# 1

# Introduction to Hypersonic Air-Breathing Propulsion

We begin a study of hypersonic air-breathing propulsion systems, engines that take the oxidizer from the surrounding atmosphere and propel vehicles to sustained speeds greatly in excess of the local speed of sound, higher than Mach 5. Hypersonic flight with air-breathing propulsion is pursued for its potential to realize cost-effective access to space and high-speed cruise. Applications include civil transports, scramjet-powered missiles to fly in the Mach 6–8 range, both tactical and strategic, single-stage space planes, and multiple-stage-to-orbit vehicle configurations. Renewed interest in hypersonic sustained flight has increased research and development activities and made substantial advances in required technologies. The remarkable performance improvements promised by high-speed air-breathing propulsion were brought within our reach by the recent development of technologies related to scramjet engines and by their demonstration in flight. Figure 1.1 depicts an artistic view of NASA's X-43A aircraft that flew at Mach 7 and 10 to demonstrate the viability of hydrogen-fueled scramjet propulsion.

Hypersonic air-breathing propulsion is based on ramjets and scramjets, the simplest jet engines to propel a vehicle to hypersonic speeds within the atmosphere. These engines have no internal moving parts, as they do not require turbomachinery (mechanical compressor/turbine) to process the ingested ambient air.

The ramjet engine has three main components: an inlet, a combustion chamber, and a nozzle. The dynamic action of the freestream air is used to produce the compression in the inlet as the vehicle flies at high speed. This action is referred to as the ram effect. The higher the velocity of the incoming air, the greater the pressure rise. The fundamental principle underlying ram compression in the ramjet inlet lies in converting the kinetic energy of the air into pressure. The compressed air then enters the combustion zone where it is mixed with the fuel and burned. The hot, high-pressure gas flow then accelerates back to a supersonic exit speed through the nozzle to develop thrust.

The most distinctive feature of the ramjet is that combustion of fuel with air takes place after the flow has been slowed internally to subsonic speeds. Moreover, the air flow is compressed in several steps, including passing through one or more oblique shock waves generated by the forebody of the vehicle or of the diffuser, deceleration of the supersonic flow in a convergent duct, transforming the supersonic flow into subsonic flow through a normal shock wave system, and further decelerating the subsonic flow in a divergent duct. Ramjets

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**Figure 1.1** Artistic rendition of scramjet-powered hypersonic cruiser. Source: NASA.

are suitable for applications where the flight Mach number is in the range 3–5 and are used mainly for supersonic flight.

When the flight Mach number exceeds about 5, deceleration of the ingested airflow to subsonic conditions would cause it to reach unacceptable high temperatures. To extend the flight regime above Mach 5, the scramjet was conceived. In this type of ramjet, the hypersonic inlet airflow is diffused only to supersonic speed prior to mixing it with fuel in the combustor. Hence, the combustion process takes place at locally supersonic conditions. The engine operating in this mode becomes a *scramjet*, an acronym standing for "supersonic combustion ramjet," a name used to emphasize that the combustion of fuel and air must occur in a supersonic flowfield relative to the engine. Scramjets in fully supersonic combustion mode begin to produce thrust flying at speeds of at least Mach 4 and would operate as long as there is sufficient air to pass and process through its inlet; the theoretical maximum operational speed for scramjets is unknown, but it could effectively reach about Mach 12.

There is a wide range of speed and altitude over which air-breathing propulsion is capable of higher specific impulse ($I_{sp}$) than is rocket propulsion. The $I_{sp}$ parameter indicates how much thrust the engine produces per every unit mass of propellant (fuel plus oxidizer) it uses per second. Since the air-breathing engine does not need to carry oxidizer on board, its specific impulse is much higher than that of the rocket. Scramjets are therefore the most efficient air-breathing engines, that is, with the highest (fuel)-specific impulse, at flight Mach numbers above 5. To capitalize on such advantage, much effort has been devoted to developing hypersonic air-breathing propulsion (HAP) systems to achieve hypersonic flight within the Earth's atmosphere. One such HAP concept is the dual-mode scramjet (DMSJ), an engine that operates both as ramjet (subsonic combustion) and as scramjet (supersonic combustion) in order to propel a vehicle in a flight Mach number ranging from 3.5 to 12 (the upper limit in scramjet operational Mach number is still unknown). However, due to its minimum functional speed, scramjets require acceleration by other means in order to become operational for takeoff.

For some military applications, air-breathing hypersonic vehicles can be air or ground-launched attached to a rocket motor that will accelerate the craft to the take-off speed of the scramjet. Other applications require to integrate the scramjet engine with a low-speed propulsion system (e.g. turbojet, turbofan) in order to provide the capability of propel a vehicle from the runway all the way to its maximum hypersonic speed.

Powered by scramjet engines, hypersonic vehicles scoop the oxygen required for fuel combustion from the atmosphere, and this reduces tankage requirements and airframe mass. In fact, for missile propulsion, the ramjet is very competitive with the rocket because it is simple in construction and has greater range for the same propellant weight. These characteristics are particularly attractive for military applications where simplicity and low initial cost are essential features of devices that must function on demand and never return. Moreover, hypersonic vehicles propelled by air-breathing propulsion promise affordable and rapid access to space and hypersonic cruise. Scramjet propulsion flight demonstrator programs (e.g. X-43A, X-51A, HIFiRE) have already proven that HAP vehicles are technically feasible. However, more flights and flight-test programs are required to demonstrate sustained cruise and acceleration to establish the DMSJ engine as a viable and mature hypersonic air-breathing propulsion system.

Moving at hypersonic speeds, a vehicle will naturally generate a massive amount of heat that must be properly managed. The vehicle and its integrated propulsion system must be fabricated with advanced materials designed to withstand those high temperatures, materials with high strength, and high toughness. Hypersonic vehicles travel very fast, getting hot enough to melt most traditional metals, so engineers are developing new material formulations for hypersonic craft to survive such harsh environment.

This book intends to provide the technical background to describe the fundamental characteristics of high-speed air-breathing engines, focusing on the technologies that are being developed to advance the DMSJ to power future hypersonic flight.

## 1.1 Hypersonic Flow and Hypersonic Flight

For air-breathing propulsion, hypersonic flight is interpreted to mean flight speeds $V_0$ higher than five times the speed of sound, that is,

$$M_0 \equiv \frac{V_0}{a_0} > 5$$

where $M_0$ denotes a vehicle's flight Mach number and $a_0$ is the local speed of sound.

For the analysis of hypersonic air-breathing propulsion, we can define hypersonic flow as the regime where the calorically perfect gas model for air becomes invalid. For calorically perfect gas or temperatures less than 400 K, the specific heats $c_p$ and $c_v$ are constant. As the air temperature increases, in the range of temperature $400\ \text{K} < T < 1700\ \text{K}$ air behaves as a thermally perfect gas, the value of the specific heats is function of temperature; and thus the specific heat ratio ($\gamma = c_p/c_v$) is also a function of temperature.

At temperatures above 1700 K (3000 °R), the equilibrium of specific heat ($c_p$) of air depends strongly upon both temperature and pressure because chemical reactions have become important. Hence, $\gamma$ reaches a value of 1.286 when the formation of nitric oxide

(NO) begins. When nitrogen is released during combustion, it combines with oxygen atoms to create NO, which then combines with oxygen to create nitrogen dioxide ($NO_2$). At temperatures above 1700 K, chemical reaction and dissociation become very complicated and cannot be treated with a simple gas model.

We can also consider the value of the freestream total or stagnation temperature that would cause real gas effects to occur. Let us consider the total to static temperature ratio,

$$\frac{T_{t0}}{T_0} = 1 + \frac{\gamma - 1}{2} M_0^2 \tag{1.1}$$

where $T_{t0}$ is the freestream total temperature, $M_0$ is the flight Mach number, and the subscript 0 denotes the undisturbed freestream flow conditions far ahead of the vehicle as seen from the reference frame of the vehicle. When we substitute a representative value of the freestream air static temperature, $T_0 = 227$ K with $\gamma = 1.4$, we find that at a Mach number $M_0 = 6$, the stagnation temperature is $T_{t0} = 1861.4$ K, a value which exceeds the limit temperature for thermal equilibrium flow. At temperatures above 1700 K, the thermally perfect model for air is no longer valid because at this condition the formation of NO begins.

From (1.1), it is clear that for hypersonic flow, we have

$$\frac{\gamma - 1}{2} M_0^2 \gg 1$$

Formally, the basic assumption for all hypersonic flow theories is $M \gg 1$. This definition implies that the internal thermodynamic energy of the freestream fluid particles is small compared with the kinetic energy of the freestream for hypersonic flows. Some textbooks also define hypersonic flow as that with Mach numbers at which supersonic linear theory fails. However, these definitions do not provide a quantitative description of the boundary between supersonic and hypersonic flows.

When a vehicle moves through the atmosphere, at supersonic or hypersonic speed, a shock curved layer forms upstream of the vehicle. Known as a bow shock, this is a curved propagating disturbance shock wave characterized by an abrupt, nearly discontinuous, change in pressure, temperature, and density, and entropy increase. In hypersonic flight, as the freestream velocity becomes very large while its freestream thermodynamic state remains fixed, this produces extremely high temperatures in the shock layer. As the freestream Mach number increases, the shock waves approach or hug the bounding surface of a body more and more closely, and the resulting thin shock layer increases the wall heating of the hypersonic vehicle. For a slender aircraft, hypersonic effects are very clear when it flies at high Mach numbers, as the bow shock gets closer to the body and aerodynamic heating dominates the physics of its flight.

From aerodynamics perspective, we define hypersonic flow when the following flow phenomena become progressively more important as Mach number increases:

- High Temperature Effects → aerodynamic heating increases proportionally with $M_0^2$.
- Low Density Flow → aerodynamic equations (Euler and Navier–Stokes equations) break down.
- Thin Shock Layers → shock layer is composed of the flowfield between the oblique shock wave and the vehicle. As the Mach number increases, the shock wave gets closer to the vehicle.

- Entropy Layer → entropy increase becomes greater as shock strength increases.
- Viscous Interaction → increased flow temperature (due to friction heat) near body surface causes boundary layer to become thicker as speed increases, resulting in high drag.

Each factor plays a huge role in the design and operation of practical hypersonic vehicles.

Hypersonic flight regime is characterized by flow velocities that exceed five times the local speed of sound ($M_0 > 5$) and where shock layers are thin and viscous drag and heating loads are very high. Inside the air-breathing engine flowpath, the term hypersonic refers to regions of high stagnation temperatures at which chemical reactions become important and simple models of gas behavior break down.

## 1.2 Chemical Propulsion Systems

A propulsion system is a sophisticated engineering device capable of generating a thrust force to propel a vehicle in a particular direction or to accelerate it in flight. All methods to produce a thrust force for propelling a vehicle are based on one principle: the time rate of change of momentum of a fluid accelerated by the system under consideration. The fluid may be a propellant stored in the vehicle and carried along during its flight, as in the case of rocket propulsion, or it can be a mixture of a fuel and an oxidizer that is taken from the surrounding environment, such as in the air-breathing propulsion systems we study herein. In both cases, the fluid is chemically reacted in a combustion chamber, and the hot products of combustion are expelled at high velocity through a propulsion nozzle. Hence, we refer to chemical propulsion systems as those in which chemical energy resulting from a chemical reaction of a fluid and an oxidizer cause breaking or forming of chemical bonds with the resulting gas achieving a high temperature, i.e. thermal energy is released by the fuel during combustion.

Chemical propulsion can be divided into two major groups: air-breathing and rocket engines, as illustrated in Figure 1.2. Air-breathing propulsion can be further divided into gas turbine jet engines (turbojet, turbofan) and non-rotor jet engines (pulsejet, ramjet, and scramjet), all based on the open air-standard power cycle. Jet propulsion is a specialized field that deals with systems in which the generation of thrust is achieved by direct expansion of a gas (the working fluid) used by the engine.

Air-breathing jet engines operate on an open air-standard power cycle known as Brayton cycle. That is, the working fluid undergoes a series of thermodynamic processes (compression, energy addition, and expansion) arranged in a manner that the processed gas can produce thrust. The Brayton cycle represents the ideal conversion of thermal energy to mechanical energy.

The low-pressure air from the surrounding atmosphere enters the engine and is compressed to a higher pressure. The compressed air is then heated by injecting fuel into it, allowing the air stream and the fuel to mix together, ignite, and burn at almost constant pressure in a combustion chamber. The high-pressure hot gaseous products of combustion

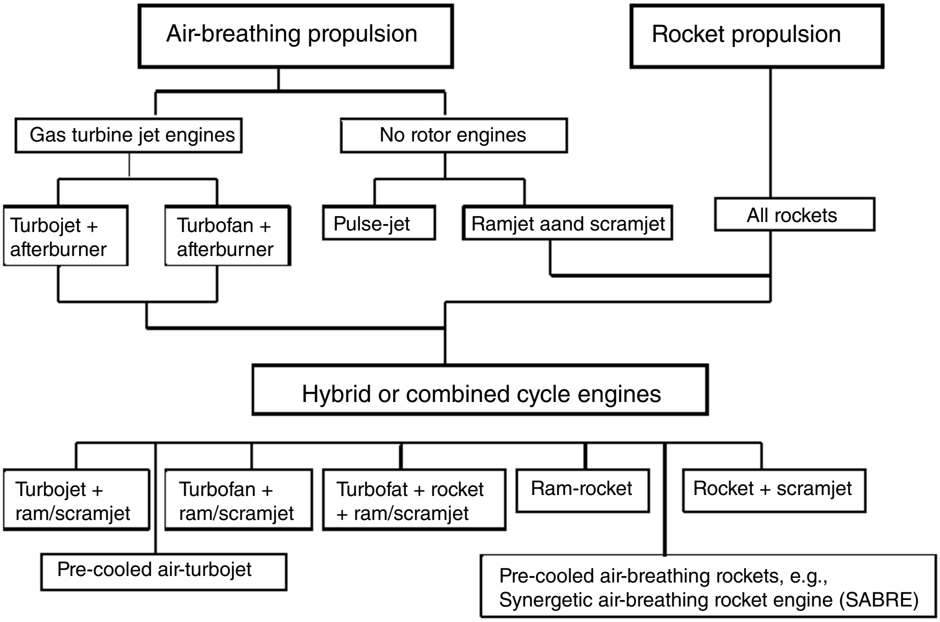

**Figure 1.2** Classification of chemical propulsion.

accelerate and are expanded in the nozzle and finally exhausts into the atmosphere. A reaction force or thrust is generated by the flow because its high temperature has more velocity and momentum leaving than it did entering the engine. This reaction force is known as the internal or uninstalled thrust.

### 1.2.1 Turbojets

For flight in the range of $0 < M_0 < 3$, the jet engine requires a mechanical compressor to increase the pressure of the incoming atmospheric air before fuel is added and combusted, particularly in the low end of the speed range. In the case of a turbojet (Figure 1.3), the ingested air is compressed mechanically by an axial compressor, and the hot gases of combustion are first expanded in a turbine attached to the compressor by a common driveshaft. The expansion process is limited so that the work necessary to drive the compressor is supplied only by the turbine, and the rest of the expansion occurs in the exhaust nozzle.

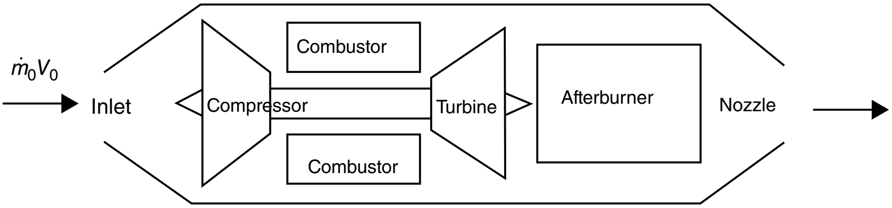

**Figure 1.3** Representation of turbojet with afterburner.

Atmospheric air taken in through the turbojet inlet is compressed up to 3–12 times its original pressure in the axial compressor. Fuel is added to the air and burned in a combustion chamber to raise the temperature of the fluid mixture to about 593–704 °C (1100–1300 °F). The resulting hot gas is passed through a turbine, which drives the compressor. If the turbine and compressor are efficient enough, the gas pressure at the turbine discharge will be nearly twice the atmospheric pressure, and this excess pressure is sent to the nozzle to produce a high-velocity stream of hot gas which produces the thrust force. Substantial increases in thrust can be obtained by employing an afterburner. This is a second combustion chamber positioned after the turbine and before the nozzle (see Figure 1.3). The afterburner increases the temperature of the gas ahead of the exhaust nozzle. The result of this increase in temperature is an increase of about 40% in thrust at takeoff, and a much larger percentage at high speeds once the vehicle is in the air.

For supersonic flight in the Mach number range of $2 < M_0 < 5$, the ram pressure produced by the inlet in slowing down the incoming air to subsonic speeds is high enough that there is no longer need for an air compressor, and therefore no need for a turbine. As a consequence, the turbomachinery is unnecessary and the engine design configuration is simplified. The resulting propulsion system is called ramjet.

The effect of Mach number on total or stagnation pressure of the freestream, denoted by $p_{t0}$, becomes immediately clear through the relation

$$p_{t0} = p_0 \left(1 + \frac{\gamma - 1}{2} M_0^2\right)^{\gamma/(\gamma - 1)} \tag{1.2}$$

where $p_0$ is the static pressure of the ambient air.

When the Mach number is $M_0 = 4$, Eq. (1.2) yields a ram pressure ratio $p_{t0}/p_0 = 151.8$, and from Eq. (1.1), we obtain a total to static temperature ratio $T_{t0}/T_0 = 4.2$; together these two ratios give air conditions more than adequate for operating an engine without turbomachinery. For this flight regime, the ramjet is the air-breathing propulsion of choice. The total pressure to static pressure ratio ($p_{t0}/p_0$) of the freestream is often referred to as *ram pressure ratio*. The natural air compression brought on by the aircraft's high speed is known as ram pressure.

### 1.2.2 Ramjets

Ramjets are the air-breathing engines of choice for supersonic flight in the Mach number range 3–5. Conceptually, a ramjet is the simplest air-breathing jet engine, consisting of three main components: an inlet diffuser, a combustor or burner, and a thrust nozzle. Figure 1.4 depicts a conventional ramjet of circular cross-section that uses a spike-like inlet diffuser.

The incoming atmospheric air flowing at supersonic speed is first compressed at the nose of the vehicle by going through the oblique shock anchored by the central spike and then after a terminal normal shock at the cowl lip, the air flows into the interior of the engine. In the diffuser, most of the air's kinetic energy is converted into a pressure raise. After compression by the inlet shocks, the air has slowed considerably, reaching subsonic velocity. In the subsonic diffuser, the air flow gains an additional increase in pressure before it reaches the combustion chamber.

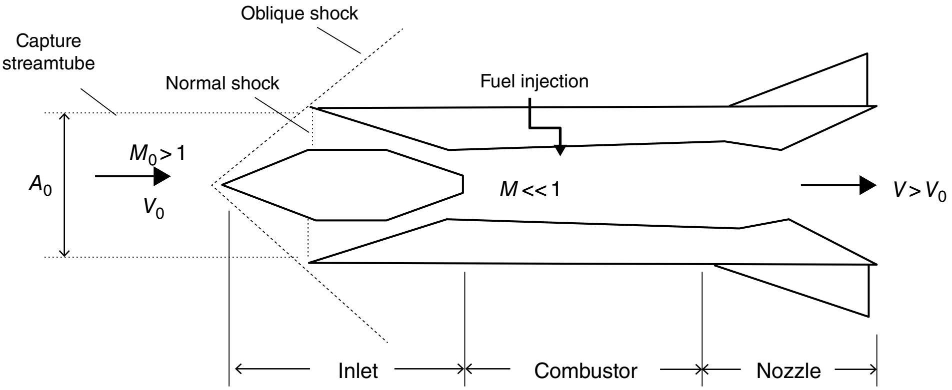

**Figure 1.4** Schematic of a conventional ramjet engine.

The combustor section in the ramjet is a chamber similar to an afterburner. In the combustor fuel is injected and mixed with the compressed air and ignited. Because the combustor's cross-section is relatively small, the airflow velocity is much higher in the ramjet combustor than in a turbojet burner. Therefore, ramjets require flame holders in order to stabilize the flame and prevent blowout. The hot combustion gas then expands, passing through a convergent–divergent nozzle before being expelled at high velocity to produce thrust. In principle, a ramjet can operate at flight Mach numbers as low as $M_0$~0.5 or as high as $M_0$~5.0. However, the specific thrust would be very low at these velocities.

At hypersonic flight velocities $M_0 > 5.0$, the temperature increase that would result from decelerating the airflow to subsonic speed in the ramjet inlet becomes so large that adding thermal energy to the flow in the combustor would not yield a significant temperature rise, mainly because the normal products of combustion would be highly dissociated. If the air temperature would raise further in the inlet (by decelerating the high velocity air to subsonic values), it would cause the total temperature change in the combustor to be reduced to eventually zero. This is the reason why the ramjet engine is not effective for operation at flight Mach numbers above 5. Since the ramjet lacks turbomachinery, it requires boosting to some minimal airspeed before it can sustain combustion and generate thrust greater than its own drag.

***Ramjet***: A propulsion system that utilizes the natural "ram effect" to compress the ingested freestream air and in which fuel/air combustion occurs at subsonic speeds. The ramjet can operate effectively in the flight Mach range of $1.0 < M_0 < 6.0$.

### 1.2.3 Scramjets

For hypersonic flight speeds, $M_0 > 5$, the temperature increase accompanying the ram compression to subsonic speeds is so high that little or no additional heat can be added in the combustor by burning fuel. The only alternative is to use the inlet to slow the flow down

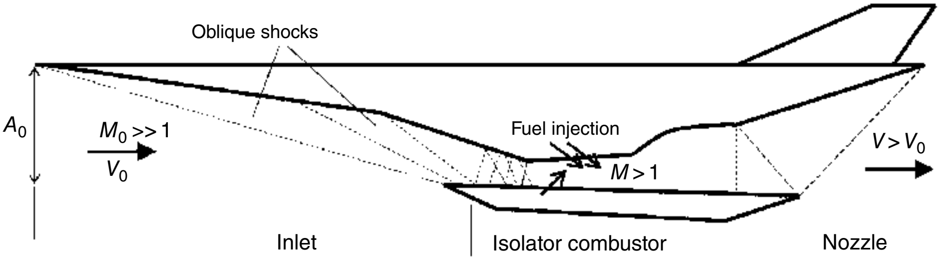

**Figure 1.5** Schematic of vehicle-integrated scramjet engine.

from the flight speed to some lower supersonic Mach number, thereby not increasing the temperature too much. However, then fuel must be added to a supersonic stream, mixed, and combusted. Such a supersonic combustion ramjet is known as a scramjet (Figure 1.5).

The scramjet is capable of operating in the hypersonic regime $M_0 > 5$. The scramjet overcomes the limitation outlined above by partially compressing and decelerating the incoming air but still keeping it at supersonic velocity throughout the engine. Hence, the inlet flow must be diffused only to the compressed state required by combustion, remaining at supersonic speed prior to entering the combustor. The scramjet engine is in fact a ramjet engine in which the combustion process takes place at supersonic conditions.

A scramjet engine (Figure 1.5) consists of four basic components; an inlet, an isolator that is used to "isolate" the supersonic inlet flow from the back pressure growth in the combustor, a combustor, and a nozzle aft of the combustor. In the scramjet inlet, the freestream air is first partially decelerated and compressed from the freestream condition (point 0) to the combustor entry condition by means of a combination of isentropic compression and oblique shock waves. This compression process must be sufficient to provide a large enough static temperature ratio across the inlet (in the range of 6–8) for optimum thermodynamic cycle efficiency, and to produce high enough values of pressure and temperature at the combustor entrance to support complete and stable combustion at supersonic flow conditions. The airflow temperature and that of the combustion products cannot be allowed to rise above the range in which the combustion of the fuel with air can be completed.

Careful design of the supersonic combustion duct is required to avoid thermal choking. The hot gases are then accelerated further through the expansion process from the combustor exit condition to the freestream ambient condition. Since the accelerating gases are supersonic, the exhaust nozzle of the scramjet is of diverging geometry. In fact, some of the expansion and acceleration occur outside the scramjet confining flowpath by using the afterbody of the vehicle as a free expanding surface.

Scramjets are mechanically simple but aerodynamically more complex than any other jet engine. Figure 1.5 depicts a scramjet engine that is closely integrated with the vehicle. In such configuration, the bottom of vehicle becomes an integral part of the high-speed air-breathing propulsion system. To capture the required airflow for maximum propulsion, it is necessary to use entire forebody underneath the vehicle as a compression surface. Since a streamtube of air enormously larger than the physical opening of the engine forms upstream of the vehicle, a long forebody is needed to increase the capture area $A_0$. In this manner, the vehicle's forebody serves as a portion of the external inlet, and the afterbody completes the nozzle expansion process. In the configuration of Figure 1.5, the engine flowpath includes the vehicle external lower surfaces and the engine cowl internal surfaces.

The inlet of the scramjet achieves air compression both externally and internally through oblique shocks. The series of oblique shock reflections inside the inlet create a shock train, which is contained in the isolator. The isolator is a duct between the inlet proper and the entrance to the combustor that serves to prepare the air flow for mixing with the fuel and supersonic combustion process. This duct acts to isolate the two main engine components. The air flow that emerges from the isolator is supersonic as it enters the combustor, requiring that it has a Mach number approximately a third of the flight Mach number.

Combustion at supersonic speeds is rather challenging. Consider this, if the air enters the combustor at a speed of 999 m/s (~Mach 3), it would transverse a meter length in about 1 ms. Achieving efficient fuel injection, mixing, and chemical reaction in such short timescales require ingenious and complex design schemes for the combustor and the fuel injection systems. We shall examine these issues in Chapter 5.

The hot gases generated in the combustor of the scramjet require a nozzle exit area even larger than the original freestream capture area in order to expand effectively and produce thrust. Hence, the entire afterbody underneath the vehicle is used as a free expansion surface, as illustrated in Figure 1.5.

There are two aspects of ram compression that are unfavorable to thrust production. These are (i) the inlet total pressure recovery that exponentially deteriorates with flight Mach number, and (ii) the rising gas temperature in the inlet that reduces the total temperature difference across the combustor to zero.

Decelerating a supersonic flow in the inlet of the ram/scramjet is accompanied by shock waves that produce a total pressure loss much greater than, and in addition to, the wall friction loss. Hence, the overall pressure ratio of the inlet is the product of the ram pressure ratio and the diffuser pressure ratio. Because of shocks, only a portion of the ram total pressure can be recovered. A well-designed inlet for a scramjet is required to minimize the sources of irreversibilities. We will address this topic in subsequent chapters.

Moreover, the deceleration process in the inlet produces a high temperature rise, and at some limiting flight speed, the temperature will approach the limit set by the wall materials and cooling methods available for the engine. Thus, when the temperature increase due to deceleration reaches the limit, the propulsion system is no longer effective.

Finally, since ram/scramjets cannot generate thrust for take-off, a vehicle needs some other propulsion device to accelerate these engines to the supersonic speeds required to start generating thrust. That is a reason why ramjets are paired with a rocket booster and often used to propel air launched missiles. Previous scramjet flight demonstration tests required that the hypersonic vehicles be air-lifted by a carrier aircraft and then boosted to the altitude test conditions using a rocket booster. After separating from the launch aircraft and booster, the scramjet performed the fueled propulsion test in free flight.

***Scramjet***: Supersonic combustion ramjet engine that can operate effectively in the Mach flight range $5.0 < M_0 < 15$. The pure scramjet is the true hypersonic air-breathing engine.

***Dual-mode Scramjet***: Air-breathing engine that can operate as a ramjet and as a scramjet, depending on whether it combusts its fuel at subsonic or supersonic conditions, transitioning to each engine mode as needed. It can propel a vehicle in the flight regime $3.0 < M_0 < 15$.

The idea of the DMSJ evolved from the conflicting requirements of the hypersonic engine to have high cycle thermal efficiency (that depends on having a high compression pressure ratio), and prevent or minimize dissociation of the working fluid (which can occur if the static compression temperature of the gas exceeds a known value). In other words, the static temperature at the beginning of combustion cannot be increased indefinitely, but must be limited. If the temperature becomes too large, adding thermal energy to the flow in the combustor (via fuel injection) would not yield a significant temperature rise, mainly because the normal products of combustion would be highly dissociated and would cause the total temperature change in the combustor to be reduced to zero. Moreover, at some limiting flight velocity, the compression temperature would approach the limit set by the wall materials and cooling methods available for the propulsion system.

Thus, to prevent or control those detrimental effects, the DMSJ must be designed so that the combustion process occurs at subsonic flow conditions (ramjet) for flight Mach numbers less than about 5, and be supersonic (scramjet) for hypersonic flight. The dual-mode combustor must transition seamlessly from subsonic combustion to supersonic combustion, and vice versa, as required by the flight speed.

To determine the maximum allowable temperatures in a scramjet requires a combination of elaborate computations and experienced judgment because these temperatures depend on many interrelated variables, including flight altitude and Mach number, inlet losses, fuel type, fuel/air ratio, and burner and exhaust system geometry. However, we shall carry out analysis based on fundamental thermo-aerodynamic equations to determine the values of compression temperature that are acceptable. The limit on compression temperature should also help us predict the values of Mach number that the compressed air must have as it enters the combustor.

### 1.2.4 Combined Cycle Propulsion

A DMSJ capable of producing thrust in the Mach 3–12 range can be combined with other engine cycles to develop efficient concepts with sufficient performance and operability to power hypersonic aircraft and spaceplanes. Many studies have considered the DMSJ as the core of combined-cycle propulsion systems for single-stage-to-orbit (SSTO) vehicles by providing most of the orbital ascent energy. Such concepts are also relevant to two-stage-to-orbit (TSTO) systems with an air breathing first stage (see Chapter 10).

An engine representative of combined air-breathing cycle is the turboramjet, an engine that can operate both as a turbojet and ramjet engine, intended for high supersonic speed flight. There are many other hybrid or combined cycle propulsion concepts that adapt the different types of engines into another propulsion cycle that yields performance characteristics needed to span a hypersonic flight regime. For example, the air turborocket (ATR) takes elements of an air-breathing jet engine and combines them with a rocket. One can also conceive a propulsion system composed of a turbojet, a scramjet, and a rocket combined in such a manner that the resulting engine can power a launch vehicle to orbital velocities.

Turbine-based combined cycle (TBCC) propulsion concepts integrate a gas turbine engine (turbojet or turbofan) and a DMSJ in a dual-flowpath configuration. Rocket-based combined cycle (RBCC) propulsion concepts integrate rocket thrusters with a DMSJ flowpath.

Precooled air-breathing propulsion utilize methods to reduce the high temperature of air entering the inlet system. The precooled air can then be compressed to combustion chamber operating pressures with reduced power requirements. This approach can be used in turbo engines, or in air-breathing rockets (e.g. SABRE).

The concept of the precooled engine is very attractive. According to Eq. (1.1), at Mach 5 air, the stagnation temperature is six times the ambient static temperature. For $T_0 = 223.5$ K (at 27 km altitude), this is $T_{t0} = 1341$ K, a high temperature that makes it impractical to compress the air mechanically due to large power required, and because the resulting compressor delivery air temperature would be too high for the combustor.

The air-breathing rocket concept is designed with an inlet to take the oxidizer for combustion from the surrounding atmosphere rather than carrying it onboard as traditional rockets do. One example of such air-breathing rocket is the Synergetic Air-Breathing Rocket Engine (SABRE) now being developed by Reaction Engines Limited (REL), a private company based in the United Kingdom. SABRE operates in both air-breathing and rocket modes, relying on precooling technology to rapidly cool the incoming air (from ~1000 °C to ambient), enabling SABRE to operate at higher speeds than existing conventional air-breathing engines. This propulsion system is scalable so that it can power hypersonic cruise aircraft and the Earth-to-orbit spaceplane Skylon.

We should note that other forms of energy – electrical, nuclear, plasma, and so on – can be and are used for deep space propulsion, and we can conceive new engineering ideas using those forms of energy to augment chemical propulsion. However, the subject matter in this book is confined to the study of hypersonic air-breathing engines (DMSJs).

## 1.3 Classes of Hypersonic Vehicles

Vehicles that fly at hypersonic speeds include rocket launchers that deliver payloads to Earth orbits, spacecraft designed to return from space intact, and aircraft to cruise through the atmosphere. For military applications, potential mission areas include long-range cruise missiles, flexible high-altitude atmospheric interceptors, and responsive hypersonic aircraft for global payload delivery. Hypersonic flight offers superior speed and range and rapid response to time-critical targets, making possible global fast-reaction reconnaissance missions. While comparable to flight time of ballistic missile, hypersonic vehicle offers advantage of flexible recall and en route re-direction.

Hypersonic flight that occurs strictly within the Earth's atmosphere is called endo-atmospheric, and if it occurs outside the atmosphere, it becomes exo-atmospheric flight. An endo-atmospheric vehicle is one that remains within the Earth's atmosphere (at altitudes below 100 km). An exo-atmospheric vehicle is a space access vehicle with speeds up to Mach

25 (orbital). Hypersonic vehicles include winged and glide re-entry vehicles and can be classified as powered and unpowered gliders. Powered vehicles can use rocket propulsion, air-breathing propulsion, or a combination of the two distinct propulsion cycle systems. In a boost glide system, a rocket accelerates its payload (a weapon or a missile) to high speeds above the atmosphere. The payload then separates from the rocket and glides unpowered to its destination.

Hypersonic air-breathing propulsion vehicles can be divided into two classes: accelerators and cruisers. The accelerator vehicle is one where the dominant design characteristic is low drag per unit inlet capture area ($D/A$), since the cross-section attributes a large percentage to propulsion. The cruiser aircraft is characterized by its high lift-to-drag ratio ($L/D$) since thin/flat fuselages with high fineness ratios are needed to reduce drag as the aircraft move through the atmosphere.

The fuel is a design-influencing parameter for shaping the hypersonic vehicle. Hydrogen-fueled vehicles must be very volumetric efficient to contain the low-density fuel. On the other hand, for hydrocarbon-fueled vehicles, the concern is loading because of high-density fuel; they tend to be more like waveriders, vehicles which, at their design point, fly with an attached shock wave all along the leading edge. A conventional hypersonic vehicle usually flies with the shock wave detached from the leading edge. Propulsion–vehicle integration places tight volume constraints on vehicle packaging requirements as this restricts available space for fuel tanks.

Hypersonic vehicles powered by air-breathing propulsion are considered for a variety of missions such as long-range civil transports, first stage launch vehicles, and a variety of military applications such as air-launch missiles, combat, and reconnaissance airplanes. Three vehicle types are summarized in Table 1.1, where we also indicated representative characteristics, including the type of fuel for each application, where $LH_2$ denotes liquid hydrogen, and LHC denotes liquid hydrocarbon fuels. The expected flight regimes of air-breathing aircraft are illustrated in Figure 1.6. One can quickly estimate that a trip across the United States from coast to coast could take 39 minutes by flying at Mach 5, whereas a Mach 6 military missile could fly a downrange distance of 2220 km in 25 minutes.

**Table 1.1** Representative air-breathing hypersonic vehicles.

| Mission | Flight Mach number $M_0$ | Propulsion system | Flow path geometry | Fuel | Flight duration | Vehicle length, ft (m) |
|---|---|---|---|---|---|---|
| Hypersonic cruise | 0–5<br>0–8 | Turbo-ramjet<br>Turbo-dual-mode scramjet | Variable geometry, actively cooled | LHC<br>$LH_2$ | 1–3 hours | 100–200 (30–61) |
| Tactical missile | 5–8 | Scramjet | Fixed geometry, passively cooled | LHC | 10–30 minutes | 5–16 (1.5–5) |
| Trans-atmospheric vehicle | 0–20 | TBCC<br>RBCC | Variable geometry, actively cooled | $LH_2$ | 20–60 minutes | 100–200 (30–61) |

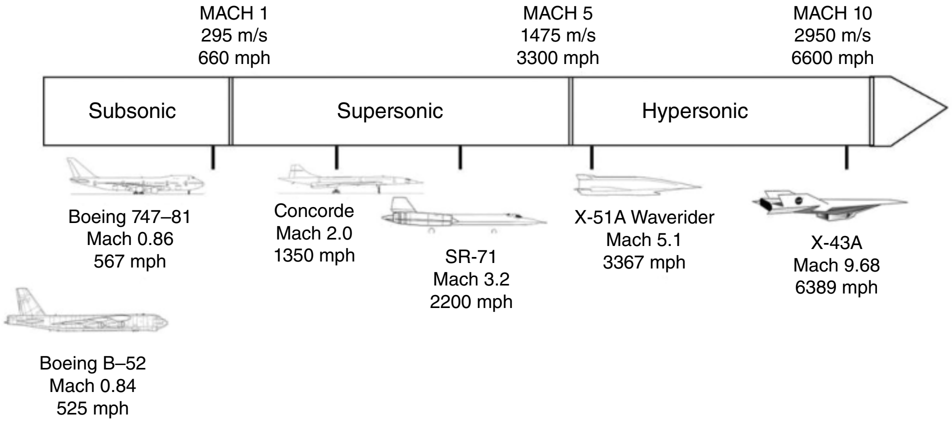

**Figure 1.6** Flight regimes for air-breathing propulsion.

A hypersonic air-breathing vehicle must follow a flight trajectory within the atmosphere, maintaining structural heating and load limits while delivering enough airflow to its propulsion system to ensure an optimum level of net thrust for acceleration. The optimal flight altitude of a stratospheric aircraft depends on the maximum Mach number and the required air dynamic pressure. To ensure these operational flight limits, hypersonic vehicles are designed to operate within a narrow range of dynamic pressure, which should be between 23 and 95 kPa (500–2000 psf; see Chapter 2). Figure 1.6 depicts the nominal velocities of representative vehicles flying within Earth's atmosphere. The speed of sound is a function of temperature and decreases with altitude. On a standard day at sea-level conditions, the speed of sound is about 340 m/s, or 761 mph, or 1100 ft/s, or 1224.7 km/h. Hence, the velocity values given in Figure 1.6 are approximated, assuming sonic speed is 295 m/s or 660 mph.

The fastest supersonic air-breathing crewed aircraft, the SR-71, flew at slightly more than Mach 3.2. In 2004, the autonomous X-43A lifting-body, scramjet-propelled hypersonic aircraft more than tripled the maximum speed of the jet-powered SR-71.

Many different scramjets have been conceived, each of which was designed for a particular application. The engine configuration and choice of fuel vary, depending on the mission requirements and thus the vehicle design and its integration with the propulsion system may be completely different.

Depending on the application, a scramjet design may require rectangular or circular combustor geometries. The engine may incorporate a variety of inlet concepts, including axisymmetric, planar two-dimensional and highly three-dimensional designs. For example, for a Mach 6 cruise missile, a round scramjet geometry with an inward-turning inlet may be more appropriate, while a Mach 10 cruise lifting-body global reach aircraft may require a planar configuration with a tightly asymmetric engine/airframe integration.

The choice of fuel depends on the mission requirements and the Mach number. Military applications may opt for hydrocarbon fuels; vehicles for access to space are more likely to use hydrogen, while civil transports can use either type of fuel. The limit cruise Mach number with hydrocarbon fuel is expected to be approximately 8, as this speed is considered the extent to which a dual-mode ramjet/scramjet can be cooled with endothermic fuels for optimum performance contraction ratios. For higher Mach number cruise, liquid hydrogen ($LH_2$) has more cooling capacity and provides considerably more range than LHC for the same cruise Mach number.

The focus of scramjet R&D is mainly concentrated in the following applications, which require ram/scramjet propulsion development in the given Mach number regimes:

- The first-stage vehicle of a TSTO system could utilize a hydrogen-fueled dual-mode scramjet operating at $3.0 < M_0 < 12$ and combined with either a turbine or rocket-based accelerator.
- A cruise aircraft could be propelled by an $LH_2$- or LHC-fueled dual-mode scramjet for flight at $3.0 < M_0 < 7$, or use a simple LHC ramjet for $3.0 < M_0 < 5$; either option would be combined with a turbine engine for the low-speed regime of its mission.
- An air-launched long-range cruise missile may be propelled by an LHC fuel ramjet for $3.0 < M_0 < 5$, boosted via a solid rocket to takeover speed.

These and many other possible applications allow for variations in flowpath and vehicle geometry to meet design and mission requirements such as weight, surface area, volume, simplicity, and affordability for more practical sustained hypersonic flight. Table 1.1 summarizes the overall characteristics of representative hypersonic vehicles. As indicated, a turboramjet is the propulsion of choice for a hypersonic Mach 5 cruiser. However, for an air-launched, rocket boosted Mach 6 tactical missile, a pure scramjet engine is a better option.

## 1.4 Scramjet Engine–Vehicle Integration

After many studies conducted in the 1960s, researchers determined that, for fast aircraft flight speeds ($M_0$~10), an air-breathing propulsion system would be too large to mount under the wings of the aircraft. Most importantly, axisymmetric, strut-mounted scramjet designs were found to incur very severe shock interaction heating and aerodynamic drag. Hence, the engine had to be closely integrated with the airframe to avoid or minimize such problems.

To reduce installation effects, the National Aeronautics and Space Administration (NASA) Hyper-X airframe-integrated scramjet was designed to be a flying engine, or a slice of the original hypersonic research engine (HRE), an axisymmetric, podded propulsion system. The vehicle forebody replaced the podded engine's spike inlet, and the vehicle afterbody replaced the plug nozzle. In subsequent designs, the scramjet had to be highly integrated with the vehicle; that is, the propulsion system would become the entire undersurface of the vehicle with the forebody providing initial compression of the engine inlet flow, and the afterbody acting

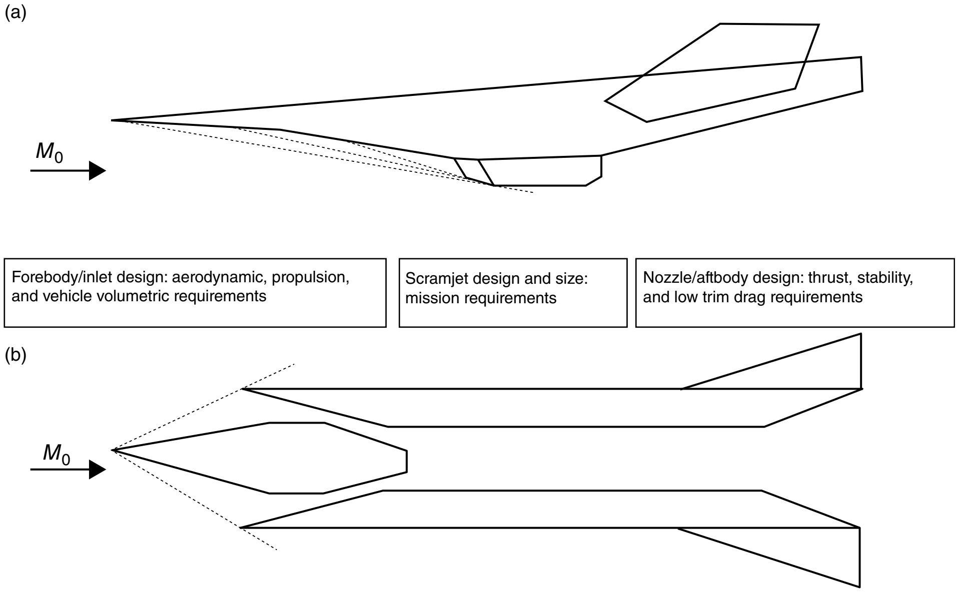

**Figure 1.7** Design features for efficient scramjet engine/airframe integration (a) asymmetric; (b) axisymmetric.

as the one-sided nozzle expanding the engine exhaust flow. The design features of this integrated system are illustrated in Figure 1.7a for the asymmetric design configuration, where the bottom of the vehicle may be regarded as the engine, and the top as the airplane.

Hypersonic missiles can be designed in typical axisymmetric configuration. As shown in Figure 1.7b, the airflow is captured near the front of the vehicle, transported internally through ducts, and exhausted axially at the aft end. This type of airframe–propulsion integration requires careful separation of thrust and drag forces during the development process, but the engine performance and missile control are relatively independent. Whether asymmetric or axisymmetric, a well-designed, highly integrated vehicle must provide both maximum inlet capture area and maximum nozzle expansion area while maintaining minimum cowl drag.

The scramjet engine–airframe integration process represents the first design opportunity to maximize the performance of hypersonic air-breathing vehicles. For example, the scramjet inlet must be designed within the forebody compression field to obtain maximum engine performance under all flight conditions. At the same time, the scramjet nozzle design is primarily governed by thrust and stability requirements. Thus, the location of the scramjet, orientation of the thrust vector, and the resulting trim penalties must be examined across the entire flight envelope. The asymmetric airframe design offers a considerably higher level of performance but requires considerably more attention to vehicle–engine integration issues than the axisymmetric design.

Ultimately, the optimum aerodynamic integration design of an air-breathing hypersonic vehicle also requires careful integration of engine and airframe structures, materials, cooling, controls, and all other required vehicle-propulsion subsystems. We will study some of these issues in subsequent chapters.

## 1.5 Chemical Propulsion Performance Comparison

All chemical propulsion systems (rockets and airbreathers) can be compared using a unifying figure of merit, namely their specific impulse, $I_{sp}$. This parameter determines the ability of a propulsion system to produce thrust with the least amount of fuel or propellant consumption. For an air-breathing engine, its specific impulse is given by this formula:

$$I_{sp,a} = \frac{F}{g_0 \dot{m}_f} \tag{1.3}$$

where $F$ is the thrust and $g_0$ is the gravitational acceleration on the surface of the Earth, that is 9.807 m/s$^2$ or 32.2 ft/s$^2$. The dimension of $g_0\dot{m}_f$ in the denominator of Eq. (1.3) is the weight flow rate of the fuel based on Earth's gravity, or force per unit time. Consequently, the dimension of specific impulse is "Force/Force/second" that simplifies to just the "second."

For a rocket, $I_{sp} = F/g_0\dot{m}_p$, where $g_0\dot{m}_p$ is the propellant weight flow rate, i.e. the sum of oxidizer and fuel weight flow rates. This means that both substances (oxidizer plus fuel) contribute to the "expenditure" in the rocket to produce thrust, and as such the oxidizer flow rate $\dot{m}_O$ needs to be accounted for as well in the calculation of specific impulse, that is

$$I_{sp,r} = \frac{F}{g_0 \dot{m}_p} = \frac{F}{g_0\left(\dot{m}_f + \dot{m}_O\right)} \tag{1.4}$$

Figure 1.8 shows representative values for $I_{sp}$ of ram/scramjet and rocket propulsion systems as a function of flight Mach number. First note that the specific impulse of air-breathing engines depends on Mach number. However, for rockets their $I_{sp}$ is independent of Mach number, and the highest value (~460 seconds) corresponds to liquid propellant rocket engines. This $I_{sp}$ is an order of magnitude lower that the specific impulse of air-breathing engines operating at Mach numbers up to 10.

Although the scramjet performance shown in this plot is theoretical, the trends depicted in Figure 1.8 are significative. Later in the book, we will address the following facts about air-breathing propulsion systems:

- At low velocities, turbojet engines produce the highest thrust with the least amount of fuel consumption. For the regime of flight Mach numbers $0 < M_0 < 3$, the $I_{sp}$ range between $\sim$2000 and 3500 seconds.
- The $I_{sp}$ of turbojets drops with flight Mach number. Near $M_0 = 3$, a conventional ramjet begins to outperform the turbojet.
- The scramjet is a better propulsion choice when the ramjet engine performance deteriorates (near $M_0 = 5$).

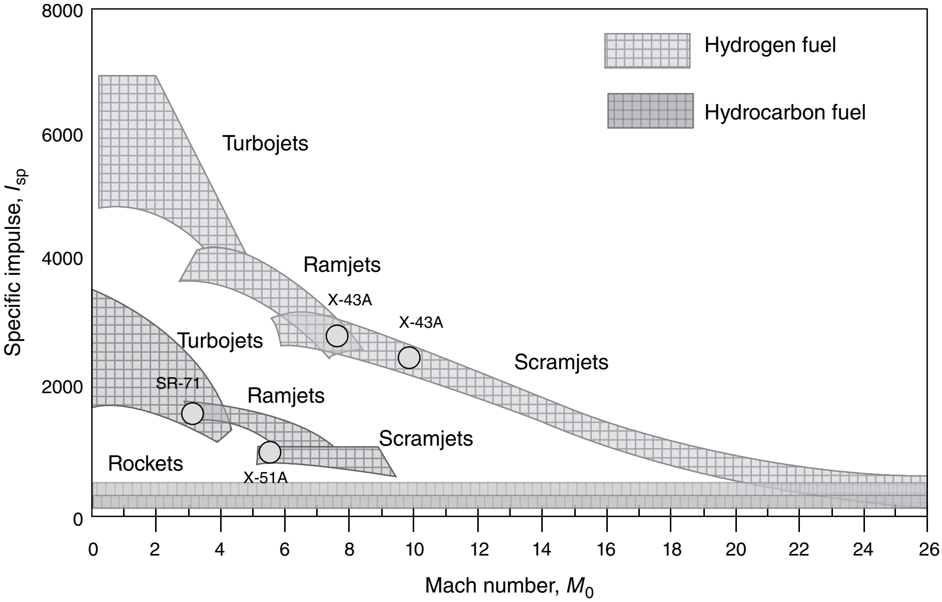

**Figure 1.8** Representative specific impulse variation with Flight Mach number for air-breathing and rocket propulsion systems. Source: Image adapted from plot by NASA and USAF.

- The specific impulse for all air-breathing engines is much higher when hydrogen is used as fuel in comparison to hydrocarbon fuels. The use of a more energetic fuel leads to higher $I_{sp}$, since a smaller (nearly two and half times lower), consumption of fuel is needed to achieve the same temperature in the combustor.
- Superimposed on this performance map are the estimated $I_{sp}$ of the scramjet engines flown to date: the X-43A fueled by liquid hydrogen, and the X-51A and HIFiRE, both fueled by hydrocarbons (see Section 1.7). Although the exact amount of thrust they generated is classified, these scramjets outperformed rocket propulsion at the flight Mach numbers at which they were flight tested.
- Rockets consume more propellants than air breathers. The specific fuel consumption for a typical cryogenic fuel rocket engine is 222 g/(kN s) or 7.83 lbm/(lbf h), a rather high value.

It is clear that no one propulsion system is optimum over the entire flight Mach number range of interest, from takeoff to orbital speeds. Hence, for sustained high-speed cruise, when the velocity exceeds the capability of conventional turbojet propulsion, a DMSJ would outperform rocket propulsion. Although the upper operational Mach number of scramjets is unknown, scramjet performance may approach that of a chemical rocket at flight Mach numbers $M_0$~12.

For space launch vehicles, the performance advantage of air-breathing propulsion over rocket propulsion is derived from the increase in performance efficiency, which results from the reduced propellant mass required. By taking a fraction of the oxidizer directly from the atmosphere, the propellant required for a mission is vastly reduced and could enable horizontal takeoff for space access. Horizontal takeoff will allow lower thrust loading thereby reducing overall engine weight. Among the propulsion technologies considered for future launch vehicles that include DMSJs are RBCC engines and TBCC engines, and the air-breathing rocket with supercooling. These concepts will be described in Chapter 10.

## 1.6 Hypersonic Air-Breathing Propulsion Historical Overview

The concept of the scramjet engine dates back to the 1950s. The potential for this type of high-speed propulsion grew as several countries in the world began studies and experiments, building scramjet models for research and development.

At the onset of the "space race," the United States (US) and the Soviet Union established hypersonics programs and built facilities for ground tests. For example, the US Air Force (USAF) started studies on hypersonic aerodynamics for both ballistic and lifting vehicles. Since the 1960s, the USAF tested hypersonic devices as intercontinental ballistic missiles, reentry and launch vehicles. In this period, "X-series" vehicles were built and tested as the United States aimed to develop a vehicle capable of reaching hypersonic speed. The experimental X-series program lasted a few decades and developed various prototypes of research aircrafts.

Initially, the challenge was to reach transonic and hypersonic flight with a piloted aircraft. The famous North American X-15 was a rocket-powered aircraft able to reach Mach 6.7. The X-15 was the first trans-atmospheric aircraft to test the high thermal load of hypersonic flight, showing the challenges to overcome the aerodynamic heating effects with the technologies available at that time.

An excellent history of hypersonics research in the United States is found in NASA History Series, "Facing the Heat Barrier: A History of Hypersonics" by Heppenheimer (2006). It includes the early work in Germany on the V-2 rocket in the 1940s, the development of Mach 3 aircraft such as the SR-71, and the technology development during the NASP Program.

### 1.6.1 Development Efforts in the United States

In 1964, NASA initiated the Hypersonic Research Engine (HRE) Project with the initial aim to develop a scramjet engine for flight testing. The goals of HRE were to design, develop, and construct a high-performance hypersonic research ram/scramjet engine for flight tests over the speed range of Mach 4–8. The three phases of the HRE project included project definition, research engine development, and flight test using the X-15A-2 research airplane, which was modified to carry hydrogen fuel for the HRE.

Because the X-15 program was canceled in 1968, the project goal of an engine flight test was eliminated. Thus, the focus of HRE became ground tests of full-scale engine models. Two axisymmetric full-scale engine models, having 18-in.-diameter cowls, were fabricated and tested: a structural model, and a combustion/propulsion model. Although never flight tested, the HRE generated a vast amount of experience with scramjet propulsion, especially during the ground-test programs. A brief historical review of the HRE project, with important features, typical data results, and lessons learned, was published by Andrews and Mackley (1994).

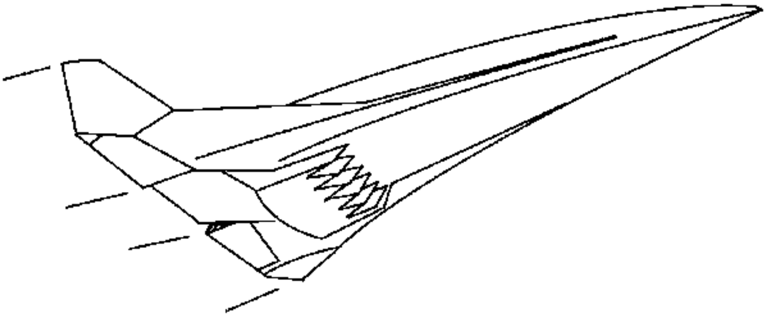

**Figure 1.9** Conceptual rendering of NASP aerospace plane flying through the atmosphere on its ascent to low-Earth orbit. Source: NASA.

The interest for hypersonic flight with air-breathing propulsion was reignited in the 1980s. From 1986 through 1993, the US invested in air-breathing hypersonics, focusing on the National Aero-Space Plane (NASP), a joint Air Force-NASA program. The piloted Rockwell X-30 was the advanced technology demonstrator vehicle concept, part of the plan to develop a SSTO spaceplane, and a hypersonic passenger cruiser capable of two-hour flights from America to Asia. A major goal of the NASP program was to test the capability of hypersonic air-breathing propulsion. Preliminary research suggested a maximum speed of Mach 8 for the scramjet engine. Figure 1.9 is an illustrative depiction of the X-30 vehicle in flight.

To develop the NASP experimental vehicles, engineers faced enormous technical challenges. Two issues in particular made the X-30 seem impossible: the required combined cycle propulsion that would take the vehicle from take-off and efficiently produce thrust up to Mach 25 to reach low Earth orbit, and developing the high-temperature materials capable of surviving the harsh aerothermodynamic environments during ascent and re-entry. There were, of course, many other technical issues brought about by the very restrictive structural weight fraction limits, the reusability requirement, and many others. The political challenges proved to be even greater. In 1994, the NASP program was de-scoped to a flight test program named the Hypersonic Systems Technology Program, HySTP. Soon, however, the HySTP was cancelled. This was a major setback to the hypersonics propulsion community.

After the Air Force's withdrawal from NASP, the NASA Langley Research Center (LaRC) opted to develop a smaller unmanned hydrogen-fueled hypersonic X-plane (see Section 1.9).

### 1.6.2 Development Programs around the World

In parallel to the American efforts to develop a spaceplane, some European nations and the Soviet Union conceived their own hypersonics programs in response to the X-30 project. In 1986, the Soviet Union began development of the Tupelov Tu-2000, an experimental crewed concept intended to test technologies for a SSTO spaceplane. The Tu-2000 would be propelled by a system consisting of seven turbojets, one scramjet, and two rockets, all fueled by liquid hydrogen. Like NASP, the Tu-2000 program was terminated in the 1990s.

### 1.6.2.1 The German Sänger TSTO

In 1987, the German Ministry for Research and Technology (BMFT) initiated a Hypersonics Technology Program (HTP) oriented toward developing the Sänger I, a two-stage fully reusable, space transportation system. The piloted first or lower stage was a blended wing/body vehicle conceived for horizontal takeoff and landing on conventional runways. This first stage was known as the European Hypersonic Transport Vehicle (EHTV) because it had commonality with a Mach 6.8 hypersonic passenger aircraft.

The first stage of the Sänger I vehicle would carry the second stage attached on top, take off horizontally from a runway, and climb to an altitude of 30 km using ramjet engines. The second stage would then detach and accelerate to orbital speeds and altitudes using its LOX/LH2 rocket engine. Later, other concepts included a hypersonic passenger airliner, and an enlarged version of the two-stage launch vehicle, named Sänger II, intended for deploying payloads and astronauts via the conceptual Horus (Horizontal Upper Stage) spaceplane. These ideas drew the support of the German Aerospace Center (DLR), leading to further detailed studies being conducted as a part of the German national-level hypersonic study.

The Sänger Space Transportation System was defined in the first phase of the German HTP, and studies began to define the lower and upper stages.

German engineers identified the most critical key technologies for the realization of a Sänger transportation system, including propulsion, aerothermodynamics, materials and structures, and subsystems. Consequently, in the last phase of the HTP, a Technology Development and Verification Plan (TDVP) was established. This plan comprised all efforts needed for ground and inflight experimentation to demonstrate the technological readiness level of these most critical technologies, including the air-breathing propulsion system of the first stage of the Sänger system. Although the baseline propulsion system was a combined cycle turbo-ram concept, the trade-offs with regard to the optimum stage separation Mach-number led also to the consideration of a dual-mode ram-scramjet propulsion system.

### 1.6.2.2 The Russian Kholod Project

In the 1970s, the Kholod project was carried out in Russia. To study ram-scramjet propulsion this project developed a flight vehicle designed to test a hypersonic propulsion system in the harsh environmental conditions that are difficult or impossible to reproduce on the ground. The Russian Central Institute of Aviation Motors (CIAM) designed and built a two-dimensional scramjet model with a three-shock inlet and divergent combustor. This scramjet was tested in the CIAM free-jet test facility in freestream at Mach numbers 5 and 6. In the 1980s, the first successful flight tests of the cold scramjet model were carried out.

The scramjet was flown atop the SA5 surface-to-air rocket-powered missile. The experimental flight support unit was known as the Hypersonic Flying Laboratory (HFL), "Kholod." The HFL included the scramjet engine and propellant, engine control, engine cooling, instrumentation, and telemetry systems. Figure 1.10 shows a schematic of the complete HFL.

In the 1990s, CIAM designed and flight tested a Mach 6 dual mode, hydrogen-fueled scramjet engine. The first flight test of the small-scale scramjet took place in November 1991. The second flight test was carried out in November 1992. The trajectory segment over which the scramjet operated lasted for 23 seconds. Researchers reported stable combustion at hydrogen injection both from the subsonic and supersonic section of the fuel manifold at

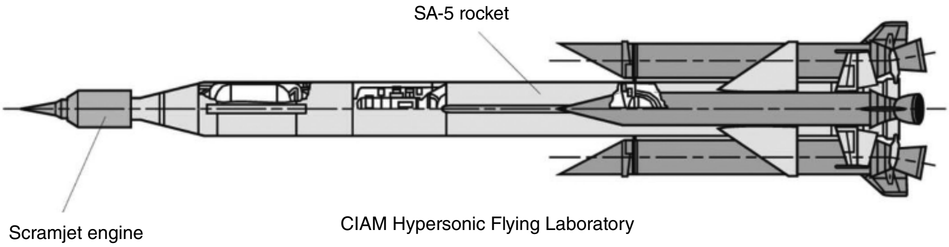

**Figure 1.10** Russia's CIAM Hypersonic Flying Laboratory. Source: Roudakov et al. (1998)/NASA/ Public Domain.

flight Mach number 5.3. In 1995, CIAM teamed with France for the third flight attempt, which unfortunately was unsuccessful. The scramjet engine failed to operate due to onboard systems problem (Sabel'nikov and Penzin 2000).

In addition to their HFL, Russia built a strong program for hypersonic technology and established a cost-effective way of developing these technologies with a complete launch system and flight test infrastructure. Valuable flight and ground test data with identical full-scale engines were obtained to hypersonic velocities.

#### 1.6.2.3 France

The French National Aerospace Research Center ONERA (*Office National d'Etudes et Recherches Aérospatiales*) and MBDA (Matra, BAe Dynamics and Alenia), the European multinational developer and manufacturer of missiles, have led a large Research and Technology effort to acquire detailed knowledge on high-speed air-breathing propulsion, and to develop corresponding technologies. For operational, civilian or military, application of the high-speed air-breathing propulsion, French researchers focused on two key points: develop technologies for a low-weight propulsion system with robust fuel-cooled structure for the combustor, and develop the capability to predict with a reasonable accuracy and to optimize the aero-propulsive balance (or generalized thrust-minus-drag).

In 1992, the French National Research and Technology Program for Advanced Hypersonic Propulsion (PREPHA) was established. PREPHA (*Programme de Recherche et Technologie sur la Propulsion Hypersonic Avancée*) focus was on the study and ground testing of a hydrogen-fueled scramjet. After the end of PREPHA, Matra, BAe Dynamics and Alenia (MBDA) and ONERA continued further work to preserve the intellectual and material investment and to improve mastery of hypersonic air-breathing propulsion. ONERA and DLR led the Joint Airbreathing Propulsion for Hypersonic Application Research (JAPHAR) program to study a hydrogen-fueled dual mode ramjet for the Mach number range from 4 to 8, defining a methodology for ground and flight performance demonstration. MBDA and EADS-Launch Vehicles (EADS-LV) pursued innovative technology for fuel-cooled composite material structures. MBDA and ONERA led the Promethee R&D military program to improve knowledge on hydrocarbon-fueled dual mode ramjet for Mach 8 missile application. Steelant (2010) provides an excellent overview of European hypersonic projects.

In January 2003, MBDA and ONERA began a flight test program named LEA (Falempin and Serre 2011). The nonrecoverable LEA experimental vehicle designed to operate in the

Mach range 4 to 8 was planned to be air-launched by rocket booster, and after booster separation and stabilization, the small-scale vehicle would fly autonomously during 20-30 seconds. It is unclear whether LEA was satisfactorily flight tested. Today, France continues the technology development effort on different aspects that contribute to ensure the performance and thermal and mechanical strength of the supersonic combustion chamber. This includes (i) variable geometry needed to optimize the performance on the overall flight Mach number range; (ii) endothermic fuel used as coolant for combustion chamber structure; and (iii) design of the fuel-cooled structure itself.

#### 1.6.2.4 Japan

In Japan, research activities related to the scramjet date back to the late 1970s. The activities during that period were limited to fundamental, laboratory-scale experiments on supersonic combustion at universities. The decade after the early 1980s was relatively less active in this field except for the experimental work at the Kakuda Research Center of the National Aerospace Laboratory (NAL-KRC), which was stimulated by previous studies.

In the past decade, the Japan Aerospace Exploration Agency (JAXA) has been promoting R&D to establish technologies for a Mach 5, 300 passenger class hypersonic aircraft that can cross the Pacific Ocean in two hours. With the main focus on a hypersonic turbojet engine that can operate continuously from takeoff to Mach 5, research and development in Japan focus on the new engine and a heat-resistant structure.

## 1.7 Scramjet Flight Demonstration Programs

After more than 40 years of ground-based scramjet research, the United States and Russia moved hypersonic air-breathing technology to the flight environment, which is the last stage preceding prototype development. In the 1990s, Russia flew several axisymmetric scramjet models in the HFL Kholod, as described earlier. In 1998, CIAM teamed with NASA to conduct the fourth successful flight test of a DMSJ at Mach 6.5. Valuable subsonic and supersonic combustion data were obtained from Mach 3.5 to greater than Mach 6.4. Preliminary flight test results were reported by Roudakov et al. (1998).

In the mid-1990s, NASA initiated the joint LaRC and DFRC Hyper-X Program to advance hypersonic air-breathing propulsion and related technologies from the laboratory to flight demonstration. The Hyper-X hypersonic research program aimed to demonstrate scramjet engine technologies that promise to increase payload capacity – or reduce vehicle size for the same payload – for future hypersonic aircraft and reusable space launch vehicles. In 2001, the Hyper-X Flight program demonstrated the viability of the hydrogen-fueled scramjet engine to power a hypersonic flight research vehicle (designated X-43A) to hypersonic speeds up to Mach 10. The X-43A was intended as the first in a series of vehicles envisioned to validate in flight air-breathing propulsion systems, operating from the ground to Mach 15 and beyond. After the X-43A, the X-43C Project was conceived to demonstrate Mach 5 to Mach 7 acceleration with a vehicle powered by a fuel-cooled scramjet engine using hydrocarbon fuel. It would use technology from the NASA Hyper-X Program and the USAF HyTech Program. Unfortunately, the X-43C project was not funded.

Prior to the NASA Hyper-X scramjet flight demonstration, the Australian Centre for Hypersonics at the University of Queensland carried out an innovative in-flight supersonic combustion experiment known as the HyShot. On 30 July 2002, the team launched a small combustor test article, lofted by a two-stage booster into the upper atmosphere over Australia's Woomera test range. HyShot demonstrated five seconds of hypersonic combustion at Mach 7.6 as it plunged toward Earth, capturing important data on scramjet combustion performance. The Australian HyShot program was only a component (combustor) flight test.

In 1994, the Defense Advanced Research Projects Agency (DARPA) sponsored the Hypersonic Collaborative Australia/US Experiment (HyCAUSE) that incorporated ground tests, and CFD analysis of two-dimensional and inward-turning scramjet engine concepts. It also included development of a Mach 10, hydrogen-fueled flight vehicle to be tested over a range of dynamic pressures. After conducting studies and wind tunnel experiments at the University of Queensland, a three-dimensional scramjet geometry was selected for flight testing. The flight test was conducted on June 2007. A two-stage booster was used to launch the vehicle to follow a ballistic trajectory, aiming to place the scramjet engine at the Mach 10 condition with dynamic pressures between 500 and 1600 psf during reentry (Walker et al. 2008). Unfortunately, an anomaly occurred during the reorientation maneuver, and the HyCAUSE experiment was unsuccessful.

Between May 2010 and 2015, the USAF partnered with DARPA, Pratt & Whitney Rocketdyne, and Boeing and established the Scramjet Engine Demonstrator-WaveRider (SED-WR) Program. The main goal was to conduct flight tests to demonstrate hypersonic air-breathing propulsion with a hydrocarbon-fueled scramjet, aiming to accelerate the vehicle through several Mach numbers. The SED-WR Program built a scaled vehicle known as the X-51A Waverider, to demonstrate scramjet operation in flight, starting from the NASA's X-43C test vehicle design.

The USAF also teamed with NASA and the Australian Defence Science and Technology Organisation (DSTO) to carry out the Hypersonic International Flight Research Experimentation (HIFiRE) Program. HIFiRE was conceived to study basic hypersonic phenomena through flight experimentation. In the following paragraphs, we review some aspects of the three hypersonic flight programs.

### 1.7.1 NASA Hyper-X Flight Program (X-43A Research Vehicle)

The Hyper-X Flight Program was a seven-year ground and flight test program that explored alternatives to rocket power for space access vehicles. Hyper-X began in late 1995 as a joint effort of NASA Langley and Dryden Research Centers with industry partnership. The main goal was to demonstrate the in-flight performance of a hydrogen-fueled, airframe-integrated scramjet at flight Mach numbers of 5, 7, and 10. The project was subsequently redirected to focus only on Mach 7 and 10 flight tests, with ground engine research continuing at Mach 5. The Mach 7 flight data were meant to allow direct comparison with ground test results for the same engine and flowpath combination, whereas the Mach 10 flight test results would provide 5–10 seconds of data at that flight Mach number, or thousands of times the duration available from ground test results (Harsha et al. 2005). The Hyper-X program goal was to verify and demonstrate experimental techniques, computational methods and analytical design tools required to advance hypersonic, hydrogen-fueled, scramjet-

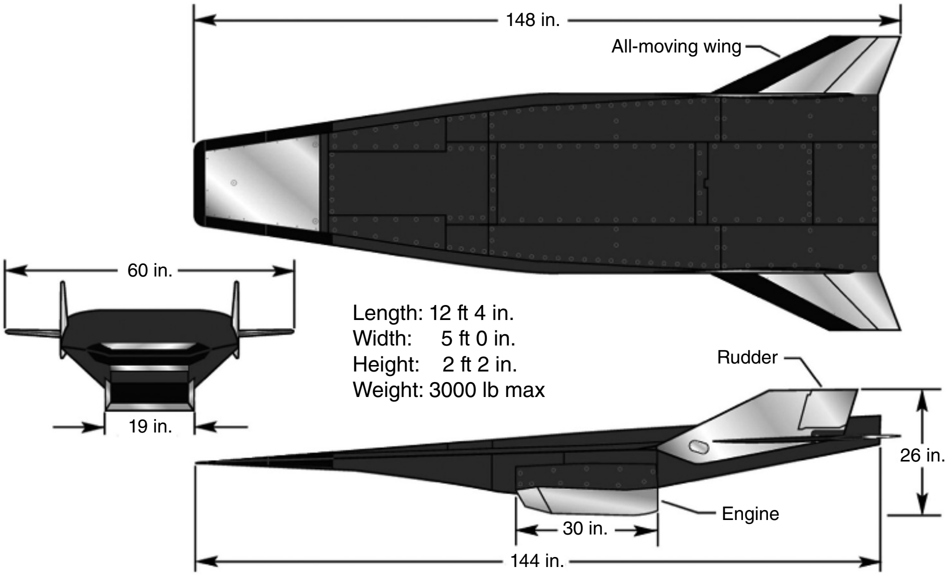

**Figure 1.11** The dimensions of the NASA Hyper-X research vehicle (X-43A). Source: From Redifer et al. (2007)/NASA/Public Domain.

powered aircraft. To keep the costs down, researchers conceived a small-scale hypersonic vehicle to be air-launched with the NASA B-52B airplane and boosted to take-off speed by an off-the-shelf rocket booster.

With a length of 3.759 m (12 ft 4 in), the 1361 kg (3000 lbm) research vehicle designated X-43A (Figure 1.11) is a subscale design based on an existing Mach 10 cruise, global-reach mission configuration, and the extensive NASP database. Since the X-43A could not be photographically scaled from the 61 m (200 ft) long Mach 10 cruise vehicle, the minimum subscale size for flight testing was determined to be about 12 ft. Three vehicles were constructed. The third had the hydrogen-fueled scramjet engine, horizontal control surfaces, tails, rudders, and carbon–carbon leading edges modified to handle thermal loads for the Mach 10 mission. The vehicle design incorporated an inlet cowl with a hinged moveable door for engine close off and inlet starting. The X-43A vehicle was designed to achieve only a few seconds of powered flight at a single point design condition with a heat-sink engine.

The Hyper-X flight stack consisted of the Pegasus solid propellant rocket booster and the subscale X-43A vehicle. The stack was mounted under the wing of the B-52B aircraft with the X-43A attached to the booster through a load carrying adaptor (Figure 1.12). The B-52B carried the stack to an altitude of about 9.144 km (30 kft), and then the booster fired to take the hypersonic vehicle to the proper flight altitude. The first flight attempted in June 2001 was unsuccessful, due to the launch rocket booster going out of control early in the flight. However, two subsequent X-43A flight tests were conducted as planned.

On 27 March 2004, the Mach 7 vehicle was boosted to approximately 28.96 km (95 kft) altitude. The X-43A separated from the booster and the scramjet engine ignited. The fully autonomous vehicle flew preprogrammed over the Western Test Range off the California coast. Test data were transmitted to aircraft and ground stations. This second hypersonic flight test at an altitude of 95 kft (980 psf dynamic pressure) demonstrated acceleration

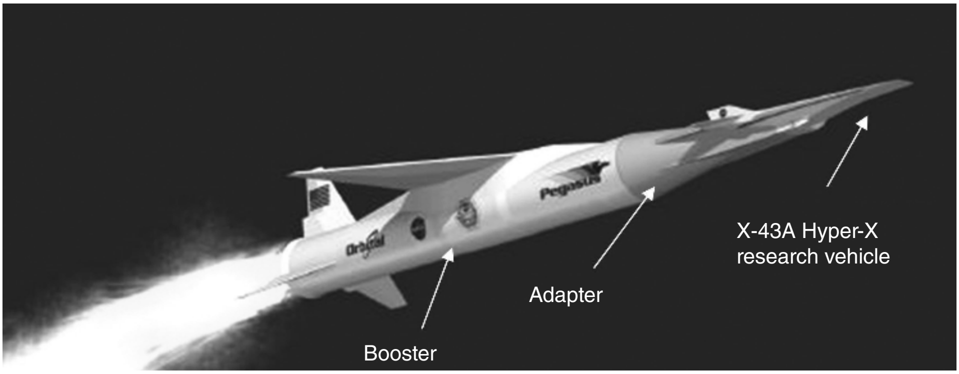

**Figure 1.12** NASA X-43A vehicle attached to the booster rocket. Source: NASA.

of the scramjet-propelled X-43A vehicle during climbing flight at Mach 6.83. The vehicle accelerated under its own power for 24 km (15 miles) in 11 seconds (Voland et al. 2005).

On 16 November 2004, the X-43A achieved the highest hypersonic speed with the hydrogen-fueled scramjet flying at an altitude of 33.53 km (110 kft). The booster delivered the stack to the stage separation point at slightly lower Mach number and dynamic pressure (930 psf) than expected. The stage separation system performed smoothly, accomplishing the first known successful nonsymmetric, high-dynamic pressure, and high Mach number stage separation. The vehicle cruised at Mach 9.68, at 110 kft altitude, covering more than 32 km (20 miles) in 10.5 seconds of scramjet powered flight, making the X-43A the world's first autonomous scramjet-propelled aircraft. The X-43A/Hyper-X program provided the first free flight data on scramjet propulsion, demonstrating that the predictive design tools were accurate. Measured scramjet thrust (classified value) matched predictions to within better than two percent.

More details on the nose-to-tail CFD solutions for the actual flight condition are given in Chapter 12. These solutions demonstrate the significant increase in computational throughput, which permit full 3D solutions for the entire X-43A vehicle, which were not possible at the earlier stages of the Hyper-X Program.

### 1.7.2 Air Force Scramjet Engine Demonstrator-WaveRider Program (X-51A)

After the successful flight demonstrations of the NASA X-43A scramjet vehicle, the most significant activity in the United States was the Air Force SED-WR Program. The joint Air Force Research Laboratory (AFRL)/Defense Advanced Research Projects Agency (DARPA) X-51A Scramjet Engine Demonstrator-WaveRider (SED) vehicle was the flight demonstration of AFRL's Hypersonic Technology (HyTech) program. The HyTech program had several successful engine ground tests, but true scramjet viability was demonstrated with the X-51A SED in a series of 4 flight tests that began in 2010. With the X-51A waverider, the program demonstrated a practical scramjet engine burning JP-7 jet fuel at flight speeds between Mach 6.0 and 7.0+. At the same time, it aimed to extend the scramjet burn time to 300 seconds or more – a full 5 minutes of hypersonic flight.

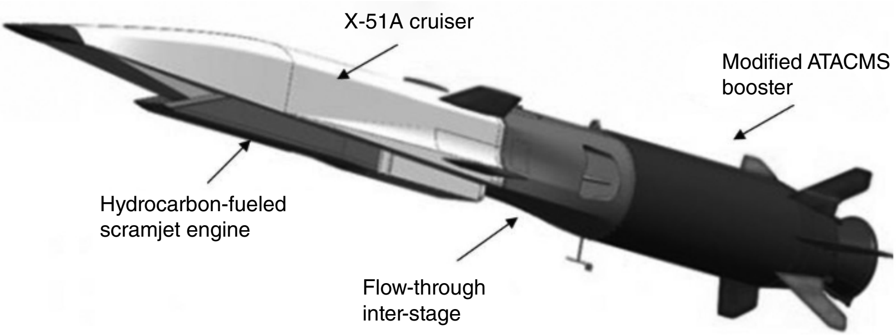

**Figure 1.13** USAF X-51A Stack. Source: From Mutzman et al. (2007)/American Institute of Aeronautics and Astronautics.

Hydrocarbons fuels are of interest because they are easier to handle than hydrogen and are most suited for missile applications. In 2005, the Propulsion Directorate of the USAF began working with Pratt & (P&W) Rocketdyne and the Boeing Company to design the X-51A flight vehicle based on technology developed under AFRL/PR's Hydrocarbon Scramjet Engine Technology (HySET) Program. Although NASA had cancelled the X-43C project, the JP-7-fueled scramjet engine had been conceived, and thus it became the basis for the design of the Pratt & Whitney Rocketdyne SJX61 scramjet, which Boeing integrated into the expendable X-51A waverider cruise vehicle (Figure 1.13). Differences between the X-43C and X-51A engines include a variable geometry versus fixed inlet, flowpath width, and bolted corner construction versus welded for the X-51A, but the scramjet engines are similar and some pieces of the fuel system are exactly the same (Hank et al. 2008).

The goals of the program were to acquire ground and flight data on an actively cooled, self-controlled operating scramjet engine. This data was intended to develop and fine-tune the "rules and tools," or the understanding of the governing physical phenomena and computational design tools used for scramjet design. An important objective was to demonstrate viability of an endothermically fueled scramjet in flight. The most important outcome was for the scramjet to produce greater thrust than drag, as only then it could be proven the viability of a free-flying, scramjet powered vehicle.

As shown in Figure 1.13, the shape of the 4.27 m (14 ft) long X-51A vehicle is different from that of the X-43A vehicle, as it was designed to ride on the shock wave to reduce drag – hence the name "waverider." Its contoured, shrouded nose hides the scramjet inlet, ensuring proper airflow into the engine, and its fuselage is boxier than the sleek surfboard design of the X-43A. However, both vehicles share some design similarities. For example, the X-51A's nose cap was made of tungsten to ensure it survived the surface temperature it would experience, which was predicted to be 816 °C (1500 °F). The fins and engine were made of Inconel. The X-51A fuselage structure was made of aluminum and, due to low melting point, the structure was covered with special Boeing materials developed for use on the Space Shuttle Orbiter. These included BRI16 tiles around the engine and inlet, lightweight sprayable ablative materials on the upper surfaces, and a high-density honeycomb around the nozzle.

The SED-WR Program planned to execute four flight tests of the SED-WR vehicle. Each waverider was to be carried aloft by a B-52 launch aircraft to an altitude of about 10.67 km

(35 000 ft) and released. For the flight test, the X-51A vehicle was attached to a flow-through interstage, a section to connect with the rocket booster, as depicted in Figure 1.13. The interstage included the B-52 attachment and served as aerodynamic fuel preheating prior to lighting the scramjet proper. During the boost phase, air flew through the scramjet engine and out a duct in the interstage. This was done to warm the engine and the fuel circulating through it, thermally cracking the JP-7 fuel to ready it for regenerative cooling of the vehicle.

Initially boosted by an Army ATACMS solid rocket, the X-51A waverider was designed to take over at approximately Mach 4.5 and then accelerate on scramjet power to a preset flight speed. The first flight of the X-51A on 26 May 2010 made history, demonstrating scramjet propulsion burning JP-7 fuel for more than two minutes, with the scramjet accelerating the waverider to Mach 4.87, nearly 3400 miles/h. The fuel-cooled scramjet performed as planned transmitting normal telemetry for 143 seconds, then observing a decrease in thrust and acceleration for another 30 seconds. An anomaly then resulted in a loss of telemetry before fuel setting for higher Mach number, and the flight test was terminated; the vehicle was destroyed by flight controllers on command.

The second flight occurred on 13 June 2011. The rocket booster took the X-51A vehicle to the proper condition, and after separation, the scramjet propelled the waverider initially burning ethylene. When the engine attempted to transition to JP-7 fuel operation, it experienced an inlet unstart. An attempt to restart and orient the vehicle to optimize the engine start condition was unsuccessful. The waverider continued in a controlled flight orientation until it descended into the ocean within the test range.

The third flight on 14 August 2012 experienced a fin failure at boost, which was unrelated to hypersonic propulsion technology. Although the X-51A and its rocket booster safely separated from the B-52 aircraft, after 16 seconds under the rocket booster, a fault was identified with one of the control fins in the vehicle. Once the X-51 separated from the rocket booster, approximately 15 seconds later, the cruiser was not able to maintain control due to the faulty control fin.

The final flight of the X-51A occurred on 1 May 2013 and was the most successful in terms of meeting all the flight demonstration test objectives. The waverider flew more than 426 km (230 nautical miles) in just over six minutes, reaching a peak speed of Mach 5.1. This was the longest (240 seconds) of four X-51A test flights and the longest air-breathing hypersonic flight on JP-7 fuel.

The X-51A is considered the world's fastest jet powered aircraft burning hydrocarbon fuels. The more than nine minutes of flight data collected from the X-51A program represents an unprecedented achievement, proving the viability of air-breathing, endothermic hydrocarbon-fueled scramjet propulsion in flight.

### 1.7.3 Australia–US HIFiRE Program

The HIFiRE program is a collaborative effort between the Australian Defense Science and Technology Office (DSTO) and the US Air Force Research Laboratory (AFRL). The overarching technical objective is to explore fundamental hypersonic flow physics phenomena through focused flight experiments, to validate ground test techniques and verify numerical prediction tools (Dolvin 2009).

A major driver for the HIFiRE program was the need to conduct flight experiments faster and at lower cost than has traditionally been achieved (e.g. air-lifted, rocket boosted). Hence, the program chose to use sounding rockets to boost experimental payloads to hypersonic test conditions, which would be at lower cost but incurred greater technical risk in performing the flight experiments. The HIFiRE opted to test in tree launch sites: Woomera Test Range (WRC) in Australia; Andoya Rocket Range in Norway, and the Pacific Missile Range Facility (PMRF) on the island of Kauai, Hawaii.

Ten flights were conceived, with each project addressing one or more technical challenges in propulsion, aerodynamics, propulsion–airframe integration, aerothermodynamics, flight control, high-temperature materials and structures, thermal management, and/or instrumentation and sensors. The successful flight tests performed to date include HIFiRE-1, a flight experiment that provided a valuable database pertaining to boundary layer transition over a 7° half-angle, circular cone model from supersonic to hypersonic Mach numbers, and a range of Reynolds numbers and angles of incidence. HIFiRE-2 was a flight to develop an alternative test technique for acquiring high enthalpy scramjet flight test data, allowing exploration of accelerating hydrocarbon-fueled scramjet performance and dual mode transition up to and beyond Mach 8 flight.

The primary objectives of HIFiRE-2 were to (i) demonstrate scramjet mode transition end evaluate engine performance and operability; (ii) achieve combustion performance at Mach 8 flight conditions using a hydrocarbon fuel; and (iii) demonstrate a scramjet flight test approach that provides a variable Mach number flight corridor at nearly constant dynamic pressure. The primary flight experiment used an inward turning, two-dimensional, hydrocarbon-fueled scramjet, as depicted in Figure 1.14. The shroud was deployed prior to the flight experiment to expose the scramjet engine.

The successful HIFiRE-2 flight mission from PMRF was carried out on 01 May 2012. Following a suppressed trajectory via delayed stage ignition and gravity turn, the scramjet accelerated under rocket boost from Mach 5.4 to 8+ at 72 kPa dynamic pressure. This was the first-time scramjet mode transition from subsonic to supersonic combustion was demonstrated with a scramjet-powered flight vehicle using unguided sounding rocket techniques.

The HIFiRE 5B flight experiment studied a three-dimensional inlet geometry, which consists of a ramp with sidewalls and gradually merges in an elliptic isolator structure. The

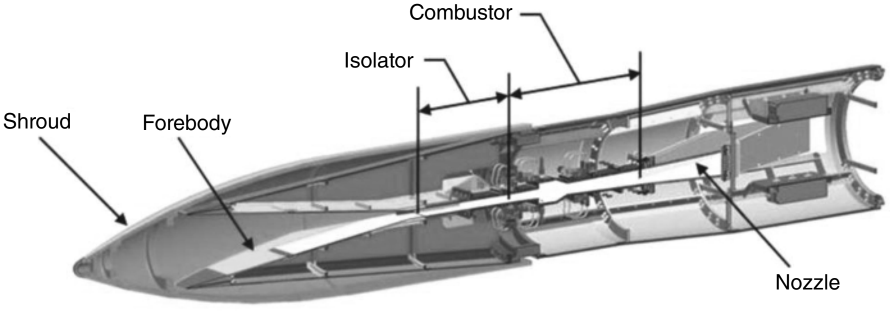

**Figure 1.14** HIFiRE-2 hydrocarbon-fueled scramjet. Source: From Cabell et al. (2011)/NASA/Public Domain.

vehicle reached Mach 7.5. The last propulsion test was the HIFiRE-7, launched from Andoya, Norway on 31 March 2015. The scramjet was boosted to a Mach 7 re-entry. As it entered the atmosphere at the correct orientation, the scramjet engine started. However, telemetry was lost when the vehicle was at an altitude of 63 km (before fuel was turned on). The telemetry failure was traced to overheating of electronics in the telemetry power system.

The HIFiRE test technology was used to test partially complete scramjet flowpaths and articles that remain attached to the second-stage booster (Dolvin 2009). Following a ballistic flight trajectory, the scramjet experiment was conducted upon re-entry to the atmosphere at very high flight path angles. The HIFiRE 8 vehicle was intended to cruise at Mach 7 under scramjet power for 30 seconds at approximately zero flight path angle after separation from the booster (Glass et al. 2013).

## 1.8 New Hypersonic Air-Breathing Propulsion Programs

A diverse set of conceptual designs are now considered for both commercial and military applications. The hypersonic cruise aircraft being developed are summarized in Table 1.2.

In the United States, the Hermeus company is now advancing a Mach 5 aircraft (Figure 1.15). At this speed – over 3000 miles/h – flight times from New York to London will be 90 minutes rather than seven hours. In November 2021, Hermeus unveiled a full-scale prototype of their first aircraft identified as Quarterhorse. The hypersonic aircraft will be propelled by a TBCC ramjet designed around a flight-proven GE J85-21 turbojet. Known for robustness and reliability, the J85 engine has been used in multiple aircraft over the years, including the Northrop F-5 aircraft. Engineers at Hermeus are modifying the turbojet to become part of the TBCC propulsion configuration.

In 2013, Lockheed Martin announced plans to develop a hypersonic unmanned aerial vehicle (UAV) intended for intelligence, surveillance, and reconnaissance. Identified as the SR-72, this aircraft would succeed the retired Lockheed SR-71 Blackbird. The SR-72 airplane would fly at Mach 6 (4000 mph; 6400 km/h). To attain such speeds, Lockheed Martin was collaborating with Aerojet Rocketdyne to develop an air-breathing hypersonic

**Table 1.2** Hypersonic cruise vehicles under development.

| Aircraft concept | Mach number |
|---|---|
| Hermeus (Quarterhorse prototype) | 5.0 |
| Boeing Cruiser | 5.0 |
| Japan JAXA Cruiser | 5.0 |
| Reaction Engines LAPCAT A2 | 5.2 |
| Lockheed Martin SR-72 | 6.0 |
| Stratolaunch Talon-A | 6.0 |
| StratoFly MR3 | 8.0 |

**Figure 1.15** Artist depiction of Hermeus Mach 5 aircraft. Source: Hermeus Corp.

propulsion system with the ability to accelerate from standstill to Mach 6.0 using the same engine. In 2018, the company pushed back on plans for advancing the SR-72, stating that when technology is matured, it could enable development of a reusable vehicle.

In 2015, the Boeing Company submitted a patent for the Small Launch Vehicle, a four-stage air-breathing space transportation system, which was planed for development in cooperation with Scaled Composites. In June 2016, Australia announced a similar project called SPARTAN, a rocket–scramjet–rocket system intended for dedicated launch capability. Building on the heritage of Sänger I horizontal take-off and landing (HOTOL) concept, the British Company REL is developing a SSTO space transportation system called Skylon, which is powered by an air-breathing rocket called SABRE. In the air-breathing mode, SABRE will pass the atmospheric air through a heat exchanger to be cooled down to 120 K, before it flows into a conventional turbine in the unique rocket engine.

Europe has added a substantial contribution to air-breathing hypersonics. MBDA France and ONERA, for example, have conducted notable research and development to improve knowledge on high-speed air-breathing propulsion, participating in different programs such as PREPHA, WRR, JAPHAR, and PROMETHEE (Falempin 2004). In 2005, the European Commission funded the Long-Term Advanced Propulsion Concepts and Technologies (LAPCAT) program aimed at examining propulsion concepts for sustained hypersonic flight. The LAPCAT project is composed of a consortium of 12 partners from industry, research institutions, and universities and is coordinated by ESA-ESTEC (Steelant et al. 2015). The ambitious mission goal is to reduce traveling time of long-distance flights, e.g. Brussels to Sydney, to about two to four hours. Advanced propulsion concepts and technologies in the flight regime from Mach 4–8 were considered, including TBCC and RBCC propulsion, in combination with corresponding vehicle system studies.

After the JAPHAR program, ONERA directed scramjet research mainly toward military applications, but still maintain a significant activity on civilian applications. In 2003, ONERA and the Japanese agency JAXA began a common experimental research effort focused on strut injectors for scramjet combustors. Between 2008 and 2013, ONERA participated in the LAPCAT II European program, while maintaining in parallel a continuous combustion modeling and CFD code development activity with internal funding. Scherrer et al. (2016) provide an overview of the most significant research activities at ONERA since 1992.

The European Space Agency established the LAPCAT II program, the follow-up of the previous, co-funded EC-project LAPCAT I. Among the several vehicles studied, only two novel concepts – for Mach 5 and Mach 8 cruise flight – are retained in the new program. The 4-year project, co-funded by the European Commission under the theme of air transportation, involves 16 partners representing six European member states. The LAPCAT-A2 Mach 5 airliner will be propelled by a precooled air-turbo ramjet, and the Mach 8 airplane will be powered by a scramjet engine, both engines fueled by liquid hydrogen ($LH_2$). Figure 1.16 depicts the conceptual design of a Mach 8 cruise waverider (Murray et al. 2009; Langener et al. 2013).

Designed by Reaction Engines, the LAPCAT-A2 is a 300-passenger aircraft conceived to fly at Mach 5 at an altitude between 25 and 28 km and will have a range of 18 700 km. The conceptual vehicle (Figure 1.17) consists of a slender fuselage with a low aspect ratio delta wing positioned slightly aft of the mid fuselage section. This design configuration is conceived to have good supersonic and subsonic lift-to-drag ratios, and acceptable low speed handling qualities for takeoff and landing. Designers selected a leading edge sweep angle of 55° in order to generate a stable separated vortex at high angle of attack. The liquid hydrogen fuel tanks occupy most of the fuselage volume and are split into two large pressurized tanks on either side of the passenger compartment. Storing the fuel in the fuselage instead of in the wings allows circular cross-section tanks, which minimizes insulation and pressure vessel mass. More details on this unique hypersonic cruise transport are given by Steelant (2010).

Under the Sharp Edge Flight Experiment (SHEFEX), the German Aerospace Center (DLR) pursues new, low cost, and safer design principles for space capsules, hypersonic vehicles, and space planes with re-entry capability and their integration into a complete system. SHEFEX III is a small space plane-like vehicle. It should fly even faster and stay in the

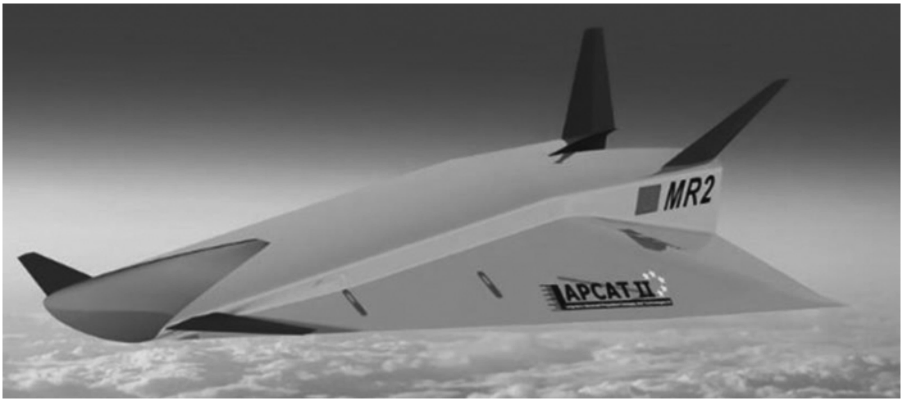

**Figure 1.16** LAPCAT-II MR2 Mach 8 waverider concept. Source: From Langener et al. (2013) / ISABE.

**Figure 1.17** Artistic depiction of LAPCAT A2 aircraft at takeoff. Source: Reaction Engines.

air for 15 minutes, far longer than the previous two experiments. Its launch was expected in 2021 on a Brazilian VLM rocket. It is unclear if the flight was successfully completed.

For military applications, development of hypersonic cruise missiles and drones is vigorously pursued. In the United States, programs have been funded to develop hypersonic vehicles as a part of an effort to acquire the capability to launch attacks against targets around the world in under an hour. Conventional prompt global strike (CPGS) weapons, including maneuverable stealth missiles, are capable of reaching velocities of up to Mach 6.4.

DARPA is pursuing a scramjet-powered Hypersonic Air-breathing Weapons Concept (HAWC). Sponsored by this program, Raytheon developed a classified hypersonic cruise missile powered by a hydrocarbon-fueled scramjet, and successfully completed its first free flight test in September 2021. This test demonstrated the capability that will make hypersonic cruise missiles a highly effective technology for US warfighters, bringing DARPA one step closer to transitioning HAWC to a program that offers next generation capability to the US military.

The US Air Force is also developing a classified air-launched hypersonic cruise missile called the Hypersonic Attack Cruise Missile (HACM), which seems to be based on research carried out under the HAWC program. Another major development effort in the United States is the AGM-183A Air-Launched Rapid Response Weapon (ARRW), a hypersonic glide vehicle designed to be carried by a B-52 bomber. Russia, India, France, and China are developing competing technologies. Due to the classified nature of military R&D programs, hypersonic cruise missiles are outside the scope of this book, and no further discussion of their design and technologies will be given.

## 1.9 Hypersonic Air-Breathing Propulsion Critical Technologies

There are a number of issues related to hypersonic air-breathing propulsion that must be fully resolved in order to develop future vehicles capable of sustained hypersonic flight. Many of those issues we will treat in subsequent chapters.

The factors that limit the operational Mach number for the various types of air-breathing engines (Figure 1.8) are different. However, it is sufficient at this point to indicate two very important technical limits. At hypersonic speeds, conversion of the air's kinetic energy to thermal energy can raise the air temperature to the level of dissociation, changing its properties considerably. The temperature can be so high (above about 2500 K) that the combustion conditions lose a large fraction of the available chemical energy to dissociation. In addition, since the air stagnation temperature raises with flight Mach number (Eq. 1.1), above about Mach 6, no conventional material can endure the high stagnation temperatures. Hence, advanced high-temperature materials and sophisticated thermal management are required for sustained hypersonic flight vehicles (see Chapter 9).

The scramjet engine is considered for powering hypersonic cruise aircraft, hypersonic missiles, or as part of combined cycle propulsion for reusable access to space vehicles. As we stated earlier, protection against aerodynamic heating drives hypersonic vehicle design, especially for reusable designs. The requirement to operate efficiently and reliably over such a wide range of flight conditions and altitudes makes hypersonic air-breathing propulsion a rather challenging field of study.

For example, for spaceplane applications, whether SSTO or first stage of a TSTO, a reusable air-breathing vehicle is much more difficult to design and develop. Unlike a rocket launcher that passes nearly vertically and quickly through the atmosphere on its way to orbit, an air-breathing space launcher would take a more leveled trajectory (see representative trajectories in Fig. 3.2). Having a lower thrust-to-weight ratio compared to rockets, air-breathing propulsion needs more time to accelerate. Following a prescribed flight path, the air-breathing vehicle will fly at hypersonic speeds for a long time, so atmospheric friction becomes a problem that must be resolved with advanced high-temperature materials and adequate thermal protection schemes.

The hypersonic aerodynamic environment is extremely harsh and hypersonic vehicles function near the edge of system and technology capability. Aerodynamic heating is a common phenomenon in hypersonic flow due to viscous dissipation. When gas flows over a surface, gas in contact is brought to rest as a result of viscosity. When the velocity near a surface decreases, the temperature increases. Aerodynamic heating increases proportionally with the square of the flight Mach number (see Chapter 3). The thin shock layer characterizing hypersonic flow over the vehicle has drastic consequences. For example, even when a weak shock wave impinges on or interferes with the bow shock wave, it yields complex aerodynamics and very high convective heat transfer rates over the hypersonic vehicle. The temperature rise associated with slowing flow near a surface is very high. This is aggravated by skin friction and shock wave heating. Hence, a huge technical challenge for hypersonic air-breathing propulsion is due to the high stagnation temperature it experiences at high Mach numbers.

The combination of high heating rates experienced by surfaces with small curvature leading edges and the long ascent times will result in large total heat loads. For the air-breathing space vehicle, the most severe heating will occur during ascent to orbit at the stagnation point and wing leading edges. For example, a heat transfer estimate for the NASP at the engine cowl lip on the ascent trajectory was about $6 \times 10^8$ W/m$^2$, which is orders of magnitude greater than the heating rates experienced by the former Space Shuttle Orbiter on its atmospheric entry. Moreover, vehicles propelled by air-breathing engines must fly at altitudes that are low enough that there is sufficient oxygen, i.e. relatively high density, for the propulsion system to operate effectively. However, the convective heat transfer and the drag increase as the density increases, i.e. as the altitude decreases. Thus, the trajectory of an air-breathing hypersonic vehicle must represent a compromise between the propulsion requirements and the heat-transfer/drag requirements for sustained flight.

Another technical challenge for hypersonic air-breathing vehicles is that of attaining stable supersonic combustion in the scramjet in order to produce continuous and sufficient thrust to overcome all drag forces. Engine unstart is a poorly understood phenomenon closely related to the dynamics of fuel injection and combustion that must also be studied in order to find control mechanisms to avoid such engine failure. The following are some of the most critical technologies to support advancing hypersonic air-breathing propulsion:

**Structures, Materials, and Thermal Management:** Aerodynamic heating caused by high-speed flight will be a significant technical challenge. In addition, heat addition produced by combustion at high velocities and temperatures is another significant factor to take into account. Materials for vehicle/propulsion structures must have excellent properties and be adequate to deal with these and other hypersonic flow phenomena.

High-temperature materials for the scramjet flowpath are expected to withstand internal wall temperatures as high as 2204 °C (4000 °F) over a brief 10-minute flight time. Cooling of scramjet's internal surfaces by fuel or regeneratively cooling combined with convection and radiation is essential. The materials for hypersonic structures must have the strength and properties to deal with these and other hypersonic flow phenomena. Ceramic matrix composites (CMC), due to their high-temperature capabilities, have the potential to provide a passive alternative for at least a portion of the scramjet flowpath, especially for nonreusable vehicles with a relatively short flight time (less than 1 minute). Chapter 9 is devoted to these topics.

**Boundary Layers and Heat Control:** As the flight velocity increases above Mach 5, the oblique shock waves move closer to the surface of the vehicle, and the flowfield between the shock and the body (the shock layer) becomes very hot. In the extreme case of hypersonic flight, the airflow becomes so hot that the air in the shock layer will dissociate or even ionize. Hence, a vehicle flying at hypersonic speeds must be designed to manage, control, and minimize aerodynamic heating, ensure the integrity of its airframe, and ensure its flight trajectory is controlled. We will discuss these issues in Chapters 3 and 9.

**Fuels and Injection Techniques:** Injecting a fuel into a supersonic airstream remains a topic of intense research and development. At high flight Mach numbers, combustor residence times are very small, and compressibility effects may suppress mixing. Hence, we require superior fuel injector performance to keep combustor length short, reduce drag, and ensure high propulsion performance. Fuel injection technology requires understanding of the fluid mechanics of mixing of fuel with air to flammable proportions, analysis of the chemistry of exothermic chemical reaction between fuel and air after they are mixed, and comprehensive studies of the aerothermochemistry (the coupling of finite-rate processes of mixing and chemical kinetics of the combustion process with one-dimensional gas dynamics) of the supersonic flow within the scramjet combustor. These topics will be covered in Chapters 5 and 6.

**CFD:** With limited ability to adequately represent hypersonic flow experimentally, hypersonic computational fluid dynamics (CFD) predictions become even more difficult because substantial experimental data for a variety of flows and flight conditions are not available. However, the fluid dynamics of hypersonic flows is complicated by interaction of boundary layer and shear layer with shock waves, leading to flow separation and instability not amenable to simple analysis. Moreover, high-speed reacting turbulent flows are challenging to simulate fully with Reynolds-Averaged Navier-Stokes Simulation (RANS) techniques. Large Eddy Simulation (LES) allows for modeling of small scales of turbulence while resolving large-scale turbulent structures, but this approach is currently limited to low Reynolds number flows.

Predictive methodologies, including CFD and other analytical tools, play a huge role in the analysis and development of hypersonic air-breathing propulsion (see Chapter 12). A significant element of such analysis is the prediction of integrated vehicle aero-propulsive performance, which includes an integration of aerodynamic and propulsion flowfields. This analysis becomes a huge challenge as hypersonic air-breathing vehicle configurations are characterized by highly integrated propulsion flowpath and airframe systems. Hence, development of this class of vehicle requires a comprehensive assessment of propulsion–airframe flowfield interactions and the integrated aero-propulsive performance of all systems.

The tools of analysis must encompass a wide range of modeling capabilities to capture all of the relevant flow physics of the complete scramjet flowpath as well as the external airframe flowfield. This analysis is normally accomplished using a multilevel approach, increasing in complexity and fidelity as the design is matured. The preliminary analysis phase may employ different engineering tools for the various flowpath components (e.g. inlet, combustor, nozzle), which necessitates the development of force accounting systems appropriate for specific configurations.

To date, CFD has been a valuable tool used to interpret aerodynamic and propulsion ground test data, and it will continue to do so as we progress in the maturation of HAP technologies. In Chapter 12, we will present an overview of the methods used in the analysis and pre-flight development of the scramjet engines flown to date and discuss the state of the art in modeling and simulation of HAP flow phenomena, including a survey of CFD codes with their capabilities and limitations.

## 1.10 Critical Design Issues

In principle, scramjet propulsion is much more efficient than rocket propulsion because scramjets extract oxygen from the air for combustion to produce thrust. This results in a higher specific impulse and greater range for a hypersonic cruise aircraft or missile, or a greater payload fraction if we integrate scramjets in a combined cycle propulsion for an orbital launch vehicle.

Scramjets are conceptually simpler as they do not need heavy turbomachinery. However, they are extremely challenging to design for optimum performance. For example, efficiently injecting, mixing, and combusting a fuel in a supersonic airflow stream is a formidable process that is coupled with turbulence and other complex flow phenomena present in the scramjet engine. Designing the flowpath is a huge challenge that requires not only to optimize all flow processes but also involves advanced materials and thermal management to protect the internal walls, and ensuring that engine thrust exceeds drag and other losses.

In addition to propulsion technical challenges, air-breathing hypersonic flight poses many other design challenges related to the vehicle itself. Sustained high-speed flight within the atmosphere imposes severe thermal loads on the vehicle's surfaces, especially on leading edges and control surfaces.

Moreover, vehicle drag is a strong function of configuration at hypersonic velocities. Thus, only a highly optimized vehicle shape, designed with a highly integrated propulsion system, can meet the flight and performance requirements. However, efficient hypersonic shapes may not be amenable to stable, controlled flight in the subsonic flight regimes that will be encountered at take-off and landing.

The effectiveness and capability of future hypersonic air-breathing vehicles depends, to a great extent, on the maximum integration of the propulsion system with the vehicle airframe. To capture the required airflow for maximum propulsion, it is necessary to use the entire forebody underneath the vehicle as compression surface, shaping it for high efficiency. A long forebody yields the largest air capture area $A_0$. The bottom of the vehicle (the windward side) becomes an integral part of the propulsion system. The entire vehicle underside must be carefully designed to satisfy engine performance under all flight conditions. Proper aerodynamic integration of propulsion system with the airframe is required for efficient hypersonic flight. This includes integration of vehicle structures, materials, thermal management, controls, and subsystems.

Hypersonic air-breathing engines must ingest sufficient air mass for propulsion. Achieving supersonic combustion is very difficult because the high speed in the combustor gives very little time for mixing and combustion to take place. Other technical issues related to scramjet combustors will be addressed in Chapters 5 and 7.

Future hypersonic vehicles capable of fulfilling a variety of missions may include cruise missiles, military or commercial transports in the Mach 5–7 regime, long-range cruisers in the Mach 5–10 flight regime, and single- or multiple-stage-to-orbit aerospace planes (Erbland 2004). The military needs to get to a target quicker (global engagement), and the commercial sector desires to take payloads into space cheaper and reliably. Hypersonic technologies are thus required to support the development of high-speed air-breathing propulsion systems whether they will power hypersonic missiles, hypersonic cruise aircraft, or space launchers.

In the following chapters, we will review some of the most important aspects of R&D for scramjet-based propulsion and the state of the required technologies for continued advances.

## Questions

1. What type of propulsion system is appropriate for a reusable Mach 5 cruise aircraft?

2. Flight range is a figure of merit for endo-atmospheric vehicles (for given payload at given cruise Mach number). How is the vehicle range impacted by the choice of fuel for its scramjet?

3. What is the most appropriate definition of hypersonic cruise flight?

4. In addition to the critical technologies mentioned in this chapter, what other advances should be made to mature hypersonic air-breathing propulsion systems and make routine hypersonic cruise flight possible?

5. What technological issues must be resolved in order to advance the development of a spaceplane powered by a combined cycle propulsion system that integrates air-breathing propulsion and rockets?

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