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Technical and Programmatic Consequences of a Hypersonic Vehicle Flight Test Ban

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ABSTRACT

The hypersonic vehicle (HV) is defined as any vehicle capable of traveling at or above five times the local speed of sound (Mach 5). Development of hypersonic flight has been pursued since the late 1950s, especially for reentry of missile warheads and returning orbiting spacecraft. Although considerable progress has been made since then, air-breathing and gliding hypersonic flight remains in the development and testing phase. Concerns have been raised, however, about continued HV flight tests because of HV's potential military use, which has the potential to encourage hair-trigger tactics that would increase crisis instability. In recent years, non-governmental organizations have called for a ban on HV flight testing for the primary purpose of halting continued development of the HV as a weapon. The emphasis on banning flight tests is due to its vital role in aerospace programs. Without it, significant technical uncertainties remain, creating safety and reliability issues that would discourage commercial development. Although the cost and time involved in flight tests have already spurred the use of other test methods, none can completely reproduce the flight test environment. Flight tests are important for reasons such as generating data unique to flight test environments to use in validating models and verifying ground test data, identifying unanticipated problems, and reducing risk. Commercial HV technology development today depends on advancements in four areas: propulsion; aerodynamics; critical guidance, navigation and control; and thermal management. This report summarizes the ramifications on HV technology development if flight tests were banned.

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EXECUTIVE SUMMARY

A hypersonic vehicle (HV) is defined as any vehicle capable of traveling at or above five times the local speed of sound (Mach 5). These vehicles, transformative and revolutionary compared to current aerospace systems, could significantly cut the cost of accessing space, lessen flight time anywhere on the planet to 2 to 3 hours, and be used as weapons that would be extremely difficult to intercept.

Currently, the United States, China, Russia, India, France, Australia, Japan, and the European Union are conducting research and development of HV technology for civilian and/or military applications.

Development of hypersonic flight has been pursued by some of these nations since the late 1950s, when it became increasingly practical and desirable, especially for reentry of missile warheads and returning orbiting spacecraft. Although considerable progress has been made since then, air-breathing and gliding hypersonic flight still remains in the development and testing phase.

Concerns have been raised, however, about continued HV flight tests because of HVs' potential military use. According to Speier et al. (2017), the HV has the potential to encourage "hair-trigger" tactics that would increase crisis instability during global confrontations. In recent years, non-governmental organizations have called for a ban on HV flight testing, primarily to halt continued development of the HV as a weapon. Many HV-related studies have investigated the status of HV technology developments, studied HVs' effect on strategic stability vs. escalation, and explored the question of whether HVs should be banned or treaty-limited.

The emphasis on banning flight tests is due to flight testing's vital role in aerospace programs. Without it, significant technical uncertainties remain, creating safety and reliability issues that could further discourage development. The future of civilian HVs generally depends on military testing, and so a flight test ban would essentially freeze today's technology while also locking in the current HV technology leader. The ban would likely discourage investment in further commercial development because developers would be unable to test their concepts. Subsystems could still be tested on the ground, but a fully integrated system in its flight environment could not. Although the cost and time involved in flight tests have already spurred the use of other test methods—modeling/simulation, component/subsystem-level testing, ground testing—none of these, either individually or in sum, can completely reproduce the flight test environment.

Six primary reasons, listed below, support the necessity of flight tests. The first five remain critical to development of operational HVs, both civilian and military:

1. Generate information unique to flight test environment that cannot be obtained on the ground
2. Use the data to anchor and validate models and verify ground test data
3. Validate system performance in its operational environment and/or for system certification
4. Identify unanticipated problems
5. Reduce risk and demonstrate technology in flight
6. Provide political messaging

As of today, HV technology development depends on advancements in four areas: propulsion; aerodynamics; critical guidance, navigation and control; and thermal management. This report summarizes the ramifications on HV technology development if flight tests were banned.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
ABM	Anti-Ballistic Missile Treaty
AHW	Advanced Hypersonic Weapon
ASAT	Anti-Satellite
ATLLAS II	Aero-Thermal Loads on Lightweight Advanced Structures
BMD	Ballistic Missile Defense
CAD	Computer Aided Design
C-C	Carbon-Carbon Composite
CFD	Computational Fluid Dynamic
CG	Center of Gravity
CMC	Ceramic Matrix Composite
CPS	Conventional Prompt Strike
CTBT	Comprehensive Nuclear-Test Ban Treaty
CTE	Coefficient of Thermal Expansion
DARPA	Defense Advanced Research Projects Agency
DF-ZF	Chinese HV in development (also known as DH-17, and previously known as WU-14).
DOE	US Department of Energy
DRDO	Defense Research and Development Organization
EU	European Union
FEA	Finite Element Analysis
GLCM	Ground Launched Cruise Missiles
GN&C	Guidance, Navigation, and Control
GPS	Global Positioning System
HAWC	Hypersonic Air-Breathing Weapon Concept
HCM	Hypersonic Cruise Missile
HGV	Hypersonic Glide Vehicle
HIFiRE	Hypersonic International Flight Research Experimentation
HSTDV	Hypersonic Technology Demonstrator Vehicle
HTRSI	High-Temperature Reusable Surface Insulation
HV	Hypersonic Vehicle
HYCAUSE	Hypersonic Collaborative Australian/US Experiment
Hytex	Hypersonic Technology Experimental Aircraft
IMU	Inertial Measurement Unit
INF	Intermediate-Range Nuclear Forces Treaty

Abbreviation	Definition
IRCPS	Intermediate Range Conventional Prompt Strike
ISR	Intelligence, Surveillance, Reconnaissance
IXV	Intermedia eXperimental Vehicle
JAXA	Japan Aerospace Exploration Agency
L/D	Lift to Drag
LAPCAT II	Long-Term Advanced Propulsion Concepts and Technologies
LEA	Hypersonic vehicle co-developed by France and Russia
LEO	Low Earth Orbit
LTRSI	Low Temperature Reusable Surface Insulation
MaRV	Maneuvering Reentry Vehicle
MDA	Missile Defense Agency
MMC	Metal Matrix Composite
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plane
NATO	North Atlantic Treaty Organization
NDE	Non-Destructive Evaluation
NGLT	Next Generation Launch Technology
NGO	Non-Governmental Organization
NW	Nuclear Weapon
R&D	Research and Development
RBCC	Rocket-Based Combined Cycle
RCS	Reaction Control System
RF	Radio Frequency
RV	Reentry Vehicle
SiC	Silicone-Carbide
SNL	Sandia National Laboratories
SPAR-TAN	Three-stage hypersonic satellite launch system in development by Australia
START	Strategic Arms Reduction Treaty
SWERVE	Sandia Winged Energetic Reentry Vehicle
TBCC	Turbine-Based Combined Cycle
TBG	Tactical Boost Glide
TPS	Thermal Protection System
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
US	United States

Abbreviation	Definition
US-UK	United States – United Kingdom
WAC	Without Any Control

1 INTRODUCTION

Hypersonic velocity is typically defined as a velocity that is at or above five times the (local) speed of sound (Leslie and Marren 2009). Hypersonic vehicles (HV), which are capable of traveling at such velocity, are transformative and revolutionary compared to today's aerospace systems. The technology that is being developed to enable hypersonic flight could also cut the cost to access space (Leslie and Marron 2009), lessen flight time anywhere on the planet to 2 to 3 hours (Jiang and Yu 2017), and create weapon delivery systems that are extremely difficult to intercept by current methods (Leslie and Marron 2009; Lewis 2017). Over the last 70 years or so, considerable progress has been made in various aspects of hypersonic flight. Despite this progress, air-breathing and gliding hypersonic flight is still in the development and testing phase (Fidan et al. 2003).

Currently, the United States, China, Russia, India, France, Australia, Japan, and the European Union* are all conducting research and development into HV technology for civilian and/or military applications (Aune et al. 2017; Gubrud 2014; Schreiner 2014; Speier et al. 2017). It is believed that, outside of the groups mentioned above, no other nation is seriously pursuing the development of hypersonic technology, except in the academic research environment (Speier et al. 2017). One notable country not on the list is Pakistan. Pakistan tends to follow India's lead in military developments (Gubrud et al. 2015d) but is not believed to have any HV projects in development. If Pakistan is to experiment with HVs, they will likely seek assistance from China or purchase these systems outright in the future (Speier et al. 2017). [Appendix A](#) summarizes some past and current hypersonic-related efforts by these entities.

In the United States, funding for HV weapons-related programs has recently increased and appears to be steady for the near term (Freedberg 2018; Stashwick 2018). However, if future U.S. administrations contemplate decreasing or eliminating funding for HV testing, this issue will surely resurface.

The link between civil and military applications has stimulated non-governmental organizations (NGO), such as the Bulletin of the Atomic Scientists, Deep Cuts, and the Carnegie Endowment for International Peace, to call for a ban of HV testing. Although the United States has stated that HV weapons would be strictly used to deliver conventional payloads, some NGOs have raised the concern that HVs could be used to deliver nuclear weapons. Even with only conventional payloads, NGOs have argued that they could potentially be used to degrade nuclear infrastructure, thus reducing stability in a crisis. Many of these NGOs are considered highly influential among members of the U.S. Congress, and their studies and opinions may influence policy and funding.

Previous HV-related studies have focused on topics such as their effect on strategic stability/escalation (e.g., (Acton 2013; National Research Council 2008), why they should be banned or treaty limited (such as (Gubrud et al. 2015a; James Martin Center 2015; Mount 2016; Speier et al. 2017), and many others on the status of HV technology development (such as Lamorte et al. 2011; Rodriguez et al. 2008; Schulte et al. 2001; Wang et al. 2010). These studies mainly focused on the geopolitical ramifications of HVs, but no study has been conducted on the technologies that would be affected by banning flight testing of HVs. This report was commissioned to help policy makers in the U.S. government understand the technical and programmatic

* Though not a country, the European Union will be considered in this list because, along with the countries listed, it is seriously pursuing the development of hypersonic technology outside of the academic research environment, through the European Space Agency (ESA).

consequences of banning tests on vehicles traveling at hypersonic speeds. A flight test ban on military HVs would cause the United States to risk falling further behind in development of the next generation of commercial airplanes, space transport, and military weaponry to nations that either do not want to join in a ban or that seek to develop hypersonic technologies only for “peaceful purposes.”

2 DESCRIPTION OF HYPERSONIC VEHICLES

Hypersonic vehicles are defined as any vehicle capable of traveling at or above five times the local speed of sound (Mach 5). To accommodate the many characteristics that can be used to describe HV types, these vehicle types can be grouped into categories (Van Wie et al. 2004). HVs can be powered (e.g., the Boeing X-51 Waverider) or unpowered (after being boosted up to speed) (e.g., the Space Shuttle during reentry). HV types are generally grouped into three categories: missiles, airplanes, and space access vehicles (Hunt et al. 1998; Leslie and Marron 2009). From a system/subsystem perspective, HVs can be grouped by take-off/launch system (horizontal, vertical, launch assisted, and air-dropped); landing type (vertical or horizontal); propulsion type (rocket, air-breathing, combined cycle engine); fuel type; expendable/reusable; civilian/military end-user; and so on (Hunt et al. 1998).

HVs are seen as the future in multiple fields such as transportation, cargo delivery, and military delivery systems. Once perfected, HVs could revolutionize space access, air travel, and military weapons. The cost to access space could be cut from the current \$5,000 to \$10,000 per pound for low Earth orbit (LEO) to as low as <\$500 per pound with a fully reusable system (Bowcutt 2014; Jiang and Yu 2017; Leslie and Marron 2009). HV technology can also be applied to military weaponry. Ideas that are being considered or developed for militaries in various countries include supersonic aircraft with high-speed dash capability, hypersonic bombers, hypersonic cruise missiles (HCM), hypersonic glide vehicles (HGV), and high-speed intelligence, surveillance, and reconnaissance (ISR) aircraft (Leslie and Marron 2009; Lewis 2017; Walker et al. 2013).

Of the hypersonic systems being researched and developed in recent years, HGVs and HCMs are the most mature. One reason is that they are designed for one-time use. According to Speier et al. (2017), “Developing hypersonic flight systems capable of sustained flight, such as HGVs or HCMs, is even more difficult. Both types of systems will be designed for one-time uses. This makes them stepping stones to the more challenging designs of reusable systems that have longer flight times and much longer operational lives” (Speier et al. 2017, 99). Also, the most advanced technologies often debut first in military systems and then trickle down to civilian uses (examples include the Global Positioning System [GPS], radar, and nylon) (Shu 2014), meaning that new technologies developed for use in military HVs could potentially make their way into civilian life. Thus, any HV flight test ban would not affect military systems as much as future civilian systems, given the number of military HV flight tests that have already been conducted.

Current HGV and HCM designs/concepts typically attain their initial speed by being boosted by a rocket. Future HCM designs may include a turbine to attain the initial speed before transitioning to other propulsion sources. Civilian HVs will likely use a propulsion system that is in a similar configuration to HCM propulsion systems. Though both HGVs and HCMs are considered HVs, their operation is very different. In the operation of an HGV (often called “boost-glide vehicles”), a booster rocket is used to launch the vehicle on a trajectory that typically is initially ballistic. The HGV may cover a substantial distance as it flies to a high altitude, and then falls back to Earth, gaining speed. Finally, at some relatively low altitude, the glider performs a pull up maneuver, flying nearly horizontal at a high velocity in an unpowered and aerodynamic flight for potentially thousands of miles (Gubrud 2014; Gubrud et al. 2015d; Leslie and Marron 2009). The HGV is able to maintain near constant velocity by trading altitude for speed (Chen 1966). According to reports, HGVs can travel at speeds up to Mach 20 (Bowcutt 2014). On the other hand, HCMs typically attain their speed by initially using a rocket, then using a supersonic combustion ramjet (scramjet) to attain hypersonic speeds (Gubrud 2014), and then are powered all the way to their final destination (Speier et al. 2017). HCMs can be launched from the wing of an airplane, out of a launch tube, off of a rail, and in other

ways. They are reported to be able to fly at speeds of Mach 5 to 10 (Bowcutt 2014) and travel up to about 1000 km (Gubrud et al. 2015d; Leslie and Marron 2009), depending on how much fuel they can carry (Gubrud et al. 2015c). According to Mark Lewis, Chief Scientist of the U.S. Air Force from 2004–2008, “A convenient way to think of these two systems is that boost gliders invest all of their propulsion energy up front, and then deplete that energy gradually, whereas cruise missiles release their energy at a steady rate until a short final terminal dive” (Lewis 2017). Current concepts for hypersonic airplanes and hypersonic transport systems use either a turbine or rocket to get to a speed where a ramjet/scramjet will take over.

Though HGVs are incredibly fast, they do not always have the same speed advantage as warheads launched from ballistic missiles and, in some cases, may actually be slower at arriving at their intended target. The real advantages of HGVs, compared to ballistic missile warheads, are the altitude at which they fly and their maneuverability. Because typical ballistic missile detection radars look for threat missiles coming from outside the atmosphere, HGVs are harder to detect since they fly at lower altitudes than ballistic missiles (usually at less than 100 km altitude) (Lewis 2017). A conventional warhead launched from a ballistic missile has a relatively predictable trajectory. Once it is released by the missile, it is not very difficult to know where it will land (with varying accuracy, depending on the method used). HGVs, on the other hand, can maneuver significantly, especially during the glide phase (Acton 2015), which makes the target unpredictable until their last moments of flight (Speier et al. 2017), and so interception by missile defenses is difficult to virtually impossible (Butt 2016; Speier et al. 2017). Like the Tomahawk Block IV subsonic cruise missile (U.S. Navy 2018), the maneuverability also makes it possible for the HGV to be re-targeted in flight to attack a different target than the one originally planned (if the necessary technology is present in the vehicle) (Speier et al. 2017). Their maneuverability and speed also make it difficult for air-defense or missile defense systems to intercept and give defenses less time to counter the incoming HGV (Butt 2016; Speier et al. 2017). Finally, their maneuverability makes it possible for HGVs to avoid flying over specific countries to prevent false alarms (James Martin Center 2015).

HCMs have a great speed advantage over traditional, subsonic cruise missiles. Though HCMs would perform in a manner similar to existing subsonic cruise missiles, a subsonic cruise missile would take an hour or more to travel the same distance that an HCM can cover in 10 minutes (Lewis 2017; Mercier 2003). This speed can be helpful in attacking targets that are stationary only for short periods of time or that must be attacked as soon as possible. Like HGVs, HCMs may also be too fast for current air-defense systems to intercept. [Appendix B](#) describes the unique operating environments of HVs.

3 PURPOSE OF FLIGHT TESTS

Flight testing has always been a vital part of aerospace programs and is conducted for a variety of reasons (Leslie and Marron 2009). The costs and time associated with flight testing are its biggest drawbacks (Jiang and Yu 2017). Many attempts have been made to reduce or eliminate the need for flight testing because of the high cost associated with each test. Modeling/simulation, component/subsystem level testing, environmental testing (on the ground), and other techniques can be used to test various parts of an aerospace system, but none of these, either individually or as the sum of the testing results, has been able to completely reproduce the information that can be gathered with a flight test. In general, flight tests are also known to be more reliable and to generate higher-quality data than ground tests or modeling/simulation drawbacks (Jiang and Yu 2017). Flight tests are currently the only way to provide all the realistic combined environments.

Recent U.S. HV tests had multiple flight test goals including design risk reduction (X-43A, HIFiRE), flight validation of design methods (X-43A, HIFiRE), enhancing the hypersonic design database (X-43A, X-51A, HIFiRE), and demonstrating scalable scramjet propulsion (X-51A) (Bowcutt 2014). Six primary reasons for performing flight tests are discussed in this report and include:

1. Generate information unique to flight test environment that is not available on the ground (Fidan et al. 2003)
2. Anchor and validate models and verify ground test data
3. Validate system performance in its operational environment and/or for system certification (Mercier 2003)
4. Identify unanticipated problems (McClinton 2006)
5. Reduce risk and demonstrate technology in flight (Bertin and Cummings 2006)
6. Provide political messaging (McClinton 2006)

A detailed description of each of the six reasons for performing flight testing can be found in [Appendix C](#).

4 THE ARGUMENT FOR A WEAPON FLIGHT TEST BAN PROPOSAL

There are two main reasons why a hypersonic flight test ban has been proposed. The first, and most common reason, is to stop the development of military HVs (mainly HGVs and HCMs). Second, the ban would serve as a potential bargaining chip in a multi-technology treaty (e.g., negotiating bans and/or limitations on HGVs, ballistic missile defense [BMD], conventional prompt strike [CPS], tactical nukes, and strategic nukes simultaneously). It is often assumed that all nations, or at least all nations with significant HV programs, would be parties to the negotiation and implementing of a flight test ban treaty. However, this can leave the door open to non-signatories to continue HV research and development and potentially leapfrog the current technology leaders. If this were to happen, the technology lead of such a nation would continue to increase because they would be unencumbered by the flight test ban treaty.

4.1 Stop the Development of Military HVs

In warfare, military advancements by one group typically generate responses from another. The U.S. CPS program that started in the early 2000s has generated responses from both China and Russia as they have been developing systems to offset United States advances and/or perceived advantages (Steff 2016), including development of their own HGVs and HCMs. The characteristics that make HGVs and HCMs attractive from the military offensive point of view (Dolvin 2008) are what could make them highly destabilizing in a crisis from the defensive point of view. According to Tong Zhao, in an article published through the *Bulletin of the Atomic Scientists*, “The greatest advantage of hypersonic missiles is their promptness, but promptness is also the technology's greatest source of risk. Decision makers in a crisis, if they wish to take advantage of hypersonic missiles' speed, will have to decide whether to launch preemptive strikes before fleeting windows of opportunity close. Risky decision making would be encouraged. And because hypersonic missiles would likely be intended for use against strategic targets—command and control centers, long-range surveillance systems, and even missile launch vehicles—conflicts could easily escalate if hypersonic missiles were used” (Gubrud et al. 2015b, 3).

According to Speier et al. (2017, xiii), “In short, hypersonic threats encourage hair-trigger tactics that would increase crisis instability.” A flight test ban has been proposed to avoid this possibility (Butt 2016; Gubrud et al. 2015d; Lewis 2017; Speier et al. 2017). Some support that proposal since fielding reliable and useful hypersonic weapons is all but impossible without flight testing (Aune et al. 2017; Gubrud et al. 2015d). Because no nations have yet fielded any hypersonic weapon systems, it is said to be the perfect time to either discuss international norms governing the use of hypersonic weapons (Butt 2016) or to ban their flight testing outright (Steff 2016). Though not the focus of the paper, a brief explanation of some of the ways that hypersonic weapons could increase crisis instability—and thus the reason why some want flight testing banned—is presented in this section to give context to the ideas presented later in this paper. For one debate on the pros and cons of banning flight tests of HVs, refer to the articles included in “Test ban for hypersonic missiles?” in the *Bulletin of the Atomic Scientists* (Gubrud et al. 2015a).

Targeting nuclear forces by conventionally armed hypersonics is one reason they can be considered as destabilizing weapons. Opponents of hypersonic weapons view them as being used only for the opening salvo of a nuclear war (a first-strike weapon), the so-called tip-of-the-spear attack (Gubrud et al. 2015d). Both Russian and Chinese officials have stated they are especially concerned that U.S. hypersonic weapons would be used as a precursor to a first-use nuclear strike (Gubrud 2014). Russia believes that if a

conventional attack could take out their nuclear weapons, even well-defended ones located deep inside their territory (Steff 2016), the United States's conventional weapon superiority would overwhelm them. This fear would be magnified if there are future reductions in the number of nuclear weapons that each country possesses (James Martin Center 2015). This type of attack could be conducted without even crossing the nuclear threshold (James Martin Center 2015), thus not raising international outrage nor setting the precedent of using nuclear weapons in whatever future conflict could theoretically happen. The Russians are said to be "sincerely paranoid" that U.S. missile defenses and CPS investments could decapitate their command structure and be used for coercion in a conflict (James Martin Center 2015). The United States fears that it will fall behind Russia and China, wants to be able to hold certain targets at risk, and also wants to counter the substantial artillery forces held by the Chinese and Russians (Freedberg 2018).

Another reason for HVs being seen as destabilizing is because of potential ambiguities with the HV itself. One ambiguity is referred to as warhead ambiguity, that is, when an adversary mistakes the launch of a conventionally armed system for a nuclear armed one (Acton 2015). In this scenario, the United States, Russia, or China could mistake a conventional warhead coming toward their territory for a nuclear one and hastily launch a nuclear response (James Martin Center 2015). This scenario could be especially dangerous in a major regional war, giving the side being attacked a strong reason to employ escalatory measures (James Martin Center 2015). Since the United States believes that China aims to arm its hypersonic weapons with nuclear warheads (Gubrud et al. 2015d) (as opposed to the United States, which has repeatedly stated that its hypersonic program is for conventional weapons only), any hypersonic weapon from Chinese forces would be assumed to be nuclear by U.S. forces, thereby likely triggering a response.

Another ambiguity is destination ambiguity. Destination ambiguity is when a country sees a hypersonic strike against a third party and incorrectly concludes that they are under attack (Acton 2015). Because hypersonic weapons will be highly maneuverable, Russian officials, including Vladimir Putin, have broached this issue saying that they may mistake an attack against a nation bordering Russia as an attack against Russia itself (James Martin Center 2015). This scenario could be destabilizing because the country that believes it is under attack may respond with an attack of its own, instead of waiting to confirm the true destination of the weapon (James Martin Center 2015).

Nations that fear being on the receiving end of a first strike by hypersonic weapons can plan various countermeasures, which are likely to cause further destabilization. The first is to adopt a "launch on warning" posture (Speier et al. 2017). Launch on warning refers to launching a retaliatory strike when a warning of an enemy attack is received and before the incoming warhead reaches its target. Because HVs typically fly at lower altitudes than ballistic missiles, and fly at a very high velocity, nations with early-warning radars would have much less warning of an incoming hypersonic attack (James Martin Center 2015; Schreiner 2014). This timing means that the decision cycle of the target forces will be significantly compressed (Lewis 2013) and may lead to that nation being disarmed before it could react (Speier et al. 2017). To avoid this, a nation could adopt the launch on warning posture instead of risking the loss of its strategic assets or trying to ride out an incoming attack, destabilizing a situation or causing further crises (Speier et al. 2017).

The second such countermeasure would be preemption. The speed and difficulty in detecting HVs until very late would dramatically decrease the decision time by the target nation during a crisis. If that target nation believes that an attack is imminent, it could choose to preempt the other sides' hypersonic weapons and attempt to destroy them prior to their launch (Steff 2016). The target nation could also preemptively use its

likely targeted weaponry (such as anti-satellite weapons or nuclear forces), thus all but guaranteeing military action on both sides and increasing crisis instability (Speier et al. 2017). This scenario can also play out in reverse with the nation possessing the hypersonic weapons choosing to preemptively attack another nation's offensive weaponry, leading to a highly unstable situation (Butt 2016).

4.2 Bargaining Chip in Multi-Technology Treaty

Besides the often-cited destabilization arguments, another intriguing possibility for an HV test ban treaty is using a military flight test ban as a bargaining chip for a multi-technology treaty.

Since the negotiation of New START (Strategic Arms Reduction Treaty), and the United States's withdrawal from the Anti-Ballistic Missile Treaty, both the United States and Russia have expressed concern over various weaponry that the other either possess or are currently developing. Russia has expressed concern about the CPS program (Hilborne, 2017), the MK 41 Vertical Launching System ("Russia: US Claims" 2014), the B61-12 (Sputnik News 2016), some UAVs (e.g., Predator and Reaper) (Adomanis 2014; "Russia: US Claims" 2014), and the United States's overall conventional superiority in general (Hilborne, 2017). The United States has concerns about the large number of tactical nuclear weapons that Russia possesses (Mehta 2018), the Iskander missile and its violation of the Intermediate-Range Nuclear Forces (INF) Treaty (Adomanis 2014), and Russia's own HGV/HCM programs (Davenport 2018). Leading up to any potential multi-technology treaty, HGVs could continue to be developed and then traded away like Pershing II and ground launched cruise missiles (GLCM) were in the INF Treaty.

Technologies or systems that can be included in such a treaty include hypersonic weapons (HGVs and HCMs), maneuvering reentry vehicles (MaRVs), BMD systems, space-control weapons including anti-satellite weapons (ASATs), space-based weapons, CPS weapons, tactical nuclear weapons, strategic nuclear weapons, intermediate range weapons (from non-INF states), and precision-guided conventional weapons, as well as limits on numbers and locations of conventional forces (Mount 2016).

Here is an example of the topics that such a treaty might include:[†]

1. The United States could give up BMD and CPS systems, plus reduce strategic system numbers. Russia may ask for forces to stay away from NATO countries on its borders.
2. Russia would greatly reduce its number of tactical nuclear weapons, reduce strategic systems, and re-adhere to the Anti-Ballistic Missile (ABM) Treaty.
3. Both would halt development of CPS-type systems and HGVs.
4. Renegotiate INF Treaty to include China (Eckstein 2017)
5. Work together on civilian HVs

Before such a treaty could even be proposed, there are major political hurdles to overcome. A multi-technology treaty would likely go beyond the historical bilateral treaties between the United States and the Russian Federation and be multilateral. Russia is not likely to agree to begin negotiating a multi-technology treaty that does not include China and possibly other nuclear nations (Arbatov 2014; Pifer 2017), because Russia believes it needs tactical nuclear weapons to offset the superior conventional weapons of the United States and NATO (Kristensen and Norris 2018). Also, Russia seems to want to counter China's increasingly

[†] Though some elements of a potential bilateral treaty are listed in this description, this paper is not proposing such a treaty. The information presented is meant to show only the complexity of a multi-technology treaty.

capable military in Russia's far east region (Kristensen and Norris 2018). In the spring of 2018, Russia conducted military exercises involving drills for using tactical nuclear weapons near the Chinese border (Hiroyuki 2018).

In theory, a multi-technology, multilateral treaty could help nations address some their most pressing security concerns. However, in order to ban any new technology such as hypersonics, all of the nations that are currently developing it and potential future entrants would need to be party to the treaty or else risk the ban failing. One can imagine a situation where a few holdouts (e.g., North Korea or Iran) decide later to build and test HVs. Doing so would give them an advantage over nations who do not possess them or who froze their programs and would allow potential use of the programs as blackmail. The treaty, therefore, would need to be a world-wide treaty with the majority of nations participating, perhaps modeled after the Comprehensive Nuclear-Test Ban Treaty (CTBT).

The implementation of such a treaty, especially banning military HV flight testing, would be a complex endeavor. Since HVs encompass not only weapons but also aircraft and spacecraft, how would a flight test ban ensure that hypersonic weapons were banned, but civilian uses of hypersonic technology were not? Mark Gubrud writes, "To speed its approval, any such moratorium would have to define hypersonic missiles in a way that does not require elimination of already existing cruise missile systems. I would propose a ban on flights of any aerodynamic vehicle of less than, say, 15 meters' length or 2 meters' diameter, traveling in powered or unpowered flight at speeds in excess of 1 kilometer per second, over a horizontal distance greater than 100 kilometers. Space and ballistic missile launches and reentries could be specifically exempt" (Gubrud 2014, 14). This statement likely represents one of many ideas regarding what a flight test ban might look like.

5 HV FLIGHT TEST BAN TECHNICAL AND PROGRAMMATIC CONSEQUENCES

The effects of an HV flight test ban are generally presented from the point of view of geopolitical impacts. How would the same flight test ban affect the development of the technology required to fly at hypersonic velocities? At the macro level, it would essentially freeze the technology that has been developed and tested because, unlike nuclear weapon testing, which is also banned, the science behind HVs is still not well understood. This freeze in technology would lock in the current HV technology leader. It would also highly discourage other nations from investing in the development of future airplanes and space transportation because they would be unable to test their concepts. Banning flight testing would also mean that any data normally gathered by means of flight tests would be much more difficult to acquire, which would limit technological advancements in areas in which they are most needed. Subsystems could still be tested on the ground, but a fully integrated system in its flight environment could not.

5.1 Lock In the Leader

One consequence of an HV flight test ban would be to lock the current leaders of hypersonic technology in their current positions. Because of the current state of their hypersonic programs, the countries mentioned earlier in the report would be considered the leaders in hypersonics. The order of such technology leadership would depend on the amount of hypersonic research each country has performed, the data captured, and information gained.

Due to the sheer number of recent HV-related tests and ongoing research (Butt 2016), one could argue that China has raced ahead of the United States with respect to some hypersonic technologies. China may be able to field their DF-ZF HGV without additional testing since they have likely acquired enough data and lessons learned from its series of tests. China is also constructing advanced wind tunnels that can be used to acquire more hypersonic data, which can then be verified against the results of its recent flight testing (James Martin Center 2015).

What happens if countries cheat on a ban? As mentioned earlier, the technology being developed for hypersonic airplanes and hypersonic space transporters will likely be dual purpose and easily repurposed for military applications. But how would such a country test their hypersonic weapons with a flight test ban? North Korea gives an example of this with its “satellite launches.” In the past, North Korea has claimed it was testing a long-range rocket with the purpose of placing a satellite in orbit. Western nations dispute this by saying that the test was actually meant to test re-entry systems for North Korean weapons.

An analogy that suggests what could happen if a hypersonic flight test ban treaty came into effect could be the effects of the CTBT. The CTBT is a multilateral treaty that bans nuclear explosions of any kind, for both military and civilian purposes (“Comprehensive Nuclear” 1996). At the time that the CTBT opened for ratification, there had been well over 2000 nuclear tests across the globe, with the United States accounting for 1054 of them (U.S. Department of Energy 2015). (The number includes some joint U.S.-U.K. tests, which are almost half of the world’s total.) Though the CTBT has not entered into force, nuclear testing by all nations that signed the CTBT has ended, which has ensured that the United States remains the nation with the most experience and data about nuclear explosions and testing (with the Soviet Union not far behind). Because of this library of data from nuclear testing (along with the other portions of the Stockpile Stewardship Program), the U.S. weapons laboratories have certified every year to date that the United States

does not have to resort to underground testing to maintain the safety, security, and effectiveness of its nuclear stockpile. In applying the CTBT analogy to prohibiting future flight tests of HVs, China would remain in the lead, and other nations/groups that could add to potential breakthroughs in the hypersonic field would likely never have the chance to even begin research. In fact, some nations (the United States, China, possibly Russia) may find it acceptable to lock in their current states of hypersonic research given their current technical positions relative to their peers. Though none of these nations has fielded any HVs, they have tested their prototypes multiple times and would likely feel the most comfortable fielding them based on their current programs, thus giving them military advantages over their peers.

5.2 Discourage Future Entrants

Another effect of an HV flight test ban would be to discourage additional nations from conducting HV-related research and development, thus making the development of civilian HVs by those nations all but impossible. Discouraging military development of HVs is obviously the goal of those calling for a hypersonic flight test ban, but such a ban would also leave whatever HV technology that has been developed to date in the hands of a small group of nations, discouraging others outside that group from their own research and development. In fact, for some countries, it could be that their support for an HV flight test ban could actually be intended to keep nations outside the current small group of States with HV technology from developing additional HV programs, including stopping the proliferation of related technologies (Speier et al. 2017). The economic and/or security implications of access to HVs might persuade a nation to push for a flight test ban simply to prevent a rival from acquiring/advancing similar technologies. It is easy to envision a country such as India pushing for an HV test flight ban to keep arch-rival Pakistan from acquiring or developing similar technologies. Potentially, Pakistan would see the flight test ban as discriminatory (Gubrud et al. 2015c) and seek other avenues to acquire HV technology.

New breakthroughs in any given technology field do not always originate with the research leaders. Often those advances come from new entrants who may bring a different perspective. Just as companies can come to dominate industries (at least temporarily) by introducing innovative technologies (Ford's moving assembly line, Intel's computer processors, Apple's iPhone), nations that currently have small hypersonic programs could make significant breakthroughs, allowing them to vault ahead of other nations in the race to develop HVs (Gubrud et al. 2015e).

5.3 Stop Development of Civilian Hypersonic Vehicle Enabling Technology

For HVs to become a reality, at least four technical areas in which challenges must be overcome have been identified for which advancements must occur: (1) propulsion (Lamorte et al. 2011; Speier et al. 2017; Tang and Chase 2008), (2) aerodynamics (Erbland, n.d.; Lamorte et al. 2011; Speier et al. 2017), (3) guidance, navigation and control (Erbland, n.d.; Mercier 2003; Speier et al. 2017), and (4) thermal management (Erbland, n.d.; Lamorte et al. 2011; Mercier 2003; Speier et al. 2017; Tang and Chase 2008). These challenges are briefly described in this section.

For a more detailed technical discussion about these enabling technologies, see [Appendix D](#). A summary of the technical challenges can be found in Table 1.

Table 1. Summary of Current HV Technology Challenges

Subsystem	Current Technology Challenges
Propulsion (Lamorte et al. 2011; Speier et al. 2017; Tang and Chase 2008)	Turbine: Enabling turbines to operate at speeds above Mach 4 (Norris 2002; Saunders et al. 2012) Rocket: Enabling a quick turnaround for reuse, including making the rocket easily refuellable Scramjet: Flying HVs as efficiently as possible at a wide range of Mach numbers, without making the design less reliable, robust, or controllable (Marimon Mateu 2013) Errors and uncertainties in the current modeling capabilities will likely introduce errors and uncertainties in the design Commencing and maintaining combustion at supersonic speeds (Marimon Mateu 2013) Shortening the ignition delay time of the fuel-air mixture without adversely affecting the integrity of the combustion chamber and/or vehicle Mixing and burning the incoming air and fuel sufficiently before it leaves the combustion chamber (Marimon Mateu 2013; Riggins 2016, 445) Managing heat generated by atmospheric friction inside the scramjet (Marimon Mateu 2013) TBCC: Avoiding engine unstart and engine stall when transitioning between modes (Foster et al. 2012) Preserving the appropriate quality and distribution of the airflow when transitioning from the turbine engine to the ramjet/scramjet (Foster et al. 2012) Giving sufficient airflow to both the turbine and scramjet, and during

Subsystem	Current Technology Challenges
	mode transition as well (Saunders et al. 2012; Segal 2004) RBCC: Enabling a quick turnaround for reuse, including making the rocket easily refuellable Sizing duct mixing lengths for air and fuel that will result in minimal weight increases (Segal 2004) The inlet must perform well over a wide range of Mach numbers (DeBonis and Yungster 1996) Maximizing efficiency by simultaneously optimizing the flowpath for rocket mode, ramjet mode, and scramjet mode
Aerodynamics (Erbland, n.d.; Lamorte et al. 2011; Speier et al. 2017)	Surface and Shape Design: Minimizing external shape changes due to bending, flexing, material ablation, or erosion of surfaces (Speier et al. 2017) Predicting and testing the transition of the boundary layer flow from laminar to turbulent (Dolvin 2008) Drag: Reduce drag during the ascension and cruise phases of flight (Sziroczak and Smith 2016) Reduce volume and cross-sectional area of the HV while not greatly reducing its payload and mass limits (Sziroczak and Smith 2016) Reaching orbital speed and gaining altitude as soon as possible Lift: Increasing lift without significantly increasing mass and drag (Sziroczak and Smith 2016)
Guidance, navigation and control (Erbland, n.d.; Mercier 2003; Speier et al. 2017)	HV dynamics and the methodologies are not well understood (Boyce et al. 2011) Shock tunnels do not provide sufficient test duration time to allow flight control strategy testing (Boyce et al. 2011)

Subsystem	Current Technology Challenges
	A significant difference between actual flight results and predictions based on wind tunnel testing data and computational models have been reported (Coleman and Faruqi 2009)
Thermal management (Erbland, n.d.; Mercier 2003; Speier et al. 2017; Tang and Chase 2008)	High-temperature materials are often difficult to produce, difficult to machine, and/or require specific environments for their manufacture, making them costly Increasing lifetime under severe environments (Dolvin 2008) Permanent oxidation and water resistance (Dolvin 2008) Material stability under a wide range of conditions (Dolvin 2008) Ability to form the material into complex shapes Fully characterizing the materials (Dolvin 2008) Improving impact damage resistance and resilience (Van Wie et al. 2004)

5.3.1 Propulsion

One of the great technological challenges preventing the development of a Mach 5+ hypersonic airplane or a hypersonic transportation system is the propulsion system drawbacks (Jiang and Yu 2017; Walker et al. 2013), which is considered a key enabling technology (Schulte et al. 2001). Currently, only a rocket engine can accelerate a vehicle from takeoff to hypersonic speeds (Smayda et al. 2012). Other types of propulsion systems must be developed, refined, and fielded so that HVs can be employed to transport people and cargo on a routine basis. The primary purpose of the propulsion system is to deliver the necessary thrust in the flight direction to accelerate the vehicle to the desired velocity and to keep the vehicle at a constant velocity (cruise). A secondary purpose for a propulsion system, specifically the fuel, is to provide a thermal heat sink for the vehicle (Riggins 2016, 445). One important item to note is that HGVs do not require a propulsion system once they are released from their booster rocket. Instead, HGVs glide unpowered to their destination at a constant velocity by trading altitude for speed (Beach 2012).

Any hypersonic test ban would affect propulsion development, especially for civilian applications. Current technological challenges that could be affected by a flight test ban are discussed below.

5.3.1.1 Turbines

Turbine-based propulsion systems are very mature. They have decades of extensive development and use, and potential problems are well sorted. Still, work is underway to enable turbines to operate at speeds above Mach 4 (Norris 2002; Saunders et al. 2012). A high Mach turbine would then be paired with a scramjet with an ignition velocity below Mach 4 in a TBCC propulsion system (Foster et al. 2012), negating the need for a ramjet.

5.3.1.2 Rockets

Like turbines, rocket-based propulsion systems are similarly mature. The technical challenges surrounding rockets include integration in an RBCC, which is described below.

5.3.1.3 Ramjets

Given the ramjet's simplicity, decades of design history, well characterized environments, and relative ease of conducting ground testing (relative to a scramjet), the technical challenges do not come from the ramjet itself but from its integration into a combined cycle propulsion system.

5.3.1.4 Scramjets

Though scramjets have been in development in some capacity since the 1950s, some formidable technical challenges must still be overcome before scramjet engines will be ready for use in passenger HVs. These challenges are generally grouped into three main areas: forebody/inlet, combustion, and structures/materials.

The function of the forebody/inlet of a scramjet is to maximize the air captured and direct it into the engine as efficiently as possible (Riggins 2016, 445). Much of the overall performance of a scramjet is determined by the inlet's aerodynamic performance and geometric size and shape (Marimon Mateu 2013) as the air captured is directly proportional to the delivered thrust produced (Riggins 2016, 445). The minimum flight speed is also dictated by the shape of the inlets because the airflow must reach supersonic speeds (Wang et al. 2010). The inlet will be a major factor in designing a scramjet that can ignite at Mach 4 or below (Saunders et al. 2012). The forebody/inlet decelerates the air to raise its pressure and temperature to ready it for ignition (Riggins 2016, 445). This deceleration of the airflow is done by the forebody oblique shock that is generated (Riggins 2016, 445), which strikes the inlet lip when the vehicle is traveling at the velocity for which this process is optimized (Marimon Mateu 2013). Since the shock angles vary with upstream Mach numbers, traveling faster or slower than the design Mach number causes lower efficiency by pressure loss, loss of pre-compressed airflow, and possible engine unstart (Marimon Mateu 2013) shows the forebody oblique shock at a lower Mach number than the one for which the vehicle was designed. A solution for this problem—variable geometry to control the ramp shock—is being widely studied (Marimon Mateu 2013). This solution is very technically challenging to design and especially to model due to the immaturity of the computer codes and lack of understanding about the causes of the physical phenomena in the flight environments (Riggins 2016, 445). Errors and uncertainties in the current modeling capabilities will likely introduce errors and uncertainties in the design. This will lead to a design that is not optimized or that may not perform as expected. Wind tunnel testing can guide the design, but realistic and accurate real results will come only from flight testing, which is a very expensive tool especially for multiple design iterations.

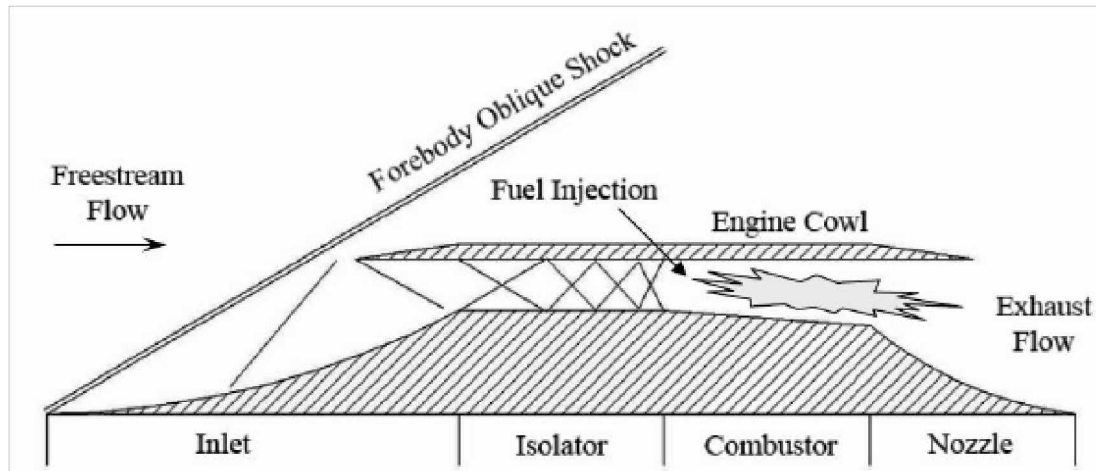


Figure 1. Diagram of a scramjet engine with a forebody oblique shock

Although designing and operating scramjet engines appears to be straightforward because of their simplicity, combustion at supersonic speeds is challenging both to commence and maintain, and it continues to be a daunting engineering challenge (Marimon Mateu 2013). Lighting a scramjet engine has been compared to lighting a match in a 3100-mph wind (Speier et al. 2017). High temperatures and pressures are needed to achieve ignition in a scramjet (Wang et al. 2010), which is a very unstable process because of gas dynamic perturbations inside the combustion chamber (Seleznev 2018).

Ignition delay time of the fuel-air mixture is one limiting factor in scramjet design and operation (Marimon Mateu 2013). A shorter delay time allows for higher velocities and/or shorter combustors (Marimon Mateu 2013). Increasing the temperature of the fuel and/or the air reduces the delay time (Marimon Mateu 2013). Increasing the pressure may or may not reduce delay time, depending on the given conditions (Marimon Mateu 2013). Increasing temperatures may have adverse structural and/or material effects, which could catastrophically affect the integrity of the vehicle. All of these effects must be taken into account in any HV design (Marimon Mateu 2013).

Mixing the incoming air and fuel is another significant problem associated with scramjet combustion (Marimon Mateu 2013). Generating maximum thrust is a direct result of sufficient mixing and heat release in the combustor and is directly related to the fuel flow rate (Wang et al. 2010). If the fuel is not properly mixed in the airstream, it will not ignite (Marimon Mateu 2013). Fuel injected into the airstream tends to get pushed against the combustor walls, leading to ineffective mixing (Marimon Mateu 2013). Since the time that the fuel and air stays within the combustion chamber is quite short (on the order of 1 ms) (Seleznev 2018), it is challenging to get the separate fuel and air streams to mix sufficiently and burn before leaving the combustion chamber (Riggins 2016, 445). As previously mentioned, accurately modeling and predicting these types of effects, including the combustion chemical reactions, is difficult because of the relative immaturity of CFD codes (Riggins 2016, 445). Also, the airflow in a hypersonic shock wind tunnel test likely does not achieve steady-state conditions because of the short test durations (1 to 40 ms drawbacks (Jiang and Yu 2017) and is different from the airflow in flight (Speier et al. 2017), making studying the combustion process difficult.

Because HVs will fly at a wide range of Mach numbers, fixed inlet and combustor geometries will only allow the HV to fly as efficiently as possible at one velocity. To increase the performance of HVs and/or

make them as efficient as possible, variable geometries for both the inlet and combustion chamber are needed (Marimon Mateu 2013). Some design concepts have been studied (Marimon Mateu 2013), but making a design that is reliable, robust, and controllable at hypersonic speeds is a difficult engineering problem.

Atmospheric friction is a major concern for a scramjet-powered HV because it must stay within Earth's atmosphere to function, unlike a rocket which passes through the atmosphere quickly on its way to orbit (Marimon Mateu 2013). The heat produced by scramjet combustion at high speeds to the friction generated by flying within the atmosphere must be taken into account in any scramjet design (Marimon Mateu 2013). Materials chosen for the HV's structure must be able to maintain their integrity when exposed to these heat loads (Marimon Mateu 2013). A discussion on materials is presented in Section [Appendix D.5.5](#).

One final note is that a scramjet optimized for use as the sole propulsion system on an HV may not be optimized for use in a TBCC/RBCC and may need to be reoptimized in that role. For more information, see the following two sections.

5.3.1.5 TBCC

Turbine-based combined cycle propulsion systems have several integration challenges that must be overcome in order to make the systems flight ready. These include transition issues between turbine/scramjet modes (Saunders et al. 2012), operability and performance issues of a combined inlet (Saunders et al. 2012) and achieving sufficient performance from the TBCC over a very wide range of Mach numbers (Foster et al. 2012).

When transitioning between turbine and ramjet/scramjet modes, interactions between the high speed and low speed engines plus interactions between the inlet and engine must be controlled to avoid engine unstart and engine stall (Foster et al. 2012). Also, the appropriate quality and distribution of the airflow must be preserved while the turbine engine is slowed and cocooned when the ramjet/scramjet takes over (Foster et al. 2012). A comprehensive understanding of the single/combined inlet characteristics, and the interactions between the inlet, engine, and nozzle is required to predict the behavior of a TBCC propulsion system during transition (Saunders et al. 2012). Furthermore, the transient nature of the airflow during mode transition needs to be understood to be addressed (Foster et al. 2012). Because much of this is vehicle- and specific-mission dependent, these characteristics will remain unknown until the design is more fully developed and the flight environments are known (Foster et al. 2012). Ideally, during transition the vehicle's velocity would be maintained, but depending on the vehicle TBCC design, vehicle deceleration could result (Foster et al. 2012). These specific issues must be addressed to ensure that the transition between modes in a TBCC is safe and reliable, while also ensuring optimal performance (Saunders et al. 2012).

The performance of an inlet is illustrated by the effect of its design and flow on the inlet's losses (Foster et al. 2012). An inlet must also be designed to maintain started flow, also known as operability (Foster et al. 2012). The inlet must be designed such that the engine can maintain high performance and operability over the wide range of flight conditions, giving sufficient airflow to both the turbine and scramjet, and during mode transition as well (Saunders et al. 2012).

Designing a TBCC that can achieve adequate performance over the whole performance envelope of an HV is a substantial challenge. The inlet must be capable of operating optimally over the range of Mach numbers while distributing the airflow to both the turbine and ram/scramjet engines with tolerable distortion and unsteadiness (Saunders et al. 2012). The inlet will need to capture as much air as needed for the turbine

during low speeds, but also have a high contraction that will provide sufficient compression when operating in scramjet mode (Segal 2004). Also, the ideal exit flowpath of the ramjet would have a convergent-divergent section, while scramjet mode requires only a straight and divergent section for optimal performance (Segal 2004). One answer, variable geometry, would add considerable weight (Segal 2004), increase complexity (Saunders et al. 2012), increase drag (Saunders et al. 2012), and could complicate vehicle integration (Saunders et al. 2012). Other solutions, such as using thermal choking and tailoring the fuel injection location and amount, can be used to alter the flowpath, but the flow needs to be better understood to be able to predict the effects and optimize these solutions, which requires more data (Segal 2004). Until those solutions are more developed, trade studies are used for a highly optimized design with a narrow Mach range, and less optimized designs for the rest of the HV velocity range (Saunders et al. 2012).

5.3.1.6 RBCC

Like TBCCs, rocket-based combined cycle systems have multiple integration challenges that must be surmounted to make them practical in HVs, such as air/fuel mixing, inlet performance, and rocket-only mode efficiency (Segal 2004). As in a rocket-only system, refueling and quick turnaround to make them viable as reusable systems is a must.

For a single, centerline-mounted rocket in an RBCC, duct mixing lengths for air and fuel can be long but result in more weight (Segal 2004). To reduce weight, the duct can be shortened, but incomplete mixing could result, which is not acceptable (Segal 2004). Using a larger number of smaller rockets can reduce mixing length (Segal 2004), but complexity increases, and the rockets must be controlled to work together and with the ramjet/scramjet engine.

Like a TBCC inlet, the inlet on an RBCC can have significant performance ramifications (DeBonis and Yungster 1996) and must perform well over a wide range of Mach numbers. These conditions again lead to complex solutions such as variable geometry in the inlet, which adds weight and can cause integration issues (Marimon Mateu 2013).

Rocket-only mode efficiency is crucial to any RBCC-powered HV. An RBCC can use the air-breathing duct as a high-expansion nozzle at low ambient pressures, which will increase overall performance (Segal 2004). But a flowpath optimized for a ramjet or scramjet likely will not result in an optimized flowpath for the rocket, decreasing its efficiency (Segal 2004). In one study, a rocket's efficiency ranged from 78% to 95% of ideal rocket performance when parameters of the flowpath were varied (Segal 2004). Simultaneously optimizing the flowpath for rocket-mode, ramjet mode, and scramjet mode may be a very difficult, if not an impossible, task.

Any future, commercial, reusable HV will need a propulsion system that can operate through a wide range of Mach regimes. Each has its own technical challenges that must be addressed before they can be viable for use. Currently, engineers have not been able to find a propulsion system that can reliably cover the entire flight envelope in a controlled and efficient manner (Speier et al. 2017). To date, scramjets are the most immature of the propulsion systems, but are also the subject of a considerable amount of development work. Unless major breakthroughs are made for any single type of propulsion system, combined-cycle systems (incorporating scramjets) will likely be employed in commercial HVs.

5.3.2 Aerodynamics

One of the most important aspects of any HV design is aerodynamic performance, which is highly dependent on the HV configuration (Sziroczak and Smith 2016). These designs often must meet several opposing requirements because of the wide range of speeds at which the vehicle may travel (Sziroczak and Smith 2016). Any changes in an aerodynamic parameter will affect other aerodynamic parameters. Therefore, the surface and shape design, aerodynamic lift and drag must all be simultaneously optimized, which is a tremendous challenge.

The aerodynamic-related technological challenges that HVs currently face generally come from the fact that the aerodynamic parameters are all highly coupled, and must all be optimized concurrently, to meet the requirements of the vehicle.

5.3.2.1 Surface and Shape Design

The entire surface and exterior shape of an HV is integral to its aerodynamic performance (Speier et al. 2017). Consequently, any change in external shape due to bending or flexing of surfaces can alter the aerodynamic characteristics of the HV (Speier et al. 2017) (including lift and drag) and limiting the external shape changes during flight is challenging. Thickening structures and increasing weights could help reduce this bending and flexing but doing so would be contradictory to the requirement to reduce HV weight for increased payload and range (Speier et al. 2017). The aerodynamic performance of the vehicle can also change when the HV's shape is altered by material ablation or other high-temperature/velocity effects such as erosion (Speier et al. 2017). The transition of the boundary layer flows from laminar to turbulent has a large impact on the HV's aerodynamics and design as well (Dolvin 2008). The transition is highly nonlinear and sensitive to boundary and initial conditions (Dolvin 2008). Testing this boundary layer on the ground is generally insufficient because of the high noise levels in ground test facilities (Dolvin 2008). This transition, and its effect on aerodynamic performance, can be measured most accurately only through flight testing (Dolvin 2008).

5.3.2.2 Drag

One of the main paths to increase aerodynamic performance is to reduce drag during the ascension and cruise phases of flight (Sziroczak and Smith 2016). Multiple types of drag affect HVs, depending on their phase of flight and specific mission. Atmospheric drag depends on the volume and cross-sectional area of the vehicle (Sziroczak and Smith 2016), which imposes volume limits on the vehicle and its payload and mass limits (Sziroczak and Smith 2016). HVs that are intended to reach orbit are not only affected by atmospheric drag, but also by gravitational drag, which requires the vehicle to gain more speed to reach a specific orbit (Sziroczak and Smith 2016). Gravitational drag can be reduced by reaching orbital speed and gaining altitude as soon as possible (Sziroczak and Smith 2016). Reducing drag is also a factor in deciding whether the HV should be designed to take off horizontally or vertically (Sziroczak and Smith 2016). Horizontal take-off is only viable when lift to drag (L/D) ratio is high enough to make up for the extra time spent in the climbing phase (Sziroczak and Smith 2016), which is accomplished by decreasing HV drag, increasing HV lift, or both.

5.3.2.3 Lift

Like drag, a vehicle's aerodynamic lift depends on its configuration (Sziroczak and Smith 2016). Gliding HVs do not depend on lift and tend to have streamlined shapes with low drag, but poor controllability and

scant cross-range abilities (Sziroczak and Smith 2016). High lift at hypersonic speeds can reduce peak heat and maximum deceleration loads and can be used to abort a launch safely (Sziroczak and Smith 2016). If an HV is designed for horizontal take-off, the vehicle must have high lift, which is required for take-off and climbing. Lift can also reduce the thrust necessary when compared to a vertically launched vehicle (Sziroczak and Smith 2016). Utilizing wings is a straightforward way to produce lift, but it comes at the expense of higher mass and drag. A lifting vehicle spends more time in the atmosphere, meaning it may be exposed to increased heat loads, thus requiring a more robust thermal protection system (TPS) (David 2012). If the wings are also/only used for reentry, they must be strong enough to survive the higher loads, which leads to increased vehicle mass (Sziroczak and Smith 2016). On the other hand, they can reduce the heat loads on the HV, possibly producing a less robust (and possibly lighter) TPS on the vehicle (Sziroczak and Smith 2016). These conflicting pros and cons must be taken into account with resulting trade-offs when designing an HV.

5.3.3 Guidance, Navigation, and Control (GN&C)

To make hypersonic transportation feasible, other key technologies need to be developed. Guidance, Navigation, and Control (GN&C) technology is identified as important to achieve the goal of developing low-cost, reliable, reusable aircraft-type systems for hypersonic aircraft and space transportation systems (Johnson et al. 2016). The role of the GN&C system is to ensure that the vehicle is always stable, that it responds to a pilot's or autopilot's commands well, and that environmental disturbances do not produce uncontrollable vehicle motion (Marrison and Stengel 1998). In this report, information GN&C technologies will be limited to control systems/techniques, sensors, and communications.

Recent programs such as the Hyper-X and the National Aerospace Plane (NASP) have shown that HVs will not be feasible, efficient, and cost effective without mature GN&C technology (Xu and Shi 2015). Typical aircraft control techniques are inadequate for HVs because of the unique and varied environments that HVs are subject to (Xu and Shi 2015). Inadequate GN&C systems can be catastrophic. The first flight of the X-43A was terminated 48.57 seconds after it was released from the B-52 carrier aircraft because of a control system error (Seleznev 2018; X-43A Mishap Investigation Board 2003). Inaccurate models in the X-43A booster stack led to underprediction of actuator loads and a deficient control system, which ultimately led to flight termination (X-43A Mishap Investigation Board 2003).

For hypersonic airplanes and hypersonic space transporters to fly, advanced GN&C systems need to be developed. Before such development, HV dynamics and the methodologies to manage them must be thoroughly understood (Boyce et al. 2011).

5.3.3.1 Controls

The principal challenge for controls in HV flight is testing control techniques during flight. Shock tunnels, which are used in ground testing, do not allow flight control strategy testing because of the extremely short duration of the test (Boyce et al. 2011). Further complicating control system design and testing is the discovery that the actual HV flight environments experienced are often not what was predicted by ground tests or computational models (Coleman and Faruqi 2009). In fact, multiple researchers have reported a significant difference between actual flight results and predictions based on wind tunnel testing data (Coleman and Faruqi 2009). Significantly large uncertainties in the parameter values required for accurate control system designs remain (Coleman and Faruqi 2009).

To date, little test information is available with respect to HV dynamic behavior and how it may be controlled by different control algorithms (Boyce et al. 2011). Unless more flight tests are conducted, new algorithms to control HVs will lack sufficient maturity to make the jump from the lab to real world usage.

5.3.3.2 Sensors

There are two main sensor-related challenges that need to be overcome. First, sensors that can withstand the harsh and varied HV flight environments (Speier et al. 2017), while continuing to function effectively and reliably, before, during, and after HV flight (Lewis 2017) must be developed further. Second, the sensors must have high bandwidth capability because of the rate at which information is received and used during hypersonic velocities (Dolvin 2008). Validation of high-bandwidth sensors for HV flight is ongoing (Dolvin 2008).

5.3.3.3 Communications

The environments experienced during hypersonic flight creates severe challenges to communication. The ionization of the surrounding air at hypersonic velocities can cause signal loss/attenuation, noise in the signal, and phase shift (Leslie and Marron 2009). This results in communication being degraded or lost (Speier et al. 2017). These same environments require that communication antennas be protected from high heat loads (Hunt et al. 1998). Because of the long range of HV flight, a dedicated system of satellites and ground stations may also be required to ensure constant communication (Hunt et al. 1998). Techniques to minimize loss of communication during hypersonic flight are being developed and improved, but still need further work.

5.3.4 Thermal Management

Because the heat load experienced by HVs during flight is extremely high (Dolvin 2008), an effective means of dissipating the thermal energy being deposited on the HV is necessary. Due to the high heat loads, commonly used aerospace materials cannot typically be used on the exterior of an HV (Sziroczak and Smith 2016). This heat load can, however, be managed via the use of a Thermal Protection System (TPS). A TPS is a system that protects the HV from the extreme heat to which it is exposed during flight and is considered another enabling technology to make HVs possible (Leslie and Marron 2009). A TPS can be the materials chosen for the skin/structure of the HV, a barrier between the heat and the HV, or a system that actively removes heat from the vehicle.

One of the biggest challenges for high-temperature material use in HVs is reducing the cost. High-temperature materials are often expensive to produce, expensive to machine, and/or require specific environments for their manufacture. Much work must be done to find ways to bring down these costs so that their use can become more widespread.

Other technical challenges include long life under severe environments (Dolvin 2008), permanent oxidation and water resistance (Dolvin 2008), material stability under a wide range of conditions (Dolvin 2008), the ability to form the material into complex shapes, and fully characterizing the material. Characterizing the material includes “understanding and modeling material behavior as a function of environmental exposure and duration, material repeatability, definition of ‘design-to’ property values, fabrication and machining, and demonstration of lightweight design approaches and repair methodologies” (Dolvin 2008, 7).

One final, major material-related concern is the behavior and resilience of the material after suffering impact damage. Striking birds, flying through severe weather, and external debris can cause physical damage to the structure and TPS of HVs in flight (Van Wie et al. 2004). After experiencing impact damage from an external source, ensuring exposure to aerothermal loading can allow the high-temperature gases to penetrate the TPS or underlying non-heat-resistant structure causing catastrophic material degradation (Van Wie et al. 2004). If a material that is not impact resistant is used on an HV, inspections must be performed before each flight to ensure that the structure and TPS remain intact and free of cracks/deformations.

6 CONCLUSIONS

Travelling at hypersonic speeds is the next step in aerospace system evolution and could reduce flight time to anywhere on the planet to 2 to 3 hours, greatly cut the cost of space access, and allow for development of weapons that are exceptionally challenging to intercept. Though hypersonic development has been ongoing since the late 1950s, it has yet to move past the developmental phase.

Flight testing is vital to any aerospace program. Although flight testing is typically expensive and time consuming, no comprehensive alternative methods currently exist. Other testing methods such as modeling/simulation, ground testing, or component/subsystem testing cannot individually or as a group reproduce the results gained by flight testing. Though computer simulations have advanced greatly, they cannot yet accurately predict hypersonic flight environments. Subsystems and individual components can be tested on the ground and in environments that partially replicate hypersonic flight environments, but they cannot be tested in a full system, in its flight environments. Without flight testing, civilian HV development will effectively be halted because of significant uncertainties in environments, safety, and reliability.

Six reasons to support flight testing have been presented, and the initial five are vital to the development and fielding of HVs, both civilian and military.

1. Generate information unique to flight test environment that cannot be obtained on the ground
2. Use the data to anchor/validate models and to verify ground test data
3. Validate system performance in its operational environment and/or for system certification
4. Identify unanticipated problems
5. Reduce risk and demonstrate technology in flight
6. Provide political messaging

Concerns have been raised about HV flight testing because of the HV's potential military use. HV technologies for civilian and military uses are inherently linked (dual use), and much of the technology that will one day enable hypersonic commercial airplanes and space transport to be commercially viable (Schulte et al. 2001) can also be used in military weaponry. Various non-governmental organizations have stated that HVs would encourage first use of HVs and decrease strategic stability. HV flight test bans have been proposed in various forms to prevent military HV systems from being developed and fielded. The emphasis on banning flight tests is due to flight testing's vital role in aerospace programs, and it would be all but impossible to develop HVs without flight testing. Because military HVs are considered a stepping stone to civilian HVs, a complete hypersonic vehicle flight test ban would hamper development of civilian HV technology in the United States for years to come. A narrow, military HV flight test ban would at best slow down military HV development and would be difficult to enforce. A test ban also will not affect those who either do not follow it or cheat it altogether because of the inherent dual-use nature of HV technology.

If HV flight testing were banned today, there would be multiple technical and programmatic consequences. First, it would lock the current HV technology leader in its place, leaving nations desiring to advance their HV technology to either cheat the ban or not to join a test ban treaty. Second, it would discourage potential future entrants from developing HV technology, leaving HV technology in the hands of a small group of nations, precluding potential new solutions from others to be developed. Finally, developing the technology to enable civilian HV development would be all but impossible without flight tests. As of today, HV

technological advancements are needed in four critical areas—propulsion; aerodynamics; guidance, navigation, and control; and thermal management—and all would be affected if HV flight tests were banned. Short-term political and stability gains may be had in banning HV flight testing, but it would come at the expense of long-term benefits.

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APPENDIX A: NATIONS DEVELOPING HYPERSONIC VEHICLES

A.1 United States

The United States has been experimenting with vehicles that travel at hypersonic speeds since the late 1940s. The technology, research, science, and engineering discoveries from these efforts have been applied to numerous efforts including reentry vehicles (RV), spacecraft, and planes. Recently the US has tested multiple hypersonic vehicles (HV) including the Army's Advanced Hypersonic Weapon (AHW) (flown twice) (Acton 2015), DARPA's (Defense Advanced Research Projects Agency) Hypersonic Technology Vehicle (HTV-2) (flown twice) (Figure A-1) (Acton 2015), the X-51 (tested four times) (Lewis 2013), and others. Some of the current HVs said to be in the research and development phase in the United States include the High-Speed Strike Weapon (Malenic 2015), Hypersonic Air-Breathing Weapon Concept (HAWC) (Keck 2017), the Tactical Boost Glide (TBG) (Keck 2017), and the Intermediate Range Conventional Prompt Strike (IRCPS) (Missile Defense Threat 2017).



Figure A-1. DARPA/Air Force HTV-2^a

A.2 China

Because hypersonics are a national priority for the Chinese, China is working on multiple HVs and HV-related facilities simultaneously (Lewis 2013). China is reported to be working on a hypersonic bomber/aircraft (Gertz 2017; Lin and Singer 2016), a hypersonic spaceplane (possibly the Shenlong Space Operations Vehicle) (Figure A-2) (David 2012; Lewis 2013; Lin and Singer 2016), hypersonic Unmanned Aerial Vehicles (UAV) (Lin and Singer 2016), a scramjet engine (Lin and Singer 2017), the DF-ZF HGV (Gubrud et al. 2015a), the JF-12 shock driven, hypersonic wind tunnel drawbacks (Jiang and Yu 2017), and many others. Of these, the most well-known HV that China is developing is the DF-ZF (also known as DH-17, and previously known as WU-14). China has tested their DF-ZF at least seven times between January 2014 and November 2017; most were successful flight tests (Gertz 2016).

^a Steven H. Walker and Fredrick Rodgers, "Falcon Hypersonic Technology Overview," AIAA/CIRA 13th International Space Planes and Hypersonics Systems and Technologies, CIRA, Italy, AIAA-2005-3253, May 2005.



Figure A-2. Rendering of China's Shenlong space plane^b

A.3 Russia

The Russian government has called hypersonic-related projects a national priority (Lewis 2013) and has a few HVs under development (Schreiner 2014). These include the Tsirkon (a.k.a. Zircon) hypersonic cruise missile (James Martin Center 2015; Lewis 2013), the Yu-71 HGV (Figure A-3) (Gubrud et al. 2015b), and the BrahMos II hypersonic cruise missile (co-developed with India) (Lewis 2013; Speier et al. 2017). Russia has also been heavily involved with the French and Indian HV development projects (Speier et al. 2017). Unlike China's success with testing HGVs, all of the recent tests of the Yu-71 have reportedly failed (Butt 2016).



Figure A-3. Notional drawing of Russia's Yu-71^c

^b "China is Building One of the World's Largest Space Launch Vehicles." Accessed September 14, 2018, <https://www.popsci.com/long-march-goes>

^c "Hypersonic 'Object 4202' and its test." Accessed October 2, 2018. <https://deborahnormansoprano.com/novosti-i-obschestvo/71966-giperzvukovoy-obekt-4202-i-ego-ispytanie.html>

A.4 France

Although a member of the National Atlantic Treaty Organization (NATO) and the European Union (EU), France often conducts its own defense programs separate from other NATO and/or EU members. Since the 1990s, France has been aggressively pursuing hypersonic technology (Speier et al. 2017). France has a number of HV projects that are currently in various stages of development, some of which are being developed in close cooperation with the Russians (Speier et al. 2017). France has researched or is researching/developing hypersonic UAVs, high speed air-to-surface missiles, ramjet/scramjet technology for satellite launchers, a nuclear weapon air-to-surface missile known as ASN4G (scheduled to replace the current ASMP-A in the 2030s), and a hypersonic technology vehicle known as LEA (co-developed with Russia) (Figure A-4) (Lewis 2013; Speier et al. 2017). France has also spent money modernizing its wind tunnel facilities, including the hypersonic wind tunnels (Speier et al. 2017).



Figure A-4. CAD drawing of LEA^d

A.5 India

India, through its Defense Research and Development Organization (DRDO), has two hypersonic weapon development programs. The first is the previously mentioned BrahMos II (Figure A-5), which is being co-developed with Russia (Lewis 2013; Speier et al. 2017). The second is the Hypersonic Technology Demonstrator Vehicle (HSTDV). The HSTDV is an indigenous project with the goal of laying the foundation for a Mach 6.5-7, 1500-kg cruise missile (Lewis 2013; Speier et al. 2017). India is also working on an air-breathing reusable two-stage-to-orbit launch vehicle for space access (Lewis 2013; Speier et al. 2017). Finally, India completed construction of a new hypersonic wind tunnel in April 2014, adding to 11 other known hypersonic wind tunnels (Speier et al. 2017).

^d“French Flight Test Program LEA Status.” Accessed October 4, 2018.
<http://www.dtic.mil/dtic/tr/fulltext/u2/a593055.pdf>



Figure A-5. Scale model of India's BrahMos II^e

A.6 Australia

The Australian government has sponsored several hypersonic projects and collaborations with U.S. agencies (Speier et al. 2017). Previous and current programs include the HyShot program, the Hypersonic Collaborative Australian/US Experiment (HYCAUSE), and the multi-year, multi-vehicle Hypersonic International Flight Research Experimentation (HIFiRE) program (Figure A-6) (Dolvin 2008; Lewis 2013; Speier et al. 2017). Indigenously, Australia's hypersonic space program developed a technology called "ScramSpace" (Speier et al. 2017). Australia is also developing a three-stage hypersonic satellite launch system, with the goal of being 95% reusable, called SPAR-TAN (Speier et al. 2017). Australia also operates hypersonic testing facilities at the Woomera Test Range, which is the largest land-based weapons test facility in the world and said to be among the world's best (Speier et al. 2017). Finally, Australia has seven hypersonic wind tunnels, which are used by both private researchers and government programs (Speier et al. 2017).



Figure A-6. HIFiRE 8 payload^f

A.7 Japan

The Japan Aerospace Exploration Agency (JAXA) is the main organization for hypersonic research in Japan (Speier et al. 2017). In 2005, JAXA released a mission statement (titled JAXA 2025), indicating that the goal of the organization is to develop a commercial hypersonic aircraft with the capability to cruise at Mach 5 (Speier et al. 2017). Overall, Japan's research mainly focuses on civilian HVs, but it also has at least one military application in progress. Japan is working with Airbus on the Zehst program, which plans to develop a near hypersonic (speeds between Mach 4 to 5) 60-passenger vehicle for the

^e"Russia and India Test Hypersonic and Supersonic Missiles," Accessed October 4, 2018, <https://www.ainonline.com/aviation-news/defense/2017-04-25/russia-and-india-test-hypersonic-and-supersonic-missiles>

^f"HIFiRE Program," Accessed October 4, 2018, <http://hypersonics.mechmining.uq.edu.au/hifire>

2050 timeframe (Speier et al. 2017). The Hikari program, which is being run in conjunction with the European Commission and the Japanese Ministry of Economy, Trade, and Industry, has a goal to experiment with an HV by 2020 and develop cost-benefit calculations by 2025 (Speier et al. 2017). The Hypersonic Technology Experimental Aircraft (Hytex) being developed by JAXA is said to be a hypersonic aircraft for traveling trans-Pacific routes (Figure A-7) (Speier et al. 2017). Finally, Japan is collaborating with Mitsubishi Heavy Industries to develop a high-supersonic (up to Mach 5) solid rocket and ramjet-powered anti-ship missile called the XASM-3 (Speier et al. 2017).

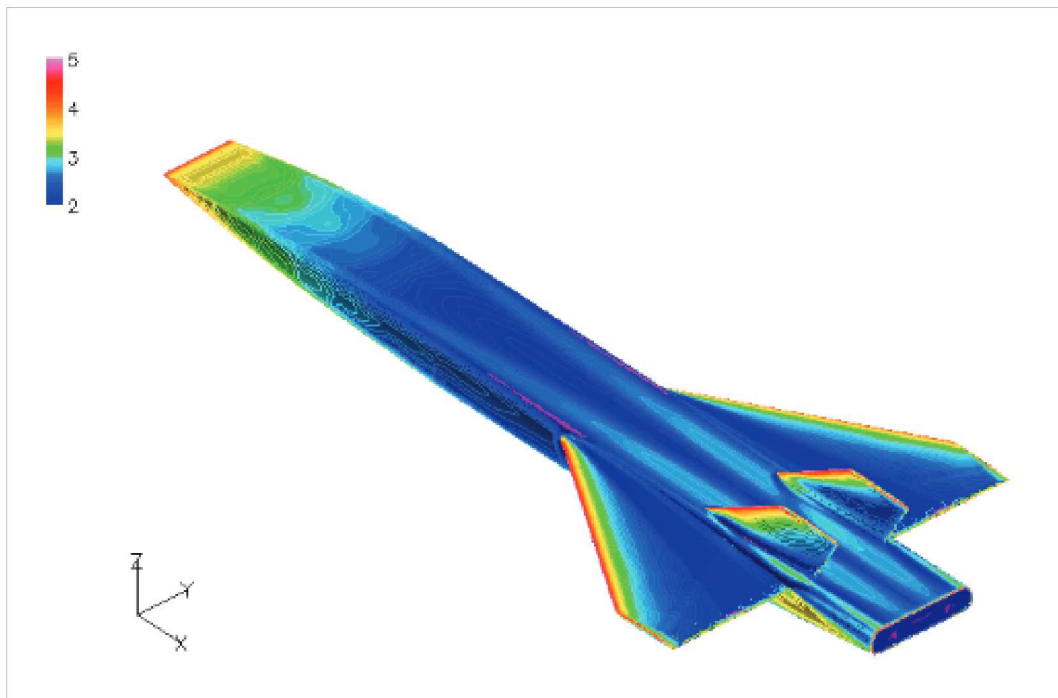


Figure A-7. Heat flux distribution evaluation of Hytex's surface^g

The European Union^h has had at least three main research and development projects focused on hypersonic technology. The Long-Term Advanced Propulsion Concepts and Technologies (LAPCAT II) is aimed at developing a civilian hypersonic transport aircraft that will reach speeds of Mach 5 to 8 using a hybrid turbo-scamjet engine designed by Reaction Engines (Figure A-8) (Speier et al. 2017). The Intermediate eXperimental Vehicle (IXV) is designed to test atmospheric reentry conditions from hypersonic orbital speeds and trajectories using an experimental suborbital reentry vehicle (Speier et al. 2017). The IXV is supposed to be a reusable satellite launch vehicle that will reach a maximum altitude of approximately 256 miles (Speier et al. 2017). The vehicle is not designed to make a full rotation around the Earth, though it is designed to reach low-Earth orbit altitudes (fractional orbital capability). Lastly, the Aero-Thermodynamic Loads on Lightweight Advanced Structures (ATLLAS II) was a four-year project that began in 2011 with a focus on the development of high-temperature, lightweight materials that can

^g"Systems Analysis on Hypersonic Airplanes using Pre-Cooled Turbojet Engine." Accessed October 4, 2018. <http://www.dtic.mil/dtic/tr/fulltext/u2/a593055.pdf>

^hIn this report, "European Union" refers to projects that either span two or more EU countries or are performed through the European Space Agency (ESA).

withstand hypersonic environments (Speier et al. 2017). The final report for the ATLLAS II project was completed in 2015 (Speier et al. 2017).



Figure A-8. Rendering of the LAPCAT-MR2 hypersonic aircraftⁱ

The nations mentioned above generally view the development of hypersonic weapons as a critical piece of their future military and/or economic security. It would be difficult for them to willingly and/or unilaterally give up their development and future deployment (Aune et al. 2017). Table A-1 provides a summary of the countries developing HVs.

ⁱ“Making Viable Hypersonic Commercial Airplane Designs Including a Mach 8 Cruise Passenger Vehicle,” Accessed October 4, 2018. <https://www.nextbigfuture.com/2015/05/making-viable-hypersonic-commercial.html>

Table A-1. Summary of Nations Developing Hypersonic Vehicles

Nations	Partial List of Known Hypersonic Vehicle Programs
United States	• Army's Advanced Hypersonic Weapon (AHW) (Acton 2015) • DARPA's Hypersonic Technology Vehicle (HTV-2) (Acton 2015) • X-51 (Lewis 2013) • High Speed Strike Weapon (Malenic 2015) • Hypersonic Air-Breathing Weapon Concept (HAWC) (Keck 2017) • Tactical Boost Glide (TBG) (Keck 2017) • Intermediate Range Conventional Prompt Strike (IRCPS) (Missile Defense Threat 2017).
China	• Hypersonic bomber/aircraft (Gertz 2017; Lin and Singer 2016), • Hypersonic spaceplane (possibly the Shenlong Space Operations Vehicle) (David 2012; Lewis 2013; Lin and Singer 2016). • Hypersonic Unmanned Arial Vehicles (UAVs) (Lin and Singer 2016) • Scramjet engine (Lin and Singer 2017) • DF-ZF HGV (also known as DH-17, and previously known as WU-14). (Gubrud et al. 2015a) • JF-12 shock driven, hypersonic wind tunnel drawbacks (Jiang and Yu 2017)
Russia	• Tsirkon (a.k.a. Zircon) (James Martin Center 2015; Lewis 2013) • Yu-71 HGV (Gubrud et al. 2015b) • BrahMos II hypersonic cruise missile (co-developed with India) (Lewis 2013; Speier et al. 2017).
France	• Hypersonic UAVs (Lewis 2013; Speier et al. 2017). • High speed air-to-surface missiles (Lewis 2013; Speier et al. 2017). • Ramjet/scramjet technology for satellite launchers (Lewis 2013; Speier et al. 2017). • ASN4G (Lewis 2013; Speier et al. 2017). • LEA (co-developed with Russia) (Lewis 2013; Speier et al. 2017).
India	• BrahMos II (co-developed with Russia) (Lewis 2013; Speier et al. 2017).] • Hypersonic Technology Demonstrator Vehicle (HSTDV) (Lewis 2013; Speier et al. 2017). • Air-breathing reusable two stage to orbit launch vehicle for space access (Lewis 2013; Speier et al. 2017).
Australia	• HyShot program (Dolvin 2008; Lewis 2013; Pittman et al. 2011; Speier et al. 2017) • Hypersonic Collaborative Australian/US Experiment (HYCAUSE) (Dolvin 2008; Lewis 2013; Speier et al. 2017) • Hypersonic International Flight Research Experimentation (HIFiRE) program (Dolvin 2008; Lewis 2013; Pittman et al. 2011; Speier et al. 2017) • ScramSpace (Speier et al. 2017) • SPAR-TAN (Speier et al. 2017)
Japan	• Zehst program (Speier et al. 2017) • Hikari program (Speier et al. 2017)

	• Hypersonic Technology Experimental Aircraft (Hytex) (Speier et al. 2017) • XASM-3 (Speier et al. 2017)
European Union	• Long-Term Advanced Propulsion Concepts and Technologies (LAPCAT II) (Speier et al. 2017). • Intermediate eXperimental Vehicle (IXV) (Speier et al. 2017). • Aero-Thermodynamic Loads on Lightweight Advanced Structures (ATLLAS II)

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APPENDIX B: ENVIRONMENTS

The environments faced by vehicles flying at hypersonic velocities are very different and harsher than vehicles flying at subsonic and supersonic speeds. Gases behave very differently at hypersonic speeds compared to subsonic and supersonic velocities drawbacks (Jiang and Yu 2017). As the Mach number is increased, certain physical variables of the gas become increasingly important in a hypersonic flow (Rodriguez et al. 2008). Physics challenges such as natural and forced boundary layer transition, separation caused by shock-boundary layer interaction, shock-shock interaction heating, isolator shock trains, boundary layer re-laminarization (McClinton 2006), non-equilibrium gas dynamics, molecular dissociations, and ionization (Leslie and Marron 2009) are all characteristics of the environment produced by hypersonic flows.

These harsh environments are the source of design difficulties for any HV. Since HVs are meant to travel long distances in the atmosphere at high speeds, they are more exposed to these extreme environments than other aerospace vehicles. As speed increases, physical phenomena, which at slower speeds contributed very little or could be excluded using simplifying assumptions, can no longer be assumed to be negligible and so must be taken into account as part of the design (Leslie and Marron 2009).

In fact, the environments become coupled at hypersonic speeds, and so the design and optimization of the vehicle must take that into consideration. Because of the highly coupled environments, the subsystems of an HV also become highly coupled. Optimizing mass, volume, shape, propulsion, fuel, materials, structure, control surfaces, communication systems, payload capacity, and other HV design subsystems becomes a complex, multivariable design problem (Starkey et al. 2002). For example, the engine of an air-breathing HV must be designed as part of the vehicle structure (instead of being optimized separately as a subassembly) (Lewis 2017) where the components provide both propulsion and lift (Rodriguez et al. 2008). Because of this, aero performance cannot be decoupled from the engine performance (Rodriguez et al. 2008), making it one of the most difficult design and optimization problems in aerospace engineering (Lewis 2017). Any small change in environment specifications that requires a change of design for an HV subsystem can quickly propagate through the entire vehicle.

At high subsonic and hypersonic speeds, the high-temperature gases in the air flow create severe aerodynamic, thermodynamic, chemical, and radio frequency (RF) environments. These environments create very high loads on the vehicle as well as expose the vehicle to a mix of hot oxygen combustion products (Leslie and Marron 2009). Despite the types of loads that hypersonic flows are known to induce on HVs, the hypersonic flow itself is not well understood (Bertin and Cummings 2006). HV flight characteristics throughout the entire flight envelope cannot yet be accurately predicted because of our limited understanding of hypersonic flow. In fact, identification of many of the phenomena that produce the extreme heating that can destroy an HV in flight were initially discovered only during flights at hypersonic speeds (Bertin and Cummings 2006).

Even though every single flight test at hypersonic speeds leads to increased knowledge about the environments experienced at those speeds, there are still substantial gaps in our understanding of high-speed flow (Lewis 2017). For example, it is not known with certainty when the air flowing past an HV will transition from laminar flow to turbulent flow along with an increase in heating and drag (Lewis 2017). Another problem with the characterization of hypersonic flows is that the resultant environment is highly dependent on the parameters of the flow, and without more knowledge of the relevant physical

processes, it is difficult to use one environment to calculate and characterize another (Witteveen et al. 2011).

Because of the high level of uncertainty in the predictions of the airflow changing from laminar to turbulent flow, conservative assumptions are applied to heating rates, which results in an HV carrying excessive thermal protection so as to not run the risk of vehicle failure (Kuntz and Potter 2008). Until more is known about the environments surrounding hypersonic flight, conservative assumptions about flight parameters will continue to be made and optimizing the entire HV will be difficult (Xu and Shi 2015).

B.1 Aerothermodynamic Environments

Failure of the HV can be caused by the severe aerodynamic heating that hypersonic flight produces (Lamorte et al. 2011). Aerodynamic and thermodynamic environments are so interdependent, especially at hypersonic speeds, that they are often referred to as aerothermodynamics (Bertin and Cummings 2006). “Slower” flying aerospace vehicles, such as passenger airplanes and subsonic cruise missiles, fly through much more benign aerothermal environments than HVs. As stated in *Critical Hypersonic Aerothermodynamic Phenomena*, “Unlike the aerodynamic and heat-transfer characteristics of conventional aircraft, these problems are characterized for reentry (or for ascending) trajectories by a wide range of Reynolds numbers, extremely high Mach numbers, and, therefore, by high temperatures immediately behind the bow shock wave (up to several tens of thousands of degrees before the temperature associated with thermochemical equilibrium is reached)” (Bertin and Cummings 2006, 131).

The high-speed and high-temperature flow field strongly influences the energy flux and the various forces acting on the exterior of an HV (Bertin and Cummings 2006). The high aerodynamic heating that an HV experiences creates difficulties in maintaining the temperature of the structure, leading edges, control surfaces, and internal components below the maximum allowable temperature limit (Speier et al. 2017). These high temperatures, along with the thin structures that HVs are typically composed of to minimize mass, create high thermal gradients that can cause bending or warping of the HV (Speier et al. 2017). Surface ablation, erosion, and oxidation of the leading edges (Speier et al. 2017) can also change the shape of the HV.

This bending, warping, ablation, erosion, and oxidation can cause changes to the control surfaces of the HV so that it responds differently than when controlled by undistorted surfaces. Consequently, the HV’s control system must also be designed to compensate for changes in the control surfaces over the flight of the vehicle, and the sensors providing feedback to the altitude control system must survive the extreme conditions as well. These unpredicted deformations can also cause structural failure due to the increased loads under this high aerothermodynamic loading (Lamorte et al. 2011).

B.2 Chemical and RF Environments

At hypersonic speeds, shockwaves that heat and compress oncoming air are formed around the vehicle. These shockwaves can heat the air to such high temperatures that chemical reactions, molecular ionization, molecular disassociation, and other changes of the atmospheric particle state are induced (Bertin and Cummings 2006). This in turn can affect the RF-based vehicle communications. These heat-induced chemical reactions and RF effects must be accounted for when designing any part of the vehicle with exposure to the flow field such as the structure, engine, thermal protection system, oxidation inhibitors, leading edges, and sensors. Because the exact nature of the chemical reactions and other high-

temperature flow physics are still not understood with unquestioned certainty, the ability to accurately model a chemically reacting hypersonic gas flow is limited drawbacks (Jiang and Yu 2017).

The chemistry effects in a hypersonic flow field are characterized by vibrational excitation, in addition to the aforementioned gas dissociation and ionization. Real gas effects, which are deviations from the ideal gas behavior of the aerodynamic properties of the flow field (Fidan et al. 2003), must also be considered at hypersonic speeds. These effects, in turn, mean that more variables are required to describe the full state of the real gas flow stream compared to an ideal gas, which in turn requires much more computing power to simulate. Currently, highly detailed modeling studies can be completed only by using supercomputing resources, which are not always readily available (Rodriguez et al. 2008; Smayda et al. 2012).

During hypersonic flight, ionized gases are normally encountered at speeds above Mach 12 (Dolvin 2008). Due to the ionized gases, the vehicle can experience degraded RF and GPS communications or a complete communication blackout (Dolvin 2008; Starkey et al. 2002) as was experienced by Mercury, Gemini, Apollo, and the Space Shuttle vehicles during reentry (Chandler 2003). The dissociated air molecules are composed mainly of nitrogen, which dissociates at temperatures above 4000 K (Starkey et al. 2002), and oxygen, which dissociates at temperatures above 2000 K (Rodriguez et al. 2008) form a layer of ionized gas around the vehicle; this layer is commonly called a plasma sheath (Figure B-1) (Starkey et al. 2002). The sheath can cause signal attenuation, phase shift of the signal, noise, or total loss of signal (Leslie and Marron 2009). This RF signal degradation can be severe and often will cause a communications blackout during some portion of the flight (Starkey et al. 2002). The behavior and magnitude of the RF signal degradation can also be increased if the HV's ablative material by-products are present in the air flow (Starkey et al. 2002). Although the mechanism through which the plasma is generated when a vehicle travels at hypersonic speeds is well known and has been studied since at least the 1950s, the means to modify or control this plasma layer are not well understood (Starkey et al. 2002). Table B-1 summarizes the environments experienced by HVs.

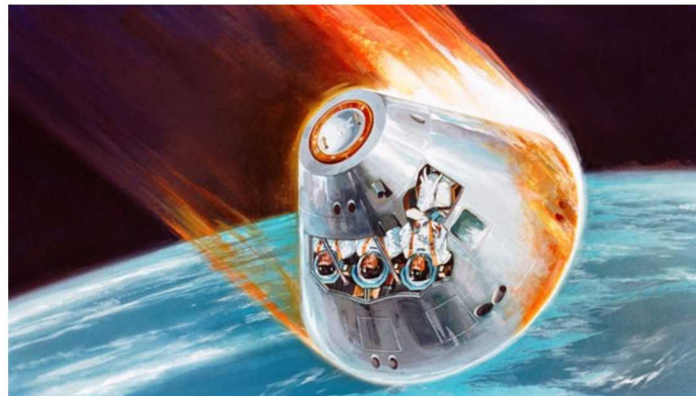


Figure B-1. Rendering of Apollo command module with plasma sheath during reentry^a

^a "Scientists Look at Communicating with Hypersonic Vehicles using Plasma Resonance," Accessed October 4, 2018. <https://newatlas.com/communicating-with-hypersonic-vehicles-in-flight/38066/>

Table B-1. Unique Hypersonic Environments

Characteristics of Environment	Effects on Vehicle
Aerothermodynamic	
Natural and forced boundary layer transition Flow separation caused by shock-boundary layer interaction Shock-shock interaction heating Isolator shock trains Boundary layer re-laminarization (McClinton 2006) Non-equilibrium gas dynamics Molecular dissociations Wide range of Reynolds numbers High temperatures immediately behind the bow shock wave	Difficulties in maintaining the temperature of the structure, leading edges, control surfaces, and internal components below the maximum allowable temperature limit (Speier et al. 2017). High thermal gradients, surface ablation, erosion, and oxidation cause bending, warping and other shape changes of the HV (Speier et al. 2017). Shape changes to the control surfaces of the HV cause different vehicle response than when controlled by undistorted surfaces.
Chemical/Radio Frequency (RF)	
Chemical reactions (heat induced) Molecular ionization Molecular disassociation Vibrational excitation Plasma sheath around vehicle	Degraded RF and GPS communications (Dolvin 2008; Starkey et al. 2002) characterized by: - Signal attenuation - Phase shift of the signal - Signal noise - Total loss of signal (Leslie and Marron 2009)

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APPENDIX C: PURPOSE OF FLIGHT TESTS

C.1 Generate Information Unique to Flight Test Environment and Not Available on the Ground

Flight tests allow for the opportunity to gather performance data that cannot be acquired elsewhere (Bertin and Cummings 2006; Lewis 2017; Rodriguez et al. 2008). Currently, no single ground-test facility can fully replicate and test all facets of hypersonic flight (Bertin and Cummings 2006), which would require simultaneously controlling flow duration, altitude, Reynolds number, gas chemistry effects, velocity, Mach number, model surface temperatures, ablation effects, and the quality of the free stream flow (Bowcutt 2014; Leslie and Marron 2009). Other test environments that cannot be duplicated on the ground include combined and interdependent environments, such as aerodynamic and propulsive or structural and thermal (Leslie and Marron 2009), and flight dynamic pressures in some of a hypersonic vehicle's (HV) operating envelope (Boyce et al. 2011). Instead, data must be approximated and extrapolated from the data that can be acquired in a hypersonic wind tunnel (Figure C-1) (Bertin and Cummings 2006).



Figure C-1. China's JF-12 hypersonic wind tunnel¹³

A lot of experimental data has been generated by facilities that were recently constructed around the world. These facilities were constructed for research on various aspects of design problems related to flying at hypersonic velocities. Yet understanding is still limited because of the relatively low accuracy and high uncertainty of data from this ground-based research drawbacks (Jiang and Yu 2017) and so it has not led to rapid development of HVs (Boyce et al. 2011). Compromises must be made in model size and structure, even in the best ground-based testing facilities, often simply to fit them in the test chamber (Mercier 2003). Compromises must also be made to the inlet air purity and composition to be able to condition the air for hypersonic flight conditions (Mercier 2003). Testing is also usually conducted at a fixed Mach number, which does not permit assessment of the engine operation and performance during transient conditions in flight (Mercier 2003).

¹³ "China's Hypersonic Wind Tunnel," accessed October 4, 2018, <https://www.datenna.com/industry/chinas-hypersonic-wind-tunnel>

Another limitation of wind tunnel testing is test duration. A typical shock tunnel test lasts between 1 (McClinton 2006) to 40 milliseconds (ms) drawbacks (Jiang and Yu 2017; Smart et al. 2006). The short duration of this test has limited aerodynamic-force and moment testing in shock tunnels for many years drawbacks (Jiang and Yu 2017). If the test time could be increased, it would be possible to test air-breathing propulsion systems and rocket/plume interactions. Aerodynamic-force and moment testing, and dynamic testing would also be possible drawbacks (Jiang and Yu 2017). The short test time in these wind tunnels also precludes observation of sustained flow and heating (Boyce et al. 2011; Smayda et al. 2012), as it takes approximately 30 seconds for the vehicle structure to reach thermal equilibrium (Mercier 2003). Knowing the heat loads that a vehicle will experience is vital to designing an HV (Boyce et al. 2011). Point measurements are regularly taken in wind tunnels, but heat load data must be extrapolated for complete vehicle design (Boyce et al. 2011).

According to Speier et al. (2017), "... hypersonic wind tunnels capable of producing flight-representative hypersonic flow for extended periods (several seconds or longer) with flight equivalent stagnation temperatures and pressures are extraordinarily difficult and expensive to build. Despite even the best efforts, ground test facilities do not perfectly represent the flight environment. The test sections are small, causing the test articles to be subscale ... Furthermore, the airflow is often contaminated with particulate matter, ionization, or excess water as a result of various means of heating the flow to flight-representative temperatures; test durations are short; and the 'noise' or turbulence levels in the test section flows are typically significantly higher than would be found in flight" (Speier et al. 2017). Because of the lack of ground test facilities that can duplicate true hypersonic flight conditions drawbacks (Jiang and Yu 2017), performing flight tests is still the only way to gather data that is not available via ground tests (Dolvin 2008).

One final limitation for gathering data on the ground is the relative immaturity of Computational Fluid Dynamics (CFD) and other physics codes. Because the hypersonic flow environment is still not well understood, many of today's codes rely on test data when the physics of certain phenomena are unknown (Walker et al. 2013). Producing data to address particular requirements with a reasonable level of confidence via modeling and simulation is arguably still beyond current capabilities (Riggins 2016, 445). As more and more flight test data are produced, the fidelity of design databases is increased (Bowcutt 2014; Dolvin 2008). The database in turn provides information needed to refine the code (Leslie and Marron 2009) and reduce aerodynamic uncertainty (McClinton 2006). Still, the use of calibrated CFD solutions is considered dangerous by some because the codes are relatively immature for predicting HV flight environments (Bertin and Cummings 2006).

Yet significant gaps in our basic knowledge of high-speed flow still exist, including when air passing over an HV changes from laminar to turbulent flow (Lewis 2017), and it is important that those gaps be addressed or understood as well as possible (Riggins 2016, 445). Modeling hypersonic flows is one of the most challenging problems for CFD and other physics codes (Bertin and Cummings 2006) and made worse by these many uncertainties (Witteveen et al. 2011). A further complication is the fact that "a variety of phenomena must be accurately simulated including high-temperature/low-density flow, stagnation heating, plasma generation and blackout, chemical reactions, ablation, transitional boundary layers, 3D separated flow, and 3D shock wave/boundary layer interactions" (Lewis 2013); however, these are currently poorly modeled by CFD codes because they are not amenable to straightforward analysis (Bertin and Cummings 2006). Also, the lack of extensive databases for a variety of trajectories and

environmental conditions (Bertin and Cummings 2006) makes CFD models less mature with regard to hypersonic flows. As a result, without additional flight testing, today's models do not have sufficient accuracy to be used to design an HV (Speier et al. 2017), and so large uncertainties remain in the models (Ouzts et al. 2009). Nevertheless, models are helpful in HV design because they can produce important data on HV performance sensitivity regarding these uncertainties (Dugundji 1962).

C.2 Obtain Data to Anchor/Validate Models and Verify Ground Test Data

Modeling and simulation (mod/sim) are an essential part of any complex system's lifecycle. Over the last two decades, many techniques have been developed to increase the fidelity of models and simulations, reduce errors, reduce computational time/resources required, and increase predictive capabilities. With mature mod/sim codes, a design can be optimized, different design configurations can be examined, and many environments that the product may encounter over its lifecycle can be tested, all without expensive manufacturing and testing. However, these models all possess fundamental limitations and are only as good as the data that was used to verify/validate them (Rodriguez et al. 2008). Such data cannot be fully validated solely by means of ground testing and, therefore, still requires flight testing (Lamorte et al. 2011).

C.2.1 Data to Validate/Anchor Models and Improve Prediction Methods

Though many computer codes, especially CFD codes, have been built to model hypersonic flight, these codes are still relatively immature. Actual test data, especially flight test data, is required to validate and anchor these codes (Mercier 2003; Moses et al. 2004). Since there is not an extensive hypersonic flight database, any hypersonic flight that is conducted adds to the database and helps improve a model's predictive capabilities. According to the Missile Defense Agency (MDA), intercept flight tests are regularly conducted to provide data to anchor models and simulations, which are then used to verify the performance of the Ballistic Missile Defense (BMD) system ("Ballistic Missile Defense" n.d.). CFD models must be validated, and as of today, flight testing is the only suitable method to test HVs at full-size aircraft scale (Dolvin 2008). Design cycles of high-speed vehicles can be reduced, and some testing requirements may be met by using modeling tools that have been anchored with high quality data (Speier et al. 2017). For the X-43 (McClinton 2006) and the HIFiRE (Dolvin 2008) programs, obtaining flight data has been a program goal in order to refine and validate computational models and advance performance-prediction capabilities for HVs.

C.2.2 Validate Ground Test Data

Flight test data are needed not only to anchor and validate models, but also to verify that the results from ground testing and modeling are accurate (Dolvin 2008). Because of the differences in the airflow from a wind tunnel vs. a flight test (Dolvin 2008), information must be extrapolated from the hypersonic wind tunnel data and correlated with the flight test data to ensure its accuracy (Bertin and Cummings 2006). If the data does not correlate well, the ground test setup may have to be changed in order to produce more accurate data (Bertin and Cummings 2006). Depending on the magnitude of the inaccuracies of the flight data (Pittman et al. 2011), there could potentially be severe ramifications for the vehicle's design or performance characteristics, including underestimation of safety margins. Ground test data can be very useful in the design of HVs when the facilities producing the data have been calibrated, especially with actual flight test data (Speier et al. 2017).

For example, during the X-15 program, the flight data revealed that the flow over the vehicle was mostly turbulent, whereas the wind tunnel test data showed the flow to be mostly laminar (Bertin and Cummings 2006). Using new instrumentation techniques (Lewis 2013), the X-43 program gathered high resolution, high precision, and coherent data (Dolvin 2008) from flight tests to build high quality databases, which were then used to validate the data that the program had produced on the ground as well as to update the physics-based computer codes (Leslie and Marron 2009). Validating short-duration ground test facility data was the goal of the HyShot program (Smart et al. 2006).

C.2.3 Validate/Certify System Performance in its Operational Environments

To validate and certify that a system is going to work properly, it must be tested in its operational environment. Currently, no single ground-based test facility is capable of replicating the environments that an HV will encounter, and CFD models are still too immature to be used as the sole basis for validating or certifying an HV drawbacks (Jiang and Yu 2017). Subsystem and component level testing, CFD simulation, and wind tunnel testing can add to the body of evidence needed to give confidence that an HV will perform as designed. Ultimately, a flight test must still be performed to fully validate and assure that the major subsystems (scramjet engine (Mercier 2003), control system, thermal protection system [TPS], etc.) in the HV, and the HV as an integrated system, perform as expected for the missions for which they were designed (Gubrud et al. 2015; Van Wie et al. 2004; U.S. Dept. of State n.d.).

As Mark Gubrud stated: “It is inconceivable that hypersonic weapons could be perfected and validated for operational use without extensive additional testing programs” (Gubrud 2014). Until there is a more intimate understanding of the physics that affect HVs, flight testing will be required to validate a system (Gubrud 2014) because it is still the best technique to provide confidence in the basic design, effectiveness, and operational capability (“Ballistic Missile Defense” n.d.).

C.3 Identify Unanticipated Problems

Since flight vehicles rarely perform completely as expected (Kuntz and Potter 2008), flight testing is required to discover issues that cannot be understood or known unless a completely integrated system has been tested (U.S. Dept. of State n.d.). Issues with design, manufacturing or environments (Bertin and Cummings 2006) may not appear until a full system test has been performed (U.S. Dept. of State n.d.). Subsystems that work well when tested by themselves may not work with one another or as anticipated in a flight environment. Finite element analysis (FEA) and/or CFD models are very helpful in guiding a design, but rigorous testing of a full system is still needed to identify unanticipated issues (Gubrud et al. 2015; KOB-TV 2018; Lewis 2013).

One example of unanticipated issues that appeared only during a flight test is first flight test of DARPA’s HTV-2. The amount of heating that the HTV-2 experienced surprised its designers (James Martin Center 2015). After analyzing the flight test data, the engineers discovered that the materials’ response and the boundary layer transition behavior had not been as expected (Lewis 2013). Though developing a fieldable system was not one of the goals of the HTV-2 project (“Falcon Hypersonic” n.d.), the early termination of both flight tests demonstrated that it is extremely difficult to design an aerospace vehicle without flight testing (Gubrud et al. 2015) to ensure that there are no unanticipated problems to be fixed.

C.4 Risk Reduction and to Demonstrate Technology In Flight

Technology demonstration and risk reduction can be discussed together because often when a technology is being demonstrated, it is both to show that it works as intended and to uncover any potential issues or show-stoppers that could prevent the technology from being applied in the future. As these technologies reach a certain level of maturity, test flights are often performed for additional design refinement and to demonstrate the technology (Coleman and Faruqi 2009). After demonstrating the technology, additional testing and analysis often must be conducted before the technology can be considered ready for application in future HVs (McClinton 2006).

The U.S. Air Force's X-51A Waverider is an example. According to the Air Force's X-51A Fact Sheet, "The X-51A program is a technology demonstrator and was not designed to be a prototype for weapon system. It was designed to pave the way to future hypersonic weapons, hypersonic intelligence, surveillance and reconnaissance, and future access to space" (U.S. Air Force 2011). By flying a vehicle that produced positive thrust, the X-51A program also demonstrated that hydrocarbon-fueled scramjets are possible (U.S. Air Force 2011). The X-51A is considered the first vehicle of its kind to fly (U.S. Air Force 2011). The X-51A program also reduced the risk of future hydrocarbon-powered scramjet programs, because these programs can build on the X-51A flight with a focus on refining the technology rather than having to prove that it works.

DARPA's Falcon HTV-2 program had similar objectives. The stated goal of the program was "to conduct flight tests that demonstrate and validate technologies crucial to flight at hypersonic speeds" ("Falcon Hypersonic" n.d.). These technologies could then be applied to future HV programs with less risk.

Another way to reduce risk and/or demonstrate the technology is via incrementally advancing select technologies to a higher Technology Readiness Level (TRL) (Coleman and Faruqi 2009). NASA's Next Generation Launch Technology (NGLT) program was one such program. It was arranged so that every iteration incrementally built on the last (Moses et al. 2004). Among other results, the program provided performance data that could be used to reduce development risks for future HVs and a flight demonstration of other chosen technologies (Moses et al. 2004). The program was also structured in a way that produced decision points and off-ramps that would allow the technology to be developed and demonstrated in a cost-effective manner (Moses et al. 2004).

The U.S. BMD system is another example of incrementally advancing a system to reduce risk and demonstrate technology. Failure of a missile defense interceptor during a conflict would have catastrophic consequences, so the risk of failure must be driven as low as possible. During the test and evaluation phase of the Aegis BMD system, the philosophy was "test, fix, test" (Leslie and Marron 2009). This method gave the United States confidence ("Ballistic Missile Defense" n.d.) that the system risk was as low as possible and demonstrated that the technology used in the BMD interceptors worked as designed. Today, the Aegis BMD system is still undergoing incremental updates and will continue to be tested.

C.5 Political Messaging

Technical goals are not the only reasons for flight testing. Occasionally, flight tests are performed to send adversaries a political message. When a country conducts a flight test of an aerospace vehicle, other nations are likely to observe the testing, both covertly and overtly. The country conducting the testing is

also generally aware that others are watching (Gubrud 2014). Knowing that others are watching (your flight test) tends to be a good time to send a political message.

In early 2007, China created a lot of debris dangerous to other satellites (Hsu 2008b) in Low Earth Orbit (LEO) by shooting down an aging weather satellite (Choi 2007; Hagt 2008). This test demonstrated to the world that China was not only developing hit-to-kill ballistic missile defenses, but also had anti-satellite (ASAT) capabilities (Hagt 2008; Lewis 2014). While officially the Chinese Foreign Ministry insisted that “[t]his test was not directed at any country and does not pose a threat to any country,” some believed otherwise. Xu Guangyu, a former Chinese Army officer who is now an official at the government-run China Arms Control and Disarmament Association, said that the test was meant to press the United States into negotiations for an international treaty limiting the use of space for military purposes [51]. This test also sent a loud message that no asset, not even those in space, is out of reach or, at least, not for long.

A little over a year later, the United States destroyed one of its own satellites with a missile launched from the sea (Hsu 2008b). The United States targeted a defunct spy satellite, stating that the satellite’s hydrazine tank could be a potential hazard to people on the ground and so wanted to “reduce the danger to human beings” (Hagt 2008). Many experts have questioned the stated motives and whether the potential benefits outweighed the risks (Hsu 2008a). Stephen Young, the senior analyst in Washington, DC, for the Union of Concerned Scientist’s Global Security Program, said that the test sent a political message to China and Russia. He believes they got the message (Hsu 2008b). The United States and other nations would likely continue to send political messages during HV, BMD, and other aerospace tests (“Ballistic Missile Defense” n.d.).

Table C-1 summarizes the six purposes of flight testing discussed in this section.

Table C-1. Summary of Flight Testing Purposes and Benefits

Purpose of Flight Testing	Benefits
Generate information unique to flight test environment that is not available on the ground	- For flight-like testing, multiple parameters must be simultaneously controlled (Bowcutt 2014; Leslie and Marron 2009) No single ground-test facility can currently do this (Bertin and Cummings 2006) - Combined and interdependent environments in some of an HV's operating envelope (Boyce et al. 2011) cannot be duplicated in ground testing
Obtain data to anchor/validate models and to verify ground test data	- Flight test data helps anchor CFD models and improve their simulation capabilities. - CFD models are used to help verify the performance of designs (Mercier 2003; Moses et al. 2004) and must be validated. - Flight testing is currently the only method to test HVs at full-size aircraft scale (Dolvin 2008). - Information must be extrapolated from hypersonic wind tunnel data and correlated with flight test data to calibrate the wind tunnel and verify its accuracy (Bertin and Cummings 2006).
Validate system performance in its operational environment and/or for certification of the system	- No way to completely replicate all environments an HV will encounter via testing on the ground. - Flight testing is the only way to validate and assure that the vehicle performs as expected in its flight environments - HV cannot be certified for operation without the body of information produced during a flight test.
Identify unanticipated problems	- Discover unknown system-level vehicle problems (U.S. Dept. of State n.d.). - Identify design, manufacturing or integration (Bertin and Cummings 2006) that may not show up until a full system test is performed (U.S. Dept. of State n.d.).
Risk reduction and to demonstrate technology in flight	- Show that technology works as intended - Find any potential issues or show-stoppers that may prevent the technology from being applied in the future - Additional design refinement - Demonstrate what the technology can do (Coleman and Faruqi 2009) - Incrementally advancing select technologies to a higher TRL (i.e. "Test, fix, test") (Coleman and Faruqi 2009) - Provided performance data that can help reduce risk (Moses et al. 2004)
Political messaging	- None of your assets, not even those in space, are out of reach or, at least, not for long - We can counter your weapons

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APPENDIX D: CIVILIAN HYPERSONIC VEHICLE ENABLING TECHNOLOGY

D.1 Propulsion

Arguably, the two most important characteristics of a propulsion system are specific impulse and available thrust (Sziroczak and Smith 2016). Specific impulse is a measure of efficiency for the propulsion system's engine. It is the ratio of the thrust generated divided by the fuel flow, which can be in either weight flow (N/s) or mass flow (kg/s) (Sziroczak and Smith 2016). If weight flow is used, the specific impulse has the dimensions of seconds (s) and could be described as the amount of time that 1 kg of fuel can deliver 1 N of thrust (Sziroczak and Smith 2016). A higher specific impulse means that more thrust is produced for the same amount of fuel. As Figure D-1 shows, a turbofan has the highest efficiency, peaking at below Mach 1, while a ramjet becomes more efficient at about Mach 3 (Segal 2004). Beyond Mach 5, a scramjet is more efficient than a ramjet and its specific impulse approaches that of a rocket at higher hypersonic speeds (Segal 2004). A rocket has the lowest, but a constant specific impulse throughout its flight speeds (Segal 2004).

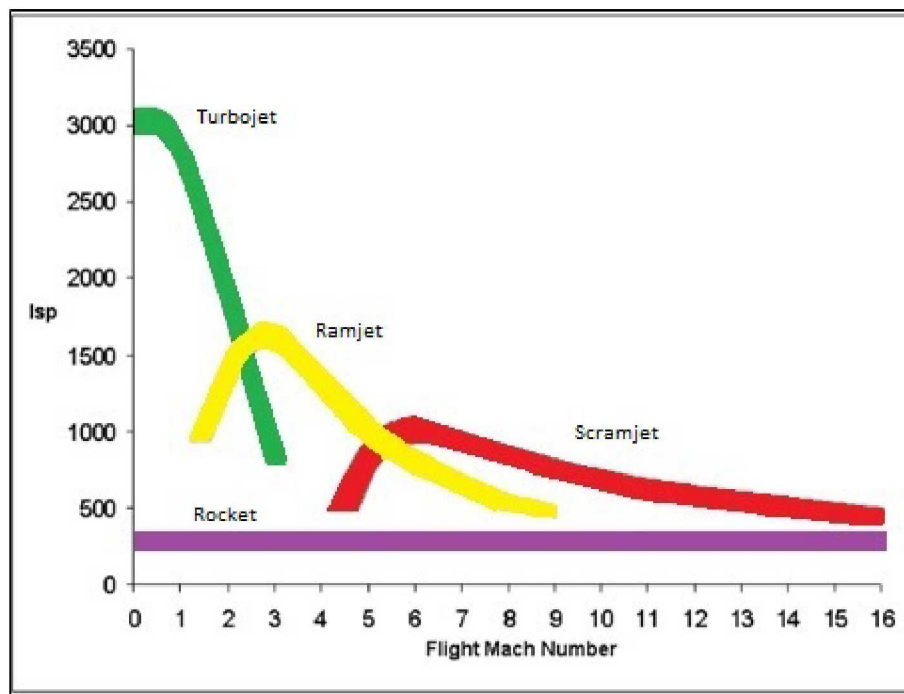


Figure D-1. Specific impulse ranges as a function of Mach number¹⁴

Available thrust is the second important characteristic of a propulsion system. A high specific impulse does not necessarily mean that the propulsion system is capable of launching a vehicle into space, or even off the ground. To do that, a propulsion system needs to have high available thrust. An example of high specific impulse/low thrust is the ion-propulsion system, which some spacecraft employ (Sziroczak and Smith 2016). Their specific impulse is on the order of 6000 to 10000 s but can only provide a thrust of around 0.05 to 3 N (Sziroczak and Smith 2016). For comparison, each of the nine Merlin 1D engines on the Falcon 9 Block 5 produces 845 kN of thrust (Space Exploration Technologies Corporation 2015).

¹⁴ Segal, C. *Propulsion Systems for Hypersonic Flight*. University of Florida, Gainesville, 2004. Available at: <https://pdfs.semanticscholar.org/0735/caedc6c67eaa57bb538f81edc920697999f.pdf>

There are numerous types of propulsion systems for aerospace vehicles. They are typically categorized by the type of engine(s) that they employ. The most common propulsion systems currently in development or in use feature one or more of the following: turbine engines, rocket, ramjet, scramjet, turbine-based combined cycle (TBCC), and rocket-based combined cycle (RBCC). A brief description of each system, including pros and cons, is presented below.

D.1.1 Turbine Engines

Turbine engines are the most common propulsion system for aeronautic vehicles. Most current airplanes, helicopters, and some cruise missiles feature a variation of the turbine engine in their propulsion systems. Turbine engine propulsion systems can be used for horizontal take-off and to propel a hypersonic vehicle (HV) to low supersonic speeds (Sziroczak and Smith 2016). Currently, turbine engines cannot themselves propel a vehicle to hypersonic speeds and cannot work outside of the atmosphere, because they rely on the atmospheric air to supply oxygen for combustion (Sziroczak and Smith 2016).

Two turbine engines in widespread use are the turbojet and the turbofan. Another common use of a turbine engine, the turboprop, does not appear to be a suitable choice for HV operations due to its low speed operating limits (Sziroczak and Smith 2016). A turbojet engine is a type of turbine engine in which all of the air taken in passes through the combustion chamber of the turbine. It is considered the first and simplest type of turbine engine (Hall 2015d). This type typically consists of an air inlet, a compressor, a combustion chamber, a turbine, and a nozzle (Hall 2015d). Though turbojets have a high specific impulse, high exhaust speed, and are relatively simple, they are much noisier and use more fuel than a turbofan (Sziroczak and Smith 2016).

Outside of some cruise missiles (“Difference Between” 2012) and military aircraft, turbojets are not widely used today. Turbojets are no longer used in commercial aircraft (Kurzke 2010) and have been supplanted in slower aircraft by turboprops and in medium speed aircraft by turbofans (Hall 2015d). Figure D-2 is a diagram of a turbofan engine. A turbofan can be thought of as a turbojet that is driving a ducted fan (Hall 2015d). In a turbofan, both the turbojet and the ducted fan sections contribute to the overall thrust of the engine (Hall 2015c). In a turbofan, some of the incoming air passes through the fan and into the combustion chamber, while the rest passes through the fan, flowing around the engine altogether (Hall 2015c). Compared to a turbojet, a turbofan is much quieter, more efficient, and often delivers more thrust (Hall 2015c). Currently, both turbojets and turbofans have a technical limit somewhere between Mach 3 and 4 (Kurzke 2010), which means that a turbine-based propulsion system would not be capable of accelerating a vehicle to hypersonic speeds. A turbine-based propulsion system would have to be combined with another type of engine to reach hypersonic speeds.

D.1.2 Rocket

Rocket engines are the most common propulsion system for astronautic vehicles. Virtually all current spacecraft feature at least one stage that is rocket powered. A rocket carries both the fuel and an oxygen source onboard, so it does not rely on atmospheric oxygen, allowing for operation outside the atmosphere (Sziroczak and Smith 2016). A rocket’s thrust varies with altitude, because the nozzle is optimized for one altitude, but its specific impulse remains constant throughout the flight (Sziroczak and Smith 2016). A rocket engine works by mixing the fuel and oxidizer in the combustion chamber where it is burned, creating a hot exhaust gas. The hot gas is passed through a nozzle, which accelerates the hot gas to high

velocities. The rocket's reaction to the accelerated exhaust gases pushes the rocket in the opposite direction (Hall 2015b). Figure D-3 is a diagram of a simple rocket and the forces acting on it.

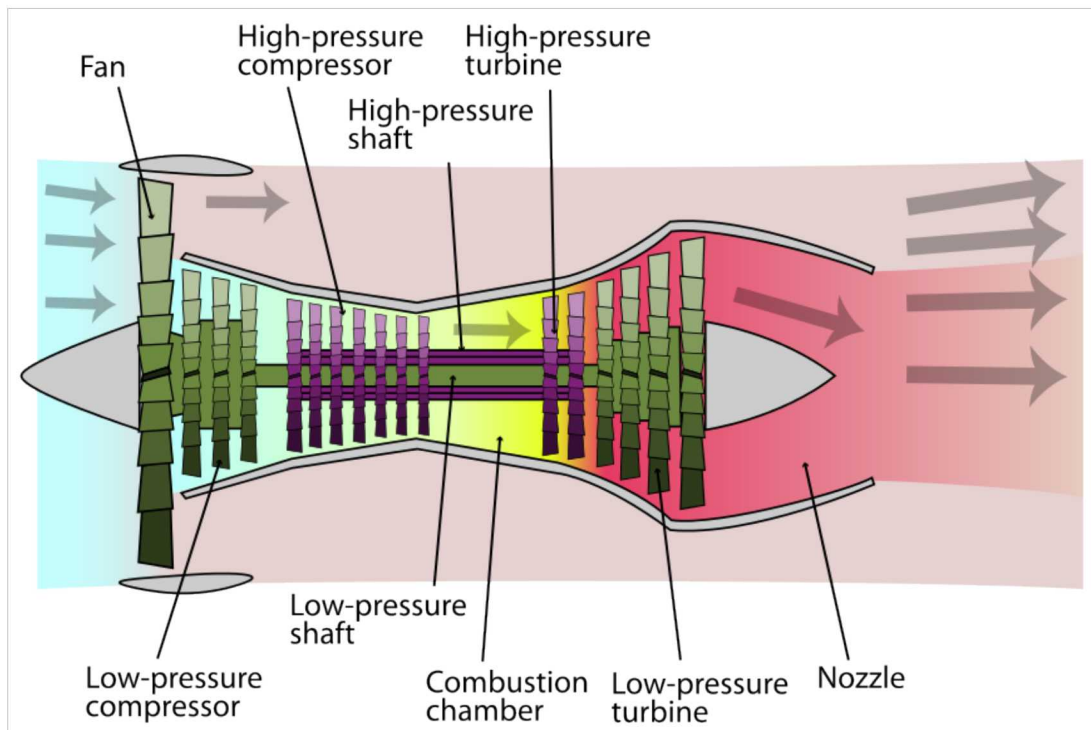


Figure D-2. Diagram of a turbofan engine¹⁵

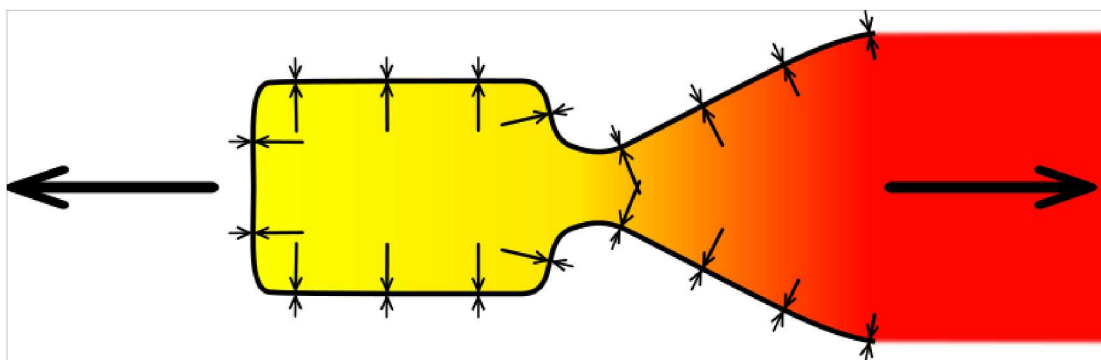


Figure D-3. Diagram of a simple rocket and the forces acting on it¹⁶

A rocket can use either liquid propellant or solid propellant. In a liquid propellant motor, the oxidizer and the fuel are stored in separate tanks and are moved and mixed in the combustion chamber via pumps. An ignition source ignites the mixture to produce hot gases. In a solid propellant motor, the oxidizer and the fuel are mixed together and stored as a solid in a cylindrical combustion chamber. The solid propellant is then ignited to produce the hot gases necessary to provide thrust. In a liquid propellant motor, the thrust can be stopped by turning off the propellant pumps, while a solid propellant motor cannot be turned off

¹⁵ By K. Aainsqatsi - Own work, CC BY 2.5, <https://commons.wikimedia.org/w/index.php?curid=4005530>

¹⁶ By Hohum - Own work, Public Domain, <https://commons.wikimedia.org/w/index.php?curid=7342187>

once ignited. Generally, a liquid propellant rocket sits empty until just before launch when the propellant is loaded; a solid motor can sit for many years filled with propellant. The biggest advantages of rockets over other engines is that they have the highest thrust, can power a vehicle from a standstill to very high hypersonic velocities, can work in and out of the atmosphere, and currently are the only engine used to insert a vehicle into orbit (Hall 2015b). The downsides to rocket-based propulsion systems are that their efficiency is low (specific impulse that is much lower than other propulsion systems) (Segal 2004), they are normally not optimized for more than one altitude because of the complexity to do so (Sziroczak and Smith 2016), and they are typically not reusable.

D.1.3 Ramjet

A ramjet engine is a relatively simple and lightweight propulsion system without moving parts (Hall 2015a). It consists of an inlet, combustor (which houses a fuel injector and a flame holder), and a nozzle (Figure D-4) (Hall 2015a). In a ramjet, external air is “rammed” into the combustor by using the forward velocity of the vehicle (Hall 2015a). Fuel is then injected into the combustor where it is ignited, resulting in the production of hot gases. The hot gases are accelerated by the nozzle and exit at a high velocity from the rear of the nozzle. The reaction to this acceleration produces thrust (Hall 2015a). For a ramjet to work properly, the air entering the engine must be slowed to subsonic speeds (Sziroczak and Smith 2016). Ramjets can operate with a vehicle velocity from approximately Mach 0.5 to 5.5 (Sziroczak and Smith 2016). Below Mach 0.5, a ramjet will produce very little to no thrust, and above Mach 5.5, the propulsion becomes very inefficient (Hall 2015a). Since a ramjet produces thrust only when the vehicle is moving, some other type of propulsion system must be used to bring the vehicle up to a speed at which the ramjet begins to produce sufficient thrust (Hall 2015a). Ramjets are a great propulsion system because they have no moving parts (with the possible exception of a fuel pump) and so are reliable; are lightweight compared to other propulsion systems; do not have to carry their own oxygen with them; and are increasingly efficient as speed increases until their upper Mach limit (Seleznev 2018). The major drawbacks of ramjets are that they cannot produce any thrust from a standstill and are only efficient up to Mach 5 where aerodynamic losses become a dominant factor (Hall 2015a). Although ramjets are capable of propelling a vehicle to low hypersonic speeds, they cannot be the sole engine in an HV’s propulsion system. They must be augmented at low speeds to achieve thrust-producing velocities and at speeds above approximately Mach 5.5 by a more efficient engine.

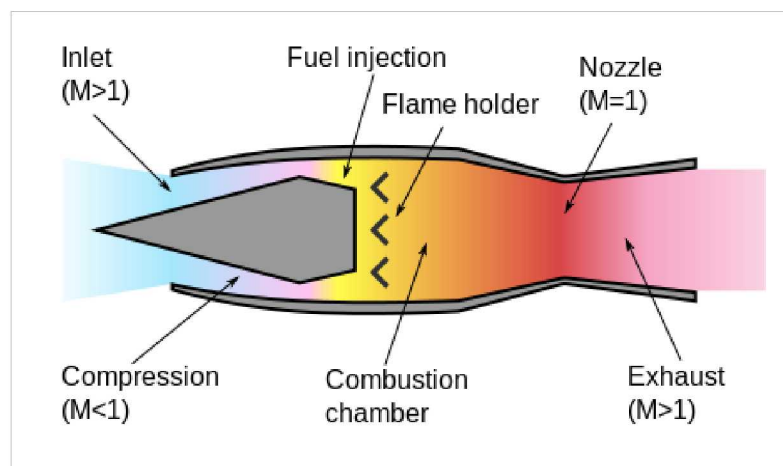


Figure D-4. Simplified diagram of a ramjet engine¹⁷

D.1.4 Scramjet

A supersonic combustion ramjet, or scramjet, is a variant of the ramjet engine (Figure D-5). It works similarly to a ramjet, except that the combustion occurs at supersonic speeds, whereas a ramjet must slow down the air to subsonic speeds before the combustion process (Sziroczak and Smith 2016). This characteristic allows the engine to operate at higher Mach numbers than a ramjet and to do so in an efficient manner (Sziroczak and Smith 2016). Like a ramjet, a scramjet has no moving parts, with the exception of a fuel pump (Wang et al. 2010). Though scramjet designs have been around for decades, scramjets only recently have been able to produce positive thrust in flight tests (Speier et al. 2017). Today, scramjets are still difficult to design and operate (Speier et al. 2017). Like a ramjet, external air comes into the compressor through a compressing inlet. Fuel is then added and ignited, producing hot gases. The hot gases flow through a diverging nozzle where they are accelerated to produce thrust (Hall 2015a). A scramjet cannot produce thrust unless it is accelerated to around Mach 5 or 6 (Marimon Mateu 2013). Because of this, a scramjet requires one or two other propulsion systems to get the vehicle to a velocity where the scramjet can start (Marimon Mateu 2013). The major advantages of scramjets are that they have no moving parts, do not need to carry onboard oxygen (unlike a rocket), are more efficient than rockets, and can operate at speeds up to around Mach 15 with current technology (Marimon Mateu 2013). Scramjets have some shortcomings including the requirement for a very high initial velocity to begin operation (Seleznev 2018), the need for keeping ignition/combustion stable during flight (Seleznev 2018), and the difficulty of testing them in ground-testing facilities drawbacks (Jiang and Yu 2017).

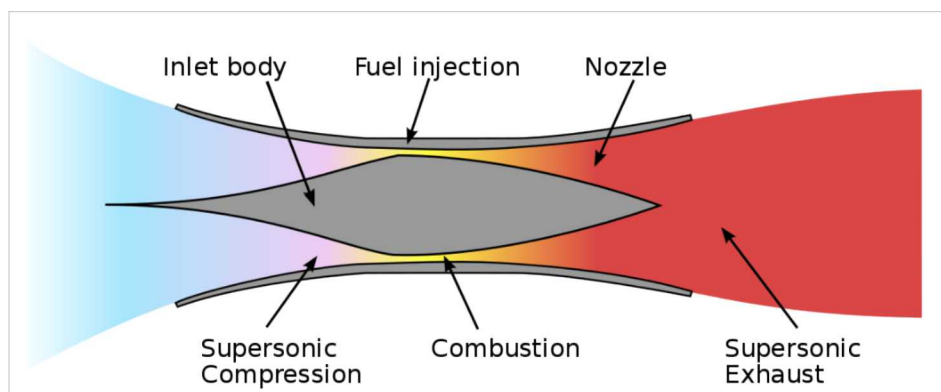


Figure D-5. Simplified diagram of a scramjet engine.¹⁸

D.1.5 Turbine-Based Combined Cycle (TBCC)

A turbine-based combined cycle engine is one of the two combined cycle propulsion systems that is being developed for future HVs. Figure D-6 shows a concept vehicle with a TBCC. It combines either a turbojet or a turbofan to bring the vehicle up to approximately Mach 3 (Sziroczak and Smith 2016). Next, either a ramjet takes over to accelerate the vehicle to low hypersonic speeds or a combination ramjet/scramjet (an engine that can transition between both modes) would take over in ramjet mode to reach low hypersonic

¹⁷ By Vector image made by Cryonic07. Sourcepng-drawing was made by Emoscopes and later slightly modified by Wolfkeeper - Based on Image: Ramjet operation.png This vector image was created with Inkscape, and then manually edited., CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=4533978>

¹⁸ By Scr30amjet_operation.png: en:User:Emoscopesderivative work: Luke490 (talk) - Scramjet_operation.png, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=10638859>

speeds (Smayda et al. 2012) and then transition to scramjet mode to accelerate to even higher velocities (Walker et al. 2013). The turbines are turned off and cocooned after the transition to ramjet mode, but before switching to scramjet mode (Walker et al. 2013). Lockheed Martin's SR-71 replacement is said to use a TBCC with a ramjet engine (Sziroczak and Smith 2016). TBCCs have multiple advantages. First, they allow an HV to take off horizontally and be powered during landing (Marimon Mateu 2013). This permits HVs to take off and land at airports (Walker et al. 2013), whereas vertical take-off vehicles need a specialized launchpad to begin flight and gives the HV the ability to abort during most of the flight (Marimon Mateu 2013). The horizontal take-off also lessens the need for additional infrastructure, reducing costs (Walker et al. 2013). Second, the TBCC can operate at or close to peak efficiency at all times. A turbine's specific impulse is unmatched at takeoff and in low Mach numbers. A switch to ramjet mode can be made when the ramjet has a higher specific impulse than the turbine, and then to scramjet mode when the ramjet's specific impulse drops below that of a ramjet (Segal 2004). TBCCs also have multiple drawbacks. They are much more complex than either a turbine-based, ramjet or scramjet propulsion system. The integration of the two systems may be the biggest issue. A TBCC propulsion system likely will have a common inlet and nozzle, which cannot easily be optimized for multiple systems (Tang and Chase 2008). Controlling the transition between modes in a reliable manner is also a difficult engineering challenge (Segal 2004). Another issue is that a TBCC requires carrying at least one propulsion engine that is not actively being used at all times (Segal 2004), meaning that there is some payload capacity that cannot be used for cargo. Finally, since a TBCC is made up entirely of air-breathing engines, they will be used only in HVs that stay within the atmosphere (Segal 2004). For exo-atmospheric flights, a rocket-based combined cycle is likely to be used (Segal 2004).

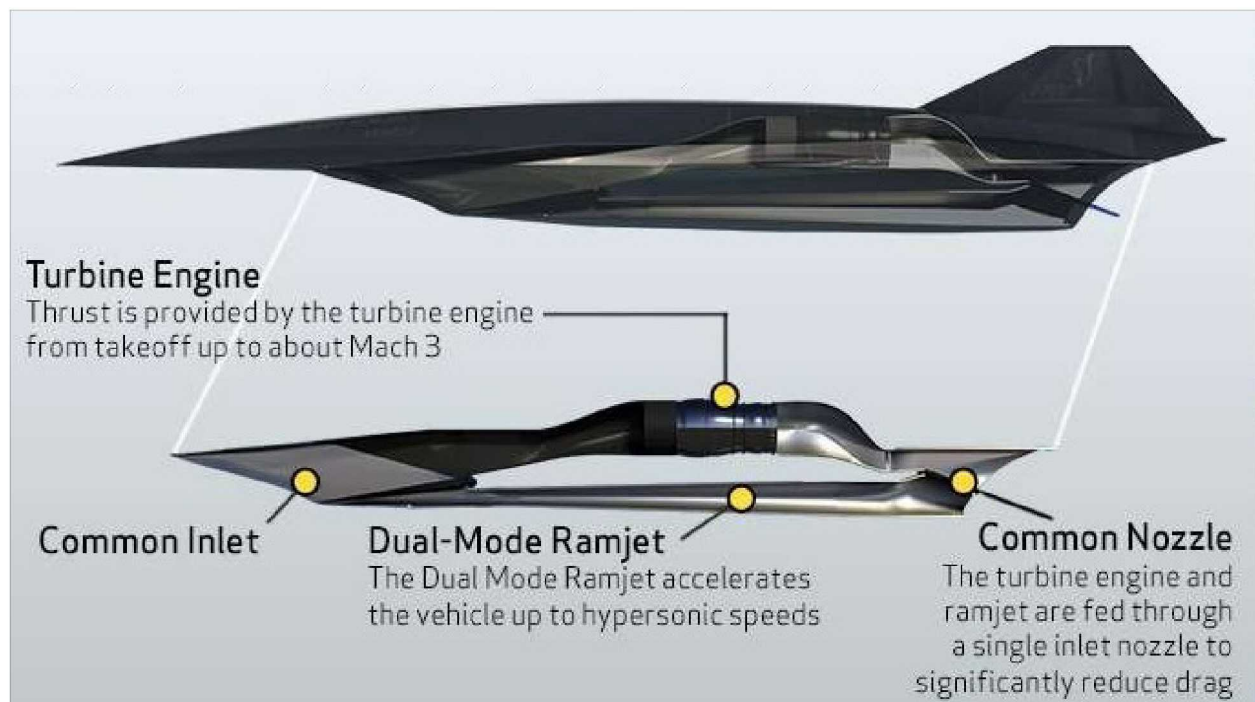


Figure D-6. Notional aircraft with a TBCC propulsion system¹⁹

¹⁹ "NASA Seed Funds SR 72 Hypersonic UAV", Accessed on 6/4/2018, <https://www.uasvision.com/2014/12/30/nasa-seed-funds-sr-72-hypersonic-uav/>

One of the most famous examples of a TBCC is the J58 engine that powered the SR-71 (Figure D-7). The J58 is considered a turboramjet because it combines a turbojet and a ramjet engine. At low speeds, the engine would operate in turbine only mode (Law n.d.). At about Mach 1.6, the TBCC would start to transition to ramjet mode and above Mach 3, over 80% of the thrust comes from the ramjet engine (Law n.d.). Though the J58 cannot propel an aircraft to hypersonic speeds, it did accelerate the SR-71 to Mach 3.2 and is likely to be a model for future combined cycle engines (Law n.d.).

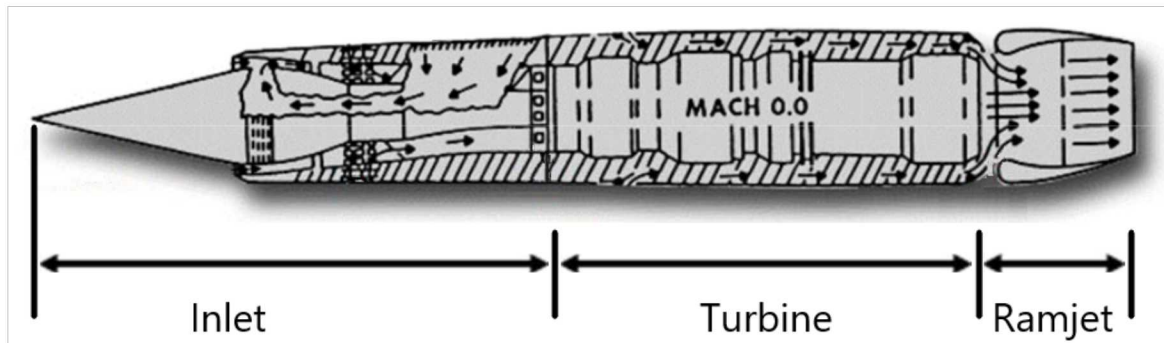


Figure D-7. J58 TBCC engine sections²⁰

D.1.6 Rocket Based Combined Cycle (RBCC)

A rocket-based combined cycle propulsion system is another type of combined propulsion system being developed for HVs. Figure D-8 shows a notional aircraft with an RBCC system. The RBCC system utilizes a rocket engine for propulsion at lower speeds. Then, depending on the design, it either switches to ramjet mode, followed by scramjet mode (Smayda et al. 2012), goes directly to scramjet mode (Segal 2004) or to ramjet followed by back-to-rocket mode (DeBonis and Yungster 1996), depending on the design. RBCC advantages include being able to give thrust from a standstill, operating more efficiently than either engine alone (DeBonis and Yungster 1996), being able to take off and land horizontally (Marimon Mateu 2013), not dropping pieces of its own structure during flight (e.g., fuel tanks or empty rocket stages) (Marimon Mateu 2013), being reliable based on the long history of rocket design, and operating outside the atmosphere to bring payloads to LEO (depending on the design) (Marimon Mateu 2013). The disadvantages are similar to the ones for TBCCs, mainly: increased system complexity compared to any single engine propulsion system, integration of multiple propulsion systems, especially the optimization of the inlet and nozzle (Tang and Chase 2008), controlling transitions between modes (Segal 2004), and having to carry an oxidizer onboard, thereby reducing payload capabilities (Segal 2004).

²⁰ “SR-71 Propulsion System P&W J58 Engine (JT11D-20)”, Accessed on 10/4/2018, <http://www.enginehistory.org/members/Convention/2013/Presentations/SR-71PropulsionSystem-2013.pdf>

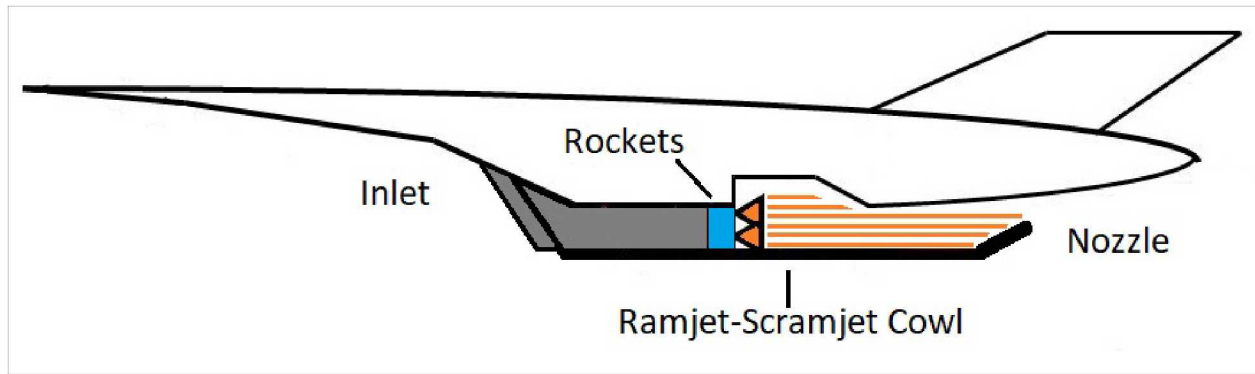


Figure D-8. Notional aircraft with a RBCC propulsion system

D.2 Aerodynamics

Designing an HV with high aerodynamic performance requires structures that change minimally during flight (or a control system that can compensate for it), understanding the transition from laminar airflow to turbulent, and optimizing drag and lift. Because there is no one method universally applicable to any shape when designing an HV, HV aerodynamic characteristics have been estimated through several compression and expansion methods, including Modified Newtonian, Newtonian-Prandtl-Meyer, VanDyke Unified, and Free Molecular Flow (Sziroczak and Smith 2016). An HV designer must have a good understanding of the fundamentals and underlying assumptions of each method (Sziroczak and Smith 2016). All these issues must be evaluated over the full range of speeds and altitudes, potentially with multiple control strategies, on a design-by-design basis (Sziroczak and Smith 2016). Experience and a database of HV flight data can help guide designers such that there is less trial and error and higher aerodynamic performance. Building a detailed database for HV design requires extensive testing, especially flight testing. HV design is further complicated by the fact that the actual HV flight environments experienced are often not what was predicted by ground tests or computational models (Coleman and Faruqi 2009). See sections 5.3.2.1, 5.3.2.2, and 5.3.2.3 for more detail about aerodynamics, including surface and shape design, lift, and drag.

D.3 Guidance, Navigation, and Control

The GN&C system is tasked with keeping the vehicle on the desired flight path, keeping the vehicle stable and steady in all known and unknown flight environments, and to ensure that unexpected vehicle motions do not become uncontrollable (Marrison and Stengel 1998). In the past, the GN&C analysis was often performed and completed after the conceptual design phase of a project was completed (Ouzts et al. 2009). This order was possible at that time because vehicle environments were well understood, past GN&C approaches and designs were well suited for the vehicle, and substantial performance margins existed (Ouzts et al. 2009). While this approach may work for many common, present-day aerospace vehicles, it is not sufficient for high-performance vehicles such as HVs. In fact, GN&C techniques used for conventional aircraft are not adequate and may lead to a design that is neither stable nor robust enough to withstand parameter uncertainties (Coleman and Faruqi 2009) because of the strong subsystem coupling experienced by HVs (Fidan et al. 2003). Since GN&C performance depends highly on the vehicle design and very small stability margins, GN&C designers must be involved in the design from the beginning. If not, GN&C designers may not be able to design a GN&C system to adequately manage the HV. This outcome could lead to a vehicle redesign, which can be very costly (Ouzts et al. 2009).

The strong coupling between the HV subsystems—such as the airframe and the propulsion system (Ouzts et al. 2009; Xu and Shi 2015), longitudinal and lateral axis coupling (Ouzts et al. 2009), aerothermo-elastic structural interactions (Ouzts et al. 2009), blackout phenomena experienced at higher Mach numbers (Hunt et al. 1998), erosion of control systems (Coleman and Faruqi 2009), rapid response times (Hunt et al. 1998), rapid change of mass distribution/movement of the center of gravity (Fidan et al. 2003), wide and varying operating conditions (Fidan et al. 2003; Xu and Shi 2015), and potentially long periods of autonomous flight (Hunt et al. 1998)—all pose substantial challenges to GN&C design for hypersonic flight conditions. These conditions cause an HV to be highly sensitive to any change in flight conditions and must be taken into account in a vehicle that is likely operating with small stability margins (Ouzts et al. 2009). This also requires sensors that can handle the wide-ranging environments, are designed and placed in such a manner so as to not detract from the HV's performance and can respond in sufficient time, given the velocity of the vehicle (Hunt et al. 1998). Furthermore, the GN&C system needs to be intelligent enough that it allows for and can compensate for those and other physical effects that may be caused by the high heat, such as wiring, electronics, and sensor damage (Coleman and Faruqi 2009).

D.3.1 Controls

The principal concerns of control systems are stability, performance, and robustness (Fidan et al. 2003; Xu and Shi 2015). A typical control system addresses these concerns during operation by adjusting a vehicle's controllable entities in response to a sensor output such that the vehicle's response follows a desired path (Fidan et al. 2003). Changes to the vehicle that were not accounted for or are outside of the control system's capabilities can cause vehicle responses to be unexpected, causing flight instability. A control system expressly designed to manage these issues simultaneously is needed.

While flying within the atmosphere, HVs experience considerable structural vibrations, which are intensified by high heating rates, thermal gradients, and aerodynamic loads (Speier et al. 2017). HVs will primarily consist of long and slender bodies that cannot be considered rigid. Thus, the effects of the body flexing during flight cannot be disregarded when designing the vehicle's GN&C systems (Banerjee 2016), though structural deformations that are allowed tend to be smaller than for subsonic vehicles (Beach 2012). The shifting of the center of gravity (CG) on HVs can be a problematic control issue as well. The large engines that HVs require are often mounted towards the back of the vehicle. Since fuel can be over 90% of the total mass of the HV, the CG tends to shift towards the heavier rear during flight (Sziroczak and Smith 2016), potentially causing vehicle instability. Pumping the fuel toward the front of the HV or using aerodynamic surfaces can help alleviate this problem (Sziroczak and Smith 2016) but must be done in a controlled and precise fashion to not cause (additional) vehicle instability. Pumping fuel to shift the CG will lose effectiveness as the fuel is combusted during flight. The effectiveness of aerodynamic surfaces also gradually falls as altitude increases and, as a result, air density decreases (Sziroczak and Smith 2016).

HV control systems must account for many possible simultaneous issues, making them very difficult to design. The control system of an HV must be able to detect and compensate these issues to keep the aircraft stable and performing optimally. Because of the speed at which the vehicle flies and at which changes can occur, any HV control system must be designed for fast changing conditions (Xu and Shi 2015). The HV control system must be robust enough to accommodate uncertainties in the flight environment (Coleman and Faruqi 2009) and in the vehicle's aerodynamics (Xu and Shi 2015). The

control system must be able to learn new information such as in-flight mission updates (Lu et al. 2013) and adapt to the information accordingly (Xu and Shi 2015). Finally, the HV control system must be fault tolerant, able to recover from damage or failures, whenever it is physically possible (Doman et al. 2006). The HV control system must do all of this actively throughout the entire flight.

Multiple strategies to control HVs during flight have been proposed including linear control, robust control, adaptive control, fuzzy logic control, and explicit control (Xu and Shi 2015), with robust and adaptive being the most common. Though the actual working of each control system will not be described in this paper, a brief overview is provided.

Adaptive Control. Adaptive control tries to maintain system performance, even when there are changes in the system's parameters (Banerjee 2016). Adaptive control systems can "learn" about parameter changes and flight issues, adjusting the system to manage the changes accordingly (Coleman and Faruqi 2009; Doman et al. 2006; Huo et al. 2006). A properly designed adaptive control system can sense changes in aerodynamic properties such as mechanical movements (flexing, bending, vibrations), material ablation/erosion (Speier et al. 2017), and movement of the CG, under a wide range of operating conditions in real time (Hunt et al. 1998), and compensate for them appropriately to maintain vehicle performance (Coleman and Faruqi 2009). Though adaptive control systems can make changes in real time, they operate better when compensating for both constant and slow-varying parameter uncertainties (Banerjee 2016). Adaptive controls can also compress preparation time for constructing mission operations plans as they can adapt to changes in mission profiles (Dolvin 2008). The biggest drawback for adaptive control systems is that they do not address disturbances, rapidly changing parameters (Banerjee 2016), modeling uncertainties (Fidan et al. 2003), or other control schemes. One recent use of adaptive guidance control was on the X-40A, which was the first display of an adaptive, fault tolerant landing system that also demonstrated the ability to withstand several control surface failures (Doman et al. 2006).

Robust Control. Uncertainties in hypersonic environments point to the need for robust control systems (Coleman and Faruqi 2009). Robust control systems are generally better at handling sudden/quick changing parameters and uncertainties in models (Banerjee 2016). Also, robust control is what has traditionally been used in aerospace vehicles for many years (Huo et al. 2006) and thus well understood. Because of these advantages, robust controls will likely be incorporated into the overall control system of an HV (Fidan et al. 2003). Current robust control techniques are insufficient to manage the broad range of environments HVs encounter because of the large uncertainties of said environments (Huo et al. 2006).

Propulsion System Control. The responsibilities of the vehicle control system do not stop with managing aerodynamic control. A separate but related issue is controlling the propulsion system. In an HV featuring a combined cycle propulsion system, the transition between the two propulsion units must be managed such that control is maintained over both engines, and both the vehicle and engines are kept within their environmental limits (Gubrud 2014) without disrupting the stability of the HV in flight. Flexing of the vehicle, especially the forebody, can affect the incoming shock waves impacting the scramjet's stability, thrust, and efficiency (Rodriguez et al. 2008). Propulsion system control compounds the already formidable technical challenge of the HV control system design.

Sensors. Sensors are a critical part of any control system, without which the control system would not function. They measure and provide vital vehicle state information such as temperature, pressure,

position, pitch, roll, yaw, velocity (Coleman and Faruqi 2009), acceleration, altitude, angle of attack, strain, heat flux (Hunt et al. 1998), combustion efficiency, fuel flow, and GPS position (Coleman and Faruqi 2009). The control system uses this sensor information to make any necessary adjustment(s) to reduce/eliminate deviations from the desired state. The control system also uses sensor information to assess vehicle health and to potentially compensate for any failures until the vehicle safely lands. Sensors for navigation are necessary for hypersonic flight so that HVs can know where they are, where they are going, and how far they might have deviated (Speier et al. 2017). The types of sensors needed for navigation and guidance include inertial measurement units (IMUs), GPS sensors, magnetometers, and visual imaging sensors (Coleman and Faruqi 2009).

D.3.2 Communications

Transmitting and receiving communication messages during flight is vital for HV flight. Communicating during hypersonic flight is challenging and requires multiple issues to be addressed. HVs can experience degraded radio and GPS communications because of the ionization of the surrounding air above Mach 5 (Speier et al. 2017). The potential resulting signal loss/attenuation, phase shift, and noise (Leslie and Marron 2009) could have a detrimental effect for a vehicle in hypersonic flight. The antennas required to send and receive these signals must be protected from the high heat environment (Hunt et al. 1998). The long range of HV flight may drive a need to develop a dedicated system of ground stations and/or satellites (Hunt et al. 1998). Possible solutions for the high heat load and blackout issues could be placing antennas away from the highest heat flux areas, using frequencies higher than the plasma cut-off frequency, and/or use other means of communicating besides RF (Hunt et al. 1998). DARPA's HTV-2 proved that solutions to communications issues are possible. HTV-2 was able to keep two-way communication and maintained GPS signal while traveling at Mach 17 (3.6 miles per second) (Erbland n.d.).

D.4 Thermal Management

As mentioned earlier, the amount of heat that the first flight of HTV-2 experienced surprised the designers (James Martin Center 2015). The extreme thermal load on the vehicle might have been managed with different thermal management techniques had the thermal environment been better understood (Figure D-9). The high thermal load that an HV experiences is dependent on the flight envelope, the heating rate, and duration of heating, all of which will influence the design decisions of an HV. To dissipate the heat that the HV is exposed to during flight (Dolvin 2008), a TPS is used. The type of TPS used is dependent on the flight vehicle and on the environments it may see (Tenney et al. 1988). TPSs are typically grouped according to function: passive cooling, semi-passive cooling, and active cooling, though most newer HVs use a combination of the three (Glass 2008).

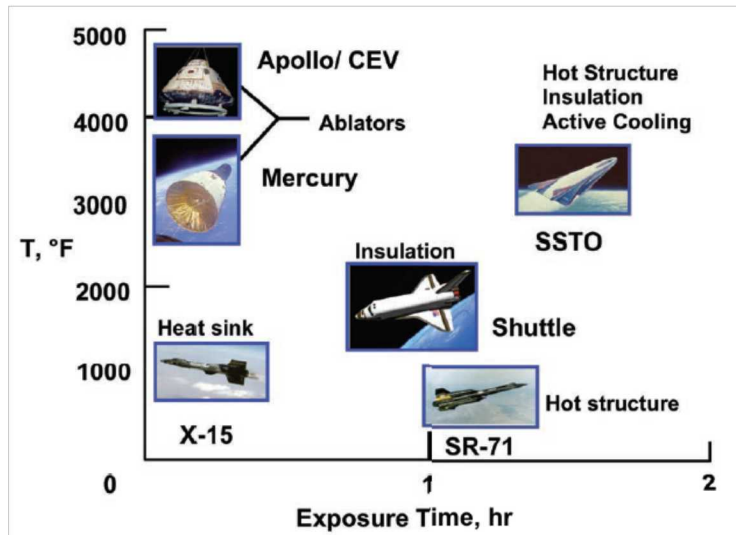


Figure D-9. Thermal management techniques, temperature vs. exposure time²¹

D.4.1 Passive Cooling

An insulated structure, a heat sink structure, or a hot structure are examples of a passive cooling TPS. Passive cooling is a non-mechanical way to cool a system and does not require a working fluid.

Insulated Structure. An insulated structure is typically suitable for moderate heat fluxes over relatively short times. This thermal management method is the most mature and most common (Glass 2008). An insulated structure works by applying a layer of insulation over the structure to reduce the amount of heat reaching the structure, thus keeping it relatively cool. Thermal radiation is the mechanism through which heat is removed from the surface of the HV using an insulated structure (Glass 2008). Because some HV designs include very small radii in the leading edges, a passive cooling system such as an insulated structure may be the only type of cooling available (Padture 2016). The Space Shuttle Orbiter's rigid and flexible ceramic tiles were used as the TPS to protect the underlying aluminum structure (Tenney et al. 1988).

Heat Sink Structure. A heat sink structure is one in which some heat is radiated away from the HV, and some heat is absorbed by the structure (Glass 2008). It has no separate insulation and is suited for moderate heat fluxes for shorter periods of time (Glass 2008). A heat sink structure relies on using a combination of materials that can withstand high temperatures and a structure that can dissipate the heat via conduction. If the heat sink structure is exposed to high heat loads for long periods of time, not enough heat may be removed, causing the structure to overheat (Glass 2008). One of the main advantages is that it is a relatively simple approach to thermal management. Disadvantages include heavy and expensive heat sink materials, and outer surfaces that must be relatively smooth (Tenney et al. 1988). The leading edges of the X-15 utilized a heat sink structure (Glass 2008).

Hot Structure. Hot structures work similarly to heat sink structures in that the structure is meant to absorb heat. Unlike a heat sink structure, a hot structure can handle moderate heat loads for longer periods of time. A hot structure relies on temperature capable (typically metallic) materials more so than a heat

²¹ Earl Thornton. 1996. "Thermal Structures for Aerospace Applications," AIAA Press.

sink structure (Huo et al. 2006), allowing the structure to reach steady state conditions (Glass 2008). Hot structures also conduct some of the heat inward and radiate the rest away from the HV. A titanium hot structure was used on the SR-71 Blackbird (Sziroczak and Smith 2016; Tenney et al. 1988).

D.4.2 Semi-Passive Cooling

A semi-passive structure uses a working fluid or other material to absorb heat from one location and move it to another for removal from the system. The two most common semi-passive cooling approaches that have been used in HVs are heat pipes and ablation. A heat pipe is a self-contained, two-phase heat transfer device (Glass 2008) (Figure D-10). The working fluid in the heat pipe absorbs the heat and evaporates. The vapor moves to a cooler section of the heat pipe, then the heat is transferred to the container via conduction, where it is radiated away from the structure. When the vapor transfers its heat to the container, it re-condenses into a liquid and flows back to the hotter section of the heat pipe (Glass 2008). Heat pipes are good for managing high heat fluxes over a relatively long period of time and are often used in leading-edge surfaces (Glass 2008). The National Aerospace Plane (NASP) program investigated using heat pipes on leading edges (Figure D-10) (Tenney et al. 1988).

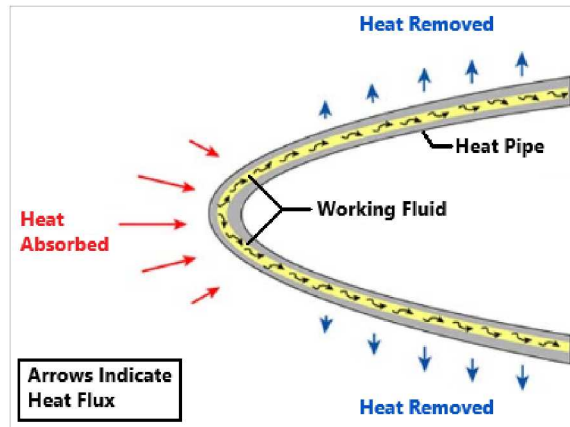


Figure D-10. Operation of a leading-edge heat pipe²²

D.4.3 Ablation

Ablation entails the use of an ablator material that is decomposed by the high heat loads of flight (Glass 2008). The ablative material absorbs the heat load and decomposes into gases, which act as a thin insulation coating on the surface of the structure (Sziroczak and Smith 2016). Ablative insulation can be used for areas that experience high heat fluxes for short periods of time. Ablation is only for single use, and thus would need rework after each use for multiple mission vehicles (Sziroczak and Smith 2016). The Apollo and Orion capsules used ablative materials in their heat shields (Glass 2008).

D.4.4 Active Cooling

For even higher heat loads over longer periods of time, active cooling will likely be required. Active cooling typically uses a coolant to protect the underlying structure. The structure operates hot but is kept within its operating limits by the active cooling (Glass 2008). Often, the HV's cryogenic (e.g., hydrogen) or hydrocarbon fuel, or a secondary coolant (e.g., water-glycol) are used as a heat sink (Sziroczak and Smith 2016; Tenney et al. 1988). This type of cooling is the most complex because it requires the design to take into account tubes, cooling passages, pumps, valves, passages, and/or additional fuels and coolants. Three types of active cooling that have been used on HVs are convective cooling, film cooling, and transpiration cooling (Glass 2008). Convective cooling works by circulating a coolant through tubes or coolant passages (Tenney et al. 1988) under the protective outer skin (Sziroczak and Smith 2016) to convect heat away from the structure, keeping the structure below its maximum operating temperature (Tenney et al. 1988). Film cooling works by injecting a coolant into the air flow as it moves over the HV in discrete areas (Tenney et al. 1988). The coolant is usually injected upstream of the air flow and can be added in one discrete location or in multiple locations as necessitated by the design. The coolant film acts as a thin insulating blanket over the structure (Tenney et al. 1988). The structure itself will still reach high temperatures and operate as a hot structure, but within its operating temperatures (Tenney et al. 1988). For transpiration cooling, coolant is injected continuously into a porous structure, over large areas, directly into the hot air flow. As with film cooling, the structure operates as a hot structure, but the heat flux into the structure is decreased by the coolant (Tenney et al. 1988). Though adding active cooling will increase the complexity, weight, and likely volume of the HV, the benefits are typically reduced modeling

²² Adapted from Glass, D. "Ceramic Matrix Composite (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles." Accessed June 4, 2018, <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080017096.pdf>

uncertainties due to aerothermodynamic effects and increased overall flight performance (Fidan et al. 2003).

D.4.5 High-Temperature Materials

High-temperature materials will play a critical role in the development and fielding of practical HVs (Dolvin 2008). While materials for ballistic missiles and their re-entry vehicles are considered mature, materials must be able to withstand even higher temperatures (Van Wie et al. 2004). Only the most temperature-resistant and robust materials will survive the extreme temperatures that HVs can experience during flight, especially at the leading edges (Hunt et al. 1998) and around the air-breathing scramjet engine (Fidan et al. 2003). These harsh environments greatly limit the materials that can be used in HV designs. Because of this, the behavior of high-temperature materials must be well understood and characterized for use in any HV (Lewis 2017). Any material that is not thoroughly understood needs to be so, or else catastrophic failures in HVs can occur. Though materials science research and development have resulted in materials that can survive severe hypersonic environments (Leslie and Marron 2009), they remain a primary bottleneck for many HVs (Padture 2016). The ideal high-temperature material for any part of an HV exposed to extreme temperature would be low density, high strength (Bowcutt 2014), high stiffness (Speier et al. 2017), durable in extreme temperature environments, easy to machine/fabricate/shape, resistant to corrosion and oxidation (Glass et al. 2006), while being available at a relative low cost. Engineers must also keep in mind the thermal conductivity, emissivity, and thermal expansion of the selected materials (Glass 2008). The temperature requirements alone typically exclude common aerospace materials such as titanium and aluminum unless they have a TPS to survive the HV environments. The principal material types used in most TPSs are metal alloys, ceramics, and composites (Sziroczak and Smith 2016).

Metal Alloys. Hypersonic metal alloys include titanium-based alloys and nickel/iron-nickel/cobalt-based superalloys (Mouritz 2012). Because of their unique combination of properties, titanium alloys are often used in aerospace applications such as jet engine parts, landing gear components, and airframe structures (Mouritz 2012). They have lower density than many other common metals, high corrosion and oxidation resistance, long fatigue life, and high strength. Titanium alloys can also be used in some HV applications, because they perform well up to 600°C (Mouritz 2012). For environments with temperatures above 600°C, titanium must have a thermal protective coating. Besides the relatively low temperature limits, the main drawback of using titanium alloys is expense and the need for specialized equipment and expertise in creating their machine/form (Mouritz 2012). Research and development on metallic alloys for use in extreme environments, such as those experienced by HVs, has occurred but research is more heavily focused on ceramics and composites.

Superalloys are a group of nickel, iron-nickel, and cobalt-based alloys that are commonly used in hot aircraft structures (Mouritz 2012). They have excellent heat-resistant properties and can be used up to 850°C environments (Mouritz 2012). Superalloys also have a high strength, long fatigue life, high fracture toughness, and high oxidation/corrosion resistance (Mouritz 2012). These superalloys also are more fully characterized, so their behavior under different operating conditions is understood better than metal matrix composites (MMC), ceramic matrix composites (CMC), and carbon-carbon composites (C-C) (Mouritz 2012). The main drawback of superalloys is that they have densities similar to steel, so their use may be limited in extremely mass sensitive applications (Mouritz 2012). The nickel-based family of alloys known as Inconel is one of the most commonly used superalloys (Dolvin 2008; Sziroczak and

Smith 2016). Inconel alloys contain at least 50% nickel by weight and 10% to 20% chromium for oxidation resistance (Mouritz 2012). They often have other alloying elements such as iron, molybdenum, niobium, and cobalt (Sziroczak and Smith 2016). As other advanced materials are better characterized and reach maturity, it is expected that use of Inconel and other nickel-based superalloys will drop (Mouritz 2012).

Ceramics. Ceramics have many desirable qualities for use in HVs. They have a high melting point, high compressive strength, high creep resistance, high modulus, and low thermal conductivity (Sziroczak and Smith 2016). The main drawbacks in using ceramics are that they are brittle, have low tensile strength, are not damage tolerant (requiring careful inspection before launch to evaluate their integrity), and may require continuous waterproofing (Sziroczak and Smith 2016; Tenney et al. 1988). The High/Low Temperature Reusable Surface Insulation (HTRSI, LTRSI) are the ceramic tiles that were used on the Space Shuttle (Tenney et al. 1988). The material, made from aluminoborosilicate and silica fibers, was developed and patented by NASA (Sziroczak and Smith 2016).

Hafnium/zirconium diboride are two new ultra-high-temperature ceramics under active development, which hold promise especially for heat shielding applications. Of the known ceramics, they have the highest melting point (3200°C, 5800°F) (Sziroczak and Smith 2016). Hafnium/zirconium diboride also have good oxidation resistance (Sziroczak and Smith 2016). Because of these properties, they could be used to create leading edges with a radius as low as 1 mm (Starkey et al. 2002) and so can be used on sharp nosecones (Sziroczak and Smith 2016). Currently, their main drawbacks are that they are difficult to manufacture in large and fully dense sizes (Padture 2016), the incorporation of reinforcement fibers may degrade other properties (Padture 2016), they rapidly oxidize in atomic oxygen (Padture 2016), and they are expensive to machine and process (Sziroczak and Smith 2016).

Composites. Composites are a class of material in which a matrix material is strengthened by the addition of fibers. The resulting material has different characteristics than the individual components. The most common composites used for aerospace applications are metal matrix composites (MMCs) and ceramic matrix composites (CMCs). The typical advantages of ceramics include higher strength, improved damage tolerance, lower thermal conductivity, and higher use temperature/melting point (Mouritz 2012). The most commonly used metals in MMCs are titanium (Ronald 1989), aluminum, copper, magnesium, and iron. The titanium aluminide superalloy, especially in the γ -TiAl form, is often used as the matrix material in MMCs and is designed to replace more conventional superalloys, such as Inconel (Ronald 1989). γ -TiAl with silicone-carbide (SiC) fibers as the reinforcement material has comparable structural performance to other superalloys, but a much lower density (Sziroczak and Smith 2016). γ -TiAl has high thermal stability, high modulus, and good oxidation resistance (Sziroczak and Smith 2016). Its drawbacks include low ductility at room temperature, low fracture toughness, fast fatigue crack growth rate (Sziroczak and Smith 2016), poor formability of the TiAl matrix, and a coefficient of thermal expansion (CTE) mismatch with the fibers, which can lead to microcracking from thermal stresses (Ronald 1989). Current manufacturing technologies are also inhibiting the wide-spread use of γ -TiAl (Shu 2014). Titanium diboride (TiB₂) and titanium carbide (TiC) are being researched to replace SiC as the strengthening material because there is less of a CTE mismatch and less possibility of developing microcracks (Ronald 1989). Further metallurgical research is ongoing to mitigate some of the other drawbacks by using different heat treatments or through alloying (Sziroczak and Smith 2016). The

integrity of the matrix-fiber interface will need to be validated by non-destructive evaluation (NDE) processes for use in HVs (Singerman and Jackson 1996).

Recently, ceramic matrix composites have been used in leading edges, external panels, and propulsion sections of HVs (Leslie and Marron 2009) (Ronald 1989). Currently, a lot of R&D activity is being conducted on CMCs (Padture 2016). CMCs are composed of a ceramic matrix material with ceramic fibers added for strength. CMCs are crafted in layers where a fiber preform in the shape of the part is first created, then the interface phase is deposited on the fibers, followed by the matrix phase being added to the empty spaces of the preform. CMCs have the advantages of ceramics (high melting point, high compressive strength, high creep resistance, high modulus, and low thermal conductivity (Sziroczak and Smith 2016)), with the added benefits of improved damage tolerance and toughness (Mouritz 2012). CMCs can survive for long periods of time in environments with temperatures well above what typical superalloys can withstand (Mouritz 2012). CMCs melting temperatures can surpass 3000°C, but their maximum use temperature will typically be closer to 1500°C (Mouritz 2012). CMCs tend to be less dense than superalloys (about 1/3 of the weight of a superalloy) (Padture 2016), and retain their stiffness, strength, and toughness properties close to their melting temperatures (Mouritz 2012). CMCs have multiple drawbacks as well. They are limited for use in less complex shapes because of their low interlaminar tension and shear strength (Mouritz 2012). Thick CMCs tend to need rework or they will have porous interior regions (Padture 2016), are more difficult than MMCs to attach to other engine parts (Padture 2016), are prone to recession of the matrix material in the presence of water vapor (Mouritz 2012), and can expose the fibers to attacks in certain environments if the matrix cracks (Mouritz 2012), though the last two can be mitigated with a barrier coating (Mouritz 2012). The low TRL levels that CMCs currently have mean that they will need to be further developed and tested before they can be viable in HV applications (Tang and Chase 2008).

Carbon/carbon (C-C), a specific type of CMC (Mouritz 2012), has been in use for many years, especially in aerospace applications. It is made of carbon fibers embedded in a carbon matrix. It is fabricated by infusing an organic matrix into fibrous carbon fabric and then pyrolyzing the resulting material to transform the organic matrix to carbon (Mouritz 2012). To obtain a stiff and strong composite, the infuse/pyrolyze process must be repeated several times since the initial composite material tends to be soft and porous (Mouritz 2012). C-C has good resistance to thermal shock, corrosion, and creep, has low CTE, high/stable mechanical properties at temperatures of 3000°C (though maximum use temperature is about 2200°C), and is mostly inert in a cosmic radiation environment (Glass 2008; Liu et al. 2014; Mouritz 2012; Rohini and Rao 1993; Sziroczak and Smith 2016; Tenney et al. 1988). It can be used to construct complex shapes as well (Sziroczak and Smith 2016). C-C has been used or is an ideal candidate for use on high-temperature areas of HVs such as the leading edges (Glass 2008; Ohlhorst et al. 2005; Sziroczak and Smith 2016), nose-cones (Tenney et al. 1988), engine nozzles (Liu et al. 2014), hot structures (Tenney et al. 1988), and load-bearing aeroshells (Glass 2008). Besides being expensive to fabricate and costly to machine (Mouritz 2012), the biggest drawback to the use of C-C in HVs is that C-C suffers from severe high-temperature oxidation, starting at 350°C (Liu et al. 2014; Mouritz 2012; Tenney et al. 1988; Van Wie et al. 2004). Without an oxidation-resistant layer, C-C composites must be restricted to short exposure times (minutes) or nonoxidizing environments (Tenney et al. 1988). An oxidation coating works by providing a diffusion-resistant layer to oxygen at elevated temperatures (Tenney et al. 1988). SiC is often used as the oxidation protection coating for C-C because it is chemically compatible with C-C and can be used in temperatures up to about 1650°C (3000°F) (Ohlhorst

et al. 2005; Tenney et al. 1988). However, SiC coating has a large CTE mismatch with C-C and is susceptible to cracking, allowing oxygen to penetrate the substrate (Tenney et al. 1988). Because of the CTE mismatch, thermal cycling due to multiple flights is a concern (Tenney et al. 1988). Were it not for the large CTE mismatch, SiC coatings would be all that is needed for effective protection against oxygen (Tenney et al. 1988). Currently, numerous research programs are focused on developing improved coatings that are more durable in HV environments (Tenney et al. 1988). Coatings based on Hf, Zr, Si, B, and Ir as well as carbides and oxides are being evaluated (Glass 2008; Ohlhorst et al. 2005; Tenney et al. 1988). Another drawback is that deformations caused during long exposures to high aerothermodynamic loads can lead to coating microcracking. This in turn can lead to hot gas contact and degradation of the C-C substrate, which can lead to a potential system loss (Van Wie et al. 2004).

D.5 Appendix D References

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