Hypersonic Speed Through Scramjet Technology

Kevin Dirscherl, Michael Riechers, Jonathan Sanders
University of Colorado at Boulder, Boulder, Colorado 80302
December 17, 2015

Scramjet technology is evaluated on a basis of ramjet comparison and design characteristics to demonstrate a detailed understanding of the engine's operation and application. Included in this characterization are the major design challenges and constraints that have limited scramjet technology to a more recent history. The scramjet engine is further evaluated in the use of past, current, and future missions, with an emphasis placed on the potential for scramjet technology in the aerospace industry. The details are given for a reader with no prior familiarity of scramjet engines, thus is completed from a higher level perspective.

I. Introduction

Developments in the aerospace industry over the last century have propelled humans to flight speeds faster than the speed of sound several times over. However, the limitations of supersonic flight using conventional engine technology have nearly been reached, creating the interest in a scramjet engine. A scramjet is a type of ramjet that travels at hypersonic speeds without the use of any moving parts. The scramjet has been in development for over fifty years, but is only just now beginning to have impact in the aerospace industry. This engine has potential to help propel rockets into space or even reduce travel time. The history, basic operational principles, and design challenges are all examined to better understand the potential and limitations of scramjet technology.

II. History

The idea of the scramjet can be traced back to World War II. Faster aircrafts or missiles meant less travel time, faster response times, and less time to respond to attacks. A tremendous amount of time and effort was put into researching high-speed jet and rocket-powered aircraft, predominantly by the Germans [1]. After the war, the US and UK took in several German scientists and military technologies through Operation Paperclip to begin putting more emphasis on their own weapon development, including jet engines. The Bell X-1 attained supersonic flight in 1947 and, by the early 1960s, rapid progress toward faster aircraft suggested that operational aircraft would be flying at hypersonic speeds within a few years. During this time the top speeds of vehicles stayed around Mach 1 to 3 and were predominately rocket propelled. The first scramjets were built and tested in the 1950's and 60's, culminating in the filing of a patent for a scramjet aircraft in 1966 by Holmen Gustav and Sanator Joseph. This file was published in 1970 furthering the possibilities of improvements and testing. The Central Institute of Aviation Motors (CIAM), in Russia, performed the first successful flight of a scramjet engine in 1991. It was an axisymmetric hydrogen-fueled dual-mode scramjet developed in the late 1970s. It was assisted in takeoff by a SA-5 surface to air missile. Over six tests, the scramjet reached speeds over Mach 6.4 and flew under scramjet propulsion for 77 seconds. These tests opened the door for other countries to build, test, and improve their own scramjet engines [1, 2].

III. Ramjets

Scramjet technology first started with the development of the ramjet. The ramjet utilizes the same process as a scramjet, but does not necessarily reach supersonic speeds. The most astounding thing about ramjets is their ability to reach supersonic speeds while utilizing no moving parts. When an object moves through air at a high speed, it generates a high-pressure area upstream. A ramjet takes advantage of this high pressure to force air through an inlet. The air is then heated through combustion with some type of fuel and forced out a nozzle to reach supersonic speeds. This is how the ramjet engine achieves thrust, moving forward faster than the speed of sound [3]. A diagram of this process can be seen in Figure 1.

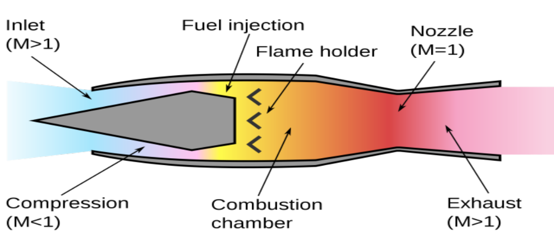

Figure 1: Schematic of a ramjet engine.

The ramjet design process is divided into three distinct parts: the inlet, the combustor, and the nozzle [4]. The inlet must be designed so that the supersonic flow is slowed to subsonic flow suitable for the combustor. This decrease in speed is obtained using conical shockwaves terminated by a normal shock. The inlet is also designed to be divergent allowing for a constant subsonic Mach number (typically around 0.5) [4]. After the air has been slowed down to the desired speed, it reaches the combustor. One of the most important pieces of the combustor is the flame holder. As with typical combustors, the ramjet's combustor is designed to burn fuel with the air, increasing the temperature, and thus the pressure. The problem with ramjet engines is that the air is moving at such high speeds that a common problem is flame blowout. The flames will actually "blowout" the nozzle, not creating the desired thrust [5]. The flame holder helps to fix this problem. A flame holder essentially creates a low speed eddy, temporarily trapping the incoming air allowing it to react fully in the combustor before being expelled [4]. The final piece of the ramjet is the nozzle. While not all ramjets achieve supersonic speeds, the focus is on supersonic travel. The largest difference between a subsonic and supersonic ramjet is in the nozzle. A supersonic ramjet makes use of a convergent-divergent nozzle (also called a de Laval nozzle). As subsonic air travels through the converging portion of the nozzle the speed increases, keeping the mass flow rate constant. At the throat of the nozzle (the transition between converging and diverging, and where the cross sectional area is at a minimum) the flow reaches a Mach number of 1.0 [6]. Then as the nozzle begins to diverge again, the gas expands and increases speed. An example of this nozzle can be seen below in Figure 2.

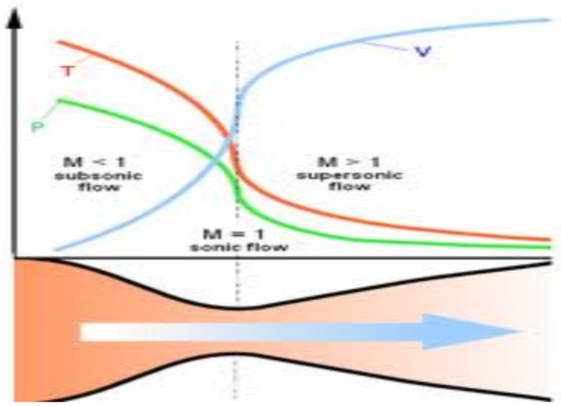

Figure 2: De Laval Nozzle with graph depicting relative temperature (T), velocity (V), and pressure (P) [6].

IV. Scramjets

As stated in the previous section, scramjets are a specific variant of ramjets. In scramjets, the air remains supersonic throughout the flow, rather than decelerating to subsonic speeds through the divergent inlet. With different inlet geometry, scramjets still decelerate the flow to a lower Mach number in the compression portion of the engine, however the flow never become subsonic. As with ramjets, there are no mechanical compressors in a scramjet, and thus rely on the energy in the incoming flow to compress the air. After the compression, the flow is accelerated to a higher speed than the initial flow through a diverging nozzle. Figure 3 shows the basic scramjet engine configuration, detailing the main stages [7].

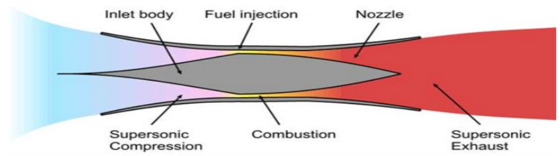

Figure 3: Schematic of a scramjet engine.

While Figure 3 provides a basic example of the components that make up a typical scramjet, a full scramjet is generally broken down into six stages. Figure 4 shows how the inlet is truly a combination of the inlet and isolator. Also shown in Figure 4 is the standard shock train that develops in the inlet. It is through this shock train that the pressure in the flow increases [8].

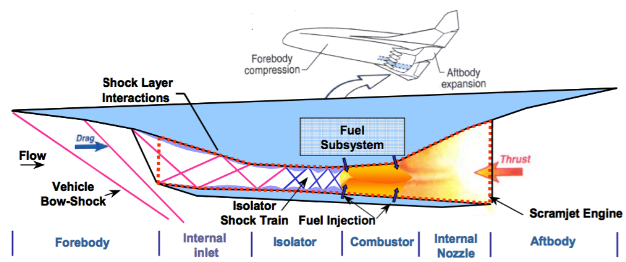

Figure 4: Scramjet full component diagram [8].

A. Purpose

Reasoning for transitioning from ramjets to scramjets is focused around temperature constraints at higher speeds. Due to the requirement of transitioning the flow to subsonic speeds in ramjet design, a large temperature jump is seen across the shock. As the desired speeds increase further, the flow must be decelerated even further, thus creating very high temperatures within the engine. An increase in efficiency of the scramjet compared to the ramjet is seen near Mach 5.0. This efficiency is characterized by isolator pressure ratio as compared to the inlet flow speed. As the scramjet is reaching this Mach 5.0 speed, the engine goes through a transitional state from operating as a ramjet to operating as a scramjet as shown in Figure 5. In this combination state, there are regions of subsonic and supersonic flow in the combustor. When the flow continues to reach higher speeds near Mach 7.0, the engine transitions to a full scramjet mode where the flow is supersonic throughout the entire engine [8, 9].

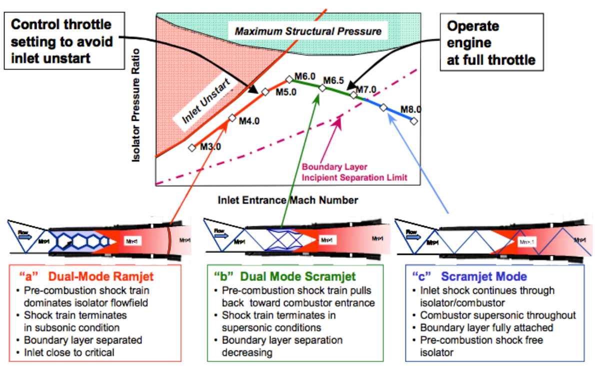

Figure 5: Ramjet to scramjet transitioning [8].

Figure 5 shows the Inlet Unstart condition shaded in red, bounding the speeds. This condition appears when the shock train reaches the inlet, and has potential to result in a loss of air capture, increased pressure and thermal loads on the structure of the aircraft, and a decrease in the thrust to drag ratio [9].

B. Design

In scramjet engines, certain factors play major roles in design decisions. These factors are predominately focused with the interaction of the flow within the engine, and thrust optimization.

a. Fuel Injection

As with conventional turbomachinery-based jet engines, scramjets utilize onboard fuel and obtain the oxidizer through ingestion of the surrounding air. In order to mix the fuel and air, fuel injectors operate within the engine, similar to that in a turbojet engine. This fuel mixing takes place in the combustor section of the engine, and achieving quick mixing and burning is a strong desire to increase performance. The compressible characteristics of the flow in scramjets greatly reduce eddy growth, reducing mixing, causing large challenges. With quick mixing, the overall length of the combustor can be smaller, reducing weight and complexity. The pressure losses that can be created through the injection process have the potential to be substantial; therefore, the main goal of the injection is to inhibit the air flow to the least degree possible, while still achieving quick mixing, and a uniformly mixed flow [10, 11].

Fuel-to-air mixing is accomplished through an injector that can be designed to inject fuel either normal (perpendicular to the flow path), parallel (along the flow path), or at an angle in-between. The choice between the methods involves a tradeoff between mixing efficiency and flow disturbance. In the first case of normal fuel injection as shown in Figure 6, the injectors are in the combustor walls, and expel the fuel up into the flow at a 90 degree angle. As expected, this configuration provides excellent fuel penetration and near-field mixing. The stream of fuel blocking the flow has the same basic effect as a stationary cylinder sitting in the flow path. The detached flow immediately behind the stream acts as a wake, which provides very efficient mixing. This, in combination with the large penetration into the flow field and the increased boundary layer, result in extremely fast mixing. However, the detached flow causes a significant pressure loss, greatly affecting the engine's efficiency [10, 11].

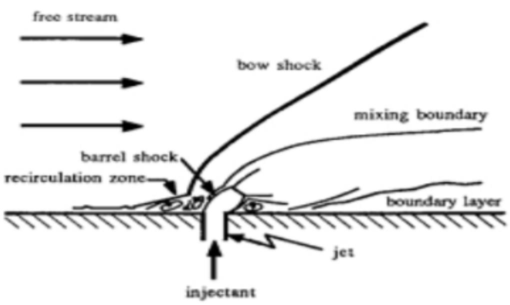

Figure 6: Normal injection diagram [12].

Parallel, or in-stream injectors have become more popular to achieve efficient injection. To mix the flow in this fashion, a strut must be placed in the flow. This strut can be manufactured with an aerodynamic shape to create less flow disturbance. Injection in this form does not disturb the flow nearly as much, but does not encourage the same amount of mixing. In order to combat this, other additions such as tabs and ramps have been introduced in the flow to create vorticity. These mixing techniques, also known as flame holders, create turbulent eddys in the flow and further encourage mixing. As a secondary benefit, parallel injectors also contribute to the total thrust of the engine. Figure 7 shows how the mixing layer propagates in a parallel injector [10-12].

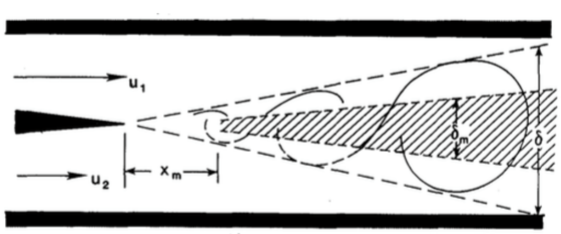

Figure 7: Parallel injection diagram [10].

In comparing normal and parallel mixing, the axial distance required for all fuel or air to fully mix, L_m, can be found using Equations 1 and 2, where x is the axial distance in the combustor, α is a fit parameter based on the spacing of the injectors (0.17-0.25), ϕ is the mixing ratio, and η is the mixing efficiency. 90° corresponds to the normal injection, and 0° to parallel injection. Examining these equations shows that as discussed, the normal injector mixes much more quickly [10].

$$\eta_{M90^\circ} = \left[\frac{x}{L_m} + \frac{1}{50 + 1000\alpha}\right]^{\alpha} \tag{1}$$

$$\eta_{M0^\circ} \cong \left\{\begin{matrix} x/L_{m,F} & \phi \le 1 \\ x/L_{m,A} & \phi > 1 \end{matrix}\right\} \tag{2}$$

Further adaptations of these two injection methods have led to multiple other designs to increase mixing efficiency. One of the most common practices is the addition of a fuel injection ramp, as shown in Figure 8. The ramp provides near streamwise injection, and the vortices that form off the ramp edges create strong mixing. Combinations of ramp and parallel injectors have been tested and have produced strong results. Figure 8 also shows an example of an alternating wedge strut that was tested and created a more uniform mixing region [10, 12].

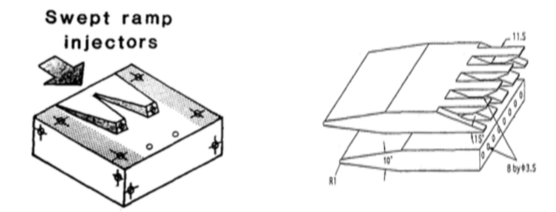

Figure 8: Swept ramp injector (left), and alternating wedge strut injector (right) [10, 12].

Another system uses a cavity in the combustor to create an area of recirculation where mixing will occur. This configuration is shown in Figure 9. Due to the increased complexity of the combustor geometry required in this case, it has not been used as frequently as the other devices.

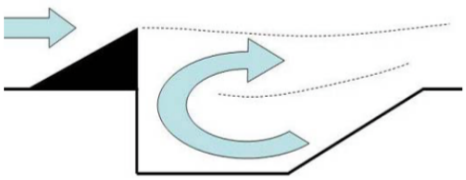

Figure 9: Step cavity mixing system [12].

b. Boundary Layer

Shown in Figure 10, the boundary layer created within the engine due to high flow velocity results in a decreased flow area. Reducing and characterizing this boundary layer thus becomes a concern in scramjet design.

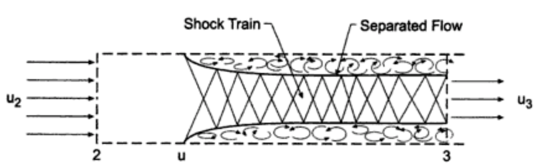

Figure 10: Boundary layer formation [10].

As demonstrated in Figure 5, the boundary layer is the largest at slower speeds. As the air velocity increases, the flow stays attached to the walls and the amount of separation becomes significantly less. Figure 11 shows the loss in inlet efficiency due to the boundary layer, as well as showing that as the speed increases, the boundary layer becomes less significant, eventually becoming nearly equivalent to the inviscid case [13].

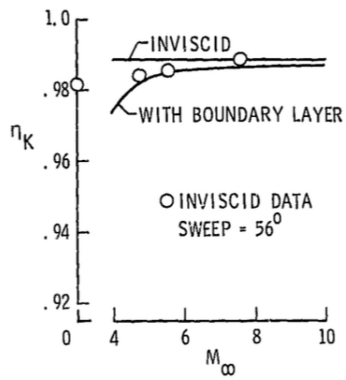

Figure 11: Inlet efficiency changes vs. Mach number due to boundary layer separation [13].

The separation of flow is most often seen in the isolator section of the scramjet, and carries over to the combustor. In Figure 12, the area ratio is shown to decrease where the separation begins, and continues to decrease until the combustion process reattaches the flow. Figure 12 provides an understanding of the scale in which the separation occurs compared to the overall area of the isolator.

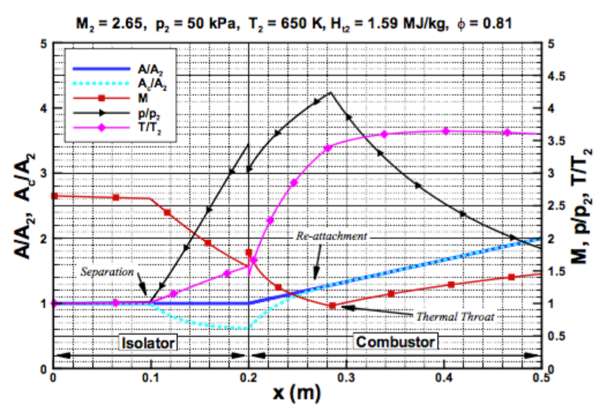

Figure 12: Scramjet characteristics, with labels showing where separation and reattachment occur within the system [14].

C. Temperature Challenges

When flying at hypersonic speeds, typically Mach 5.0 and greater, there is a large increase in flow temperature due to large pressure changes across shock waves, viscous dissipation, and a large increase in heat transfer to the vehicle. At these speeds a calorically perfect gas assumption is no longer viable for flow characterization as the vibrational and electronic excitation energy modes are now in flux, in addition to the translational and rotational energy modes of the total internal energy of the fluid. At hypersonic speeds, the temperature increase can be so great, that dissociation and ionization of particles can occur as noted in Table 1, however this typically only occurs for reentry vehicles [8, 9].

Table 1: Fluid particle effects with respect to temperature [8].

Temperature (K)	Particle Effects
$T \leq 800$	Calorically Perfect Gas
$800 < T < 2000$	Thermally Perfect Gas. Vibrational and electronic excitation energy modes active.
$2000 \leq T < 4000$	Dissociation of O_2
$4000 \leq T < 9000$	Dissociation of N_2
$T > 9000$	Ionization of O and N. Plasma begins to form

Scramjet engine technology operates in the flight regime that results in flow temperatures between 800 and 3000 degrees Kelvin [8].

D. Structural Challenges

Hypersonic vehicles have the additional challenge of utilizing materials that can not only support the high flight loads exerted on the surfaces of the vehicle, but the high thermal loads present in a hypersonic flow regime on the leading edges of the vehicle. The temperatures on the leading edges of hypersonic vehicles are high enough that traditional aircraft materials cannot be used without imminently melting during flight. For these flight surfaces, there are typically three options available: ablatives, ceramics, and high-temperature, high-density metals [8, 9].

Ablative materials introduce a cool film of air into the boundary layer, thereby reducing the heat transfer to the vehicle by vaporizing above a given temperature. Ablative materials are effective cooling mechanisms but are eroded over time, making them poor candidates for extended flight times or reusable vehicles. In addition, ablatives are structurally weak without a stronger material behind them. An example of this material is the PICA tiles and SPAM coating on the SpaceX Dragon Space Capsule [8, 9].

Ceramic materials have incredibly high melting temperatures and typically have lower heat transfer rates to the vehicle than metals, but are expensive to produce, are very fragile, and are difficult to adhere to the vehicle. Ceramic materials are also considerably heavier than ablative materials. Ceramic materials are generally used on flight surfaces with high thermal loads and low aerodynamic loads. An example of ceramic materials is seen on the space shuttle tiles [8, 9].

High temperature, high density metals such as tungsten and Inconel have high melting temperatures compared to traditional metals, are easy to manufacture and integrate with the vehicle compared to ablatives and ceramics, but are very heavy. These metals are often used on the leading edges of the vehicles that operate on the low end of the hypersonic flight regime ($5 < M < 10$). An example of these materials in use are the noses of the X-43 and X-51 scramjet test vehicles.

These materials are often used in combination with each other and traditional aircraft materials such as aluminum, steel, and composites, to create an optimized vehicle. A distribution of materials used in the X-51 hypersonic test vehicle can be seen in Figure 13 [8, 9].

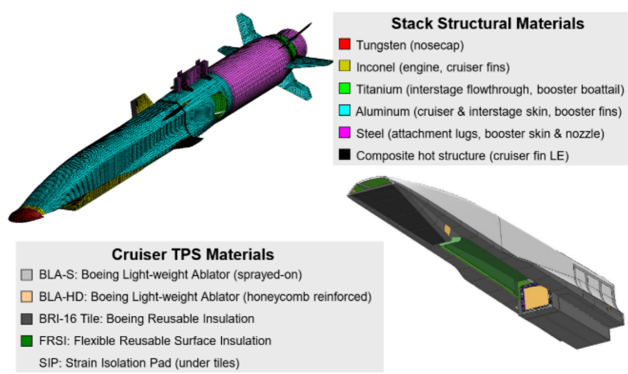

Figure 13: Material distribution of the X-51 [8].

E. Other Challenges

While the fluid flow for a hypersonic vehicle can be approximated as a thermally perfect gas and can be solved for directly when calculating vehicle flight characteristics, it is generally much more accurate to use an iterative approach for a chemically reacting flow. Approaches such as the Newtonian Method, Modified Newtonian Method, Tangent-Wedge Method, Tangent-Cone Method, and numerous others are used to obtain more accurate results for the higher temperature portion of the flight regime. In addition to the difficulties of calculating the flow characteristics for a hypersonic fluid flow, hypersonic flight vehicles are not perfect cone/wedge bodies and a large portion of the flow of a hypersonic flight vehicle is actually compressible subsonic and supersonic flow. Thus extensive use of high fidelity computational fluid dynamics (CFD) software is required to solve for the mixed flow-field around the flight vehicle.

Performance testing on the ground for hypersonic vehicles utilizing scramjets is even more difficult. There are very few facilities in the world capable of testing these vehicles and all of them are limited in their capacity (test duration, fixed Mach number, downscaled test model, etc.). The X-51 scramjet engine was tested at NASA Langley Research Center's High Temperature Tunnel, shown in Figure 14, which is capable of Mach numbers of 4, 5, and 7 [8].

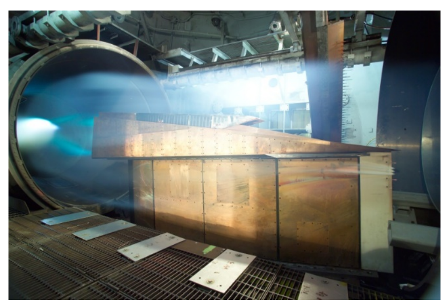

Figure 14: X-51 Engine Test [9].

F. Advantages, Disadvantages

Scramjet vehicles are easy to manufacture, have a considerably reduced number of moving parts compared to conventional aircraft, are capable of very high flight speeds, and are relatively inexpensive to manufacture.

However, for all of their benefits, scramjet engines have high development and testing costs, have short flight times, cannot operate in vacuum such as space, require robust designs, and require a secondary form of propulsion to achieve ignition flight speeds. This limits the feasibility of using current scramjet technology to unmanned flight vehicles [8].

G. Typical Mission Profile

The standard mission profile for a scramjet has been fairly standard across most tests. All of the American launches are accomplished using the same technique. The engine and craft are attached under the wing of a large aircraft and flown to a height of around 50,000 feet. The engine needs to be moving at supersonic speeds before being able to function under its own power. These speeds are accomplished in one of two ways. The first is simply letting the craft fall from the large aircraft until it reaches the correct speed. Other, newer crafts have needed a larger increase in speed and require the use of a solid rocket booster to reach operating speeds. An example of the mission profile for the X-43A can be seen below in Figure 15 [4].

Figure 15: Typical scramjet mission profile [4].

H. Recent Missions

Significant progress has been made since the 2000’s. The HyShot project successfully demonstrated scramjet combustion on July 30, 2002. The team took a unique approach to the problem of accelerating the engine to the necessary speed by using a Terrier-Orion sounding rocket to take the aircraft up on a parabolic trajectory to an altitude of 314 km. As the craft re-entered the atmosphere, it dropped to a speed of Mach 7.6. The scramjet engine then started, and it flew at about Mach 7.6 for 6 seconds. On March 25, 2006, researchers at the University of Queensland conducted another successful test flight of a HyShot Scramjet at the Woomera Test Range in South Australia. The Hyshot III reached speeds of roughly Mach 7.6. While these seem to outperform the American vehicle, the American vehicle has an engine fully incorporated into an airframe with a full complement of flight control surfaces available, while the HyShot engine does not [4, 6]. Recent HyShor launches can be seen in Table 2.

Table 2: Recent HyShot launches.

Mission	Result	Description
Hyshot 1	Failed	Failed launch due to rocket fin puncture by a rock on the landing pad.
Hyshot 2	Successful	UQ 2-D scramjet, Mach 7.6
Hyshot 3-7	Cancelled	
Hyshot 8/ HyShot III	Successful	QinetiQ 4-chamber scramjet, Mach 7.6
Hyshot 9/ HyShot IV	Successful	JAXA launch of UQ 2D scramjet with JAXA hypermixer.
Hyshot 10/ HyCAUSE	Successful	DSTO scramjet

While many countries were testing Scramjet technology at this time, American testing was the most funded, resulting in the X-43A, the first scramjet powered vehicle with full aerodynamic maneuvering surfaces, in 2004. The X-43a still holds the scramjet speed record at Mach 9.68, and is shown in Figure 16 [4].

Figure 16: NASA X-43 scramjet [4].

Then in 2007, the U.S. Defense Advanced Research Project Agency (DARPA) and the Australian Defence Science and Technology Organisation (DSTO) announced successful scramjet propulsion up to Mach 10.

On May 22, 2009, Woomera hosted the first successful test flight of a hypersonic aircraft in HIFiRE. The launch was one of up to 10 planned test flights as a joint research project between the Defense Science and Technology and the Hypersonic Flight Research Experimentation (HiFiRE), a group of the United States Air Force. A series of scramjet ground tests was completed at NASA Langley Arc-Heated Scramjet Test Facility at simulated Mach 8 flight conditions. These experiments were used to support HIFiRE flight 2. HIFiRE is continuing to look into hypersonic technology and the objective is to support the new Boeing X-51 scramjet demonstrator (Figure 17) while also building a strong base of flight test data for quick-reaction space launch development and hypersonic quick-strike weapons [4, 6].

On March 22 and 23, 2010, Australian and American defense scientists successfully tested a HIFiRE rocket. It reached an atmospheric velocity of more than 5,000 kilometers per hour (Roughly Mach 4) after taking off from the Woomera Test Range in South Australia. This was followed by a successful flight of the X-51A Waverider on May 27, 2010. NASA and the United States Air Force set a new world record hypersonic airspeed, flying at Mach 5 for approximately 200 seconds. The Waverider destroyed itself autonomously after losing acceleration. While the reason for the deceleration is unknown, the mission was still deemed a success as the self-destruction was planned [4, 6].

Figure 17: Boeing X-51A scramjet mounted underneath a B-52 wing.

The X-51A was carried aboard a B-52, accelerated to Mach 4.5 via a solid rocket booster, and then the Pratt & Whitney Rocketdyne scramjet engine ignited to reach Mach 5 at 70,000 feet. A second test flight on June 13, 2001 failed to transition to its primary JP-7 fuel, causing the engine to never reach its full power. A further X-51A Waverider test failed on August 15, 2012. The aircraft was again carried by a B-52 and the goal was to fly at Mach 6 for an extended period of time. Unfortunately, the craft lost control and broke apart 15 seconds into the unmanned flight portion of the test due to a faulty control fin. In May 2013 an unmanned X-51A WaveRider reached Mach 5.1 during a three-minute flight under scramjet power [4, 6]. In all cases, a controlled self-destruct of the vehicle is planned, as landing schemes are not in place.

I. Future Developments

There are currently numerous programs in operation today developing scramjet technology. DARPA is establishing a program to develop a hypersonic vehicle utilizing scramjet technology. Brazil is currently developing a hypersonic aircraft known as the 14-X. Perhaps one of the more interesting scramjet development programs is the AVATAR program. AVATAR is a single stage reusable spacecraft that uses scramjet technology to reach low earth orbit with a 1-ton payload. With the recent successful test flights of several scramjet engines and their potential for fast response missiles and access to low orbit space, it can be expected that funding for scramjet technology will continue to rise in the near future.

V. Conclusion

Scramjets have made significant technological advances in the last three decades. While scramjet technology does not appear to be a candidate for improving commercial supersonic travel due to the complex flight regime, the required robustness of the vehicle, and the propulsive requirements to achieve ignition velocity, scramjets are an excellent candidate for small and medium launch system hypersonic missiles and hold the potential for access to low orbit space at reduced cost.

References

[1] H. Gustav, S Joseph, “Scramjet aircraft.” United States of America. US3535882 A, Oct 27, 1970.

[2] E. Curran, " Scramjet Engines: The First Forty Years," Journal of Propulsion and Power, Vol. 17, no. 6, pp. 1138-1148, December 2001.[Web]. [Accessed 11/01/14].

[3] "Aeronautics: Here Comes the Flying Stovepipe," Time, Vol. 86, no. 22, pp. 58, 1965.[Web].:content.time.com/time/magazine/article/0,9171,834721,00.html. [Accessed 11/01/14]

[4] C. Segal, The Scramjet Engine: Processes and Characteristics : Cambridge University Press, 2009

[5] G. Dugger, "Recent Advances in Ramjet Combustion," ARS, Vol. 29, no. 11, pp. 819-827,1959.[Web].:arc.aiaa.org/doi/abs/10.2514/8.4917 . [Accessed 11/12/14].

[6] R. Fry, "A Century of Ramjet Propulsion Technology Evolution," Journal of Propulsion and Power, Vol. 20, no. 1, pp. 27-37, 2004.[Web].:arc.aiaa.org/doi/abs/10.2514/1.9178. [Accessed 11/10/14]

[7] J. J. Bertin, J.J., “Hypersonic Aerodynamics,” AIAA, 1994.

[8] Andreadis, Dean, “Scramjet Engines Enabling The Seamless Integration Of Air & Space Operations,” Pratt & Whitney.

[9] Le, Daniel B., “Scramjet Isolator Flow Studies,” University of Virginia, http://www.vsgc.odu.edu/src/Papers/Paper%20-%20D.%20Le.pdf [retrieved 15 December 2015].

[10] Curran, E. T., Heiser, W. H., and Pratt, D. T., “Fluid Phenomena in Scramjet Combustion Systems,” Annu. Rev. Fluid Mech. Annual Review of Fluid Mechanics, 1996, pp. 323–360.

[11] Drummond, J. P., and Diskin, G. S., “Fuel-Air Mixing And Combustion In Scramjets,” NASA, pp. 121-135.

[12] Curran, E. T., Heiser, W. H., and Pratt, D. T., "Fluid Phenomena in Scramjet Combustion Systems," Annu. Rev. Fluid Mech. Annual Review of Fluid Mechanics, 1996, pp. 323–360.

[13] Henry, R. H., and Anderson, G. Y., "Design Considerations For The Airframe-Integrated Scramjet," NASA TM X-2895, December 1973.

[14] Smart, M. K., "Scramjet Isolators," University of Queensland ADA581901, September 2010.

[15] John, J., and Anderson, D., "Hypersonic and High-Temperature Gas Dyanmics,", 2nd ed., AIAA, 2006.

[16] Liepmann, H.W., and Roshko, A., "Elements of Gasdynamics," 2nd ed., Dover Publishing, 1957.