Section 2.0: History, Development, Obstacles and Proposed Solutions of Hypersonic Technology

Supersonic combustion air-breathing engines have long been recognized as the most well-suited for hypersonic propulsion in the Mach 5-10 range. Designs for hypersonic engines have been around since the early 1900's. Ramjet technology has been developing over the past eight decades and, except for marginal improvements, has been shown to be suited for atmospheric flight speeds up to Mach 5. The desire for faster, more efficient engines gave birth to the idea of a scramjet, utilizing supersonic combustion and potentially expanding the speed envelope to the Mach 15 range. The promise of covering the entire planet at high speed from horizontal takeoff for both civil and military aircraft is an attractive prospect. However, along with new technology and discoveries also come new obstacles to be addressed.

2.1: Scramjet History and Design

The first planes were propelled by means of a propeller driven by a gasoline engine. Late World War II and the early 50's brought about the use of fighters employing turbojets, a wholly internal, ducted engine using rotating blade stages to compress air and produce thrust. Today, this means of propulsion is found on a majority of today's airplanes whether in the form of a turbofan on a 747 to a high-powered afterburning turbojet with bypass, as in the new YF-22. However, rotating blades in these types of engines limit the flight speed to about Mach 3. Ramjets do not suffer from these types of limits since they do not employ moving parts of any kind. They compress the incoming air using fixed aerodynamic shapes, operate with subsonic throughflow and combustion, igniting the fuel-air mixture and forcing the hot gases through a nozzle, producing thrust. Ramjets have been flown up to speeds of Mach 5, above which losses become prohibitive because of the strong deceleration of the flow required to produce stable combustion. Another limitation of ramjets comes from the inability to take off from a static position. Some means of propulsion, whether it be a solid rocket booster or turbojet, is needed to propel the ramjet up to speeds where it can produce enough thrust to sustain flight on its own. Scramjets are similar to ramjets, but employ supersonic combustion rather than subsonic combustion. Burning the air-fuel mixture at supersonic speeds minimizes the loss from slowing the airflow in order to burn to the fuel. However, along with this innovative idea also came an extensive problem: without assistance, fuel-air mixtures will not burn at sufficiently high speed to keep the combustor flame from blowing out. In addition, materials capable of withstanding the extreme temperatures within the scramjet combustor are not readily available.

2.1.1: Scramjet Cycle Analysis

Dissociation caused by the large temperature increase of decelerating the flow from supersonic to subsonic speeds was a major drawback of the ramjet (Weber and MacKay, 1958). To minimize these effects, attention was focused on performing the combustion at supersonic speeds (i.e. a scramjet). A diagram of a simplified scramjet is shown in Fig. 2.1.

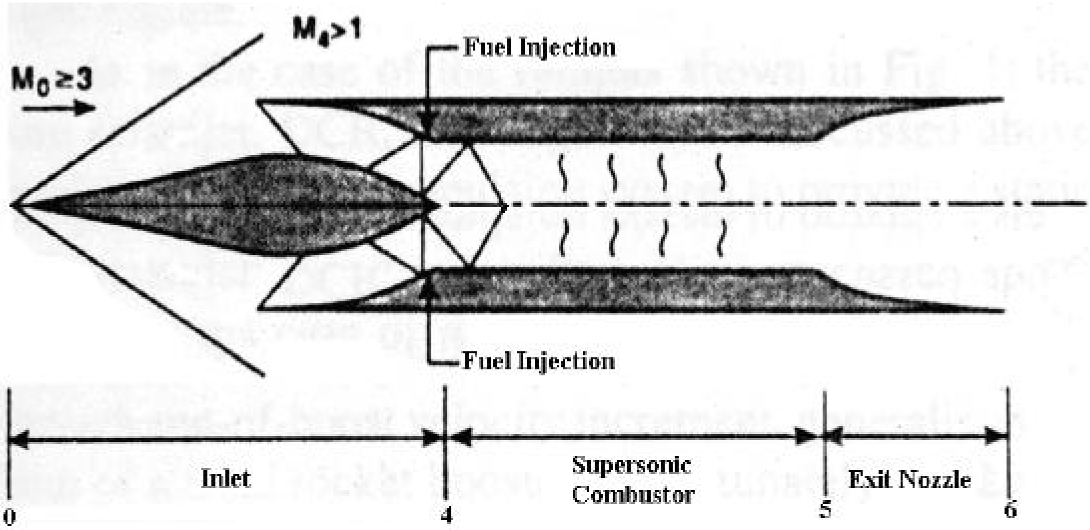

Figure 2.1: Schematic Diagram of a Generic Scramjet Engine

The three main components of a scramjet engine are the air inlet, the combustor and the exit nozzle. The inlet region acts as a compressor. As the air approaches the engine, it passes through shock waves produced by the inlet cone and edges of the air intake, reducing its velocity. The air velocity passing through the inlet is reduced slightly (but is still supersonic), while the static pressure increases by one or two orders of magnitude. At this point, the air enters the combustion chamber and fuel is added. Fuel injection ports can either be mounted on the wall of the combustor chamber or on struts, allowing the fuel to be injected closer to the centerline of the chamber. The fuel-air mixture is then ignited and burned in a supersonic environment. This combustion process accelerates the flow to a speed slightly above the flight speed of the vehicle. After passing through the combustor, the gases enter the exit nozzle and are accelerated out the back of the engine. The thrust of a scramjet is produced by the change in momentum of the gases and pressure differences between the inlet and exit regions. Several variations and improvements have been implemented over the years to enhance this general scramjet cycle.

2.1.2: The History of Scramjets

The earliest scramjet development facilities were located in NASA research centers in the early 1950's (Waltrup and White, 1996). The Navy's support of hypersonic technology began shortly after and produced the first demonstration of combustion in a Mach 5 airstream. Subsequent developments provided insight that higher levels of thrust and efficiency could be produced by ducted scramjets. Ducted scramjets presented formidable technological obstacles, which continue today. Scramjet technology must address the need for higher temperature materials, surface skin friction, fuel ignition and chemical kinetics among others. The Navy began supporting efforts for development of these ducted scramjets in 1961. The project was to be known as the Supersonic Combustion Ramjet Missile, or "SCRAM". The SCRAM program successfully demonstrated that supersonic combustion was feasible, but was cancelled in 1977 due to technical shortcomings. However, before the termination of the project, a new design was being developed which overcame many of the SCRAM's limitations, the Dual-Combustor Ramjet (DCR). The project was later cancelled in 1986, despite being a success. Since the inception of the SCRAM concept, many different types of scramjet engines have been developed, each employing unique characteristics in an attempt to overcome the problems associated with supersonic combustion and fuel preconditioning.

The project directly succeeding the SCRAM project, and also the most developed concept design, is the Dual-Combustor Ramjet (DCR). The DCR contains all the features of a scramjet with the addition of a small subsonic combustor. A portion of the intake air is diverted into this combustor where all of the hydrocarbon fuel is injected. In this region a pilot flame is easily maintained (as compared to the supersonic combustor) and the heat released chemically cracks any unburned fuel as it passes out of the combustor into the supersonic airstream. The notion of using a pilot flame to aid combustion has also been recently developed in supersonic environments with the use of plasma torches. The remaining processes are similar to that of a standard scramjet. This subsonic combustor acts as fuel preconditioner, cracking the fuel and preparing it for the supersonic combustor. A difficulty with this design is the nontrivial amount of space taken up by the subsonic combustor. Other variants have been introduced since the DCR, but will not be discussed here for the sake of brevity.

2.2: Obstacles Encountered with Scramjet Combustion

Although the concept of scramjet engines appears simple, supersonic combustion remains a complex field of study. Chemical kinetics, temperature, pressure, equivalence ratio, mixing rate and stream velocity all affect the combustion process. As it stands, supersonic combustion is very difficult to maintain and continues to be a formidable task.

The ignition delay time of a fuel-air mixture continues to be the limiting factor for all scramjet engine designs. Decreasing the delay time allows for shorter combustors and/or higher flight velocities. Initially, the ignition delay time of a fuel is fixed for a given set of conditions and the type of fuel. Increasing the temperature of the fuel and/or air stream reduces this time. Pressure plays a somewhat more complex role. Increasing the pressure, usually, but not always, improves the combustion conditions. Increasing pressure usually reduces the ignition delay time, but there exists a critical value of pressure, above which, the delay time increases dramatically, followed by a slow decrease. This effect is shown in Fig. 2.2.

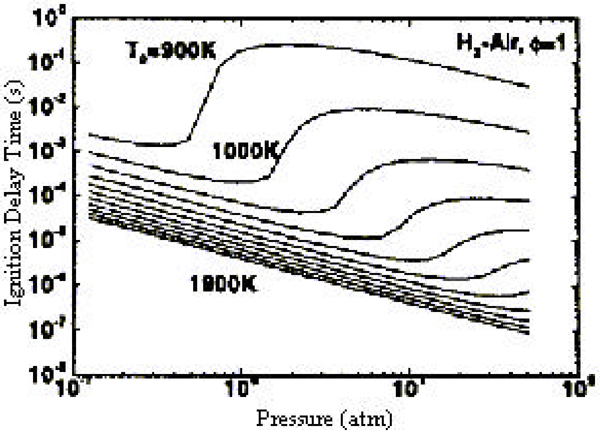

Figure 2.2: Effect of Pressure on Ignition Delay Time (Deshaies et al., 1997)

Therefore, it is not always advantageous to increase the pressure. The equivalence ratio does not strongly affect the ignition delay time, except for equivalence ratios below 0.3, where the delay time increases sharply. Therefore, these effects need to be considered in designs.

Perhaps the largest problem associated with combustion is that of mixing. If fuel can not be properly injected and mixed into the air stream it will not ignite, regardless of the pressure, temperature or equivalence ratio. Due to compressibility effects, fuel injection presents challenging obstacles. The air stream is at such a high pressure and velocity, that fuel injected into the stream has a tendency to be pushed against the wall and rendered ineffective. In addition to the problem of mixing, ignition at these high velocities is extremely difficult. To overcome these challenges, several solutions have been proposed.

2.3: Proposed Solutions to Supersonic Combustion Difficulties

Improved schemes for injection patterns have been designed and studied to overcome the obstacles of inadequate fuel penetration and mixing (Huber et al., 1979, Baurle et al., 1998, Schetz et al., 1996 and King, 1989). In addition, the problem of ignition and flameholding can be handled in one of two ways; injecting combustion-enhancing radicals by use of a plasma torch can reduce the induction time of the mixture (Sato et al., 1992, Kato et al., 1996, Wagner et al., 1986, Barbi et al., 1989 and Kimura et al., 1981), or recirculation zones can be created using aerodynamic bodies such as wedges, ramps or cavities to slow down the flow and provide an environment where combustion can occur (Fujimori et al., 1997, Davis and Bowersox, 1997, Yu et al., 1998, Baurle and Gruber, 1998 and Sands et al., 1997). A combination of these methods can also be used.

2.3.1: Fuel Injection

Advanced fuel injector designs hold promise for solving mixing concerns. Numerous geometries have been tested to improve the mixing characteristics of fuel injection ports. These include swept ramps (Hartfield et al., 1994 and Donohue et al., 1994), multiple ports (Cox et al., 1994 and Fuller et al., 1996), inclined injection (McCann and Bowersox, 1996) and circular and non-circular geometries (Gruber et al., 1995). One interesting concept using fuel injection is that of initiating detonation by interacting supersonic jets. Achasov et al. (1997), discovered that a jet recessed into a small cavity with incident jets focused towards the center of the cavity could produce a region of high energy density which can lead to the onset of detonation. These jets enhanced the pressure and temperature within the volume of the cavity and produced a region of fast turbulent mixing.

Another design implementing the use of jet interaction is one proposed by Schetz et al. (1996), in which an aerodynamic ramp, rather than a physical one, is produced by means of nine differently-angled fuel ports. These ports were arranged to produce fuel-vortex interactions to enhance mixing in a supersonic cross-flow. Experiments conducted with this aero-ramp showed that with increased jet momentum, penetration increased, while a comparable physical ramp showed no significant improvement. Also noteworthy was that the total pressure losses induced by the aero-ramp were less than those of the physical ramp.

Another method of fuel injection is to position the injectors on a strut. Huber et al. (1979) reported that autoignition of hydrogen occurred easier when injected from a strut than from a wall because of the smaller boundary layer and higher surface temperature of the strut. Masuya et al. (1995) later confirmed these findings, testing different strut designs in a Mach 2.5 airstream. In some cases, struts are superior to other aerodynamic shapes, such as wedges and cavities, because they do not significantly disturb the flow and have fewer losses associated with them.

The shape of the jet is also important. Gruber et al. (1995) discovered that elliptical jets could enhance the mixing rate of fuel into a supersonic airstream. Elliptical jets tested in a Mach 2 cross-flow demonstrated increased spanwise spreading of the shear layer and greater turbulence intensity when compared to a circular jet. Shadowgraphs revealed that the elongated structure of the elliptical jet produced a smaller separation region upstream of the jet and also produced a weaker bow shock. However, the elliptical jet also had reduced lateral penetration compared to the circular jet.

2.3.2: Recessed Cavity Flameholders

Another promising method of mixing and flameholding in supersonic environments comes from the use of recessed cavities. Experiments conducted by Yu et al. (1998) were designed to determine how the shape and interaction between multiple cavities affected the mixing capabilities of the flow. Normalized flame intensity images suggested that short cavities provided steady flameholding. Longer cavities resulted in more compact, but intense flame structures. Finally, cavities with inclined downstream walls had very poor flameholding capabilities. In general, cavities with small aspect ratios (L/d) and vertical downstream walls appeared to be good flameholders. In addition, Baurle and Gruber determined how the dimensions of the cavity affect the mixing characteristics (1998). They determined that the length of the cavity determined its mass entrainment capabilities, while the depth of the cavity determined the residence time. They also found that longer cavities had higher drag coefficients.

2.3.3: Ramps and Wedges

Ramps and wedges have long been used as bluff body flameholders. The shock waves produced by their edges, and the rapid change of duct area just past the bluff body enhance mixing. Typically, a fuel injector is located just downstream of the bluff body to take full advantage of the turbulence produced. Shock-induced combustion behind a wedge and ramp has been studied extensively. Shock waves are unavoidable in a scramjet combustor, but are not necessarily detrimental. These shock waves can change the local temperature, velocity and flame characteristics, affecting the combustion process. Fujimori et al. (1997) found that the recirculation zone behind a wedge in a supersonic airstream was very sensitive to the fuel flowrate. With low fuel flowrates, most of the reaction occurred within the recirculation zone, but with higher flowrates, the reaction zone moved away from the wedge and extinguished completely. Sands, et al. (1997) also proved both analytically and experimentally, that flameholding was possible with a rectangular ramp. Although they have certainly been proven to be adequate flameholders, bluff bodies also incur large flow losses due to low back pressure as their cross-sectional area increases.

2.3.4: Plasma Torches

Plasma torches (also known as plasma igniters or plasma generators) have a wide range of application in today's industry and also come in many different forms. Many are used in waste management, emissions control (Behbahani and Muller-Dethlefs, 1982), metal cutting (Costley et al., 1997) and internal combustion engine applications (Weinberg, 1978), among others (Chan et al., 1980 and Miller et al., 1996). However, the plasma torches of interest to this study are those that are used for ignition and flameholding in a supersonic fuel-air stream (Sato et al., 1992, Kato et al., 1996, Kimura et al., 1981 and Weinberg and Warris, 1985). Plasma torches have been proven to be effective igniters and flameholders in scramjet engine tests up to Mach 6 (Masuya et al., 1997, Tomioka et al., 1996, Mitani et al., 1996 and Sato et al., 1997). Regardless of the design, the main purpose of any plasma torch is to ionize and dissociate the feedstock gas into hot, reactive plasma. This plasma, depending on the torch design and feedstock, can be used to cut metal, enhance combustion, destroy waste, etc. Plasma torches used in supersonic combustion applications are designed to produce combustion-enhancing radicals such as hydrogen, nitrogen and oxygen atoms, OH, C_2, OH and CH_3.

Typically, the power range of these devices is limited to a few kilowatts to consume only the smallest possible fraction of the total engine power. The feedstock is generally hydrogen, nitrogen or a mixture of these, combined with argon. As the feedstock gas passes through an electric arc it is ionized, and in the case of more complex gases, also dissociated. This process produces combustion-enhancing radicals that reduce the reaction time for the combustion processes. This plasma is then injected into the fuel-air stream where the combustion reactions take place. Unlike a common candle or diffusion flame, plasma torches with choked constrictors are extremely difficult to blow out. For this reason they are well suited for supersonic combustion applications.

2.3.5: Integration of a Plasma Torch and Fuel Injector Design

Combinations of supersonic combustion enhancement devices frequently prove very effective. Plasma torches are often partnered with some form of recirculation device such as a ramp or wedge. Each device has its own special capabilities and drawbacks (e.g. ramps can create recirculation zones, but can not ignite the fuel-air mixture). Combinations of these devices can create systems that contain most of the advantages and few of the drawbacks of each component. The near-future scope of the present project is to integrate a new, low power plasma torch, designed by Phoenix Solutions co. and based on the design of the Virginia Tech Plasma Torch, with a fuel injector, known as the aero-ramp, designed by Dr. Joseph Schetz (Schetz et al., 1996) here at Virginia Tech. The aero-ramp consists of a three-by-three array of fuel injectors at different angles, creating the effect of an aerodynamic, rather than a physical, ramp. The plasma torch will replace one of these injectors and hopefully ignite the surrounding fuel jets as they enter the combustion chamber. From a supersonic combustion application viewpoint, this design looks promising.

2.4: Effectiveness of Plasma Torches in Supersonic Combustors

Plasma torches have been proven to be effective igniters and flameholders in a supersonic environment. However, the choice of feedstock, power requirements and methods for integrating the torch into the combustor are still under investigation. Sato, et al. (1992) studied the effect of the torch feedstock on the autoiginition temperature of a hydrogen-air mixture and the integration of the torch into a scramjet combustor. The test setup is shown in Fig. 2.3. Four feedstocks were chosen; air, oxygen, nitrogen and a 1:1 volumetric mixture of argon and hydrogen, suggested by Wagner et al. (1986) as being an excellent flameholding mixture. All tests were conducted at close to the same power level and flowrate. Sato's experiments revealed that air or oxygen as a torch feedstock, is just as effective as nitrogen or an argon-hydrogen mixture. This finding is significant in that, if air is used as the torch feedstock, no onboard fuel needs to be stored for the torch. This will save space onboard the vehicle, provide for a simpler design and save money in construction costs. Another significant finding by Sato was that the torch was unable to ignite the fuel coming from the five fuel injectors mounted on the opposite wall. However, the torch had sufficient ignition capability to ignite the four fuel injectors located directly downstream of it.

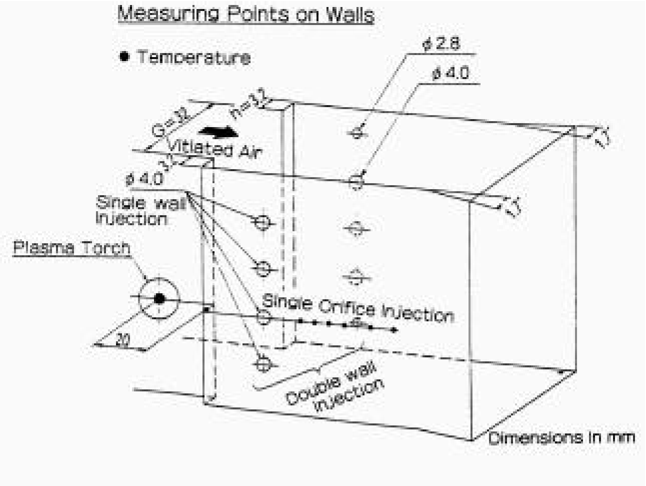

Figure 2.3: Setup for Plasma Torch and Fuel Injectors in Supersonic Test Cell
(Sato et al., 1992)

Northam, et al. (1984) took a different approach than that prescribed by Sato. He decided to determine how a torch operating on a 1:1 volumetric mixture of argon and hydrogen would affect the autoignition temperature and flameholding characteristics of hydrogen and several hydrocarbon fuels in a Mach 2 flow. The torch was found to be an effective ignitor and flameholder for hydrogen, ethylene, ethane and methane, when operating at about 2 kW. In some cases, the flame was observed to propagate upstream to the point of fuel injection. Wagner, et al. (1986) also discovered that the effectiveness of the mixture did not significantly improve as the volumetric ratio of hydrogen to argon was increased past 1:1.

Complimentary to these findings by Wagner, Northam and Sato, Kato and Kimura (1996) performed numerical analyses of flame stabilization and combustion promotion by plasma jets in supersonic air streams. They concluded that the role of input power is very important in determining the effectiveness of a plasma torch as a flameholder and that the effectiveness increases with input electric power. This agrees with the findings of Northam, et al. (1984) who found that torches operating with low power had difficulty flameholding fuel-air mixtures with low total temperatures. Also, they found that plasma torches operating with oxygen feedstocks are more effective for flameholding than those with hydrogen feedstocks. In regards to plasma torch integration, they recommended that the plasma torch be located downstream of fuel injection ports, stating that the required input power and feedstock flowrate requirements are generally smaller.

The effectiveness of plasma torches in supersonic combustion applications has been proven in other studies as well (Kimura et al., 1981 and Masuya et al., 1993). Perhaps the highest praise of plasma torches can be summed up by the words of Weinberg et al. (1985),

> "…the effects of a chemically active plasma jet so much exceed those of a bluff body, that when they come into play, the aerodynamic contribution to stabilization [by the bluff body] is insignificant."

2.5: Summary

Hypersonic air-breathing engines hold promise for shrinking the size of the world and bringing in a new age of propulsion. Technological developments over the past eight decades have brought the reality of hypersonic travel close to fruition. With practical scramjet models in operation, flight tests are soon to follow. From the earliest SCRAM project to the current DCR-Counterforce in the component-testing phase, scramjets have held the eye of the engineering public.

Throughout the recent decades, scramjet developers have overcome problems with material capabilities, ignition, flameholding and internal drag, to name a few.

Aerodynamic devices such as ramps and wedges were employed to provide zones of recirculation where combustion can occur. These devices were followed by advanced fuel injection schemes and plasma igniters, capable of flameholding in air streams well above Mach 5. These technological breakthroughs can bring hypersonic travel to actuality.

Plasma igniters hold promise for future supersonic combustion applications. With their ability to produce combustion-enhancing radicals at relatively low power and their robust performance, they are ideal candidates to overcome many of the obstacles scramjet combustor designers face. Plasma igniters possess the capability to push the combustion envelope well beyond currently known limits. The ability to propel air-breathing vehicles to speeds approaching Mach 15 is an attractive prospect and, with plasma igniters providing the needed reliability, is certainly within our reach.