in geometry inflow profiles and provides efficient fuel air mixing within the available combustor length as shown in Figure 6. The fuel supply subsystem is required to deliver fuel to the flowpath at appropriate locations with the desired physical properties. The combustor fuel is scheduled to stay within the engine operability limits while optimizing engine thrust potential.

The expansion system, consisting of the internal nozzle and vehicle aftbody, completes the propulsion flowpath and controls the expansion of the high pressure and temperature gas mixture to produce net thrust. During the expansion process, the potential energy generated by the combustor is converted into kinetic energy. The nozzle must process the accumulated flow distortions generated by the air induction system, isolator and combustor. The important scramjet nozzle physical phenomena, as illustrated in Figure 7, includes flow chemistry, boundary layer effects, non-uniform flow conditions, shear layer interaction, and three-dimensional effects. The design of the nozzle has a major effect on the efficiency of the propulsion system and the vehicle due to its ability to influence vehicle pitching moment and lift.

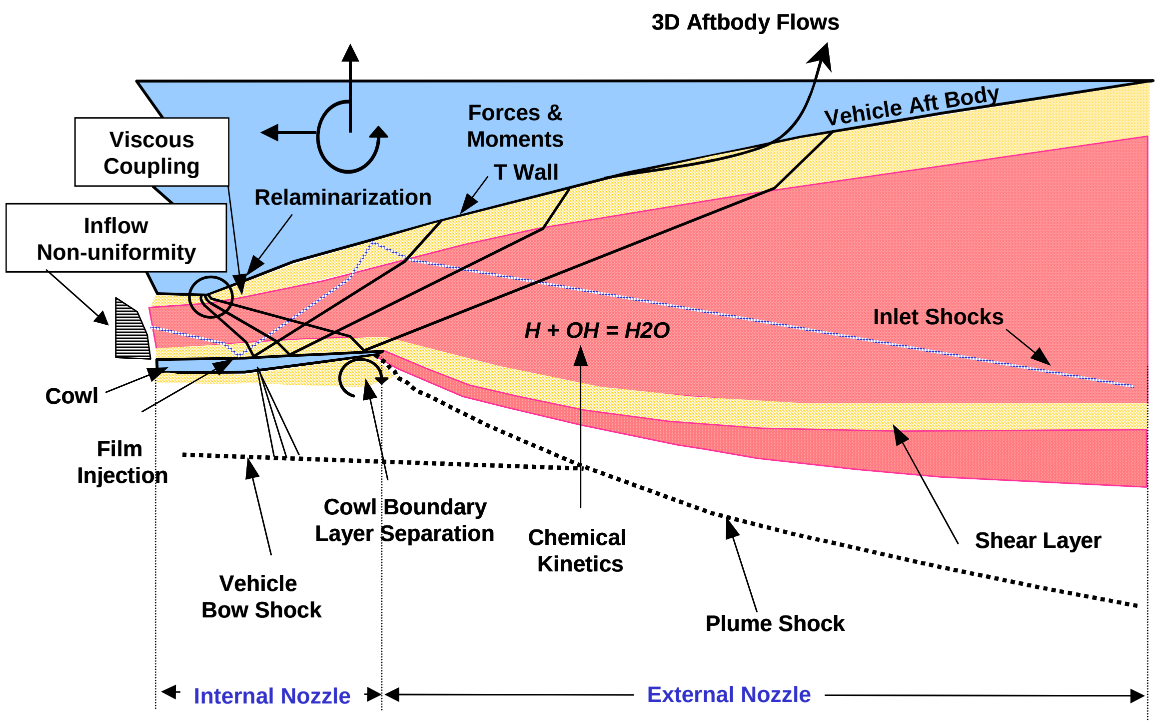

Figure 7. Summary of important scramjet nozzle physics

Operational Characteristics

An air-breathing hypersonic vehicle operates in multiple engine cycles and modes to reach scramjet operating speeds. A typical air-breathing hypersonic flight corridor with operation limits is presented in Figure 8. The lower bound of this envelope is set by thermal and structural limitations and is typically found at a dynamic pressure about 2000 psf. The upper bound of the envelope is set by combustion stability considerations, and is typically found at a dynamic pressure of 500-1000 psf.

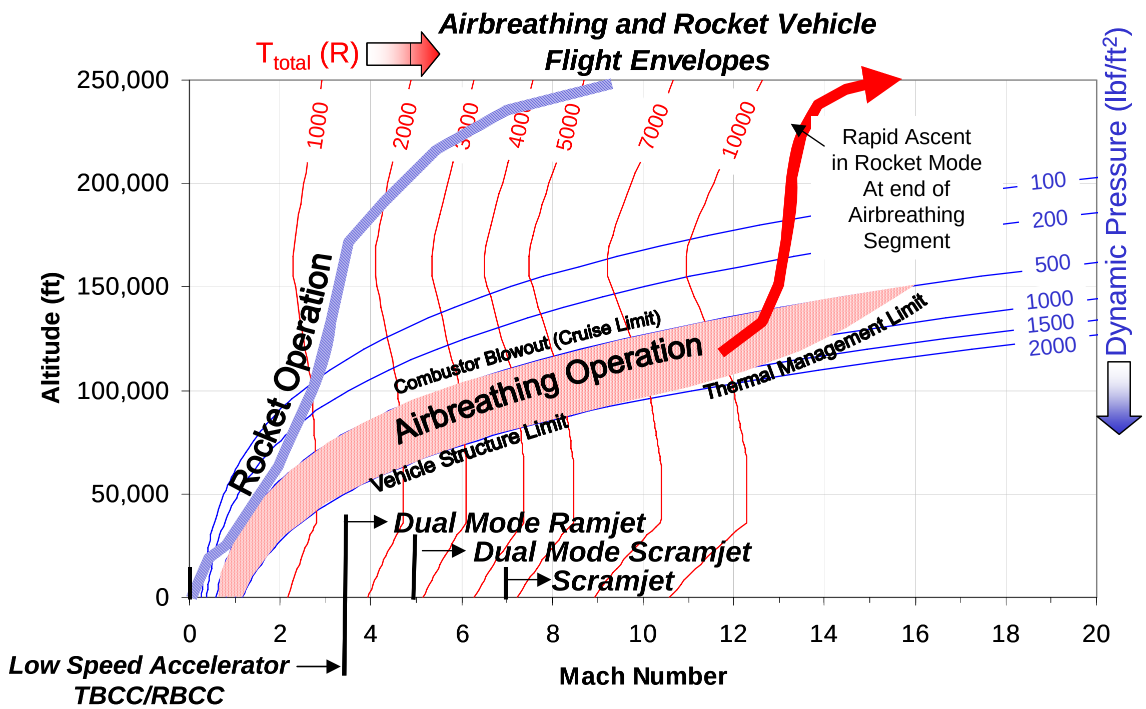

Figure 8. Air-breathing hypersonic vehicle flight trajectory and operational limits

In the low-speed regime (Mach 0-3) the vehicle may utilize one of several possible propulsion cycles such as Turbine Based Combined Cycle (TBCC), consists of a bank of gas turbine engines in the vehicle, or Rocket Based Combined Cycle (RBCC), with integrated rockets, internal or external to the engine, to accelerate the vehicle from takeoff to Mach 3.0.

In the range of flight Mach numbers 3.0-4.0, the air-breathing scramjet engine transitions from low speed propulsion cycles (i.e. TBCC or RBCC) to a dual mode ramjet combustion system. Dual-mode ramjet operation occurs when the terminal shock system (Figure 6) is of sufficient strength to create a region(s) of subsonic flow at the entrance to the combustor. In a conventional ramjet, the inlet and diffuser decelerate the air to low subsonic speeds by increasing the diffuser area; this ensures complete combustion process will occur at subsonic speeds. A converging-diverging nozzle follows the combustor to create a physical throat and generate the desired engine thrust. A scramjet engine synergistically designed to operate as a dual mode ramjet and scramjet has no physical throat between the combustor and expansion system thus providing an optimum cycle over a wider operating range. The required choking is provided within the combustor by means of thermal throat and can be brought about by choosing the right combination of area distribution, fuel air mixing and combustion efficiency, as represented by total temperature distribution.

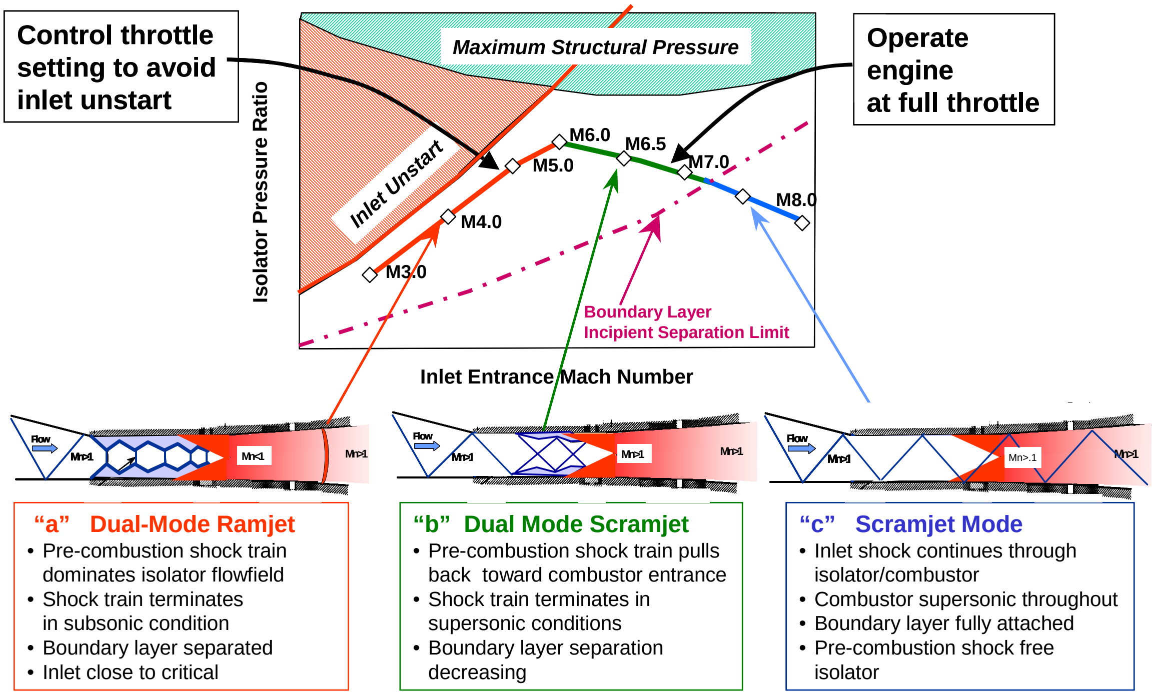

Figure 9. Isolator Provides Dual Mode Scramjet Seamless Transition to Scramjet

As the scramjet-powered vehicle accelerates along its flight trajectory from Mach numbers 3 to 8, the scramjet engine operates as a dual-mode ramjet in the Mach 3 to 6 regime along the isolator capability limit to avoid inlet unstart and remain within the structural limits. Scramjet air-breathing propulsion systems have an inevitable mid-speed transition region from flight Mach 5 to 7 in which neither ramjet nor scramjet operation is sufficient to describe the internal flow-field. The total temperature rise across the combustor begins to decrease along with the pressure rise produced by the combustion process. Consequently, a weaker pre-combustion system is required and the pre-combustion shock is pulled back from the inlet throat towards the entrance to the combustor. Operation of a scramjet engine in this critical regime is generally referred to as dual-mode scramjet, implying mixed characteristics of both subsonic and supersonic flow or active transitioning between subsonic and supersonic combustion within the scramjet.

As the vehicle continues to accelerate beyond Mach 7, the combustion process is unable to separate the flow and the engine operates in scramjet mode with a pre-combustion shock-free isolator. The inlet shocks propagate through the entire engine. The scramjet operational line and isolator physical phenomena during mode transition are illustrated in Figure 9 (solid red, green, blue lines and foot notes "a, b, c").

Fuel Choice

Fuel choice, between hydrocarbon and hydrogen, is typically driven by heat-sink requirements and vehicle system-level requirements (Figure 10). Missiles and short-range aircraft may use hydrocarbon fuels for their storability and volumetric energy density. Long cruise range aircraft or space access systems tend toward hydrogen because it has superior energy release per pound of fuel, and heat absorption capability, critical to actively cooled structures exposed to scramjet environment.

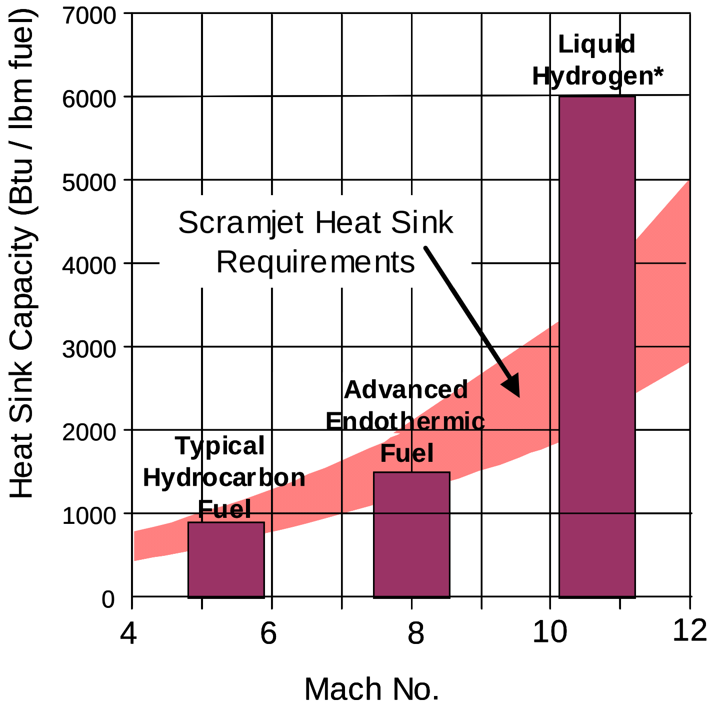

Figure 10. Heat Sink Capacity of Hydrocarbon and Hydrogen Fuels Relative to Scramjet Requirements

Applications

The development of scramjet propulsion technology will enable affordable and reusable hypersonic propulsion systems that can be divided into three categories: (1) *weapons* systems such as hypersonic cruise missiles (Figure 10a); (2) *aircraft* systems such as global strike / reconnaissance (Figure 10b) (3) *space access* systems that will take off and land horizontally like commercial airplanes as shown in (Figure 10c).

Cruise Missiles

Long-Range Strike

Access to Space

Figure 11. Scramjet Engine Applications

Challenges

Scramjet operation (Mach 5-15) presents several technical challenges[10] to achieving efficiency such as fuel air mixing, thermal management of engine heat loads and leading edge heat flux amplification, and structures and materials to withstanding the hypersonic flight environment.

When injected fuel stream velocity equals air stream velocity (i.e. approximately Mach number 12) entering the scramjet combustor, it becomes difficult to mix the air with the fuel. Also at higher Mach numbers, dissociation and ionization occur due to the high temperatures in the combustor. These, coupled with already complex flow phenomena such as supersonic mixing, isolator/combustor interactions, and flame propagation, make the flowpath design, fuel injection approach, and thermal management of the combustor a significant challenge. For these reasons, model development and test verification are required to fully understand these high-speed phenomena.

Several sources contribute to the heating of a hypersonic flight system with the most common being the viscous aeroheating of the vehicle skin (Figure 12) from subsystems such as pumps, hydraulics and electronics, and engine combustion. The scramjet engine is the focus for thermal management schemes in hypersonic vehicles because of its potential for extremely high heat loads. The engine represents a particularly challenging problem because of the severe combustion environment in the flowpath. This environment is characterized by very high thermal, mechanical, and acoustic loading along with a hostile, corrosive mix of hot oxygen and combustion products. If left uncooled, temperatures would exceed the melting point of most metallic structural materials, and temperatures in the combustor could exceed 5000 ^{o}F. Fortunately, the thermal environment can be effectively managed through a combination of structural design, material selection and active cooling.

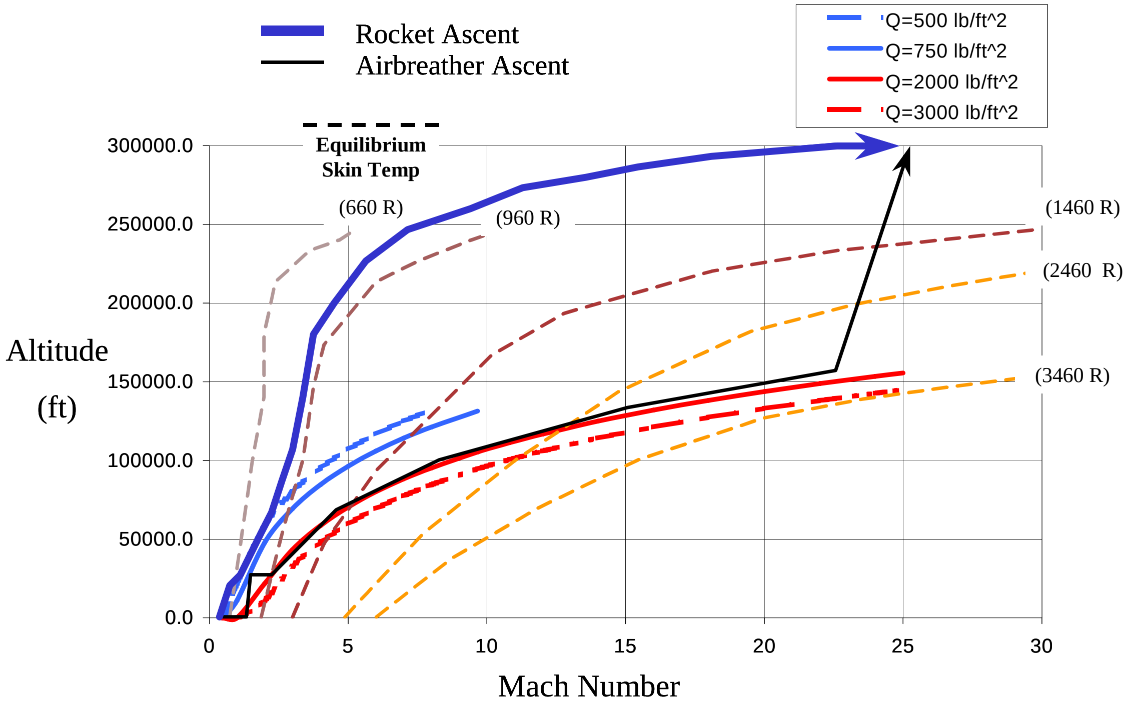

Figure 12. Equilibrium Skin Friction Temperatures

Hypersonic vehicles also pose an extraordinary challenge for structures and materials. The airframe and engine require lightweight, high temperature materials and structural configurations that can withstand the severe conditions of the hypersonic flight environment. Characteristics typical of the extreme environment in hypersonic flight include:

- Very high temperatures
- Heating of the whole vehicle
- Steady state and transient localized heating from shock waves
- High aerodynamic loads
- High fluctuating pressure loads
- Potential for severe flutter, vibration, fluctuating, and thermally induced stresses
- Erosion from the airflow over the vehicle and through the engine.

Summary
After, the recent successful X-43A flight test, along with several full-sized ground-tested demonstration engines, confidence in the viability of the hydrogen- and hydrocarbon-fueled scramjet engines has been significantly increased. NASA plans to launch another hypersonic vehicle this fall with the goal of flying the aircraft at 10 times the speed of

sound, or 6750 mph. The U.S. Air Force, Pratt & Whitney, and Boeing's Phantom Works will conduct flight tests of a supersonic combustion ramjet propulsion system under the Scramjet Engine Demonstrator-Wave Rider (SED-WR) program starting 2007-08. This engine test program will be unique since it will demonstrate significant acceleration, operate the engine for several minutes using hydrocarbon fuel, fly autonomously (sensors and computers will control the engine and flight), using an engine that is relatively easy to manufacture. Demonstrating these technologies, along with additional ground- and flight-test experiments, will pave the way for affordable and reusable airbreathing hypersonic propulsion systems such as missiles, long range aircraft and space-access vehicles around 2010, 2015, 2025, respectively.

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