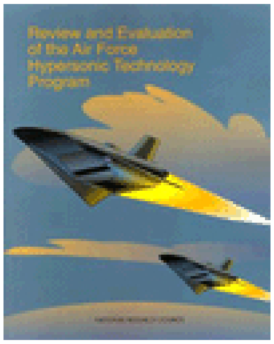

Review and Evaluation of the Air Force Hypersonic Technology Program

Committee on Review and Evaluation of the Air Force Hypersonic Technology Program, National Research Council

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Review and Evaluation of the Air Force Hypersonic Technology Program

Committee on Review and Evaluation of the
Air Force Hypersonic Technology Program

Air Force Science and Technology Board

Commission on Engineering and Technical Systems

National Research Council

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Acknowledgment

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the National Research Council in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

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While the individuals listed above have provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the National Research Council.

Preface

The U.S. Air Force has been investigating the enabling technologies for hypersonic systems for decades but has not produced an operational, air-breathing, hypersonic aircraft or cruise missile system. The National Research Council (NRC) was asked to examine the question of whether the technologies that are required for a hypersonic, air-breathing, hydrocarbon-fueled missile can be demonstrated in time to achieve an initial operational capability by 2015 (see the Statement of Task in Chapter 1 for the official charge to the NRC).

The members of the NRC study committee that I had the privilege to lead are experts in hypersonics and related technologies that are germane to the development of air-breathing hypersonic vehicles, and to aerospace management. The report deals directly with the questions asked by the Air Force and is as objective as possible. For this display of professionalism on the part of the committee, I am very grateful. The remarkable talents of the committee members made serving as their chair a special pleasure.

I also want to recognize the important contributions of the NRC staff, whose support of this study, which was often taken for granted, was monumental. Their behind-the-scenes efforts ensured a quality product. For their hard work and advice, I and the committee thank them.

A. Richard Seebass, *chair*
Committee on Review and Evaluation of the
Air Force Hypersonic Technology Program

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Abbreviations and Acronyms

DOD	U.S. Department of Defense
GPS	Global Positioning System
HyTech	Air Force Hypersonic Technology Program
NASA	National Aeronautics and Space Administration
NRC	National Research Council

Executive Summary

This study was undertaken in response to a request by the U.S. Air Force that the National Research Council (NRC) examine whether the technologies that underlie the concept of a hypersonic, air-launched, air-breathing, hydrocarbon-fueled missile with speeds up to Mach 8[1] can be demonstrated in time to be initially operational by 2015. To conduct the study, the NRC appointed the Committee on Review and Evaluation of the Air Force Hypersonic Technology Program, under the auspices of the Air Force Science and Technology Board.

BACKGROUND

Since 1935, engineers have been developing technologies for hypersonic aircraft and missile systems that can fly faster than the speed of sound in the atmosphere. More than 30 years ago, the rocket-powered X-15 reached hypersonic speeds (i.e., greater than Mach 5) in the atmosphere. However, other hypersonic projects (e.g., the ambitious national aerospace plane) have not led to the development of an operational aircraft.

Hypersonic systems would have many benefits. For example, a hypersonic missile capable of an average speed of Mach 6 (i.e., approximately one nautical mile per second at the planned operating altitudes) could strike a time-sensitive target 250 to 500 nautical miles away in four to eight minutes.

Hypersonic Technology Program

The Air Force Hypersonic Technology (HyTech) Program was established in 1995. Originally, the program was focused primarily on scramjet[2] engine technology, with a companion program in airframe technology. Soon after it was begun, however, the program was restructured to concentrate its very limited funds exclusively on developing scramjet engine technology. Two prime contractors investigating two engine concepts constituted the technical core of the program until early 1998, at which time one concept was selected. The selected engine concept is slated to be tested in ground test facilities in the 2001 to 2003 time frame.

Technical Problems

The characteristics of an operational, air-breathing, hypersonic missile will be determined by a combination of the desired capabilities, the necessary technologies, and the resources allocated by the Air Force. The magnitude of the technical problems for hypersonic vehicles depends on the maximum speed of the vehicle. From a technical standpoint, technology for a missile with Mach 8 speed would have to overcome several difficult problems to become operational by 2015. These technical problems are more challenging than those for a missile with a maximum speed of Mach 4 or Mach 6 and will require several step-changes in the technology.

Many examples could be cited showing how the difficulty of the technical problems escalates as the Mach number increases. The stagnation temperature of the oncoming air flow, for instance, increases from about 1,100°F at Mach 4 to about 2,500°F at Mach 6 and to about 4,200°F at Mach 8. The temperatures after combustion inside the engine are even higher (e.g., more than 5,000°F at Mach 8). No materials are known or projected that would be practical for a scramjet engine and could survive without active cooling at the maximum internal engine temperatures reached during Mach 8 flight in the atmosphere. At Mach 8, for example, an endothermic fuel-cracking system is necessary to cool some parts of the missile so they can survive the demanding flight environment.

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[1] "Mach 8" means eight times the speed of sound.

[2] A "scramjet" is a supersonic combustion ramjet (see Glossary).

Statement of Task

In discussions with the Air Force about this study, it was evident to the committee that the time has come for the Air Force to decide whether or not hypersonic technology can lead to a militarily useful product within a reasonable time. The main element of the Statement of Task was that the committee evaluate the HyTech Program by (1) focusing on "the technologies needed to demonstrate a hypersonic, air-breathing missile concept" and (2) emphasizing "the underlying strategy and key components of the program, the critical technologies that have been identified by the Air Force and by other sources, as appropriate (e.g., advanced propulsion systems using ramjet and scramjet technologies); and the assumptions that underlie technical performance objectives and the operational requirements for hypersonic technology." The committee was also asked to make recommendations based on its evaluation of the program.

To perform its task, the committee had to address specific questions, such as whether or not the HyTech Program would lead to a capability that could satisfy the operational requirements for hypersonic technology applications; what technologies (besides propulsion) should be pursued next, and with what priorities, for a hypersonic, air-breathing, air-to-surface weapon; and whether or not the technical components of a hypersonic Mach 8 regime propulsion technology program have been identified and are in place. The committee was also asked to estimate reasonable milestone dates for the development and initial production of a hypersonic missile system.

PRINCIPAL FINDINGS

When the committee began this study, many members assumed that the HyTech Program was a component of a broader program to demonstrate the technologies for a hypersonic, air-breathing missile system capable of speeds up to approximately Mach 8. Instead the committee found that, because the program has very limited funding, the underlying strategy has been to concentrate on the propulsion subsystem of a representative hypersonic vehicle and to conduct a limited ground-test demonstration of a single Mach 8 hydrocarbon-fueled engine flow path. Under the circumstances, the committee considers this a wise decision. However, the committee recognizes that the program does not include either full integration of the propulsion subsystem with a flight vehicle (which is especially important for a compact missile system) or flight testing. Furthermore, the Air Force's reliance on one propulsion contractor limits the alternatives for the engine design. To the committee's knowledge, the collateral technologies required for the entire missile system are not currently being developed.

Because the words "operational requirements" were emphasized in the Statement of Task, the committee was surprised to learn that the Air Force has not established operational requirements for a hypersonic missile system, although both the Air Force and Navy have established some general performance goals (e.g., top speeds of Mach 8 and Mach 6, respectively). The speed, standoff range, and kinetic energy of a hypersonic, scramjet-powered, air-to-surface missile could potentially enhance the warfighting capability of the U.S. military.

Reaching a maximum speed of Mach 8 will require significant technological breakthroughs. Thus, controlling risks will be crucial for the technology validation program, including flight testing of a prototype vehicle. The committee proposes a carefully designed program below. The completion of the HyTech Program by 2003, followed expeditiously by flight testing of a prototype vehicle, could enable an operational, air-breathing hypersonic missile with a maximum Mach number in the range of 6 to 8 by 2015.

SUMMARY OF RESPONSES TO QUESTIONS

The Air Force HyTech Program, as currently structured, will not lead to an operational capability because the Air Force is not developing several critical, enabling technologies for the realization of an operational hypersonic air-to-surface weapon. The HyTech Program is investigating many of the propulsion flow path technologies that would support the development of a Mach 8 missile. Nevertheless, because of budgetary limitations, there are still several significant technical uncertainties about the overall propulsion system. These uncertainties are manifested by the program's lack of focus on reducing technology risk and by the lack of flight tests.

The current HyTech Program does not have either a mandate or funds to provide a sound technical foundation for a weapon system. The Air Force will have to conduct extensive trade-off studies before it can establish operational requirements and determine specific design goals for a hypersonic missile system of the kind envisaged in the HyTech Program. Because of the committee's concern that the Air Force has not adequately analyzed the survivability of this class of missile, the committee undertook an additional study, which indicated that even at Mach 8 speed the missile will be vulnerable to surface-to-air missiles.

The committee's experience indicates that it will take until 2015 to develop, test, and produce the type of missile contemplated by the Air Force. A prototype missile phase would have to be initiated in 2003, and prototype flight testing would have to be completed by 2007 to reduce the risk for the engineering and manufacturing development phase.

The HyTech Program is not formally coordinated with or intentionally dependent on hypersonic initiatives of the U.S. Department of Defense or the National Aeronautics and Space Administration, although they are sharing relevant technical information. Organizations throughout the world have developed expertise on scramjet-powered hypersonic vehicles, but no system-level hardware seems to be available.

The committee believes that the Air Force should continue to evaluate potentially significant foreign technologies.

The implications for the Air Force support infrastructure of acquiring a hydrocarbon-fueled hypersonic missile are strongly dependent on the maximum speed of the missile. The implications include the amount of investment in ground testing and flight testing, as well as the analytical resources required to determine the performance and operability of the propulsion system. If the maximum Mach number is below 7, an existing test facility could be used with relatively minor modifications. The Air Force is also considering making modifications to at least one facility to support a Mach 8 capability. Regardless of the maximum Mach number, the Air Force must have the capability for periodic destructive testing of selected missiles from storage.

The Air Force could benefit from using hypersonic vehicles after 2015, particularly for enhancing its global reach and access to space. Hypersonic technologies could be pursued either along a broad front or through a more focused program of evolutionary development to meet clearly stated requirements. The committee believes that only the focused program will result in operational systems. Therefore, the committee developed a long-range planning process with four components to guide the Air Force's development of hypersonic systems for 2015 and beyond.

CONCLUSIONS AND RECOMMENDATIONS

Conclusion 1. The Air Force's HyTech Program, which is a Mach 4 to Mach 8 propulsion technology flow path program, is necessary but not sufficient for the development of a scramjet engine as an integral part of a missile system. Although the limited testing (ground testing only) planned for the propulsion subsystem should indicate its potential engine performance, flight testing over a representative range of operating conditions will be necessary to determine the engine's operability, reliability, and durability in an integrated system. These parameters are prerequisites to understanding the engine's utility in an operational system.

Recommendation 1. The Air Force should commit appropriate resources to integrated airframe-engine flight testing, which is vital to demonstrating a hydrocarbon-fueled scramjet in the Mach 4 to Mach 8 range. This recommendation (and the related recommendations that follow) assumes that the Air Force will decide that a hypersonic air-breathing propulsion capability is a potential candidate for fulfilling future system needs (e.g., as part of a hypersonic missile or space access application). If the Air Force is not willing to commit to flight testing, it should reevaluate its goals for the development of air-breathing hypersonic technology.

Conclusion 2a. The HyTech Program itself will not provide the basis for an operational missile system because the development of critical enabling technologies for hypersonic air-breathing missiles are not included in the program and, to the committee's knowledge, the Air Force is not pursuing them. These critical technologies will have to be mature and validated before the Air Force can proceed with a low-to-moderate risk acquisition program.

Conclusion 2b. Besides propulsion, the five most critical enabling technologies for air-breathing hypersonic missile systems, in order of priority, are (1) airframe and engine thermostructural systems; (2) vehicle integration; (3) stability, guidance and control, navigation, and communications systems; (4) terminal guidance and sensors; and (5) tailored munitions.

Conclusion 2c. If the HyTech Program were expanded to include a full-scale, integrated airframe-engine flight test program, and if the critical enabling technologies were mature, an operational air-breathing hypersonic missile system could be developed with low-to-moderate risk and without concurrency in support of an initial operational capability by 2015.

Recommendation 2a. If the Air Force determines that there is a requirement for a hypersonic missile system, then it should establish a system-oriented program office to manage the system design and the development, integration, and flight testing of critical enabling technologies for a hypersonic missile system.

Recommendation 2b. The program office should establish a road map to reach initial operational capability by 2015. The road map should include six phases: (1) system specification development; (2) system concept development; (3) technology risk reduction; (4) prototype design and flight test; (5) engineering and manufacturing development; and (6) low rate initial production.

Conclusion 3. The Air Force has not established operational requirements or conducted design and requirements trade-off studies in support of an air-launched hypersonic missile system.

Recommendation 3. If the Air Force intends to pursue the development of an air-launched hypersonic missile system as a viable candidate to meet its future warfighting needs, then it must initiate design and requirements trade-off analyses in the following areas: targets, speed, range, survivability, lethality, aircraft compatibility, risk, and cost.

Conclusion 4. The risk and cost associated with the development of hypersonic air-breathing systems increase significantly with higher cruise speeds. Scramjet technology or existing ramjet technology with nonendothermic fuel-cooled metallic structures could be used for Mach 4 to Mach 6 systems. Systems with a maximum cruise speed of Mach 6 to Mach 6.5 will require a scramjet, which uses nonendothermic fuel cooling or uncooled ceramic composite materials. Mach 8 systems powered by a hydrocarbon-fueled scramjet will require endothermic fuel-cooled engine structures.

Recommendation 4. The Air Force should expedite tradeoff studies in three areas: (1) mission parameters, to establish operational requirements; (2) system concepts, to define candidate configurations with optimum ranges of performance, operability, reliability, and affordability; and (3) technology, to redirect HyTech projects toward the most promising alternatives, if necessary.

Conclusion 5. A hypersonic air-breathing missile will affect primarily one aspect of the Air Force support infrastructure, namely, ground testing facilities. Existing test facilities can support full-scale propulsion performance testing only at flight speeds up to approximately Mach 7. Existing test facilities for testing propulsion system operability and reliability are limited. The HyTech Program has plans to upgrade an existing facility for propulsion reliability testing at the Mach 8 cruise condition. Hypersonic missile systems will have no obvious implications for two other areas of the Air Force support infrastructure, high-speed computational facilities and test ranges. Periodic destructive testing of scramjet engines will be necessary in the future.

Recommendation 5. The Air Force should begin planning for the ground test infrastructure to support the development and qualification of the operability, durability, reliability, and performance of integrated hypersonic propulsion systems over the Mach number range from the speed at the end of the rocket-boost phase to the maximum cruise speed. This infrastructure should be completed expeditiously.

Conclusion 6. The Air Force has two broad options for the development of hypersonic technologies for 2015 and beyond. The first is to pursue a broad range of technologies covering a variety of potential applications. The second is to pursue the evolutionary development and deployment of hypersonic weapon systems that derive from established capabilities and clearly stated Air Force requirements.

Recommendation 6. For 2015 and beyond, the Air Force should pursue the evolutionary development of hypersonic weapon systems and develop a long-range plan that incorporates the following four components: operational concepts for future systems and preliminary system designs; scramjet-powered weapon systems using hydrocarbon fuels; hypersonic weapon systems using hydrogen fuel; and combined-cycle systems for space access.

Conclusion 7. The committee is not aware of any other nation that has operational hypersonic scramjet-powered missiles; however, several nations have been working on development, evaluation, and testing, including flight testing, for several years. The Air Force is monitoring foreign developments in hypersonics technology adequately.

1

Introduction

In this chapter the committee discusses the background of the study, provides a brief technical prologue, presents the Statement of Task for the study, describes the strategy for conducting the study, and delineates the plan for the remainder of the report.

BACKGROUND

Since the historic fifth Volta Congress on High Speeds in Aviation,[1] which was held in Rome, Italy, in 1935, military and civilian engineers have developed aircraft and missile systems that can fly faster than the speed of sound in the atmosphere. The first official, manned, supersonic flight took place only 12 years later, in 1947. Yet today only one supersonic airliner, the Concorde, is in regularly scheduled operation. Although the Concorde is a marvel of technology, its development required significant investments by two nations, France and England. Larger, faster, more efficient supersonic commercial aircraft are under consideration, but they are still only a future possibility. Military aircraft and missile systems, worldwide, have routinely operated above the speed of sound for the past 40 years; some, like the SR-71 reconnaissance aircraft, can cruise at three times the speed of sound (i.e., at Mach 3). Missile and experimental aircraft systems have reached much higher speeds.

More than 30 years ago, the rocket-powered X-15 reached hypersonic speeds in the atmosphere (in this case, top speeds of six to seven times the speed of sound, or Mach 6 to Mach 7). Since that time, hypersonic projects have come and gone, including the air-breathing National Aero-Space Plane[2] Program. Air-breathing vehicles are more efficient and promise more flexible operations than rocket-powered vehicles. Most orbital air-breathing vehicle concepts would be gradually changed from air-breathing to rocket propulsion at speeds of Mach 10 to Mach 15, depending on the mission requirements. During the transition phase, the vehicle would rapidly gain altitude to avoid the weight penalties caused by high aerodynamic and thermal loads at lower altitudes. Very high speeds are best achieved outside the sensible atmosphere.[3]

For a variety of reasons, including that more was promised than the available technologies and underlying physics could provide, none of the hypersonic projects has resulted in an advanced operational capability for missiles or aircraft that can cruise at high speeds in the atmosphere. Some key reasons are discussed below.

PROLOGUE

The purpose of this section is to provide readers with some background for understanding the remainder of the report, which is focused on the content and pace of the Air Force program for the development of hypersonic propulsion technology. The objective of the program is to develop a technology base to support the future development of a hypersonic, scramjet-powered, hydrocarbon-fueled, air-launched missile that can reach speeds up to Mach 8.[4] The speed of Mach 8 appears to be the upper limit of what may be technically feasible using hydrocarbon fuels (Curran, 1997).

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[1] Interested readers should see recollections of the last surviving member of the historic conference (Professor Carlo Ferrari), Recalling the Vth Volta Congress, Annual Review of Fluid Mechanics 28:1–9.

[2] The national aerospace plane was to be a single-stage vehicle that could take off horizontally, proceed to orbit without staging, and return to earth and land horizontally. The primary propulsion system was a hydrogen-fueled engine.

[3] "Sensible atmosphere" is defined by the committee to be the portion of the atmosphere where the dynamic pressure remains significant. For example, the dynamic pressure is about one pound per square foot (48 Newtons per square meter) at a speed of Mach 10 at 270,500 feet (82,500 meters) and at Mach 15 at an altitude of 285,500 feet (87,000 meters). At these altitudes, the dynamic pressure increases by about a factor of 10 with a reduction in altitude of 46,000 feet (14,000 meters).

[4] See the glossary at the end of this report for definitions of technical terms, such as "scramjet."

The characteristics of an operational air-breathing hypersonic missile will be determined by a combination of the desired capabilities, the necessary technologies, and the resources allocated by the Air Force. The magnitude of the technical problems for hypersonic aircraft depends on the maximum Mach number. From a technical standpoint, technology for a missile with Mach 8 speed would have to overcome several difficult problems to become operational by 2015. These technical problems are more challenging than the problems associated with a missile with a maximum speed of Mach 4 or Mach 6.

Many examples could be cited of how the difficulty of the technical problems escalates rapidly as the Mach number increases. The best known example is that the stagnation temperature of the oncoming air flow increases from about 1,100°F at Mach 4 to about 2,500°F at Mach 6 and about 4,200°F at Mach 8. The temperatures after combustion inside the engine are even higher, about 4,000, 4,400, and 5,100°F for Mach 4, Mach 6, and Mach 8, respectively. A few brittle materials could survive the very high temperatures inside the engine, but they oxidize readily. No combination of base material and oxidation-resistant coating that could survive has been developed. No known or projected materials are both practical for use in a scramjet engine and able to survive the maximum temperatures without active fuel-cooling at Mach 8 flight in the atmosphere.

Step-changes in the technology will be required as the Mach number increases. Although the exact Mach number at which any step-change occurs depends on several factors, the changes that will be necessary in the Mach number range of 6 to 8 will be very challenging. These include, for example: (1) an endothermic fuel-cracking system to provide adequate cooling capacity (the cooling results when heat is absorbed to crack, or reform, the fuel into its lighter parts); (2) cooled engine structures that can function throughout the operational envelope of the missile; (3) high-temperature materials for leading edges subjected to external air flow; and (4) methods of piloting and stabilizing the combustion process. Some of this technology has already been developed and is available for specific engineering applications. Some requires further development. (See Chapter 2 for a discussion of the most pressing technical challenges.)

Figures 1-1 and 1-2 illustrate the flight environment of a typical hypersonic missile of the type considered in this study. The first figure shows the flight profiles for the notional Air Force Mach 8 scramjet missile and for a Mach 6 variant with the same metallic engine structure. Both engines are actively cooled with endothermic fuel. The Mach 6 missile has a range of approximately 1,200 nautical miles, which is about a 60 percent increase over the range of the Mach 8 missile (780 nautical miles). However, the Mach 6 missile takes about two minutes longer to travel 780 nautical

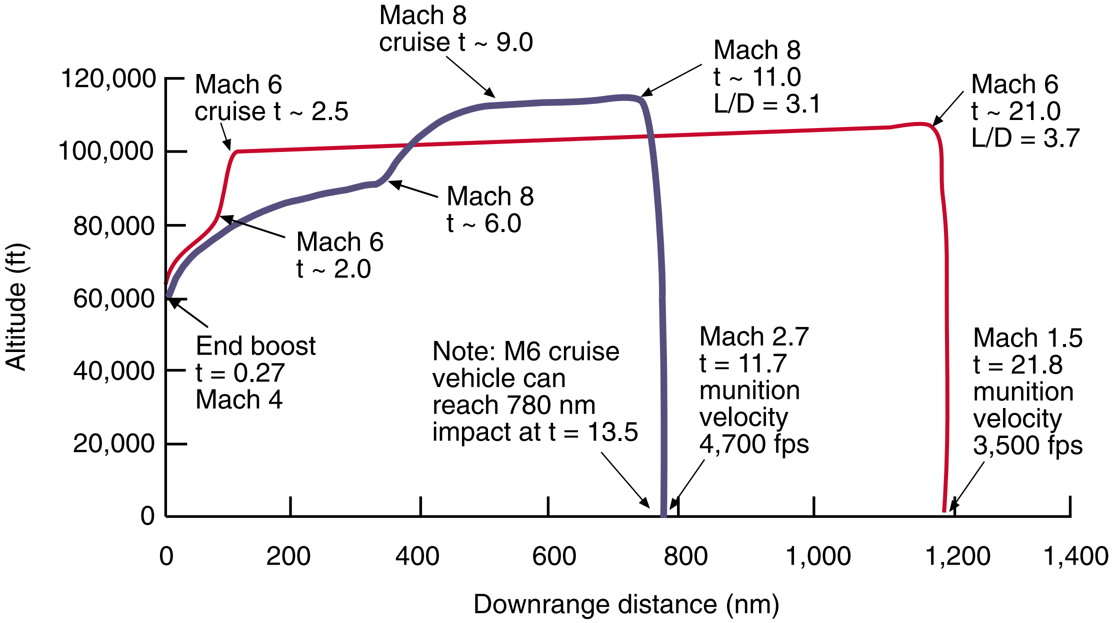

FIGURE 1-1 Altitude and range profiles for Mach 8 and Mach 6 missiles. Legend: Profile of missile altitude as a function of downrange distance (nautical miles) for nominal Mach 8 and Mach 6 air-launched, scramjet-powered missiles. Both missiles are assumed to use the same propulsion system and endothermic fuels for cooling, although endothermic fuels may not be necessary for a Mach 6 missile. Sample flight times (in minutes) and sample lift/drag ratios are also shown. For these plots, the vehicle's angle of attack was adjusted to maintain altitude as weight decreased. To maintain munitions kinetic energy, the profiles incorporate a payload ejection segment. (See the legend of Figure 1-2 for more information regarding the munitions.) Source: Air Force Hypersonic Technology Program Office, United Technologies Corporation (Pratt & Whitney), and Boeing North American.

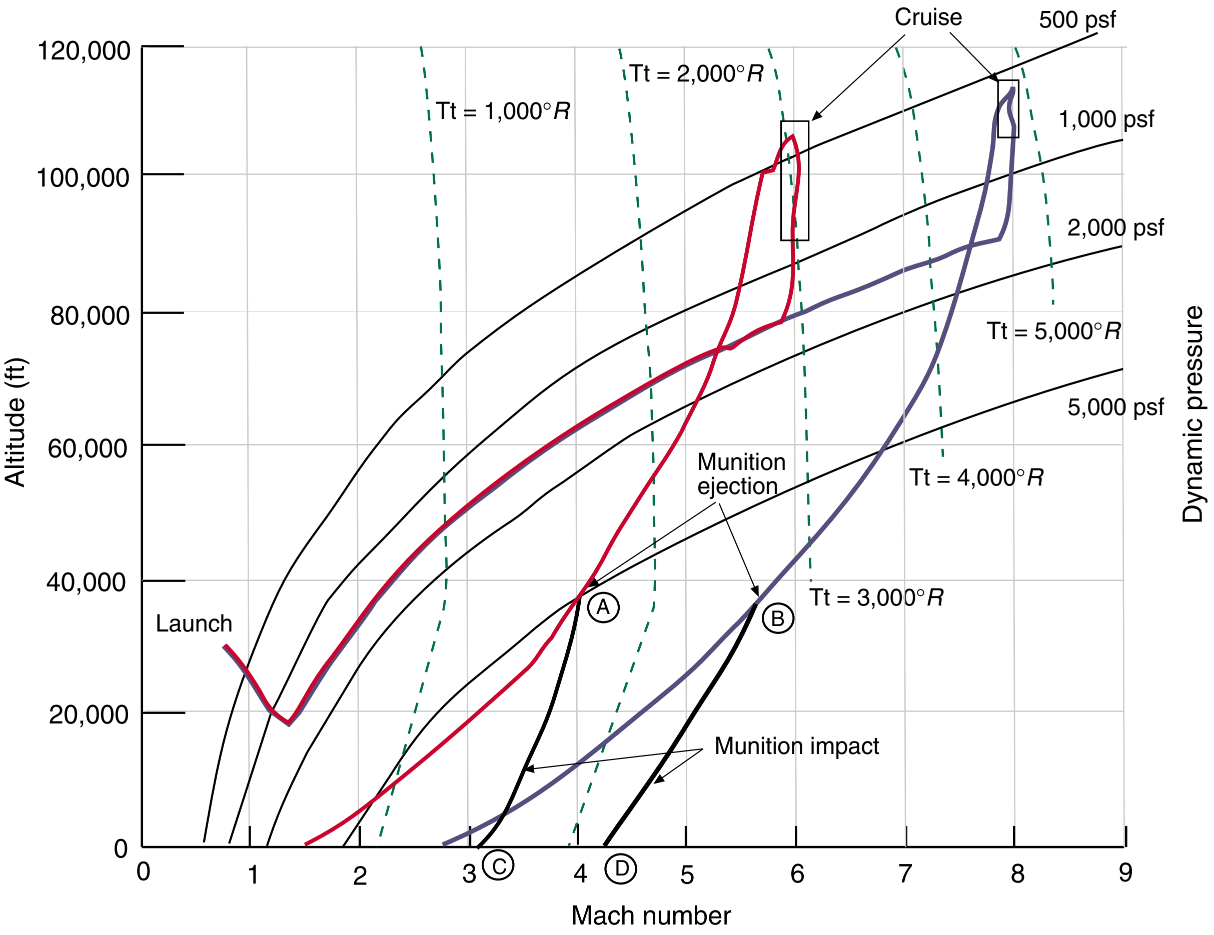

FIGURE 1-2 Altitude and Mach number profiles. Legend: Profile of missile altitude as a function of Mach number for the two missiles in Figure 1-1, showing flight dynamic pressures and air total temperatures (T_t in degrees Rankine). The Mach 8 profile separates the munition at about 39,000 feet, allowing the 250 pound low-drag penetrator to impact at about 4,700 feet per second for an impact kinetic energy of 8.6×10^7 foot-pounds. For the Mach 6 profile, engineering estimates indicate that a similar ejection would result in munition impact at about 3,500 feet per second for an impact kinetic energy of 4.8×10^7 foot-pounds. The small dive maneuver shown directly after launch is an artifact of the trajectory analysis; the simulation program was limited to a dynamic pressure during climb of 1,500 pounds per square foot (psf) and sought altitude solutions that would satisfy that criterion. More realistic boost trajectories will be developed early in HyTech Phase 2. Dynamic pressures at points A, B, C, and D are, respectively, 4,700 psf, 9,500 psf, 15,200 psf, and 26,300 psf. Note: The technical community commonly calculates temperatures in degrees Rankine, which is a scale that has the freezing point of water at 492° and the boiling point of water at 672° (i.e., 460° higher than on the Fahrenheit scale). Source: Air Force Hypersonic Technology Program Office, United Technologies Corporation (Pratt & Whitney), and Boeing North American.

miles. It may be possible at Mach 6 to use a composite structure that is not actively cooled, which could result in perhaps a 25 percent weight saving and, thereby, longer range, better acceleration, and lower cost. Alternatively, the longer range could be translated into a smaller, lighter missile. The terminal velocities of the munitions are also indicated (see the legend regarding the munitions).

Figure 1-2 shows altitude and Mach number corridors of flight for both missiles in terms of equilibrium air total temperatures and dynamic pressures. This figure also shows the separate trajectories of the munitions. Table 1-1 shows combuster maximum temperatures and static pressures for Mach 6 and Mach 8 missiles at a constant dynamic pressure.

In the United States and elsewhere, air-breathing propulsion systems that operate at these speeds are being studied, as are related technologies for a missile system. However, the integration of these technologies into a complete operational system is problematic. Can it be done? Yes, the committee believes it can. Whether it can be done at a reasonable cost and whether it should be done are more difficult questions facing decision makers.

The U.S. military could reap important benefits from affordable hypersonic systems. For example, a hypersonic missile capable of an average speed of Mach 6 (i.e., approximately one nautical mile per second at the planned operating altitudes) could strike a time-sensitive target 250 to 500 nautical miles

TABLE 1-1 Engine Parameters for Two Nominal Missiles

Flight Conditions		Combustor Maximum Pressure Location			Combustor Maximum Temperature Location		
Cruise Mach Number	Dynamic Pressure (psf)	P_{max} (psf)	T_{total} (°F)	$T_{wall\ cooled}$ (°F)	P_{local} (psf)	T_{total} (°F)	$T_{wall\ cooled}$ (°F)
6	1,500	6,300	4,000	1,400	1,400	4,400	1,300
8	1,500	4,100	5,000	1,600	1,100	5,100	1,400

Note: This table shows static pressures (pounds per square foot) and total temperatures in the engine combustor for the nominal Mach 8 and Mach 6 missiles shown in Figures 1-1 and 1-2. Total temperatures and cooled-wall temperatures are given. Both missiles are assumed to use the same propulsion system and endothermic fuels for cooling, although endothermic fuels may not be necessary for a Mach 6 missile.

Source: Air Force Hypersonic Technology Program Office, United Technologies Corporation (Pratt & Whitney), and Boeing North American.

way in about four to eight minutes.[5] Moving a mobile target in less than five minutes would be difficult (see Chapter 2). A subsonic Tomahawk missile, although very capable, would take 30 to 60 minutes to reach the same target, in which time a mobile target could be moved to a safe location. Also, the kinetic energy of a missile warhead that strikes a target on the ground at terminal speeds on the order of several thousand feet per second is significant, even without high explosives (see Figure 1-1). A hypersonic missile could strike and destroy buried, reinforced installations. Operation at hypersonic speeds also improves the survivability of the system.

On the surface, given these potential benefits, the decision to develop and field hypersonic weapons might seem obvious. In reality, the decision is not straightforward, which is one reason the committee was asked to undertake this study.

STATEMENT OF TASK

During the discussions that led to this study, it was evident that the time has come for the Air Force to decide whether or not hypersonic technology can lead to a militarily useful product within a reasonable time frame. The Air Force's ongoing Hypersonic Technology (HyTech) Program is being managed at Wright-Patterson Air Force Base, Dayton, Ohio, by the Propulsion Directorate, which is part of the newly consolidated Air Force Research Laboratory in the Air Force Materiel Command. The HyTech Program is the subject of this study.

The committee operated under the following Statement of Task from the Air Force.

> The examination of the Air Force Hypersonics Technology Program is to concentrate on program strategy and content. The results of the examination will be documented in a study report that will be provided to the Air Force. That report will also contain recommendations concerning possible topics that could be the subjects of investigations of longer-term (2015 and beyond) hypersonic technology applications. The NRC will base its examination on information supplied by the Air Force and other appropriate sources during the course of the study.
>
> The following tasks are to be accomplished:
>
> (1) Evaluate and make recommendations regarding the Air Force Hypersonics Technology Program. The NRC should focus its initial efforts on the technologies needed to demonstrate a hypersonic, air-breathing missile concept, using hydrocarbon-based propulsion technology for the Mach 8 regime, in time to achieve an initial operational capability of 2015 or sooner. Emphasize the underlying strategy and key components of the program, the critical technologies that have been identified by the Air Force and by other sources, as appropriate (e.g., advanced propulsion systems using ramjet and scramjet technologies); and the assumptions that underlie technical performance objectives and the operational requirements for hypersonic technology.
>
> (2) Address the following specific questions:
>
> a(i). Will the Hypersonic Technology Program, as planned by the Air Force Materiel Command (all references to the hypersonic program are directed at this specific program rather than broader contexts), lead to a capability which will meet operational requirements for hypersonic technology applications?
>
> a(ii). What technologies (beside propulsion) should next be pursued, and in what priority, for a hypersonic air-to-surface weapon?
>
> b. Are all the necessary technical components of a hypersonic Mach 8 regime propulsion technology program identified and in place, or if not, what is missing?
>
> c(i). What are the salient uncertainties in the propulsion component of the hypersonic technology program, and are the uncertainties technical, schedule related, or bound by resource limitations as a result of the technical nature of the task (e.g., materials sources, qualifications of support personnel, or technology driven costs that affect affordability), to the extent it is possible to enunciate them?
>
> c(ii). What are the salient uncertainties for the other main technology components of the hypersonic technology program (e.g., materials, thermodynamics, etc.)?

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[5] The Air Force's goal for its hypersonic technology program is to fly 750 nautical miles in 12 minutes (see Chapter 2, response to Question 2d), which is approximately Mach 6, on the average, even though the top speed is Mach 8.

> c(iii). Does the program provide a sound technical foundation for a weapon system program that could meet operational requirements as presently defined?
>
> d. How does the Air Force hypersonic program interrelate with other Department of Defense hypersonic initiatives, e.g., the Defense Advanced Research Projects Agency's Advanced Concept Technology Demonstration on hypersonic vehicles?
>
> e(i). From an engineering perspective, what are reasonable milestone dates for a hypersonic missile system development program leading up to production, i.e., concept development, engineering and manufacturing development, etc. For example, with a 2015 target date for operational capability, does the current program have a coherent plan and road map to build and test a Mach 8 regime hydrocarbon-fueled scramjet engine?
>
> e(ii). Are there foreign hypersonic technology applications that are significantly more developed than those of the United States, that, if acquired by the U.S. government or industry through cooperative venture, license, or sale, could positively affect the development process or schedule for Air Force hypersonic vehicles?
>
> e(iii). Based on these assessments, the committee will make recommendations on the technical content and pace of the program.
>
> f. Are there any evident implications for the Air Force support infrastructure for a hypersonic missile system? For example, will other technologies need to be developed in parallel to support a hypersonic vehicle and are those likely to pose significant barriers to eventual success in demonstrating the missile concept or in fielding a viable weapon system by 2015?
>
> (3) To the extent possible, identify technology areas that merit further investigation by the Air Force in the application of hypersonics technology to manned or other unmanned weapon systems by 2015 or beyond.

The principal purpose of this study is to determine whether a hypersonic, scramjet-powered, hydrocarbon-fueled missile with speeds up to Mach 8 can be developed and can reach an initial operational capability by the year 2015. The secondary purpose is to identify technologies that merit consideration for other systems by 2015 or beyond.

STRATEGY FOR THIS STUDY

At initial meetings, the committee developed a strategy to fulfill the Statement of Task. To complete the work of the committee within the time and resource constraints of the study, the committee focused on the specific questions set forth in the Statement of Task.

The committee members included experts with substantial experience in both research and technology development programs in a wide range of disciplines (e.g., high-speed aerodynamics; basic fluid mechanics; aeronautics; high-speed air-breathing and rocket-propelled vehicles; the development and testing of propulsion systems; military systems acquisition and operational issues; sensors; guidance and control; materials science and engineering; and advanced technology development and systems engineering). The committee also familiarized itself with the diverse work being done on enabling technologies by government agencies that could support the development of hypersonic systems for the Air Force, including the HyTech Program, Navy programs, Defense Advanced Research Projects Agency programs, and National Aeronautics and Space Administration (NASA) programs. The committee determined that an understanding of current work by industry that relates directly to scramjet propulsion and, more broadly, to hypersonic flight and access to space would also be necessary.

The data-gathering goals were met over the course of the committee's five meetings through briefings by representatives of the Air Force and other government agencies describing existing programs and military needs and by industry representatives who responded to committee questions. These meetings are summarized below (see Appendix A for details).

- At the first meeting, in July 1997, the committee was briefed by Air Force officials at Wright-Patterson Air Force Base and their contractors on the technical content and pace of the HyTech Program. The committee was also briefed by a representative of the Defense Advanced Research Projects Agency on a program to demonstrate an advanced, low-cost, hypersonic missile concept and by representatives of NASA on its hypersonic programs.
- At the second meeting, in Irvine, California, in August 1997, the committee was briefed by Navy and NASA officials on their hypersonics technology programs and conceptual design results. The committee was also briefed by representatives of six companies that have research and technology development programs on engines or vehicles for hypersonic flight or access to space.
- The committee met a third time, in October 1997 in Washington, D.C., to be briefed by Air Force officials on the mission needs and operational requirements for a hypersonic missile. The committee was also briefed by industry representatives concerning the system-level issues associated with the development of a hypersonic missile.
- At the fourth meeting, in December 1997, the committee was briefed at the Air Force Research Laboratory (Phillips Laboratory) in Albuquerque, New Mexico, by Air Force officials who discussed international developments in hypersonic technology and the Air Force military space plane program.[6] The committee also met with a representative of a company developing a

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[6] A space plane is a vehicle concept for providing access to space through "airplane-like" operations. Designs may incorporate a variety of propulsion systems and employ various numbers of stages to reach orbit.

vehicle for commercial access to space and an independent expert who discussed lessons learned from past scramjet programs.

- During the committee's fifth meeting, in January 1998 in Washington, D.C., a representative of the HyTech Program described the Air Force's decision-making process in selecting one propulsion contractor.

While the committee continued to gather data, it also began writing the report. By consensus, the committee decided to resist the tendency to review the history or project the future of the development of hypersonic technology. Instead, the committee decided to respond to the Statement of Task and to organize the report around answers to the questions.

REPORT FORMAT

Chapter 2 contains the committee's responses to Parts 1 and 2, which are answered in the following format: (1) the question is repeated, verbatim, from the Statement of Task; (2) the answer is summarized; (3) a detailed response, including requisite background information, is given to justify the summary answer and detail the committee's reasoning. In Chapter 3, the committee addresses paragraph 3 in the Statement of Task in a discussion of applications, other than a Mach 8 missile, of hypersonic technology that merit further investigation for use after 2015. In Chapter 4, the committee summarizes its principal conclusions and recommendations.

2

Responses to Parts 1 and 2 of the Statement of Task

The first section of this chapter describes the overall picture that emerged from briefings to the committee on the Air Force HyTech Program. Next, the committee presents its question-by-question responses to Part 2 of the Statement of Task. The committee's responses are based on its expertise and the technical information gathered during the study.

OVERALL PICTURE

The opening paragraph of the Statement of Task indicated that the committee should concentrate on the "strategy and content" of the Air Force HyTech Program (see Box 2-1 for a summary of the program and Appendix B for a detailed description). Part 1 of the Statement of Task asked the committee to focus on the "technologies needed to demonstrate a hypersonic, air-breathing missile concept, using hydrocarbon-based propulsion technology for the Mach 8 regime, in time to achieve an initial operational capability of 2015 or sooner."

When this study began, many committee members assumed that the HyTech Program was a component of a broader program to demonstrate the technologies for a hypersonic, air-breathing missile system capable of speeds up to approximately Mach 8. During the initial visit to Wright-Patterson Air Force Base in July 1997, the committee learned that, because of very limited funding, the Air Force had decided to concentrate almost solely on the propulsion subsystem of a representative hypersonic vehicle and to conduct only a limited ground-test demonstration of a single Mach 8 hydrocarbon-fueled engine flow path. Under the circumstances, the committee considers that this was a wise decision, although full integration with a flight vehicle and flight testing, which are especially important for a compact missile system, were not included in the program. The HyTech Program now has only one propulsion contractor, which limits the alternatives for the engine design.[1] The program should consider using design reviews by independent experienced engineers, who could challenge the configuration selections and accompanying analyses and suggest alternatives for evaluation. Collateral development of the airframe, munitions, and the guidance and control and navigation system, as well as their integration, will have to be the subjects of follow-on programs. To the committee's knowledge, the Air Force is not pursuing these collateral areas.

Because Part 1 of the Statement of Task asked the committee to emphasize the "assumptions that underlie technical performance objectives and the operational requirements for hypersonic technology," the committee assumed that the Air Force had established a valid operational requirement (with specific performance objectives) for this kind of missile. To the committee's surprise, no operational requirements for a system using this technology have been established, although the committee found several statements by the Air Force and the Navy describing missions for which an air-breathing hypersonic missile would be valuable. In the absence of operational requirements, there has been considerable speculation in the technical community about the operational parameters of such a weapon. The Air Force and Navy have established only general technical performance goals that clarify the parameters of the missile systems (e.g., top speeds of Mach 8 and Mach 6, respectively).

The potential improvements in warfighting capability offered by a hypersonic, scramjet-powered, air-to-surface missile (e.g., speed, standoff range, and kinetic energy) could be substantial. However, the technical challenges escalate as the maximum Mach number increases (e.g., from Mach 6 to Mach 8), and the development of a vehicle with a maximum speed of Mach 8 would require significant technological breakthroughs. Thus, the Air Force will need a carefully planned technology validation program that includes a prototype flight vehicle to control risks. The committee proposes a validation program in this chapter. The committee believes that, if the completion of the HyTech Program by 2003 is followed expeditiously by prototype flight testing,

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[1] See discussion of the original plan in Appendix B. Also, see response to Question 2d for a discussion of the engine performance goals.

BOX 2-1
Summary of the HyTech Program

The HyTech Program was established in 1995 at the direction of the Secretary of the Air Force as a follow-on program to the National Aero-Space Plane Program. The HyTech Program focuses on the development of generic, hypersonic technology. The program was designed to follow a stepping-stone approach focusing initially on hydrocarbon-fueled scramjet missiles with speeds up to Mach 8. The speed of Mach 8 was chosen in part by technical factors and the results of studies indicating to the Air Force that this speed could have a significant payoff for projected missions (e.g., the ability to attack time-critical targets). The choice of Mach 8 also appears to have been driven by a desire to explore the upper limits of hydrocarbon-fueled scramjet technology. Originally, the program was intended to address primarily engine technology, with a companion program in airframe technology. However, soon after it began, the HyTech Program was restructured to concentrate its very limited funds exclusively on engine technology. (HyTech was given a nominal $20 million per year funding, but the actual funding has consistently fallen short of that figure.)

Currently, engine development is the critical path of the program, which is managed by the Air Force and carried out by industry under contract. Two prime contractors working on two engine concepts constituted the technical core of the program when this study began. Since then, the Air Force has selected one contractor to continue the program. The selected engine concept is slated to be tested in ground-test facilities in the 2001 to 2003 time frame. The managers of the program were directed to coordinate their activities with other programs in the U.S. Department of Defense, as well as with other government organizations (e.g., NASA), industry, and academia, if doing so would accelerate engine development or extend the U.S. hypersonics technology base.

the Air Force could have, by 2015, an initially operational air-breathing hypersonic missile with a maximum speed in the range of Mach 6 to Mach 8.

The current HyTech Program, which is a propulsion technology flow path program for a missile boosted to Mach 4 and then accelerated by its scramjet engine to Mach 8, is not sufficient for the development of a design concept with the engine integrated into a missile system. The planned ground testing of a non-integrated propulsion subsystem should indicate potential engine performance, but only flight testing over a representative range of operating conditions will determine the operability, reliability, and durability[2] of the engine in an integrated system. These parameters are prerequisites to determining the utility of the engine in an operational system.

The HyTech Program will not, by itself, provide the basis for an operational missile system because critical enabling technologies for hypersonic, air-breathing missiles are not part of the program. To the committee's knowledge, these critical technologies are not being pursued by the Air Force. These technologies will have to be matured and validated before the Air Force can proceed with a low-to-moderate risk acquisition program. (The critical technologies are discussed in the responses to specific questions.)

To develop an operational hypersonic missile system, the Air Force would have to take a two-part approach. First, the HyTech Program would have to be expanded to include a full-scale, airframe-integrated, engine flight test program; if the critical enabling technologies were mature, an operational air-breathing hypersonic missile system could be developed with low-to-moderate risk and without concurrency (almost certainly for a speed of Mach 6 and probably for a speed of Mach 8). This expanded HyTech Program could lead to an initial operational capability by 2015.

Second, the Air Force would have to establish operational requirements for the system. The committee believes the Air Force has not yet undertaken design and requirements trade-off studies in support of an air-launched hypersonic missile system. The committee recognizes the difficulty of attempting to make trade-offs between systems that have not yet been developed, especially systems that require technologies that are not mature enough to indicate potential risks relating to performance and affordability. Trade-off studies would be especially difficult for a Mach 8 missile, which would require technologies at the leading edge of development. The committee considered this point carefully when attempting to differentiate between a Mach 6 system, for which the committee believes the technologies are within reach, and a Mach 8 system, which would stretch current technological boundaries. The necessity of having data about the cutting edge technologies in hand for an effective engineering and manufacturing development phase is the basis

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[2] The word "durability" in this report implies that the missile system and its components must be designed to operate successfully for a one-time 12-to-15 minute flight. The committee points out, however, that durability considerations must go beyond the rigors of the boost, cruise, and terminal phase flight environments and include storage, handling, and in-flight carriage.

for the committee's opinion that flight demonstration should be the next phase of the HyTech Program.

The committee believes that the problems raised by the cutting edge technologies could be overcome in the Air Force's time frame. The Air Force can be reasonably confident that early, fundamental trade-off studies will yield useful conclusions, especially in terms of cost and mission effectiveness. The most basic trade-off study has yet to be done to determine the Mach number of the first scramjet missile system. Many parameters of the basic weapon system could then be determined, even with the current state of development of the various technologies.

During one briefing, the committee was informed that a hypersonic missile with range parameters similar to the Air Force concept (i.e., 750 nautical miles) would be subject to the limitations of existing arms control treaties. The committee did not verify this information or attempt to determine how the design, development, testing, or deployment of a hypersonic missile might be influenced by specific treaty provisions. Nevertheless, because there is a possibility that arms control treaty limitations could affect either missile design parameters or the designation of the launch aircraft, the Air Force should consider all missile design parameters, all aspects of the development and testing program, and all steps leading to initial operational capability in light of applicable treaties.

In the following sections, the committee responds to each question in part 2 of the Statement of Task. These responses contain findings, conclusions, and suggestions, the most important of which are drawn together and sharpened in Chapter 4, Conclusions and Recommendations. The committee also created a technological road map for an acquisition program that would lead to the subject missile system in response to Question 2e(i) and made some first-order mission analyses in response to Questions 2a(ii) and 2c(iii) (Appendix C contains supporting details). Both the road map and the analyses are offered as starting points for more extensive work and future decisions by the Air Force.

MEETING OPERATIONAL REQUIREMENTS, QUESTION 2a(i)

> Will the Hypersonic Technology Program, as planned by the Air Force Materiel Command (all references to the hypersonic program are directed at this specific program rather than broader contexts), lead to a capability which will meet operational requirements for hypersonic technology applications?

Summary Answer

The Air Force HyTech Program, as currently structured, will not lead to an operational capability. Furthermore, the Air Force has not defined operational requirements for the system.

Detailed Answer

The Air Force HyTech Program described to the committee appears to be well thought out and has made efficient use of available funding. However, the program, as currently structured, will not enable the development of an initial operational capability by 2015. The program lacks the breadth, depth, and funding necessary "to demonstrate a hypersonic, air-breathing missile concept" (Statement of Task, Part 1).

The HyTech Program includes a test demonstration of a flight-like configuration of each engine component in a wind tunnel or test cell environment in fiscal years 2001 and 2002. The program concludes with a ground test demonstration of a complete engine flow path with flight-like components in a free-jet wind tunnel in fiscal year 2003. The program apparently does not include plans or funding (which would be considerable) for flight tests. The committee was not informed of collateral plans to address in depth the critical technologies beyond the propulsion system (e.g., thermal structures or guidance and control systems) or of a comprehensive plan to integrate the diverse technologies critical to air-breathing hypersonic flight.

Although the committee was briefed on mission needs (e.g., the need to strike time-critical and exceptionally hardened targets), there was no indication that the Air Force had conducted trade-off studies or assessments to determine if an air-launched, air-breathing hypersonic missile would be the best way to satisfy them.

Recommendation. The Air Force should initiate trade-off studies for the design and requirements of a hypersonic missile system. Analyses should include the following parameters: targets, speed, range, survivability, lethality, aircraft compatibility, risk, and cost.

These analyses would provide a basis for articulating valid operational requirements for a hypersonic missile system. The HyTech Program, which is focused on technologies for a hydrocarbon-fueled scramjet, is currently structured as though its goal is to provide an evolutionary improvement of the propulsion subsystem of a mature, state-of-the-art vehicle development process (e.g., manned, tactical aircraft). In fact, the United States has no capability to engineer or manufacture operational, hypersonic, air-breathing missiles. The HyTech Program is the descendant of ramjet and scramjet propulsion programs. Unfortunately, these early programs provide little data on the performance, operability, reliability, and affordability of hydrocarbon-fueled engines, especially in the Mach 4 to Mach 8 range. The committee believes that developing these data will require investments of money and time that are well beyond the HyTech Program.

The HyTech Program does not have the funds to inspire confidence in the design and development of an operational propulsion subsystem. In fact, the committee has learned that the HyTech Program has actually received much less than the planned $20 million per year (see Appendix B). If this situation persists, the current HyTech Program may not be able to meet its completion date of 2003, which would make an initial operational capability by 2015 difficult. The HyTech Program is just one of many ongoing laboratory Air Force programs. The deficiencies in the HyTech Program reflect both funding shortfalls and the highly competitive nature of these science and technology programs.

In light of the Air Force's lack of commitment to flight testing a hypersonic air-breathing missile, and of the United States' limited experience with scramjet propulsion, the committee makes the following recommendation.

Recommendation. The Air Force should commit appropriate resources to completing integrated airframe-engine flight testing. Flight tests are vital to demonstrating a hydrocarbon-fueled scramjet in the Mach 4 to Mach 8 regime. If the Air Force decides not to make this commitment, it should re-evaluate its goals for the development of air-breathing hypersonics technology.

Because critical technologies will have to be developed, integrated, and tested, the program will have to be much more substantial than an ordinary laboratory program.

Recommendation. If the Air Force determines that there is a requirement for a hypersonic missile system, then it should establish a system-oriented program office to manage the design and development, integration, and flight testing of critical enabling technologies for a hypersonic missile system. The program office should report directly to a senior official in a weapon system organization and should have multidisciplinary participation, including experienced design engineers of air-breathing propulsion systems. The committee believes the Air Force must take these steps in the near term for the successful development and application of hypersonic technology by 2015.

In its response to Question 2e(i), the committee provides a notional road map for an air-launched hypersonic missile that would be operational by 2015. Based on the road map, the demonstration of a Mach 4 to Mach 8 air-breathing missile configuration with first-generation capability (i.e., delivery of a useful payload over a useful range at an affordable cost) will require a joint, shared-risk venture among technologists, acquisition offices, and operators of the system. The development of a system with first-generation operational capability will take a strong team effort.

TECHNOLOGIES OTHER THAN PROPULSION, QUESTION 2a(ii)

> What technologies (beside propulsion) should next be pursued, and in what priority, for a hypersonic air-to-surface weapon?

Summary Answer

Several critical enabling technologies besides propulsion will have to be developed for a hypersonic air-to-surface weapon. In order of priority, the five most critical technologies are (1) airframe and engine thermostructural systems; (2) vehicle integration; (3) stability, guidance and control, navigation, and communications systems; (4) terminal guidance and sensors; and (5) tailored munitions.

Detailed Answer

The committee believes that the development of a hypersonic vehicle will require much more than the current HyTech Program is scheduled to accomplish. Five critical technologies will also have to be developed. In order of priority, these are (1) airframe and engine thermostructural systems; (2) vehicle integration; (3) stability, guidance and control, navigation, and communications systems; (4) terminal guidance and sensors; and (5) tailored munitions. Each of these technologies is discussed below.

Airframe and Engine Thermostructural Systems

Hypersonic vehicles with air-breathing engines will have to fly at high dynamic pressures to capture sufficient air for a combustion rate of fuel that will produce thrust levels significantly greater than the drag of the vehicle. The combinations of Mach number and dynamic pressure will mean vehicle and engine flight environments with high temperatures and heating rates and large aerodynamic forces. (Figure 1-2 in Chapter 1 illustrates the dynamic pressures and total temperatures.) Figure 2-1 shows that the thermal environment ranges from temperatures of about 1,100°F at Mach 4 (the temperature of the incoming airflow on the radiatively cooled surface) to about 4,200°F at Mach 8. Figure 2-1 also shows the likely range of temperatures of critical components of the surface of an airframe structure that is not actively cooled, as well as of an airframe structure that uses liquid cooling at roughly Mach 6 to Mach 8.

The temperatures in Figure 2-1 for the airframe structure that is not actively cooled agree with recent calculations based on computational fluid dynamics presented to the committee by the Air Force. These temperatures indicate the maximum temperature of the vehicle inlet compression ramp. Slightly lower temperatures would be expected for the swept leading edges of the control surfaces. Much lower temperatures would be expected on the remaining external vehicle structures.

Some flight maneuvers could cause shock waves that could intersect the leading edges of the airframe and engine surfaces, creating localized regions of much higher temperatures. The committee was informed by the Air Force that the thermal and mechanical loads, which include heating of edges and amplification of shock waves at the missile's

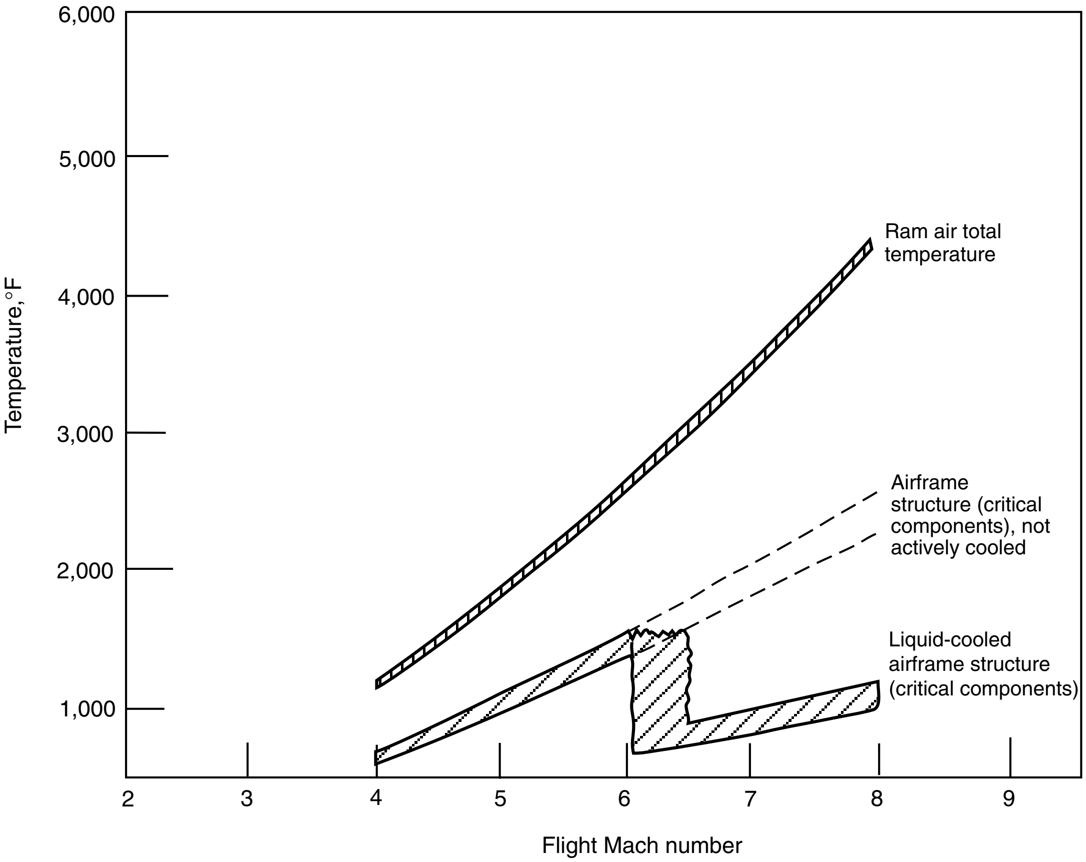

FIGURE 2-1 Airframe structural temperature requirements. Source: Ram air total temperatures for air in chemical equilibrium are from Pruitt, 1987. Temperatures of the cooled and not actively cooled airframe structures were calculated by the committee.

surface, were compared with analytical predictions for engine components at Mach 5.6. However, the environment of the engine and airframe at Mach 6 to Mach 8 is not fully known because no extensive testing has been done under relevant conditions or in flight.

The engine of an air-breathing hypersonic missile will operate in the most demanding environment in the structure. The effects of Mach number on the temperatures for the engine combustors and nozzles are shown in Figure 2-2; temperatures for the inlets are shown in Figure 2-3.

As Figure 2-2 shows, at Mach 8 the maximum gas total temperature at the combustor exit could exceed 5,000°F, which is in keeping with estimates by the HyTech Program. Air and radiation cooling will reduce the structural temperatures in the engine combustor at Mach 4 to Mach 6 to a range of 2,100°F to about 3,000°F; a fuel-cooled engine combustor operating at Mach 6 to Mach 8 will be subject to structural temperatures of about 1,300°F to 1,500°F. The engine inlet, shown in Figure 2-3, will be subject to significantly lower temperatures.

One major challenge in designing hypersonic vehicles is developing airframe and engine thermostructural systems that can withstand the thermal environments and the aerodynamic forces for the required life of the vehicle, which must have acceptable weight and damage tolerance and adequate operating margins. The Air Force must take into account the weight and cost associated with complex active cooling systems and with even more complex endothermic fuel-cooled systems.

The hypersonic environment is extremely demanding for aircraft and space access vehicles that must be reusable and reliable over many flights during their lifetime. However, an expendable hypersonic missile would be used for only one short flight and would not be subject to the same creep and low cycle fatigue challenges. Therefore, thermostructural designs for a hypersonic missile could use well characterized, reliable, high-temperature materials, coatings, and processes, in combination with passive or active cooling.

A hypersonic missile system will require the integration of materials with widely different thermal and mechanical properties into one structure. These materials must maintain their useful properties at elevated working temperatures; they must have high specific strength and stiffness, be oxidation resistant, and have high damage tolerance (fracture toughness) and adequate creep resistance to withstand the thermal and aerodynamic stresses. Perhaps most important, they must have several other desirable properties, including ease of fabrication, ease of joining and assembly, reasonable cost,

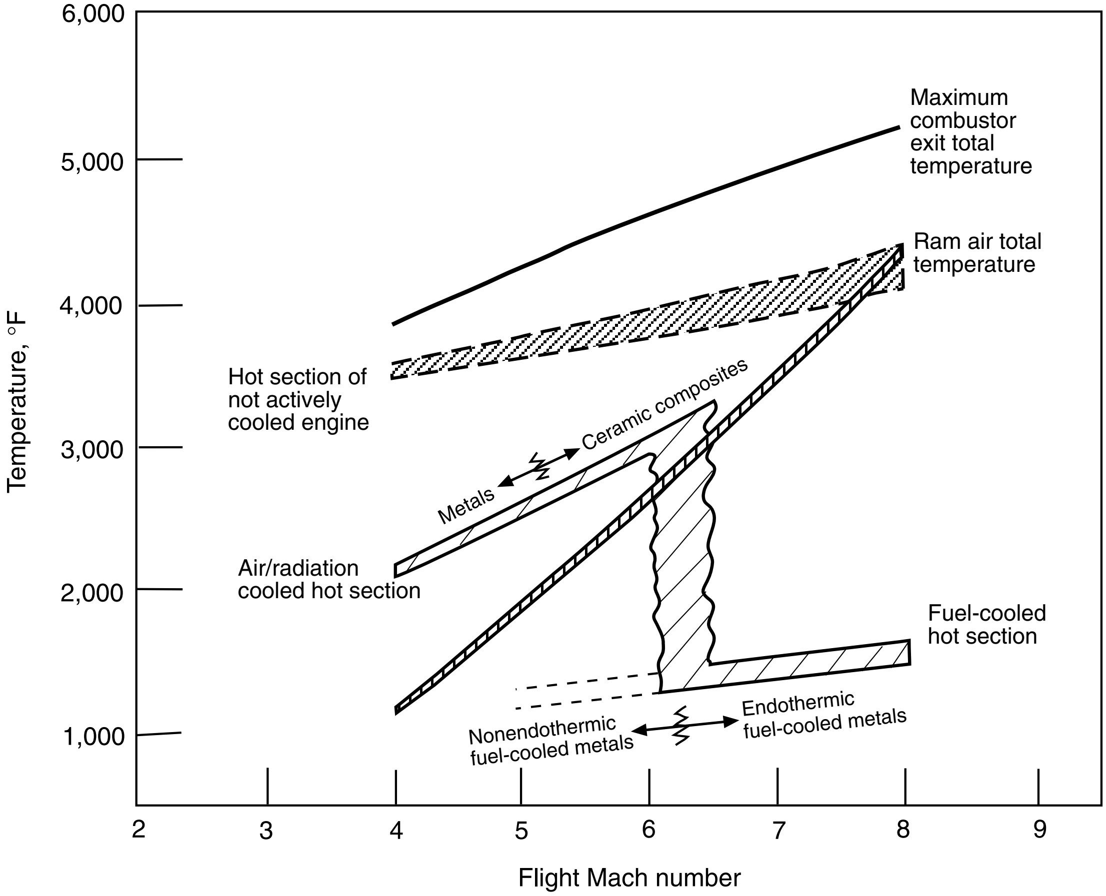

FIGURE 2-2 Structural temperature requirements of the engine hot section. Source: Ram air total temperatures for air in chemical equilibrium are from Pruitt, 1987. Engine cycle temperatures for the HyTech baseline hydrocarbon scramjet engine were provided in Mercier, 1998. Temperatures of the cooled and not actively cooled engine structures were calculated by the committee.

reproducible properties, and an adequate supply base with sizes, quantities, and shapes suitable for fabrication.

Recent HyTech evaluations of subscale coupon-sized specimens (e.g., 1 in. × 2 in. × 4 in.) of candidate materials encompass a range of conventional materials (e.g., metallic alloys and superalloys) and advanced structural materials (e.g., composites, ceramics, refractory-based systems, and coatings). The facilities simulated, to various degrees, the relevant hypersonic engine thermal and flow path environment. Coupon tests so far have revealed that subscale specimens of many existing conventional and advanced structural materials and coatings can survive the simulated hypersonic conditions. More testing is being done.

Advances in manufacturing technology and fabrication methods will be required for the routine production of cost effective, reliable structures in appropriate sizes. With tests under relevant conditions of structural components made of very dissimilar materials, the Air Force can make preliminary evaluations of their performance. To ensure that the structural designs can withstand the projected environment for the required time, actual conditions that the airframe and engine will encounter will have to be determined.

Advanced structural materials often are subject to problems associated with scale-up because the properties of bulk materials processed in production quantities may not be identical to materials manufactured, synthesized, and tested in the laboratory. Other problems include the small number of materials suppliers and batch-to-batch and company-to-company differences in material properties. These problems are heightened with advanced materials, which may be particularly sensitive to minor changes in processing, chemistry, and secondary processing. Effective manufacturing technology and fabrication methods based on a systems approach will be necessary to minimize these problems.

Thermostructural designs and technology developments for the engine are being pursued in the HyTech Program, which plans to fabricate the inlet and nozzle structure of either a carbon-carbon composite or a passively cooled ceramic composite (silicon carbide matrix with carbon fibers), both of which have sufficient thermal capability (with antioxidation coating) and would not require active cooling. In contrast, the conditions in the combustor would require active fuel-cooling of the metallic structure (known as Haynes 188).

Actively cooled engine structures, including combustors, have been used for many years in reusable systems. The Space Shuttle main engine, for example, has an actively cooled combustor and nozzle, cooled with the hydrogen fuel. The main combustor chamber operates at a pressure of 3,000 pounds per square inch and a temperature of about 5,500°F. The combustor material is NARloy-Z, a high conductivity, high strength copper-based alloy. The engine design life is 55 missions, or 450 minutes.

A challenge for the hydrocarbon-fuel actively cooled system in the HyTech Program will be designing a system in which coking (i.e., carbon deposition) does not occur in the cooling passages, which would reduce the cooling of the structure. The design of the thermostructural system will require careful attention to the active cooling system, attachment techniques, and joining techniques for materials with different thermal expansion characteristics. The entire system will have to be tested and validated at the required operating conditions.

On the leading tips and edges, and on portions of the control surfaces, the airframe will require materials that retain their strength at very high temperatures in the presence of high-temperature gradients and significant aerodynamic loads. Aerodynamic design and the associated pressure loads must be considered in combination with the thermal loads. The metallic structure for the nose will probably have to be actively cooled with the fuel. Uncooled ceramic structures could probably be used for the control surfaces, depending on their configuration and degree of sweep. If not, passive heat pipes or active fuel cooling could be used. For radomes or windows, active surface film cooling would probably be required to protect them from the heat. All protuberances would require thermal protection. The remainder of the airframe could be made entirely of metal, such as a titanium-based or nickel-based superalloy. Many of the internal systems would have to be insulated. Low weight and high strength design structures could be, for example, monocoque structures for circular airframe configurations or honeycomb-sandwich structures for other configurations.

One of the primary challenges for the thermostructural design of the entire vehicle is optimizing the selection of materials and structural architecture so it can not only

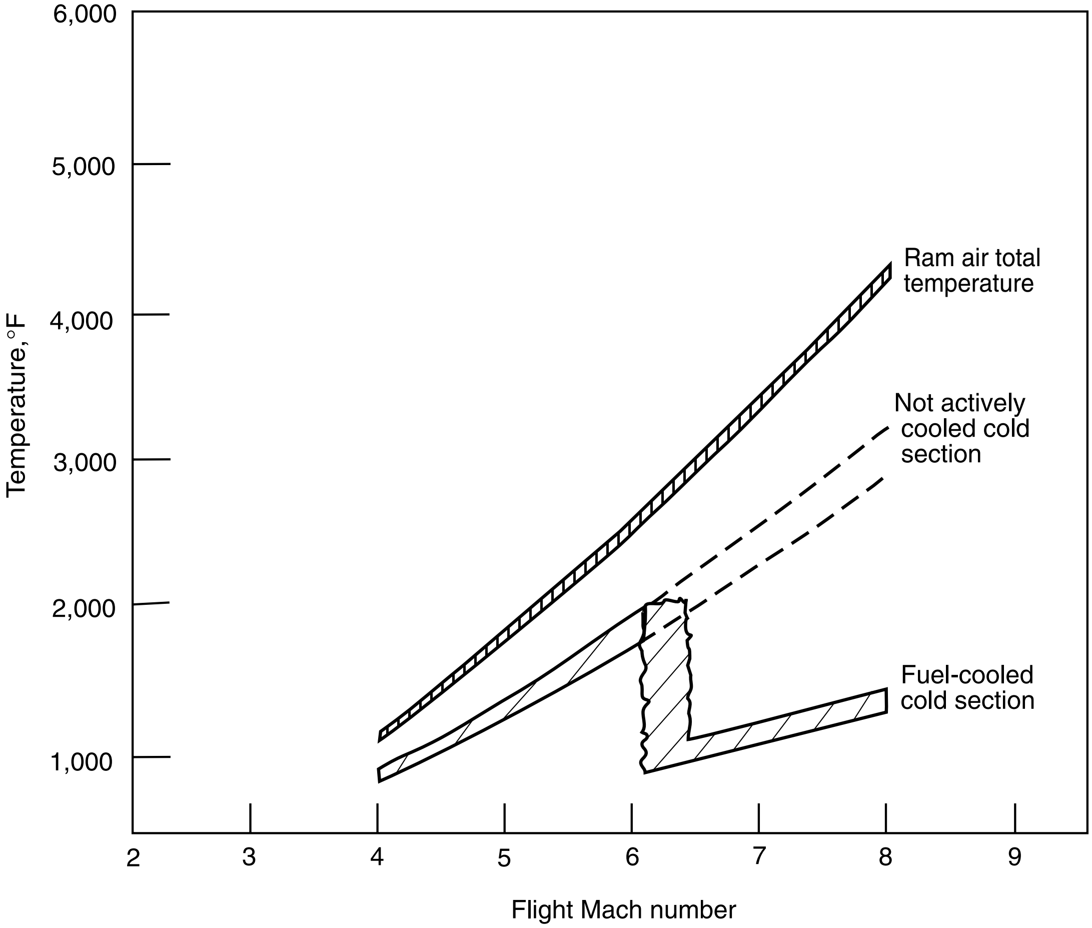

FIGURE 2-3 Structural temperature requirements of the engine cold section. Source: Ram air total temperatures for air in chemical equilibrium are from Pruitt, 1987. Engine cycle temperatures for the HyTech baseline hydrocarbon scramjet engine were provided in Mercier, 1998. Temperatures of the cooled and not actively cooled engine structures were calculated by the committee.

withstand the conditions of the flight environment but can also meet the missile size and weight requirements. Although technologies are available that can meet these requirements, vehicle design should be combined with cost-effective manufacturing techniques and fabrication methods, as well as with adequate testing and validation, to produce an affordable integrated vehicle design that can survive the hypersonic environment.

Vehicle Integration

Because no one has extensive experience with hypersonic vehicles powered by air-breathing engines, there are many uncertainties in vehicle integration. Nevertheless, the committee believes that, with careful attention to integration issues and the development of coordinated analysis tools, integration of the vehicle will be possible.

Scramjet-powered missiles, by their very nature, demand high levels of vehicle integration. The airframe is part of the engine. Volume and weight constraints also make the job of subsystem packaging difficult and require complex component interactions, which can be crucial in the areas of the integration of engine and airframe and sensors and munitions. Vehicle-level requirements, including the requirements for acceleration and maneuverability, will have a first-order effect on the integrated vehicle-engine design.

Integration of the missile with a carrier aircraft will place weight and size constraints on the missile design that may affect the engine configuration. Deployment of the missile from the aircraft will require that attention be paid to vehicle aerodynamics. Because a scramjet engine does not produce thrust in its ramjet mode until it reaches a speed of Mach 3 or higher, the scramjet-powered vehicle will be the second stage of the system; the first stage will use a rocket booster. The rocket booster, its integration with the missile, and the associated separation will obviously affect the integrated vehicle-engine design.

Notwithstanding their superior performance, air-breathing engines are inherently more difficult to integrate into missiles than rocket engines. Depending on the configuration, integration can be similar to the integration of air-breathing engines in vehicles that operate at lower speeds. Consider the two notional missile configurations shown in Figure 2-4, for example.

The axisymmetric design in Figure 2-4 shows that the engine airflow is captured near the front of the vehicle, transported internally through ducts, and exhausted axially at the aft end of the vehicle. This type of integration requires

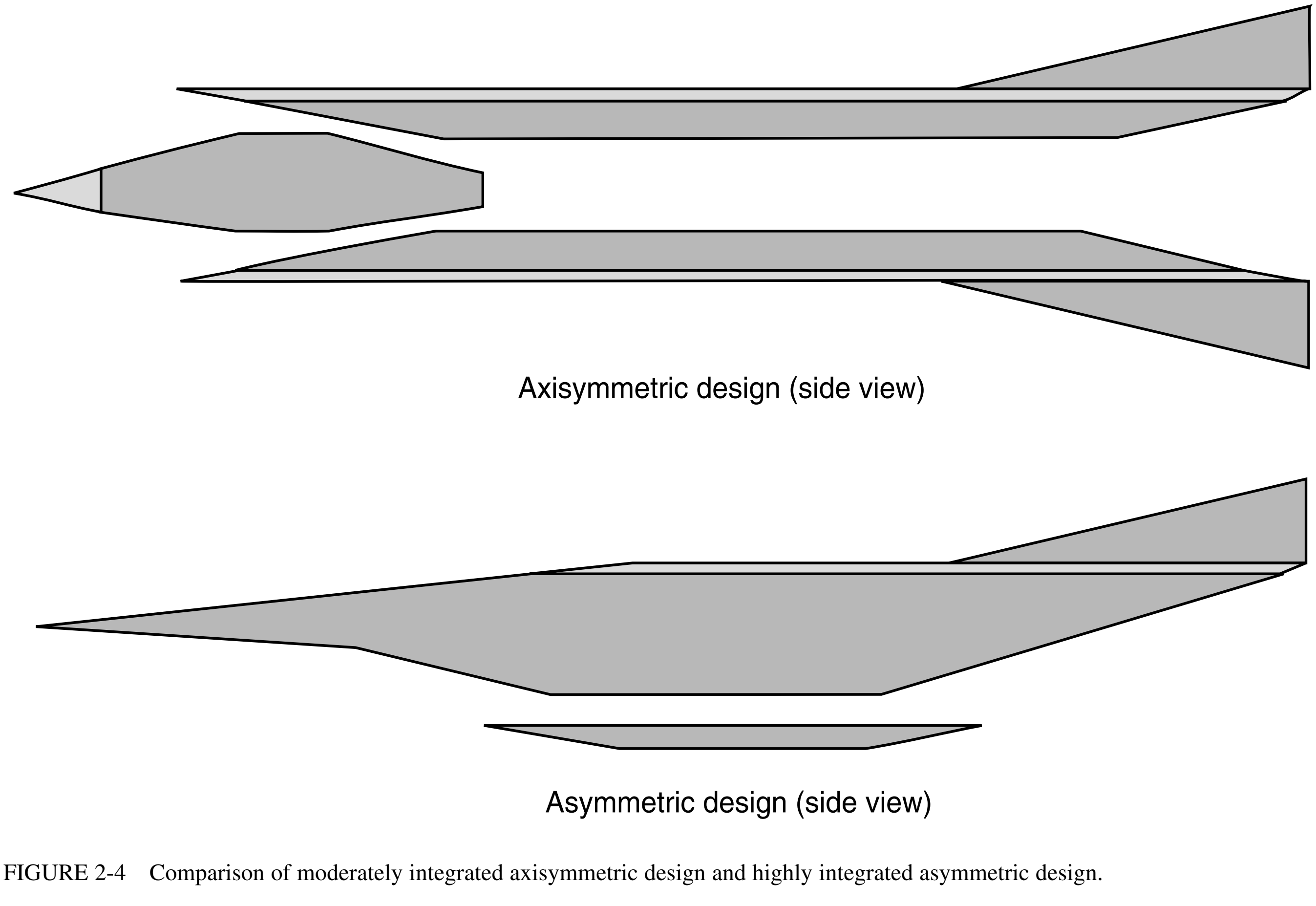

FIGURE 2-4 Comparison of moderately integrated axisymmetric design and highly integrated asymmetric design.

careful separation of thrust and drag forces during the development process, but the engine performance and vehicle control are relatively independent. By contrast, the asymmetric configuration suggests a highly integrated engine and airframe design.[3]

The development of the vehicle control system requires a detailed understanding of engine operation because the internal and external flow fields are coupled (i.e., through the engine and around the exterior of the missile). Ground test facilities will have to simulate both flow fields accurately to demonstrate the integrated engine performance accurately. The asymmetric airframe design offers a considerably higher level of performance but requires considerably more attention to vehicle-engine integration issues than the axisymmetric design.

In addition to the issues of engine and airframe integration, several other integration issues must be addressed. If system studies indicate the need for a terminal guidance system, the vehicle design will have to accommodate forward-looking radomes or windows. If a seeker is required, it may affect the design of the scramjet inlet and overall vehicle aerodynamics. Cooling requirements or temperature limitations would affect either the design or the allowable trajectory. The integration of munitions in the missile would affect the allowable size and volume of subsystems and could require that the missile size and shape be modified. If the munition is to be separated before detonation, vehicle trajectories may have to be modified. The dynamic pressure levels of 4,700 to 26,300 pounds per square foot, depending on payload separation altitude (see Figure 1-2), will significantly affect the vehicle structural and control authority requirements during the unpowered descent.

Stability, Guidance and Control, Navigation, and Communications Systems

Guidance and control encompasses the following phases of a hypersonic missile's flight: boost phase, cruise phase, and terminal phase. Only the first two phases will be addressed here; the terminal phase will be addressed in the next subsection.

Stability, guidance, and control during the boost phase are performed by avionics on the vehicle. The vehicle will be equipped with an inertial navigation system that tells the avionics the location and orientation of the booster. The avionics will use fins or a thrust-vectoring system to maintain the stability of the booster and control its speed and location (longitude, latitude, and altitude), which depends on the location of the target, and the proper velocity for ignition of the missile's air-breathing propulsion subsystem. When the hypersonic vehicle separates from the booster, the scramjet engine will be ignited, and the missile will accelerate to the cruise phase.

During acceleration to cruising speed and during the cruise phase, the vehicle will use onboard sensors to stabilize and maneuver during free flight until it is close enough to the target to enter the terminal phase. The global positioning system (GPS—a constellation of satellites that determines precise location) will provide navigation commands and guide the vehicle to the point where it will dive toward the target. GPS units can be designed to operate on the vehicle. Onboard inertial sensors will provide the vehicle-based body measurements (e.g., angular rates) necessary for stabilizing the vehicle in its six degrees of freedom. The scramjet engine is expected to exert significant, and varying, forces orthogonal to the primary velocity vector of the vehicle. Based on detailed knowledge of the scramjet engine's thrust vector, the control surfaces can be properly sized and the flight control system modeled to maintain vehicle direction and speed.

A hypersonic missile will operate mostly autonomously, with various portions of the flight specified in preprogrammed onboard memory. Informing the missile of the target location can vary from simple to moderately complex, depending on the overall system philosophy. If the missile flies autonomously from the launch aircraft to the target, then only simple communications will be required, namely, a means to tell the missile where the target is prior to launch. A hard-wired command link through a pull-away connector could be used for simple communications. In this scenario, the target would have to be located very accurately, perhaps 15 minutes before intended missile impact. Another possibility would be low-rate radio frequency updates during flight. In this scenario, the antenna system would probably be designed to look in a specific direction (e.g., back at the launch aircraft, at the sky, or both) to avoid jamming. Messages could be relayed via satellite. An operational hypersonic missile might have no need to transmit information back to a base station.

The hypersonic vehicle guidance and control system consists of several technical components (see simplified block diagram in Figure 2-5). Among these are several types of onboard sensors: (1) vehicle attitude and stabilization sensors (e.g., angular-rate sensors, linear accelerometers, and vertical gyros); (2) vehicle navigation sensors (e.g., GPS and an inertial navigation system); and (3) target-seeking sensors (e.g., radar, infrared, or visible sensors). Air data (e.g., angle of attack, dynamic pressure) are also necessary for the guidance and control system. Conventional air data sensors will probably not be suitable, but new sensors for this high-speed, streamlined vehicle could probably be developed. Most likely, air data will be derived from the inertial data and a vehicle aero-model in software. The guidance and control system will have to be able to effect changes in the vehicle's angular attitude and lateral, longitudinal, or vertical position (i.e., control surfaces, such as ailerons, fins, and

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[3] The asymmetric HyTech engine configuration, which is fully integrated into the airframe, is the baseline configuration considered in this study.

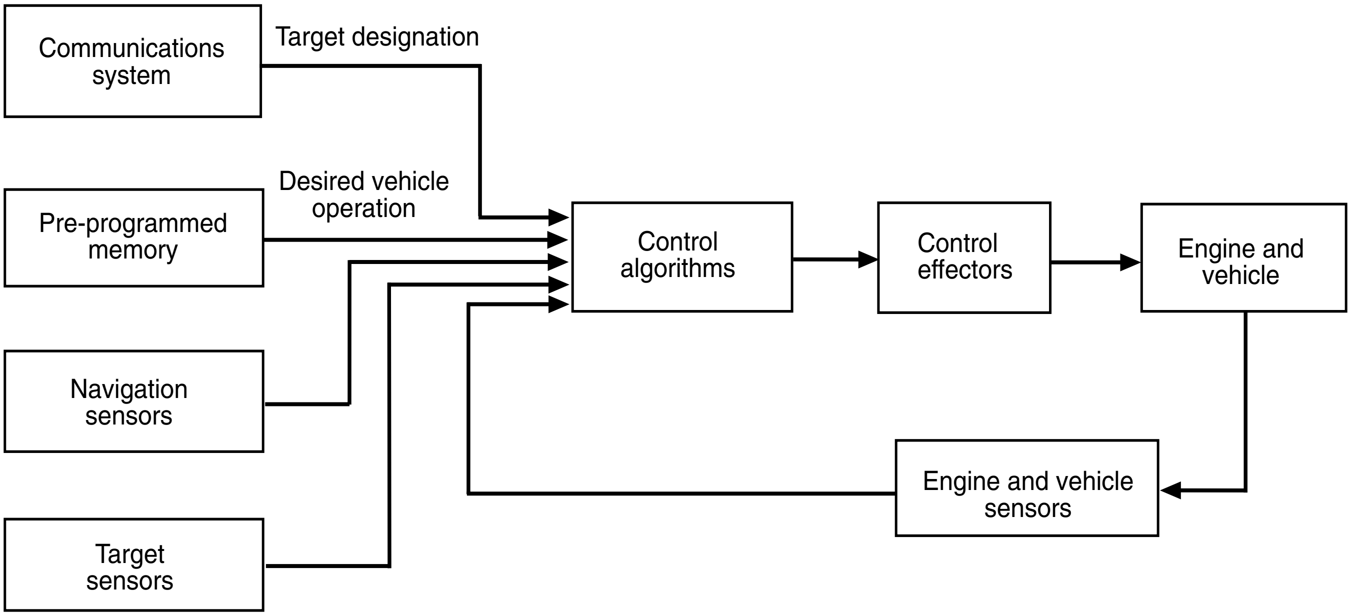

FIGURE 2-5 Block diagram of a guidance and control system of a nominal air-breathing hypersonic missile.

rudders, or thrust-vectoring could be used). Control algorithms will have to be developed for software that can take in information from all of the sensors, compare it with what the vehicle should be doing, and send commands to the control effectors to correct the vehicle's operation.

Another important feedback control system in the vehicle is the engine control system, which will regulate the fuel flow to generate thrust, and hence the speed of the vehicle, and perhaps also cool the engine. The flight computer will contain the engine control system algorithms. The guidance and control system and the engine control system will have to be closely and intricately coordinated. Adding to the complexity will be asymmetric geometries and active cooling systems. Typical engine control effectors will be fuel pumps and valves; engine sensors will measure fuel flow, temperatures, and pressures.

As far as the committee could ascertain, the Air Force has done no significant work so far on the guidance and control system, sensors, control effectors, or control algorithms for an air-launched, air-breathing hypersonic missile. The NASA HYPER-X program[4] addresses a few of these issues but does not include work on relevant overall guidance and control issues important to a hypersonic missile system. The primary uncertainty in the guidance and control system prior to the terminal phase is in the control algorithms. The committee believes that substantial work on the design, analysis, and simulation remains to be done. Some of the work done on fighter aircraft and experience with other missiles may be applicable, but stabilization during the boost phase, during separation of the missile from the rocket booster, during scramjet ignition, and during re-ignition if the scramjet experiences a flame-out, are issues that have yet to be addressed. Another issue is the transition from the cruise phase to dive, at which point the dynamic pressure will be increasing, the speed will be decreasing, and the control authority of the control effectors will be increasing. The missile may have to have maneuvering capability to hit the target. The control algorithms will have to change the control loop characteristics dynamically (e.g., by scheduling the gain of the loop) during the dive.

The design and validation of the control algorithms will require realistic simulation of the scramjet's performance (including forces and moments) and of the vehicle's aerothermodynamic environment throughout all engine operating conditions and all phases of the missile's flight. The development of the simulation will be a significant project in its own right.

The main uncertainty in the navigation system is the effectiveness of the GPS, which could be jammed by an enemy. A supplementary inertial navigation system will probably be used to provide continuity in case the GPS is not available and during intervals when the onboard GPS receiver is recontacting satellites. Studies will have to be conducted to determine how well the GPS and inertial system combination will perform in various scenarios. Because of the high speed of the hypersonic missile, the missile will travel through the zone of effective jamming rather quickly, thereby reducing the GPS-dropout interval, which could readily be filled in by the inertial navigation system. During

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[4] The HYPER-X program includes the development of technology and flight validation at Mach 7 and Mach 10 for a hypersonic aircraft configuration using a hydrogen-fueled, airframe-integrated scramjet. The program is discussed in more detail in the answer to Question 2d.

the cruise phase, the missile would be flying at high altitude with the GPS antenna[5] on the top of the vehicle (shielded from an aircraft jammer), which should also reduce the chances of jamming. The GPS may not be as reliable during the dive because attempts at jamming will probably be intensified, and fewer GPS satellites will be in view of the antenna.

Another concern with GPS is the potential destruction of GPS satellites by an adversary during a conflict. The loss of a single satellite would have no effect, but the loss of several would. A backup inertial navigation system, which would be less accurate, could also be incorporated.

The main uncertainty in the radio frequency communications system involves the antennas, which must withstand the aerodynamic heating. The antennas may be on the underside of the vehicle, which is probably where the engine will be, and may protrude from the surface of the vehicle.

Terminal Guidance and Sensors

The terminal phase will begin at a designated point when the vehicle executes a high-g downward maneuver to head for the target. One concern during the terminal phase is the durability of the control surfaces, which will be subjected to aerodynamic heating and high dynamic pressures. Similar surfaces have been successfully developed for use under similar conditions on the Space Shuttle and on maneuvering re-entry vehicles. The terminal phase will require a combination of existing technologies for high-speed (e.g., re-entry) vehicles and new technologies.

Regardless of the target, the terminal guidance and control system poses several difficult challenges and stresses for the system. The maneuver from level flight at an altitude of approximately 100,000 feet into a steep-angled dive and striking the target on the ground will take less than a minute with speeds varying from Mach 8 to Mach 4 and will require very high accuracy. Control of the missile will be similar to the control of a re-entry vehicle, but with a more stringent accuracy requirement. Moreover, finding and hitting mobile, imperfectly located targets will require that the missile have target-seeking sensors and probably a large maneuvering footprint. Therefore, the committee believes that significant work, which is not yet funded, will be required for the development of an effective terminal sensing, guidance, and control capability.

Proponents of an air-breathing hypersonic missile claim that one of its main advantages is that it can be used to destroy time-critical targets (i.e., it can be fired "from a fighter aircraft outside a heavily defended target area and yet reach time-critical targets, such as mobile launchers, before they could move any significant distance" [see Appendix B]). Whether the target is mobile or fixed, the committee believes (for reasons explained below) that sensing and guidance in the terminal phase of flight will be necessary. The requirements for hitting mobile, time-critical targets are considerably different than they are for fixed, hardened targets. Therefore, these two cases are treated separately below.

Mobile, Time-Critical Targets. These targets include mobile tactical ballistic missile launchers and mobile air defense missile systems. Mobile systems are not hard to destroy if they can be hit; however, they are difficult to find and, once they have been found, they can be moved before they can be hit. Some mobile systems can be moved into or out of action in as little as five minutes (Yefremov and Svirin, 1998).

To protect the aircraft launch platform and still provide coverage of the target, the range for a U.S. hypersonic missile may have to be 500 nautical miles or more. The range and average speed of the missile will determine the time line. It takes a missile with a top speed of Mach 8 about 12 minutes to fly 750 nautical miles, which is approximately one nautical mile per second. If the target is more than about 300 nautical miles away, the mobile target can be moved during the flight of the missile. Therefore, the missile will require a highly accurate terminal guidance and sensing capability that can direct the missile to the target area, which might be several nautical miles in diameter, and can subsequently search for and select the most important target.

A hypersonic missile system should be able to operate in any weather. Cloud layers can interfere with the operation of optical or infrared sensors, and a cloud layer could mask the target until the final few seconds. If the target area has a diameter of several nautical miles, once the target is located, the missile (or its munition) must be capable of enough lateral acceleration to reach it. Developing a system with this level of agility will certainly be challenging.

Radar sensors can be used to penetrate cloud cover and have the potential for longer range target detection. Synthetic aperture radars can be used to form images of stationary targets on the ground with resolutions on the order of one foot. Images of moving targets can be formed with Doppler tracking of strong scatters from a target. For a synthetic aperture radar on the missile[6] to work effectively, the missile must either do a fly-over or must spiral toward the target.

The deployment of munitions from the diving hypersonic missile would transfer this problem to the munitions, which would avoid many technical problems with the sensors, including heating of the infrared window and radome-induced thermal distortions, but would create new challenges for the munitions and their deployment. The committee is aware that the Air Force is developing "smart" submunitions that

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[5] Use of the GPS assumes the availability of antennas that can withstand the heat.

[6] A synthetic aperture radar on another platform could be used to provide the missile with target information. However, the other platform would have to operate far enough from the target to be out of harm's way.

utilize short-range, three-dimensional imaging laser radars to locate and destroy ground targets.

Fixed, Hardened Targets. Fixed, hardened targets present another set of challenges to a hypersonic missile. These targets may include buried command and control facilities, buried manufacturing and storage facilities for chemical, biological, or nuclear weapons, or fixed launch sites for tactical ballistic missiles. Some of these targets must be disabled quickly in any conflict. The first problem is locating the target and determining the aim-point for destroying it. Accurate location of the target is easier if the target has been surveyed on the ground (not likely in hostile territory). As satellite and airborne reconnaissance sensors improve and multiple measurements can be taken prior to the start of a conflict, target location errors may eventually be less than 10 feet. Determining the location of critical aim-points introduces complex technical issues, which the Air Force is addressing through several initiatives.

The destruction of a hardened target typically requires an accuracy of 10 feet circular error probable, the accuracy level of a typical laser-guided bomb. Unfortunately, laser-guided bombs are direct attack weapons and cannot operate in all weather conditions. Weapons guided by the GPS in combination with an inertial navigation system, such as conventional air-launched cruise missiles, are often cited as precision weapons that can operate in any weather. But their accuracy is currently limited to approximately 30 feet circular error probable.

More accurate GPS positions for both military and civilian applications are in great demand, and the committee has no doubt that substantial improvements will be made by the time the hypersonic missile could be deployed. In fact, an augmented GPS could very likely have an accuracy of 10 feet circular error probable by 2015. Other technologies that would support the use of GPS in the terminal phase of a hypersonic missile's flight include high-temperature radomes and, if jamming is considered a threat, antijamming techniques.

Munitions

The committee believes that a hypersonic missile will not require fundamentally new munitions technology. However, the proposed hypersonic missile system will require highly tailored munitions, which will have to be designed according to the planned target set (which is not yet well defined), stringent weight requirements, and configuration requirements of the airframe. Preliminary analyses by potential weapon system contractors indicate that each munition will have to weigh no more than about 250 pounds. The highest priority munition design is likely to be a conventional high explosive warhead for the destruction of ballistic missiles on their launchers. Another valuable munition would be a tailored warhead that could exploit the kinetic energy of the missile by being integrated into a penetration assembly for deeply buried targets. Once the requirements for munitions have been defined, a substantive effort can be directed toward engineering tailored munitions designs that would complement the unique capabilities and maximize the target kill probability of an air-launched, air-breathing hypersonic missile.

TECHNICAL COMPONENTS, QUESTION 2b

> Are all the necessary technical components of a hypersonic Mach 8 regime propulsion technology program identified and in place, or if not, what is missing?

Summary Answer

The HyTech Program addresses many, but not all, of the propulsion flow path technologies needed to support the development of a Mach 8 missile. The most significant omissions are in the transition to flight, including the development of an operational envelope, a ground-to-flight correlation, and an engine control system. The HyTech Program should also consider a wider range of hypersonic air-breathing propulsion technologies (e.g., uncooled structures and liquid fuel ignition).

Detailed Answer

The HyTech Program has been structured on the assumption that Mach 8 is the optimum cruising speed of a hypersonic missile. The technologies being investigated support an engine concept that operates between Mach 4 and Mach 8. After reviewing the information furnished by the Air Force (e.g., see Appendix B), the committee concluded that the selection of Mach 8 speed was based on a very limited requirements analysis. Therefore, the committee will answer this question for two speed ranges. First, the propulsion technologies applicable to a Mach 4 to Mach 8 propulsion system will be addressed, with a focus on the demands of flight at Mach 8. Second, the committee will address the propulsion technology implications of operation at Mach 4 to approximately Mach 6.5.[7]

The HyTech Program is addressing many of the critical technologies that will be required for operation of a Mach 4 to Mach 8 propulsion system, including starting the inlet at the scramjet takeover point, initiating the combustor process from a cold-start condition, piloting the hydrocarbon-fueled combustion process, controlling the dehydrogenation and cracking of the endothermic fuel as a means of cooling the vehicle, developing the necessary materials and structures for the engine, and assessing the performance penalties associated with component inefficiencies including nozzle recombination losses. Shortfalls in any of these technologies

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[7] The committee chose Mach 6.5 to be the nominal value in the Mach 6 to Mach 7 region, above which the technological challenges increase significantly.

could significantly affect overall system performance. Unfortunately, funding limitations have precluded the development of multiple approaches as a risk reduction measure. The committee believes that the selection of only one propulsion system contractor has increased the program risk.

In addition to the technology areas listed above, several other propulsion-related technologies will have to be developed before a Mach 8 missile is ready for final development. These technologies include a fuel control system (pumps, piping, valves, regulators, and bladders) capable of controlling both liquid and gaseous fuel at temperatures between –65°F and 1,000°F, a complete thermal management system, and an electronic control system coupled with an active missile control system. A significant amount of work will be required to model the dynamics of the propulsion system. The HyTech Program plans to culminate with only a ground-test, free-jet demonstration of an engine with flight-like components. Therefore, complete engine demonstrations will have to be conducted in subsequent programs.

Because no flight demonstration is planned for the HyTech Program, follow-on programs for the development of prototypes will be necessary before the Air Force can commit to the development of an operational system (see Question 2e(i)). The ground test demonstration will not be able to validate technologies in a complete simulation of the flight environment (e.g., the effects of simulated air, Reynolds numbers, and angles of attack) or to develop the testing methodology for integrating the engine into an airframe (e.g., test techniques and force and moment accounting schemes) or to evaluate missile concepts throughout the operational envelope (e.g., maximum and minimum altitudes, g-loading, and off-design performance). All of these will require further development after completion of the HyTech Program.

Because the HyTech Program has been structured to develop the technologies for a missile that can cruise at Mach 8, the committee concluded that certain technologies, such as endothermic fuel-cooled engine structures, a two-phase fuel control system, and a cold-start combustion system, will have to be developed. All of these technologies are challenging, and their development may be expensive.

The risk and cost associated with the development of hypersonic air-breathing systems increase significantly with higher cruise speeds. Scramjet technology or existing ramjet technology using (nonendothermic) fuel-cooled metallic structures could be used for Mach 4 to Mach 6 systems. But systems with a maximum cruise speed of about Mach 6 to Mach 6.5 will require a scramjet; nonendothermic fuel cooling or uncooled ceramic composite materials could be used. Above Mach 6.5, active cooling using endothermic fuels will be required. A missile designed for Mach 6 or Mach 6.5 will not survive operations at a significantly higher Mach number. A Mach 8 missile, although heavier, more costly, and less efficient than a Mach 6 to Mach 6.5 missile, could be operated at a lower Mach number to increase its range (see Figure 1-1). System studies should be done to determine the maximum required Mach number for the missile because it will affect both the capability and affordability of the system.

Roughly speaking, Mach 6 to Mach 7 (nominally referred to as Mach 6.5) represents a boundary above which the technological challenges increase significantly and at which the technologies being addressed by the HyTech Program will be required. At speeds of less than Mach 6.5, the engine could be operated with a hot structure, which means the engine operation could be separate from the cooling requirements of the vehicle. Instead of endothermic fuel-cooled engine structures, for example, uncooled ceramic composite materials and structures,[8] liquid fuel control systems, and liquid fuel ignition and combustion could be used. These technologies would probably be easier and less expensive to develop. The Air Force should complete the analyses and establish an operational requirement for a hypersonic missile so that the technologies being investigated by the HyTech Program can be affirmed or the program can be modified.

PROPULSION UNCERTAINTIES, QUESTION 2c(i)

> What are the salient uncertainties in the propulsion component of the hypersonic technology program, and are the uncertainties technical, schedule related, or bound by resource limitations as a result of the technical nature of the task (e.g., materials sources, qualifications of support personnel, or technology driven costs that affect affordability), to the extent it is possible to enunciate them?

Summary Answer

The significant technical uncertainties in the overall propulsion system derive from budgetary limitations, are manifested by a lack of focus on risk reduction and on flight demonstration, and cannot be resolved until the current program is completed in 2003. Additional uncertainties exist in the areas of weight, reliability, and affordability. The HyTech Program has not adequately addressed trade-offs at the system concept level between propulsion system capabilities, mission performance, and reliability and affordability.

Detailed Answer

The uncertainties in the component performance and engine operation of the propulsion system fall into four broad categories: low-speed engine operation; high-speed engine operation; high-speed performance; and the engine thermostructural system. Each of these categories is addressed below.

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[8] The use of ceramic composite materials would presume they are available in the sizes, shapes, and quantities required and can be manufactured reliably, reproducibly, and cost effectively.

At low speeds, the air-breathing engine must operate from the end-of-boost condition, which the HyTech Program has set at Mach 4. Critical technologies to be addressed include starting the inlet, maximizing the inlet contraction, realizing diffuser performance, developing an engine cold-start capability, piloting the combustor process, and providing an effective flame-holding mechanism.

The air-breathing engine must operate up to the high-speed cruise condition, which the HyTech Program has set at Mach 8. Critical engine technologies to be addressed include boundary layer transition in the inlet, combustion piloting at high altitude, integration of engine operation and the flight control system (see response to Question 2a(ii)), and matching the heat load on the vehicle and engine with the cooling capacity of the endothermic fuel system. During this study, the committee was briefed by representatives of industry and the HyTech Program on an array of fuels and fuel blends. The committee was not able to delve deeply into the question of the fuel composition but notes that the choice of fuel is an important factor in the successful operation of a scramjet propulsion system. In addition to cooling capacity, other important fuel characteristics include energy density per unit weight and per unit volume, ignition limits, flame speed, and long-term physical and chemical stability. The Air Force should carefully consider these characteristics in system trade-off studies.

The air-breathing engine must perform efficiently through a range of Mach numbers and at the high-speed cruise condition. Critical engine technologies include maximizing the inlet efficiency, minimizing losses associated with the combustor piloting system, minimizing the heat transfer and shear force losses in the combustor, and limiting recombination losses in the nozzle over the operating range of Mach numbers, altitudes, and angles of attack and sideslip.

Engine concepts incorporate a combination of materials to satisfy thermostructural design requirements. Significant technology risks are associated with the design and fabrication of an actively cooled engine combustor. However, the risks are mitigated for single use, short duration vehicles like missiles.

Although pursuing multiple solutions could alleviate potential problems, budget limitations have restricted investigations, and the current program does not include flight demonstrations. Therefore, many uncertainties will not be resolved until after the HyTech Program is completed in 2003.

In spite of system uncertainties in the areas of reliability and affordability, technology decisions are being made. Management of the HyTech Program should analyze and evaluate the trade-offs between maximum Mach number, mission performance, and the reliability and affordability of the propulsion system. Earlier, the committee recommended that the Air Force initiate trade-off analyses. The following recommendation is based on the responses to this question and to the previous question (as well as other parts of this report).

Recommendation. The Air Force should expedite trade-off studies in three separate areas: (1) mission parameters, to establish operational requirements; (2) system concepts, to define candidate configurations with optimum ranges of performance, operability, reliability, and affordability; and (3) technology, to redirect the HyTech projects toward the most promising alternatives, if necessary.

OTHER UNCERTAINTIES, QUESTION 2c(ii)

> What are the salient uncertainties for the other main technology components of the hypersonic technology program (e.g., materials, thermodynamics, etc.)?

Summary Answer

See the detailed response to the technology uncertainties under Question 2a(ii).

TECHNICAL FOUNDATION, QUESTION 2c(iii)

> Does the program provide a sound technical foundation for a weapon system program that could meet operational requirements as presently defined?

Summary Answer

The current HyTech Program does not have the mandate or the funds to provide a sound technical foundation for a weapon system. The Air Force will have to conduct extensive trade-off studies before it can establish an operational requirement for a hypersonic missile system and determine specific design goals. As a result of concerns that the survivability of this class of missile had not been adequately analyzed, the committee performed an additional study of the survivability trade-offs.

Detailed Answer

The committee's response to this question is a resounding "no." The HyTech Program will not provide a sound technical foundation for a weapon system for reasons that have been explained in the Overall Picture section of this chapter and in the responses to Questions 2a(i) and 2a(ii). The formulation of operational requirements for an air-breathing hypersonic missile system will require comprehensive mission analyses. The definitions (CJCS, 1997) of two elements in the formulation of operational requirements are described below.

A **mission need statement** is not system specific but defines necessary operational capabilities in broad operational terms. The operational capabilities and constraints are then studied during the concept exploration and definition phase of the acquisition process.

An **operational requirements document** is a statement of performance and related operational parameters for the proposed concept or system. The document is prepared by the user or user's representative at each milestone of the acquisition process, beginning with the approval of concept demonstration.

The committee was informed of some mission needs that could be met by a hypersonic air-breathing missile system. However, the Air Force has not performed trade-off analyses or studies that could lead to the establishment of an operational requirement for a specific type of weapon.

As a result of concerns about the vulnerability of a hypersonic missile, the committee conducted an analysis (see Appendix C) to examine one of the main reasons given in support of a Mach 8 missile—namely, that it would be "nearly invulnerable to countermeasures because of the high speed" (see Appendix B). The committee attempted to determine if there were significant differences in the vulnerabilities of hypersonic missiles with top speeds of Mach 8, Mach 6.5, and Mach 4 to a surface-to-air defensive missile system. The summary result was that modern air defensive systems could successfully engage hypersonic missiles at all three speeds. Therefore, even missiles operating at high speeds may require radar cross-section reduction to reduce their vulnerability. The decreased vulnerability of a Mach 8 missile can be achieved by a Mach 6.5 missile with a moderate reduction in radar cross section.

The Air Force has yet to determine the effects of various parameters (e.g., top speed, radar cross section, maneuverability, and altitude) on missile vulnerability. The Air Force will have to assess the full range of parameters (e.g., average speed over various ranges, maximum and minimum ranges of flight, appropriate standoff distances from the target before launch of the missile) and technical trade-offs (e.g., between airframe and engine thermostructural systems and speed) to establish operational requirements for the hypersonic missile system.

INTERACTIONS WITH OTHER PROGRAMS, QUESTION 2d

> How does the Air Force hypersonic program interrelate with other Department of Defense hypersonic initiatives, e.g., the Defense Advanced Research Projects Agency's Advanced Concept Technology Demonstration on hypersonic vehicles?

Summary Answer

The HyTech Program is neither formally coordinated with nor intentionally dependent upon hypersonic initiatives by the U.S. Department of Defense (DOD) or NASA, although relevant technical information is being shared. The committee encourages the Air Force to continue this exchange of information.

Detailed Answer

In addition to evaluating the HyTech Program, the committee received briefings on the Navy Hypersonic Weapons Technology Program and the Defense Advanced Research Projects Agency Affordable Rapid Response Missile Demonstrator Program. These DOD programs, the parameters of which are summarized in Table 2-1, are for vehicles that rely on hydrocarbon fuel. The committee also received briefings

TABLE 2-1 Summary of Parameters of Various DOD Hypersonic Programs

	Air Force HyTech	Navy Hypersonic Weapons Technology	Defense Advanced Research Projects Agency Program
Main thrust of program	Engine ground test 1998–2003	Propulsion airframe guidance and control and ordnance	Build and demonstrate an affordable missile
Propulsion	Dual-mode scramjet	Dual-combustion ramjet	Dual-mode scramjet
Fuel	Hydrocarbon	Hydrocarbon	Hydrocarbon
Mach number	4 to 8	5 to 6	6 to 8
Range	750 nautical miles, nominal	400 to 700 nautical miles	100 to 600 nautical miles
Initial operational capability date	2015	2010	N/A
Year start/stop	1995/continuous	Fiscal year 1998/2003	Fiscal year 1998 Phase I/ Phase II optional
Funding goal	$20 million per year nominal	$8 million per year nominal	Phase I–$10 million Phase II–$50 million
Weapon cost goal	not applicable	$400,000	$200,000

Source: Information furnished by representatives of the Air Force, Navy, and Defense Advanced Research Projects Agency on two NASA programs that involve hydrogen fuel (HYPER-X and the Advanced Reusable Transportation Technology Project). Some technical challenges are common to all of these programs (e.g., air-breathing propulsion at hypersonic speeds), but each program also faces specific technical challenges (e.g., speed and type of fuel). Each program is discussed briefly below.

HyTech Program

The HyTech Program is summarized in Box 2-1 and described in more detail in Appendix B. The objectives of the program are to develop and demonstrate air-breathing, storable-fuel (hydrocarbon), scramjet propulsion technologies for missile (and aircraft) applications at speeds of Mach 4 to Mach 8. Performance goals have been established for specific impulse, specific thrust, and durability consistent with requirements for expendable hypersonic air vehicles, with a projected initial operational capability in 2015. The program goals are to demonstrate, by 1998, stable scramjet combustor operations between Mach 4 and Mach 8 with 90 percent of the final specific-impulse goal; to demonstrate by 2000 95 percent of the final specific-impulse goal; to demonstrate by 2001 scramjet structural durability for 12 minutes; and to demonstrate by 2003 integrated engine performance at 100 percent of the final specific-impulse goal. The program will demonstrate technologies through ground tests in appropriate facilities that can simulate Mach 8 flight conditions. The Air Force hopes these tests will be sufficient for a follow-on flight demonstration program that could eventually lead to a practical application. The HyTech Program was initiated in fiscal year 1995 at the direction of the secretary of the Air Force with a nominal $20 million per year funding profile, although the program has experienced a shortfall every year.

Navy Hypersonic Weapons Technology Program

In its draft mission needs statement, *Tactical High-Speed Strike Capability*, dated April 28, 1997, the Navy stated that the capability to attack, destroy, and hold at risk short-dwell, time-critical targets at long standoff ranges is critical to joint strike operations, joint littoral operations, and joint suppressions of enemy air defenses. Navy studies have shown that covering 80 percent of the spectrum of time-critical targets requires engagements at ranges of up to 600 nautical miles and speed requirements of Mach 3.5 to Mach 7, depending on the launch point.

The Navy has concluded that current state-of-the-art missile technology will not support the demonstration and validation or engineering and manufacturing development of a high-speed weapon that meets the mission needs. The thrust of the Navy Hypersonic Weapons Technology Program is to develop and demonstrate technologies for a hypersonic strike weapon in the concept exploration and definition phase. By fiscal year 2003, the Navy hopes to demonstrate enabling technologies for a hypersonic air-launched or surface-launched weapon that meets the Navy's requirements. Specifically, the goals are to demonstrate[9] critical technologies in the areas of propulsion, airframe, guidance and control, and ordnance for a hypersonic strike weapon that will have initial operational capability by about 2010. The weapon would have an average speed of Mach 5 to Mach 6, a range of 400 to 700 nautical miles, a cost of less than $400,000 per unit, a circular error probable of less than 10 feet, and the ability to deliver ordnance that can penetrate 18 feet or more of concrete**.** The principal configuration is an axisymmetric, dual-combustion ramjet[10] with a hot structure. The ramjet will be demonstrated in a free-jet test configuration. Navy project funding starts in fiscal year 1998 and ends in fiscal year 2003. The program is funded at a nominal $8 million per year, which is even lower than funding for the HyTech Program.

Defense Advanced Research Projects Agency Affordable Rapid Response Missile Demonstrator Program

This concept definition program relies on the design tools and hardware being refined by Air Force, Navy, NASA, and industry programs to develop the basis for an affordable hypersonic missile. The program objective is to build and demonstrate in flight a test vehicle that will enable the development of an affordable, Mach 6 to Mach 8, scramjet-powered, hydrocarbon-fueled missile to support rapid-response, long-range (100 to 600 nautical miles) missions against time-critical (two to eight minutes) targets. In addition, this missile would enhance advanced penetrators with much higher impact velocities for the destruction of hardened and deeply buried targets. The emphasis of the program is on affordability. Program goals include the demonstration of affordable manufacturing processes to produce units with an average flyaway price of $200,000; the development of a concept of operations with the warfighting user; the demonstration of propulsion performance compatibility with tactical aircraft and the Navy's vertical launching system; and the achievement of cruise speeds of Mach 6 to Mach 8 with a maximum range of 600 nautical miles.

The program is divided into two phases of 18 months each, the second phase of which is optional. In the initial phase, critical risk-reduction measures will be taken, including detailed cost estimates. The second phase, if implemented, would include the assembly and flight of demonstration vehicles. The cost of the initial phase is projected to be $10 million; the cost of the second phase is projected to be $50 million.

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[9] This means a physical demonstration that provides a reasonable expectation (i.e., low-to-moderate risk) that the technologies are in hand.

[10] A dual-combustion ramjet is a hybrid engine that combines the features of a ramjet and scramjet engine to operate over a wide Mach number range.

NASA HYPER-X Program

The HYPER-X Program is intended to demonstrate and validate the technology, the experimental techniques, and the computational methods and tools for design and performance predictions of hypersonic aircraft using airframe-integrated, dual-mode, hydrogen-fueled, scramjet propulsion technologies. The program strategy is to evaluate the performance of scramjet-powered research vehicles at Mach 7 and Mach 10; demonstrate controlled, powered air-breathing and unpowered hypersonic aircraft flight; provide ground and flight data to validate computational methods, prediction analyses, test techniques, and operability for future hypersonic cruise and space-access vehicles; execute an affordable plan focused on key technologies using existing designs, design methods, databases, and off-the-shelf hardware and systems wherever possible; and conduct three flights of very short duration. The flight schedule is as follows: flight 1 (Mach 7) is planned for January 2000; flight 2 (Mach 7) for October 2000; and flight 3 (Mach 10) for September 2001. The total program budget is $170 million, starting in fiscal year 1997 and ending in fiscal year 2001.

NASA Advanced Reusable Transportation Technology Project

The Advanced Reusable Transportation Technology Project is one element of the NASA Advanced Space Transportation Technology Program. The primary goal of the project is to demonstrate technologies mature enough to reduce the development risk of hydrogen-fueled, rocket-based, combined-cycle propulsion systems for future launch vehicles. Most of these systems are ramjets or dual-mode scramjets with small, fully integrated rocket ejectors installed in the flow path to provide low-speed propulsion. This type of propulsion has the potential to improve performance significantly over pure rocket engine systems for space launch because it uses atmospheric oxygen during the boost phase. Compared to pure rocket propulsion, the gross weight of the launch vehicle should be lower because less oxidizer has to be carried by the launch system. The project has the following milestones: test critical propulsion component technologies by the end of 1998; develop a flight demonstrator engine by 2003; and conduct a flight demonstration by 2004.

Comparison and Interrelationships of Programs

Table 2-1 summarizes various parameters of the DOD programs discussed above. The vehicles being developed in DOD programs are limited in speed to Mach 6 or Mach 8, whereas the short duration NASA flight test program for hydrogen-fueled vehicles is intended to reach Mach 10. The NASA HYPER-X Program is currently the only U.S. hypersonics program that is funded for flight tests. The committee believes this flight experience will be valuable for all of the DOD programs.

Although there are some interactions among these programs, they are not part of an overall DOD or national strategy. Each program has its own objectives, goals, and milestones; however, Appendix B suggests that the goals of the HyTech Program "are fully coordinated" with the other programs and "complement their activities." The committee found no evidence that the HyTech Program is formally coordinated with (i.e., operating under a rigorously structured arrangement controlled jointly by the Air Force, other DOD entities, and NASA) or dependent on current DOD or NASA initiatives. However, much relevant technical information is being appropriately shared. The exchange of information should be encouraged, especially with the NASA HYPER-X Program, which will be the first U.S. flight test of scramjet propulsion.

MILESTONE DATES, QUESTION 2e(i)

> From an engineering perspective, what are reasonable milestone dates for a hypersonic missile system development program leading up to production, i.e., concept development, engineering and manufacturing development, etc. For example, with a 2015 target date for operational capability, does the current program have a coherent plan and road map to build and test a Mach 8 regime hydrocarbon-fueled scramjet engine?

Summary Answer

The committee finds that initial operational capability for a hydrocarbon-fueled scramjet missile system in 2015 is technically feasible. The committee's experience indicates that it will take until 2015 to develop the type of missile contemplated by the Air Force with moderate risk. A prototype missile phase will have to be initiated in 2003 and prototype flight testing completed by 2007, which would reduce the risk of entering the engineering and manufacturing development phase. Figure 2-6 is the committee's suggested road map, which includes a complementary program to the current HyTech Program that will be necessary to reach initial operational capability by 2015.

Detailed Answer

During this study, the Air Force presented a road map for the current HyTech Program (see earlier description and Appendix B). The program ends in 2003 with limited ground demonstrations of a Mach 8 scramjet. Although the program makes wise use of available funding, it does not provide realistic criteria for the engineering and manufacturing development phase of an acquisition program. The committee did not find a road map for achieving operational capability.

The committee, therefore, developed its own road map in keeping with the Statement of Task to show the required steps to an initial operational capability of an air-launched,

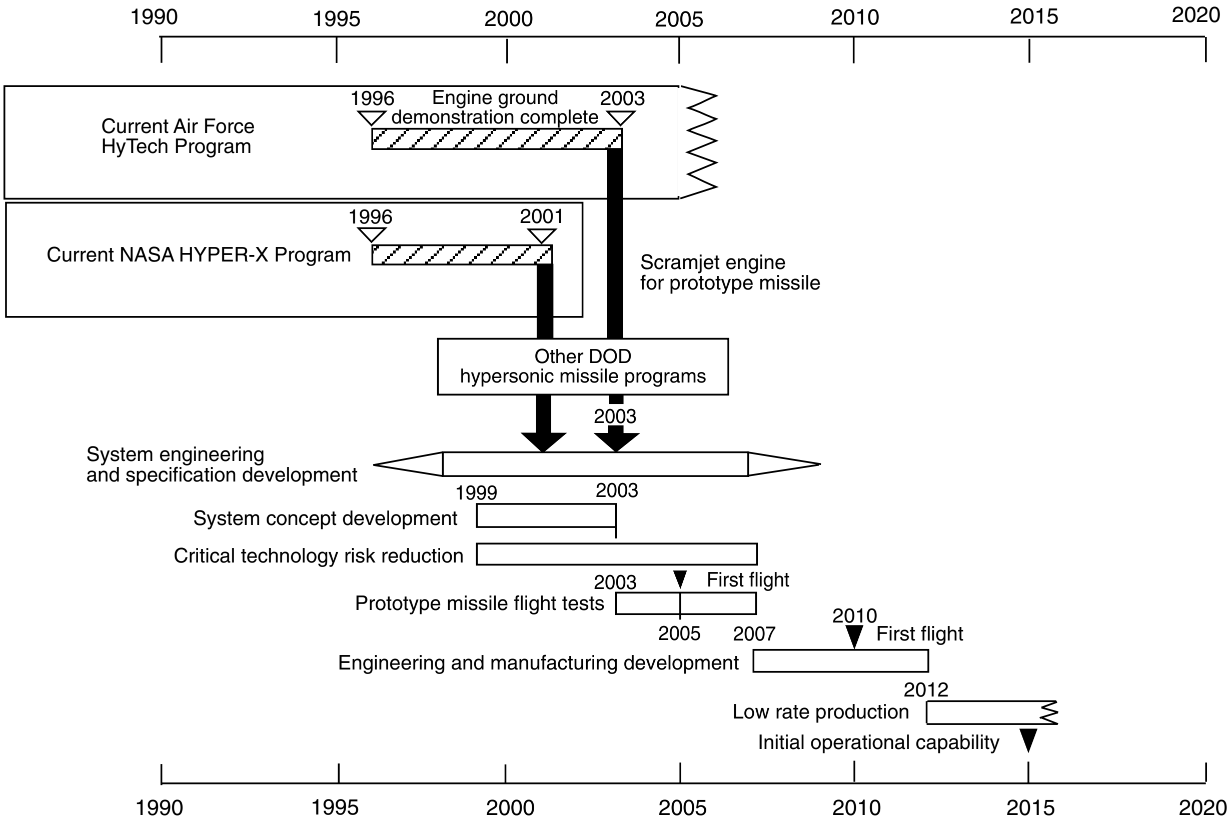

FIGURE 2-6 A six-phase road map to achieve initial operational capability of a Mach 6 to Mach 8 hypersonic missile system by 2015.

scramjet, hypersonic missile system by 2015. The current Air Force program plan does not include flight testing of prototype vehicles to demonstrate the readiness of the scramjet engine technology for a Mach 8 missile system. The committee believes that this is a crucial step. The committee also believes that the competitive tests of prototype missiles would be extremely valuable for achieving the technical performance and cost objectives of the operational missile system. Prototype test flights would also be the most important factor for justifying the engineering and manufacturing development program.

The time spans and scope for the committee's road map are based on the experience of generally comparable past programs. In other words, the committee did not take the 2015 date as a given, but the committee's experience indicates that it will take that long for the Air Force to establish an initial operational capability. Overall, the committee's proposed schedule is of moderate risk (e.g., it has virtually no concurrency; many believe that the lack of concurrency is a priceless asset). However, a major feature of the program is the development of a prototype missile; to ensure that the engineering and manufacturing development phase incurs only moderate risk, the prototype missile program will necessarily incur significant risk.

The road map is based on several general principles, which will make it easier to obtain funding from DOD and Congress. The first is minimal concurrency. The second is an orderly funding profile with no precipitous changes. The third is the ability to change the direction of the program, if necessary.

In preparing the road map, the committee recognized that the current NASA HYPER-X Program, which is based on hydrogen-fueled propulsion, and other planned DOD programs will contribute substantially to the technology base for a hydrocarbon-fueled hypersonic missile system and will reduce the risk of an Air Force program. The Defense Advanced Research Projects Agency is formulating a very aggressive advanced concept technology demonstration program for a hypersonic missile, with an intense focus on the cost of a missile system. However, at the time of this report, the committee did not have enough information to ascertain how an advanced concept technology demonstration would feed into the road map.

The six phases of the road map (depicted in Figure 2-6) are described below, followed by a rough cost estimate for the entire program.

System Specification Development (An Iterative Process, 1998 to 2007)

This is the classical iterative process for evolving a technically sound weapon system design that meets critical operational requirements (e.g., speed, range, and survivability) but also satisfies weight, volume, and, most important, production cost objectives. System specification development, which is continuously executed, is critical to the long-term viability of the program but has not been given enough emphasis or resources thus far. Producing a missile with a range of 600 to 750 nautical miles and a nominal gross weight of 3,000 pounds at launch will be difficult. Numerous trade-off studies and evaluations of many alternate system configurations will be essential to a balanced system design that meets all critical operational requirements (which might evolve) within acceptable weight and production cost constraints. The highest level of activity during this phase is estimated to occur from 1999 to 2003.

System Concept Development (Two Competitors, 1999 to 2003)

This phase is closely related to system specification development. Concept development studies should be competitive to evolve the most cost effective system design. Although plausible, preliminary system designs were presented to the committee, additional detailed engineering will be required before a detailed design of the prototype missiles can be initiated in 2003. An initial measure of effectiveness could be range with a fixed gross weight at launch, which could be changed later by specific measures of system effectiveness developed by the Air Force (e.g., in connection with the establishment of an operational requirement). A hypersonic missile poses a very difficult challenge in design integration. The best design will emerge only after several highly creative alternative concepts have been developed.

Technology Risk Reduction (1999 to 2007)

In addition to the scramjet propulsion system that is being developed under the HyTech Program, appropriate technology development programs should be initiated in the following areas in order to be ready for engineering and manufacturing development in 2007 (see response to Question 2a(ii)): affordable airframe and engine thermostructural systems (including a full definition of the environment to which these systems will be exposed); optimization of vehicle system design, integration, and performance; low-cost and integrated stability, guidance and control, navigation, and communications equipment; appropriate terminal guidance and sensing equipment to ensure accuracy in all weather conditions; and two types of tailored munitions (e.g., a lightweight, high energy, explosive warhead and a high-speed penetrating warhead for hardened targets). The Air Force will have to develop a high fidelity, full-mission simulation model for a hypersonic missile system. The highest level of activity for this phase will be from 2000 to 2003.

Prototype Design and Flight Testing (2003 to 2007; First Flight in 2005)

Prototype design and flight testing is a crucial and risky phase of the program. The committee is not proposing a specific program in terms of the number of prototype missiles or detailed flight test objectives. Three to five fully instrumented flight test vehicles will probably be adequate, especially if they can be recovered for inspection (water or ground recovery of some of the propulsion systems should be a program requirement). This phase must demonstrate that the integrated scramjet and missile structure and vehicle control system perform as predicted, repeatably, under flight conditions. Prototype flight tests will validate analytical predictions, confirm the results of simulations, and provide essential flight test data for low-risk engineering and manufacturing development. These prototypes must have prioritized, carefully selected, limited objectives. Munitions and target engagement capabilities are not required, nor is a production configuration of the solid rocket booster.

This phase will also have important nontechnical value because it will provide convincing evidence to the DOD and the Congress that the Air Force can field a long-range missile with speeds up to Mach 8 to defeat specific threats. No matter how successful ground testing is, it will not demonstrate the level of technology readiness for entry into engineering and manufacturing development.

Engineering and Manufacturing Development (2007 to 2012; First Flight in 2010)

This phase would include the conventional steps (i.e., detailed production design, rigorous full-mission system simulation, initial tooling and test equipment, production of two small lots of missiles, complete ground testing, development flight testing, and initial operational testing and evaluation). The proposed schedule assumes that the baseline missile configuration will not include active sensors and that only two warhead options will be implemented, one for fixed above-ground targets and the other for hardened underground targets. The number of missiles assembled during this phase and the number of missiles that are flight tested with live munitions can only be determined after further analysis. A first approximation is 10 to 15 missiles without munitions and 10 to 15 with munitions. These numbers may seem low, but with rigorous full-mission simulation and very high fidelity modeling, the number of flight tested missiles can be kept to a minimum.

Low-Rate Initial Production Leading to Initial Operational Capability (2012 to 2015)

Initial operational capability requires that a specified number of operational missiles be in the hands of an operational command and ready for immediate use in combat. The committee is not in a position to estimate an appropriate initial operational inventory. However, from the standpoint of industrial production, a reasonable number, based on the proposed road map, would be 30 to 50 missiles.

Costs

The committee's very rough, preliminary estimate of the cost of the entire program is $750 million to $1.5 billion (in 1998 dollars). In production quantities (e.g., about 1,000 missiles), the committee believes the resulting missile will be considerably more expensive in 1998 dollars—by at least a factor of two—than the $200,000 goal for the vehicle contemplated in the Defense Advanced Research Projects Agency program (see Question 2d).

FOREIGN HYPERSONIC APPLICATIONS, QUESTION 2e(ii)

> Are there foreign hypersonic technology applications that are significantly more developed than those of the United States, that, if acquired by the U.S. government or industry through cooperative venture, license, or sale, could positively affect the development process or schedule for Air Force hypersonic vehicles?

Summary Answer

Several organizations throughout the world have significant expertise related to scramjet-powered hypersonic vehicles. Although no system-level hardware seems to be available internationally, many technologies of potential use in hypersonic vehicles are being investigated. The committee believes that the Air Force should continue to evaluate potentially significant foreign technologies.

Detailed Answer

During this study, the committee was not informed of any hypersonic, scramjet-powered vehicle that has reached the operational stage or engineering and manufacturing development stage elsewhere. From the committee's review of the development of hypersonic technologies abroad (based on information furnished by the Air Force), it is evident that technologies associated with vehicles capable of hypersonic flight are being actively investigated by several other countries (including the flight testing of large-scale scramjet propulsion systems), and several international collaborations are in the formative stages.

Russia has the most significant technical capabilities related to hypersonic systems. The Soviet Union invested heavily in advanced air-breathing missiles and fielded several operational ramjet-powered systems (e.g., SA-6, SS-N-22, M-31) for use on land and at sea. The Soviet Union, and now Russia, also invested heavily in hypersonic technologies. Russian centers with strong programs in hypersonics are the Central Institute of Aviation Motors, the Central Aerohydrodynamic Institute, the Central Institute of Machine Building, and the Institute for Theoretical and Applied Mechanics. The technologies being explored at one or more of these institutes include hypersonic aerodynamics, scramjet propulsion systems, endothermic fuel systems, ground testing facilities, measurement systems, and flight demonstration techniques.

In addition to the classical hypersonic technologies, Russia has also invested in several novel technologies whose advocates claim will improve hypersonic systems significantly. At the present time, researchers in the United States are evaluating these technologies to ascertain their potential.

Ramjet-powered vehicles originated in France, where the first flight of a piloted, ramjet-powered aircraft (the Leduc 001) took place in 1949. France has continued to investigate ramjet-powered vehicles, including the operational, ramjet-powered air-to-ground Missile Air-Sol-Moyenne-Portée. French experience with ramjet-powered vehicles has provided them with significant experience in the areas of high-temperature materials and flight testing. The Office National d'Etudes et de Recherches Aerospatiales and Aerospatiale have particular areas of expertise. Many other countries, including Great Britain, Canada, Australia, Germany, Italy, Japan, and China, also have some experience with hypersonics.

The committee was not informed of any system-level hardware available on the international market. However, considering the diverse technologies that are associated with the development of hypersonic vehicles, the acquisition of foreign technologies has the potential to enhance the development of Air Force hypersonic vehicles. Acquisitions could be made through cooperative ventures at the basic technology level or through licenses or sales. The committee believes the Air Force should continue to evaluate foreign technologies, but the committee does not have the expertise to make specific recommendations involving cooperative ventures, licenses, or sales. Technologies that should be evaluated include scramjet technologies (e.g., fuel preparation, injection, mixing, ignition, and flame-holding); endothermic fuel and fuel-control systems; and advanced materials and structures.

CONTENT AND PACE OF THE PROGRAM, QUESTION 2e(iii)

> Based on these assessments, the committee will make recommendations on the technical content and pace of the program.

Answer

If the Air Force determines that there is a requirement for a hypersonic missile system, the committee recommends that the Air Force adopt the road map in Figure 2-6. To achieve initial operational capability by 2015, the program office recommended in response to Question 2a(i) should establish a road map similar to the one developed by the committee. The program should proceed step by step through the various phases, including flight testing, and should address all critical technologies.

INFRASTRUCTURE, QUESTION 2f

> Are there any evident implications for the Air Force support infrastructure for a hypersonic missile system? For example, will other technologies need to be developed in parallel to support a hypersonic vehicle and are those likely to pose significant barriers to eventual success in demonstrating the missile concept or in fielding a viable weapon system by 2015?

Summary Answer

The implications for the Air Force support infrastructure of a hydrocarbon-fueled hypersonic missile will depend on the maximum speed of the missile. Some investment will be necessary in ground testing facilities, flight testing, and analyses to determine the performance and operability of the propulsion system. Ground testing facilities will have to support both technology development and demonstration and system development and qualification of a complete missile. Full-scale ground testing facilities are currently limited to about Mach 7, although modifications to at least one facility are under consideration to support a Mach 8 capability. If a maximum nominal Mach number of 7 or lower is selected, the only modification to a test facility might be to provide for hydrocarbon fuel testing at the NASA 8-Foot High Temperature Tunnel. Regardless of the maximum Mach number, a capability for the periodic destructive testing of selected missiles from storage must also be provided.

Detailed Answer

This question addresses several different aspects of the infrastructure support required for hypersonic air-breathing missiles, including ground testing facilities; ancillary test equipment and instrumentation and computational facilities; test ranges; and missile storage capabilities. The committee was advised that about 12 percent of the HyTech Program funding (approximately $12 to $13 million) has been allocated to test facilities and instrumentation for Mach 8 scramjet development. This allocation was based on an average projected funding of $16 million per year.

Ground Testing Facilities

Ground testing facilities will be required to test technologies in at least four areas: propulsion, fuels, thermal structures, and airframe-engine integration. The committee focused its attention primarily on existing facilities that have the capacity for testing full-scale, integrated propulsion systems for an air-launched tactical missile at true inlet temperature in the Mach 4 to Mach 8 range, in the altitude range of 50,000 to 100,000 feet, and for test durations of up to 12 minutes. The committee considered several facilities, including the Air Force Arnold Engineering Development Center Aerodynamic and Propulsion Test Unit and the NASA-Langley 8-Foot High Temperature Tunnel. Several special-purpose facilities that are only capable of supporting component technology development were also considered. The committee assumed that these facilities would not be affected by the realignment or closing of bases.

The existing thermostructural and propulsion capability of the NASA-Langley 8-Foot High Temperature Tunnel can support the development and demonstration of several of the required hypersonic integrated propulsion technologies at Mach numbers of 4, 5, and, nominally, 7. However, the test duration time is limited to about two minutes, which is not long enough to demonstrate the reliability of the propulsion system in a single continuous test.

None of the test facilities can support the critical integrated-engine demonstration phase of the HyTech Program at a higher Mach number than nominal 7. However, several facilities can support component or subscale testing above nominal Mach 7. Validation of integrated-engine performance at Mach 8 will require flight testing.

The committee was informed that modifications to the Arnold Engineering Development Center's facility have been planned and partially funded to increase the maximum Mach number to about 8 and the test duration to approximately 10 minutes. These modifications directly support the integrated-engine demonstration phase of the HyTech Program.

A major uncertainty in the performance, operability, and reliability test data from all of the test facilities considered by the committee is whether or not the ground testing results (e.g., specific net thrust, combustion efficiency and stability limits, and combustor starting limits) simulate flight operations within usable limits of error. To date, the ground test results of scramjet propulsion systems have not been validated with flight data. The HYPER-X Program will provide flight data for hydrogen-fueled scramjets, but it will not provide data on reliability and range of operability. The committee was advised that tests by Russia and France have shown a substantial correlation between ground test data and flight test data for hydrogen-fueled scramjets.

The high-temperature gas supplied to the engine inlet from each of the existing facilities is modified or reconstituted air rather than atmospheric air. These "pseudo-air" working fluids contain significant quantities of gaseous contaminants, and possibly particulate matter. The quantitative effects of these gaseous contaminants and particles on some parameters, such as specific net thrust, ignition limits, and heat transfers, are not currently known. These effects must be defined to ensure that valid test data will be available for a system acquisition program. The NASA HYPER-X Program will provide some data for a hydrogen-fueled scramjet, but the validity of these data for a hydrocarbon-fueled scramjet has not been determined. The committee believes the HyTech hydrocarbon-fueled propulsion technologies should be flight tested to validate the ground facility data and test performance at flight conditions.

The committee also evaluated test facilities that could support both technology development and follow-on system acquisition of the rocket booster, hypersonic airframe, and the related guidance, sensor, and munitions subsystems. Existing DOD, NASA, and industrial aerodynamic and aerothermal facilities are adequate to support the development and qualification of the airframe, including lift and drag, stability and control, thermal protection, and structural integrity. But they are not adequate to test the full flight envelope of the integrated vehicle-engine, which will require flight tests. Existing facilities are adequate to support the development and qualification of the guidance, sensor, and munitions subsystems.

Recommendation. The Air Force should begin planning for the ground test infrastructure to support the development and qualification of the operability, reliability, durability, and performance of integrated hypersonic propulsion systems over the Mach number range from the speed at the end of the rocket-boost phase to the maximum cruise speed. This infrastructure should be completed expeditiously.

Ancillary Test Equipment and Instrumentation and Computational Facilities

Current facilities have free-jet test sections with the size and strength to support full-scale propulsion testing in the nominal Mach number range of 4 to 7. However, the technology development and demonstration of a fixed-geometry, dual-mode propulsion system fueled with endothermic hydrocarbons will involve iterative design and test challenges to optimize the engine components, such as inlet, isolator, combustor, and nozzle, for flight in the Mach 4 to Mach 8 range. Developing a propulsion system that can maintain stable operation through at least two transitions will require iterative designs and tests. One of these transitions is from ramjet mode (subsonic combustion) to scramjet mode (supersonic combustion); the other is from liquid hydrocarbon fuel injection to two-phase (vapor and liquid) pyrolyzed hydrocarbon fuel injection.

Ancillary test equipment is available to test the design optimization of the integrated engine and control system at discrete Mach numbers from approximately Mach 4 to approximately Mach 7. Equipment is also available to test the mode transitions at the component level. But testing mode transition of the full-scale integrated engine and engine fuel control system will require flight testing.

Ancillary test equipment to support both technology development and follow-on system acquisition for the rocket booster, hypersonic airframe, and the related guidance, sensor, and munitions subsystems is adequate. Existing capabilities extend from typical subsonic air launch Mach number and altitude windows to well above Mach 8 and 100,000 feet in altitude.

Because of the complexity of hypersonic test facilities and hypersonic test articles, automated control networks will be necessary to ensure safe and efficient operation. Most of the candidate test facilities have been operating successfully for decades. However, it would be prudent for the Air Force to assess the capability and reliability of the test control networks to limit the risk of disruptions or damage to test articles.

The committee also evaluated the requirements for instrumentation and computational facilities to support development and demonstration testing. Existing instrumentation technologies in several areas (e.g., force, flow, temperature, and pressure) are adequate. The existing high-speed computational facilities are also adequate. The committee believes that existing facilities can support the computational fluid dynamics, computational structural mechanics, and system modeling, as well as the follow-on prototype and engineering and manufacturing development programs proposed by this committee.

Test Ranges

Several test ranges can accommodate a flight test program for a missile with a nominal maximum Mach number of 8 and a range of about 750 nautical miles. The options vary depending on the flight test requirements, such as whether the test vehicle is expendable or recoverable and whether it is air launched or ground launched. The flight test requirements are similar to the requirements for the NASA HYPER-X Program, which initially included flights planned for Mach 5 to Mach 10 with minimum to maximum trajectory ground ranges of 600 to 1,200 nautical miles. The requirements that might be similar for a missile test program included the following: conventional flight termination for the rocket-boost phase; flight termination capability throughout the flight; telemetry coverage throughout the flight (assuming data rates are consistent with the test range capabilities); ground-launched options using a rail launcher for better inclination toward air-breathing flight corridors; air-launched options from appropriate platforms; environmental impact statements for some ranges; subsonic operation prior to recovery sequence for recoverable test vehicles; and flight tests on Air Force, Navy, Army, or NASA test ranges.

The ground-launched range options that were deemed feasible for a HYPER-X flight test vehicle boosted by a Castor IVB class booster included: the Wallops Flight Facility, from Virginia down the Atlantic Test Range; Vandenberg Air Force Base, from California down the Pacific Western Test

Range; Poker Flat Range in Alaska; and Wake Island to Kwajalein Atoll in the Pacific. None of these flight paths is toward a populated area. Both the Wallops facility and Wake Island have rail launchers and the required facilities, but both would require a water recovery. The Vandenberg and Poker Flat ranges would require environmental impact statements and, depending on launch trajectory, may require the installation of rail-launchers. Poker Flat would also require facility upgrades. All four test ranges can meet the requirements for telemetry and safety.

The air-launched range options that meet the flight program requirements include: the Air Force Development Test Center (at Eglin Air Force Base) Missile Range from the Gulf of Mexico; Vandenberg Air Force Base/Pacific Test Range; Edwards Air Force Base/Utah Test Range; and Poker Flat Range in Alaska. All of these test ranges have ground recovery locations (pack ice location at Poker Flat). But ground recovery at the Air Force Development Test Center and Vandenberg would require flight toward a major population center. Water recovery is available at all ranges except Utah. All of the facilities are capable of air-launched tests and can meet telemetry coverage and range safety requirements.

Missile Storage

For an operational hypersonic missile to be affordable, it should not entail significant changes to the Air Force support structure in the field. An affordable hypersonic missile will have to approach the "wooden round" concept as much as possible. The Navy's experience with the liquid-hydrocarbon fueled Tomahawk missile is directly applicable to the present situation. Tomahawk missiles have been stored for up to 10 years, with only periodic electronic system checks and computer reprogramming, and then fired successfully.

The two aspects of missile support that must be considered are storage and systems checking. Experience suggests that the design problems with the subsystems (e.g., batteries, electrical and mechanical actuators, lubricants, seals, computers, and codes) can be solved, especially if the special circumstances are recognized from the outset. All aspects of the fuel system (i.e., the fuel, storage tank, pump, catalysts, and cooling system) will require special attention for proper storage. A system that uses endothermic fuels would be unique.

Experience has shown that the subsystems can be periodically interrogated and computers reprogrammed. However, in contrast to the Tomahawk, which has a multiple-use turbojet engine, a scramjet propulsion subsystem will be designed for a life of one cycle. During testing, pyrotechnics will be fired, coatings will ablate, materials will heat up and yield, and catalyst beds will be polluted. This situation is similar to the situation of a solid-fueled rocket where the motor must be fired to be thoroughly tested. Special procedures, such as the random sampling program used for intercontinental ballistic missiles, must be developed for testing scramjet missiles. A good deal can be learned from tested vehicles even if they are not reusable.

Selected scramjet propulsion subsystems and rocket boosters must be periodically removed from long-term storage and test fired to confirm system storage life. These test firings, combined with the required inspections of the post-test hardware, will provide an objective basis for extending or terminating storage. The propulsion subsystem components would be consumed in the test and inspection processes and could not be returned to storage.

3

Other Applications of Hypersonic Technologies

In Part 3 of the Statement of Task, the committee was asked to consider applications of hypersonic technology for 2015 and beyond:

> To the extent possible, identify technology areas that merit further investigation by the Air Force in the application of hypersonics technology to manned or other unmanned weapon systems by 2015 or beyond.

FUNDAMENTAL CONSIDERATIONS

The application of air-breathing hypersonics technology to future manned or unmanned weapon systems was too big an issue to be systematically and comprehensively considered in the limited time for this study. The committee does not have enough information to make recommendations regarding the hypersonic weapon systems capabilities the Air Force might require in the twenty-first century. But the subject is clearly important and worthy of an in-depth study once operational premises and priorities have been better defined by the Air Force.

In this chapter, the committee briefly discusses the possible applications of air-breathing hypersonic propulsion, as well as two approaches the Air Force could adopt, either (1) the expansion of the hypersonic technology base without developing real systems, or (2) the evolutionary development and deployment of systems to meet clearly stated Air Force requirements. The committee also provides a four-part process to guide the Air Force's long-range development of future hypersonic systems.

Recommendation. The Air Force should work on the evolutionary development and deployment of systems to meet clearly stated requirements.

HYPERSONIC VEHICLES

Hypersonic vehicles propelled by air-breathing propulsion systems, in addition to the scramjet missile currently under consideration, might include higher Mach number, long-range missiles; theater-reach and global-reach aircraft designed to deliver weapons or for reconnaissance missions; and space launch vehicles. Two Air Force goals that might benefit from air-breathing propulsion are global reach and access to space. These are not mutually exclusive.

For global reach, a vehicle must be able to reach any military target on the globe quickly and carry out a critical military mission. Whether global reach may be best obtained by vehicles that operate primarily inside or outside the earth's sensible atmosphere depends on the specific mission requirements. The payloads of a global-reach hypersonic vehicle could range from missiles to reconnaissance equipment to orbiting systems.

Because an enemy could attack U.S. space-launch facilities or space-based assets, access to space from military bases that survive an initial attack (especially if the United States has lost some of its space infrastructure) could be a critical capability. Access to space includes the capability to repair or replace satellites, to add mission-specific satellites, and to defend U.S. space assets. Access to space will rely, in part, on rocket propulsion systems, including the propulsion systems of orbiting vehicles.

TECHNOLOGY AREAS FOR FURTHER INVESTIGATION

In Chapter 2, the committee discussed the required technologies for an air-breathing hypersonic missile boosted to Mach 4, at which point the scramjet would take over and accelerate the missile to a top speed of Mach 8. The technologies developed in the HyTech Program will be important for all future hypersonic vehicles, especially if the technologies have been validated in a flight test program. The technologies might be directly applicable to some types of vehicles and might provide a valuable information base for building others. Potential vehicles that would directly benefit from the technologies developed by the HyTech

Program include hydrocarbon-fueled hypersonic aircraft and space-launch vehicles operating in the nominal Mach 4 to Mach 8 range. NASA's HYPER-X Program and Advanced Reusable Transportation Technology Project (described in Chapter 2) are developing engine and airframe technologies that will also benefit the development of hypersonic systems.

Future investigations should focus on the development of low-speed (zero to Mach 4) propulsion system technologies, such as turboramjets, ejector ramjets, and pulse detonation engines. For manned systems, the emphasis should be on the development of life support systems to protect and sustain pilots and crews in the demanding thermal environment of hypersonic flight.

Vehicles with maximum speeds of about Mach 8, such as long-range missiles, aircraft, and space-launch vehicles, should benefit from the information gained in the HyTech Program and, depending on the specific concept, might directly use some of the technologies. Vehicles with top speeds above Mach 8 will require cryogenic hydrogen-fueled propulsion systems because of hydrogen's additional cooling capacity and energy content. Higher speed vehicles, whether dual fueled or hydrogen fueled, will require the development of higher Mach number propulsion system technologies. Three critical technologies—airframe and engine thermostructural systems; vehicle integration; and stability, guidance and control, navigation, and communications systems—will also have to be investigated further (see detailed response to Question 2a(ii)). These vehicles will require durability, as well as reliability. Reusable space-launch vehicles would require the same technology development as lower-speed aircraft but would have much more demanding performance, reliability, and durability requirements.

To date, space access has been based on rocket-based propulsion systems. Advances in air-breathing propulsion system technologies may be useful for future space-access applications. Space-launch vehicles propelled by a combination of air-breathing and rocket propulsion would allow the substitution of higher payloads for onboard oxidizer not needed by the air-breathing engine. In addition, these vehicles would have other interesting capabilities, including gradual engine start-up and shutdown, horizontal takeoff and abort, subsonic or supersonic self-ferry, mission flexibility (e.g., rerouting and retargeting after takeoff, large launch windows, and substantial cross-range ability), and reusable structures.

PROGRAM OPTIONS FOR FUTURE HYPERSONIC SYSTEMS

If the Air Force chooses to pursue a broad range of hypersonic air-breathing technologies with a variety of potential applications, it could provide a technology base to support the design, development, procurement, and operation of hypersonic weapon systems to meet several mission needs. This type of program could pursue technology in the following disciplines: propulsion, propulsion and airframe integration, airframe and engine thermostructural systems, guidance and control systems, aerothermodynamic environment, human factors, and operations.

Another option for the Air Force is to pursue the evolutionary development and deployment of hypersonic weapon systems powered by air-breathing or combined-cycle engines that derive from established capabilities and clearly stated Air Force requirements. The committee believes this narrower approach is the only one that will result in operational systems, which would capitalize on a technology base that supports them directly. In other words, the Air Force would start with a requirement, develop the technology to support a system to meet that requirement, and build and test (in flight) a prototype of the desired system. This approach is described below in terms of the notional components of a long-range planning process. *The committee strongly recommends this approach.* Otherwise we may never know whether or not air-breathing propulsion will be useful and affordable at hypersonic speeds.

Based on presentations to the committee by the best technical experts, the committee believes that Air Force plans for future hypersonic weapon systems employing air-breathing propulsion should include at least four components. These components are based on the premise that hypersonic technologies should be developed to meet future weapon systems requirements.

Recommendation. The Air Force should develop a long-range plan incorporating four components as a primary document to guide the development of future hypersonic weapon systems. The four components are: operational concepts for future systems and preliminary system designs; scramjet-powered weapon systems using hydrocarbon fuels; hypersonic weapon systems using hydrogen fuel; and combined-cycle systems for space access.

Component 1. Operational Concepts for Future Systems and Preliminary System Designs

The tasks in this component are not usually considered to be technologies, but in this context they are extremely important. A focused, prioritized list of requirements for the development of hypersonic technology will require practical operational concepts and the evaluation of several alternate preliminary system designs.

The committee found the Air Force's current plans for technology development to be fragmented because concepts and preliminary designs were not well developed. In other words, the Air Force has apparently not given system engineering and system design integration for hypersonic technologies a high priority or commensurate resources. The committee believes that system engineering and design integration should be leading the technology development and providing a basis for prioritizing specific technology developments.

Component 2. Scramjet-Powered, Hydrocarbon-Fueled Weapon Systems

The committee believes that emerging scramjet propulsion technology will support the development of Mach 6 to Mach 8 class hypersonic weapon systems. The committee suggests that tentative operational requirements be established, that operational concepts be formulated, and that competitive preliminary design studies be carried out for an unmanned reusable weapon system in this speed range. The purpose would be to generate focused requirements for the development of hypersonic technology. An advanced concept like an uninhabited combat air vehicle would provide a solid foundation for the development of a manned air-breathing hypersonic weapon system, which could conceivably be a requirement in the early part of the twenty-first century.

Component 3. Hypersonic, Hydrogen-Fueled Weapon Systems

The same approach should be applied to a hydrogen-fueled hypersonic weapon system. The process should begin with a definition of Air Force requirements, followed by user-driven operational concepts with a focus based on competitive system design studies. This class of weapon system would be able to take full advantage of NASA's development of propulsion systems. Formulation of this weapon system would lead to preliminary system designs for both unmanned and manned weapons operating above Mach 8 and would illuminate and crystallize the priorities for hypersonic technologies for hydrogen-fueled weapon systems of this class. Based on the vision statements, strategic plans, and study results made available to the committee, the Air Force should consider hydrogen-fueled hypersonic weapon systems. The tasks outlined here are the logical next steps in that direction.

Component 4. Combined-Cycle Systems for Space Access

The capabilities derived from the previous components, as well as from NASA's Advanced Reusable Transportation Technology Project, would provide a basis for a dual-mode scramjet with small, fully integrated rocket ejectors installed in the flow path for low-speed propulsion. Low-speed propulsion could potentially improve performance significantly over pure rocket engine systems for space launch because it would use atmospheric oxygen during the boost phase. The gross weight of the launch vehicle would be lower than for a vehicle with pure rocket propulsion because not as much oxidizer would have to be carried onboard.

SUMMARY

The committee considered possible roles that hypersonic vehicles might play in future Air Force capabilities, particularly global reach and access to space. The committee then identified two program options: (1) the broad pursuit of hypersonic technologies and (2) the evolutionary development of hypersonic technologies based on clearly stated requirements. The committee believes the latter option is the only one that will result in operational systems. On that basis, the committee provided a four-component long-range planning process to guide the Air Force's development of future hypersonic systems.

4

Conclusions and Recommendations

In the course of responding to the Statement of Task in Chapters 2 and 3, the committee made findings, reached conclusions, and offered suggestions for current and future hypersonics programs. The major conclusions and recommendations are presented below.

Conclusion 1. The Air Force's HyTech Program, which is a Mach 4 to Mach 8 propulsion technology flow path program, is necessary but not sufficient for the development of a scramjet engine as an integral part of a missile system. Although the limited testing (ground testing only) planned for the propulsion subsystem should indicate its potential engine performance, flight testing over a representative range of operating conditions will be necessary to determine the engine's operability, reliability, and durability in an integrated system. These parameters are prerequisites to understanding the engine's utility in an operational system.

Recommendation 1. The Air Force should commit appropriate resources to integrated airframe-engine flight testing, which is vital to demonstrating a hydrocarbon-fueled scramjet in the Mach 4 to Mach 8 range. This recommendation (and the related recommendations that follow) assumes that the Air Force will decide that a hypersonic air-breathing propulsion capability is a potential candidate for fulfilling future system needs (e.g., as part of a hypersonic missile or space access application). If the Air Force is not willing to commit to flight testing, it should reevaluate its goals for the development of air-breathing hypersonic technology.

Conclusion 2a. The HyTech Program itself will not provide the basis for an operational missile system because the development of critical enabling technologies for hypersonic air-breathing missiles are not included in the program and, to the committee's knowledge, the Air Force is not pursuing them. These critical technologies will have to be mature and validated before the Air Force can proceed with a low-to-moderate risk acquisition program.

Conclusion 2b. Besides propulsion, the five most critical enabling technologies for air-breathing hypersonic missile systems, in order of priority, are (1) airframe and engine thermostructural systems; (2) vehicle integration; (3) stability, guidance and control, navigation, and communications systems; (4) terminal guidance and sensors; and (5) tailored munitions.

Conclusion 2c. If the HyTech Program were expanded to include a full-scale, integrated airframe-engine flight test program, and if the critical enabling technologies were mature, an operational air-breathing hypersonic missile system could be developed with low-to-moderate risk and without concurrency in support of an initial operational capability by 2015.

Recommendation 2a. If the Air Force determines that there is a requirement for a hypersonic missile system, then it should establish a system-oriented program office to manage the system design and the development, integration, and flight testing of critical enabling technologies for a hypersonic missile system.

Recommendation 2b. The program office should establish a road map to reach initial operational capability by 2015. The road map should include six phases: (1) system specification development; (2) system concept development; (3) technology risk reduction; (4) prototype design and flight test; (5) engineering and manufacturing development; and (6) low rate initial production.

Conclusion 3. The Air Force has not established operational requirements or conducted design and requirements tradeoff studies in support of an air-launched hypersonic missile system.

Recommendation 3. If the Air Force intends to pursue the development of an air-launched hypersonic missile system as a viable candidate to meet its future warfighting needs, then it must initiate design and requirements trade-off analyses in the following areas: targets, speed, range, survivability, lethality, aircraft compatibility, risk, and cost.

Conclusion 4. The risk and cost associated with the development of hypersonic air-breathing systems increase significantly with higher cruise speeds. Scramjet technology or existing ramjet technology with nonendothermic fuel-cooled metallic structures could be used for Mach 4 to Mach 6 systems. Systems with a maximum cruise speed of Mach 6 to Mach 6.5 will require a scramjet, which uses nonendothermic fuel cooling or uncooled ceramic composite materials. Mach 8 systems powered by a hydrocarbon-fueled scramjet will require endothermic fuel-cooled engine structures.

Recommendation 4. The Air Force should expedite trade-off studies in three areas: (1) mission parameters, to establish operational requirements; (2) system concepts, to define candidate configurations with optimum ranges of performance, operability, reliability, and affordability; and (3) technology, to redirect HyTech projects toward the most promising alternatives, if necessary.

Conclusion 5. A hypersonic air-breathing missile will affect primarily one aspect of the Air Force support infrastructure, namely, ground testing facilities. Existing test facilities can support full-scale propulsion performance testing only at flight speeds up to approximately Mach 7. Existing test facilities for testing propulsion system operability and reliability are limited. The HyTech Program has plans to upgrade an existing facility for propulsion reliability testing at the Mach 8 cruise condition. Hypersonic missile systems will have no obvious implications for two other areas of the Air Force support infrastructure, high-speed computational facilities and test ranges. Periodic destructive testing of scramjet engines will be necessary in the future.

Recommendation 5. The Air Force should begin planning for the ground test infrastructure to support the development and qualification of the operability, durability, reliability, and performance of integrated hypersonic propulsion systems over the Mach number range from the speed at the end of the rocket-boost phase to the maximum cruise speed. This infrastructure should be completed expeditiously.

Conclusion 6. The Air Force has two broad options for the development of hypersonic technologies for 2015 and beyond. The first is to pursue a broad range of technologies covering a variety of potential applications. The second is to pursue the evolutionary development and deployment of hypersonic weapon systems that derive from established capabilities and clearly stated Air Force requirements.

Recommendation 6. For 2015 and beyond, the Air Force should pursue the evolutionary development of hypersonic weapon systems and develop a long-range plan that incorporates the following four components: operational concepts for future systems and preliminary system designs; scramjet-powered weapon systems using hydrocarbon fuels; hypersonic weapon systems using hydrogen fuel; and combined-cycle systems for space access.

Conclusion 7. The committee is not aware of any other nation that has operational hypersonic scramjet-powered missiles; however, several nations have been working on development, evaluation, and testing, including flight testing, for several years. The Air Force is monitoring foreign developments in hypersonics technology adequately.

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APPENDICES

APPENDIX
A

Committee Meetings and Other Activities

This appendix provides details about committee meetings, site visits, and the individuals and organizations contacted during the course of the study.

JULY 14–16, 1997, DAYTON, OHIO

Meeting objectives: complete administrative business, including introductions and composition/balance discussions for new members, introduction to the National Research Council, committee and report procedures, and committee administrative support methodology; briefings by Air Force and Wright Laboratory on the Hypersonic Technology Program; briefing by the Defense Advanced Research Projects Agency on the Affordable Rapid Response Missile Demonstrator Program; briefings by NASA on the HYPER-X Program and the Advanced Reusable Transportation Technology Project; develop program contacts; develop committee assignments and report strategy; approve report concept; determine location and date of next committee meeting.

Presenters

WRIGHT LABORATORY
Dr. Tom Curran
Robert Mercier
Keith Numbers
James Weber
Dr. Terrry Ronald
Glen Liston

WRIGHT-PATTERSON AIR FORCE BASE, OHIO
Maj. Ira Wade, ASC/VXX
Joe Reiman, ASC/XR

NATIONAL AIR INTELLIGENCE CENTER
Jeff Drouhard

THE JOHNS HOPKINS UNIVERSITY/
APPLIED PHYSICS LABORATORY
Mike White

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
Lt. Col. Walt Price

EGLIN AIR FORCE BASE, FLORIDA
Maj. Dave Bunker, WL/MNAV

NASA MARSHALL SPACE FLIGHT CENTER
Uwe Hueter

NASA LANGLEY RESEARCH CENTER
Richard Tyson

BOEING NORTH AMERICAN
Dr. Kevin Bowcut

AUGUST 21–22, 1997, IRVINE, CALIFORNIA

Meeting objectives: composition/balance discussions for new members; briefings by the Navy, NASA, and industry on hypersonic technology; discussions on report strategy; modify report outline/concept; set goals for the October committee meeting in Washington, D.C.

Presenters

NASA LANGLEY RESEARCH CENTER
James L. Hunt

OFFICE OF NAVAL RESEARCH
Dave Siegel
Albert J. DeSanti, Naval Air Warfare Center, China Lake
Mike Mumford, Naval Air Warfare Center, China Lake

THE JOHNS HOPKINS UNIVERSITY/
APPLIED PHYSICS LABORATORY
Mike White

BOEING PHANTOMWORKS
George Orton

ROCKETDYNE DIVISION OF BOEING NORTH AMERICAN
Raymond B. Edelman

BOEING NORTH AMERICAN
Kevin Bowcutt
Ray Bartlett
Alan Boutilier
Thad Sanford
Curt Wiler

PRATT AND WHITNEY
Ted Langston
Steve Beckel
Robert Faulkner

AEROJET
Mel Bulman
Adam Siebenhaar

KAISER MARQUARDT
Jeff Jensen

LOCKHEED MARTIN
Craig Johnston
Ed Glasgow

U.S. AIR FORCE
Ray Moszee

HYPERSONIC TECHNOLOGY PROGRAM OFFICE
Edward S. Gravlin
Terrence M.F. Ronald

OCTOBER 8–9, 1997, WASHINGTON, D.C.

Meeting objectives: briefing and discussion of Air Force hypersonic missile requirements and missile survivability; briefing by Hughes on hypersonic missile system-level issues; discuss report strategy and updated report outline/ concept; integrate written portions of report; set goals for the next committee meeting.

Presenters

LINCOLN LABORATORY
Bill Keicher

HUGHES CORPORATION
Vern Mullikin
Bob Boriss

AIR FORCE OPERATIONAL REQUIREMENTS
Lt. Col. Dennis Miner

DECEMBER 4–5, 1997, ALBUQUERQUE, NEW MEXICO

Meeting objectives: briefing by the Air Force on the military space plane technology program and aspects of the program that might require development of enabling hypersonic technologies; briefing by the Air Force on international developments in hypersonic technologies that might affect the study; briefings on other applications of hypersonic technologies and on commercial space developments; discussion of report strategy and creation of first full message draft of the report; set goals for next meeting and committee member assignments.

Presenters

AIR FORCE RESEARCH LABORATORY
Lt. Col. Craig McPherson

WRIGHT LABORATORY
Lee Bain
Jeff Drouhard

SPACE ACCESS, INC.
Steve Wurst

HYTECH CONSULTANT
Fred Billig

JANUARY 27–28, 1998, WASHINGTON, D.C.

Meeting objectives: complete writing assignments for concurrence draft; update information on Air Force Hypersonic Technology Program.

Presenter

WRIGHT LABORATORY
Robert Mercier

APPENDIX
B

Air Force Hypersonic Technology Program

The description that follows was provided by the Air Force HyTech office at Wright-Patterson Air Force Base, Ohio, and is reproduced verbatim. An overview of the HyTech Program and a road map for the development of hydrocarbon scramjet missile propulsion, both provided to the committee by the HyTech office, follow (see Figures B-1 and B-2).

HISTORY OF HYTECH CHARTER, OBJECTIVES AND PROGRAM CONTENT

Background

The HyTech Program was established in Jan 1995 to provide a continuing AF hypersonic development activity after the cancellation of the NASP program. This point paper describes the evolution of the overall direction and current technical content of the HyTech Program as it has changed from its inception to the present. It references two documents included as attachments: Attachment 1–AFMC/ST letter directing refocusing of HyTech to concentrate exclusively on propulsion technology, and Attachment 2–Programmatic history of HyTech. It concludes with an assessment of the current state of the program and the probability of meeting its goals.

Program Objectives and Technical Content

- After the decision to terminate the NASP/HySTP program, effective in Jan 1995, the Secretary of the Air Force decided to initiate a follow-on generic hypersonic technology program to be funded at $20M/year
- In response, HyTech was established as a Wright Laboratory program and a planning team was formed in Jan 1995 to determine the direction and content of the program. The team consisted of individuals from the various WL directorates, together with representatives of other organizations, including ASC/EN, ASC/XR, Phillips Laboratory, NASA, Navy, the NASP program office and industry. The team reported to an Executive Steering Group consisting initially of the directors of the WL Flight Dynamics, Materials, and Aeropropulsion & Power Directorates. Later in 1995, the steering group was expanded to include representation from the WL Armament Directorate, Phillips Laboratory and ASC/EN
- In spring 1995, the Steering Group approved a program that adopted a stepping-stone approach to hypersonic technology development that focused initially on the technologies needed for hydrocarbon-fueled scramjet missiles that could fly at speeds of up to Mach 8. The choice of Mach 8 was driven by several factors, including the results of studies that indicated it could have a significant payoff for projected AF mission requirements
  - —ASC/XR studies showed that hypersonics has the potential to impact a large number of warfighter deficiencies across the board. The identified attributes of high speed included survivability, lethality, timeliness and range—basically the result of the high speed and the efficiency of ramjet/scramjet powered vehicles
  - —The benefits also were documented in studies undertaken by the AF/XOM Revolutionary Planning Office in 1995. The payoffs of a scramjet-powered Mach 8 missile were stated in terms of its ability to travel 750 nm in 15 minutes while remaining nearly invulnerable to countermeasures because of the high speed. As an example, it indicated that such a missile could be launched from a fighter aircraft outside a heavily defended target area and yet reach time critical targets such as mobile launchers before they could move any significant distance
  - —Further endorsement of a Mach 8, 750 nm weapon is evidenced in the Air-to-Surface Development Plan prepared by the ASC Air-to-Surface Integrated

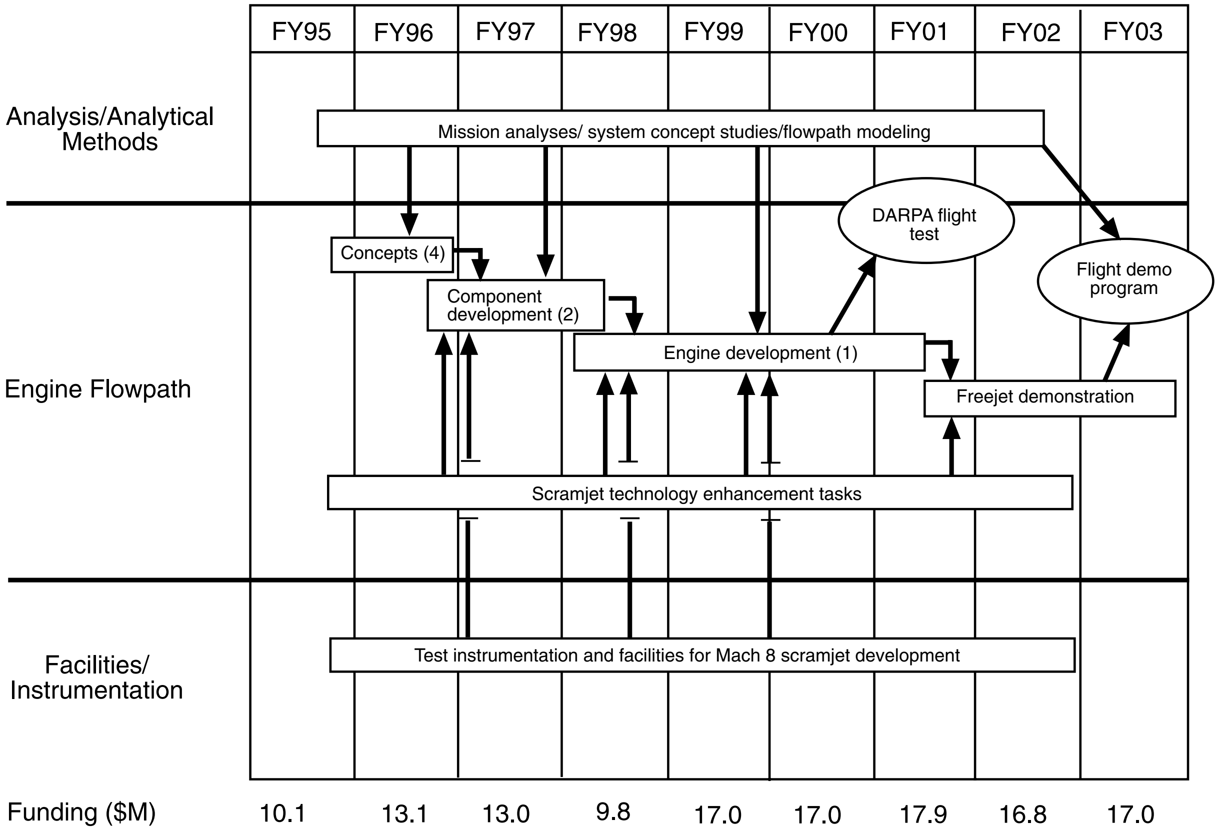

FIGURE B-1 Overview of HyTech Program. Note: DARPA = Defense Advanced Research Projects Agency

Product Team and endorsed by ACC. Such a system conceptually is beneficial in that it addresses user deficiencies related to defeating hard and deeply buried targets and time-critical targets

- The approved HyTech Program was implemented when initial funds were received in the summer of 1995. It addressed primarily engine technology but at that time it also included a significant effort in airframe technology. However, following AFMC/ST reviews of the program plan in late 1995 and subsequent formal direction in Feb 1996 (Attachment 1), the program was restructured to concentrate its limited funds exclusively on engine technology development. The program technical content and associated tasks were revised in accordance with this direction
  - — The Mach 8 hydrocarbon-fueled engine development critical path was made the focus of the program and it was set up to be a moderate (or lower) risk program managed by WL and executed by industry
    - — In addition to the primary activity in engine design, the program included engine-related materials, structures, analysis and test facilities tasks
  - — In parallel, the WL Directorates, using their own resources and funding lines, were encouraged by AFMC/ST to investigate the other promising high-payoff, but possibly higher risk technologies for both the scramjet engine and for overall vehicle needs
    - — This included technologies for airframe structures, antenna and sensor window materials, long-term test facility development, etc., as well as engine risk-reduction activities
  - — The HyTech Program was also directed to coordinate with, and leverage technology investments in other Services, DARPA, NASA, the national laboratories, academia, industry, and other nations if doing so could accelerate the scramjet engine development and/or further extend and deepen the US's hypersonics technology base
- The revised HyTech plan was implemented early in 1996 and is underway. A more detailed history of the whole planning process, the refocusing, and the impact of various funding changes that have occurred is given in Attachment 2
  - — The activity is now centered around two prime engine contractors, representing two engine concepts that were selected from several evaluated in the first year of the program
    - — This activity is the core of the technical program and will culminate in the design, building and

eventual freejet ground testing of one of the engine concepts. The downselect to one engine concept will be made at the end of 1997 and it will be tested in the 2001-2003 timeframe

— The goals are fully coordinated with Navy, NASA, DARPA, etc., and complement their activities

— At this point, the WL Directorates have not specifically established additional research or development activities aimed specifically at hypersonic needs, although parts of their core programs would have application to hypersonics, even though directed primarily toward other requirements

- Overall, the HyTech program is addressing solid, realistic, appropriate goals—in the sense that the near-term application clearly would be a hypersonic missile and the engines under development would be suitable as a starting point for such an application. Unfortunately, before and after the refocusing occurred, the program content and schedule was revised several times to take account of a series of funding cuts received over the last two years. These reductions in funding necessarily have resulted in a significant accumulated schedule slip of more than two years and have diluted the technical depth of the program

— The longer schedule for completion of the integrated engine testing moves the program outside the window of opportunity for flight testing on near-term programs planned by other organizations

— The DARPA Low Cost Missile program—recognizing that a flight-type engine will not be available from HyTech in time to meet its schedule—plans to flight test a fixed-Mach heavyweight engine; the NASA Hyper-X program, designed to perform limited-duration flight testing of scramjet engines at discrete Mach numbers, also is incompatible with the present HyTech schedule

— In a related issue, the extended schedule also makes HyTech more vulnerable to further cuts if it becomes regarded as a long-term technology program with no apparent event-driven end-point—in other words, a classical "lab program" instead of an intensive, focused, visibly milestone-centered project that must meet time-critical goals if it is to satisfy user requirements in a timely manner

— HyTech is an opportunity to build off the many years of work accomplished on scramjet technology and to bring it to fruition with a real, flight-type engine demonstration. It would be unfortunate if history is repeated and this momentum is allowed to dissipate yet again

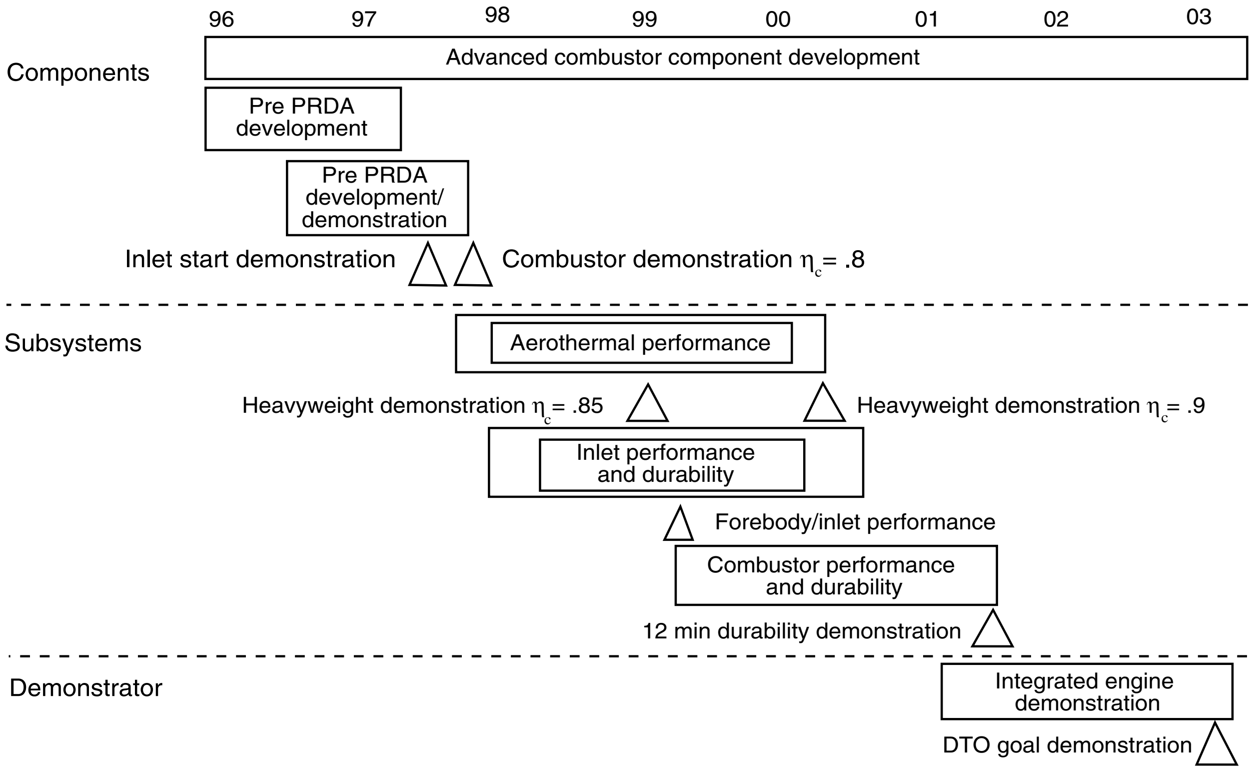

FIGURE B-2 Road map for the development of hydrocarbon-fueled scramjet missile propulsion. Note: PRDA = Program Research and Development Announcement; DTO = defense technology objective; η_c = combustion efficiency

- — In terms of programmatics, the reduced and stretched-out funding profile does not allow HyTech to follow the original intention of supporting two engine contractors for Phase 2. The initial plan was to fully fund one contractor to proceed full-bore to design, build and test an engine—to act as the prime contractor for the core of the program. In parallel, a second one would have been funded at a lower level to draw on the experience gained from the investment in their approach. In this way, work could have continued work on selected, promising, alternative approaches to some of the technological requirements that are known to be especially challenging and for which a solution may not be successfully achieved using only the primary engine designer's approach (e.g., fuel injector concepts, fuel ignition techniques, etc.)
  - — This tactic would have served a double purpose: it would have continued work on selected key technical issues that may prove to be needed for successful engine development; it also would have maintained a broader core of industry involvement in air-breathing hypersonic technology—an especially important consideration for the US when many personnel experienced in hypersonics are reaching retirement age
- — The reduced funding level also has resulted in the loss of other tasks working parallel risk-reduction and alternative approaches, although—to the maximum extent possible—the program preserves the in-house work on high-risk, high payoff combustor component items that includes evaluations of alternative combustor subcomponent designs. Also retained are small-scale activities that are examining emerging materials and structures and developing advanced endothermic fuel technology

Attachments:
1. Gen Paul Letter Directing Refocusing of HyTech
2. Programmatic History of HyTech

ATTACHMENT 1

MEMORANDUM FOR WL/CC 1 Feb '96
FROM: HQ AFMC/ST
SUBJECT: Hypersonic Technology (HyTech) Program Restructure

1. Thank you for the recent meetings regarding HyTech. The program strategy options briefed and discussed at those meetings were very useful in establishing the direction of hypersonic technology development in the Air Force. This letter summarizes the results of the discussions, provides program guidance to Wright Laboratory and documents my commitment to support the restructured HyTech program.

2. Expendable Mach 8 scramjet engines offer the potential for very high payoff for the Air Force's future warfighting capability. Specifically, they give us the potential for the development of near-term, very high-speed, long-range missiles, and they allow the longer-term possibility of fielding reusable hypersonic weapon systems. Therefore, I fully support the consensus reached at our strategy meetings as described below:

   a. Concentrate the entire HyTech budget on technology development for expendable, Mach 8 hydrocarbon scramjet engines, including the materials, structures, analysis and test facilities required exclusively for this near-term scramjet effort. The engine development critical path-the major focus of the overall program—should be moderate (or lower) risk program managed by Wright Laboratory and executed by industry. In parallel, Wright Laboratory should investigate other promising high-payoff, but possible higher-risk, scramjet engine approaches that complement the primary effort and provide risk mitigation. The major milestone of the program should be a freejet test of a flight-type scramjet engine in FY01-02. The HyTech Program should be consistent with the FYDP's current funding profile, as noted below. The HyTech Program will not be excluded from normal burdens that are levied on all 6.2 PEs; therefore, the HyTech Program must include planning allowances for its share of these burdens.

Fiscal Year	FY96	FY97	FY98	FY99	FY00	FY01
PE62269F	$19.9M	$7.6M	$19.2M	$17.4M	$17.5M	$18.9M

   b. Because HyTech is now focused exclusively on the scramjet engine, I encourage Wright Laboratory to develop other technologies in the areas of airframes, materials, avionics, munitions, and other propulsion systems, etc., that complement the HyTech-funded efforts by contributing to the technology base for sustained hypersonic flight. Optimally, these technologies will also contribute to other high temperature and/or high-speed air vehicle applications. The HyTech office should maintain cognizance of these related efforts in order to create a broad hypersonics technology base efficiently and effectively.

   c. The HyTech Program should also coordinate with, and leverage technology investments in, other services, ARPA, NASA, the national laboratories, academia, industry, and other nations. This would be appropriate when it could accelerate the scramjet engine development and/or further extend and deepen the US's hypersonics technology base.

3. In order to maximize the effectiveness of the HyTech Program, I will take several steps. First I will continue to support HyTech's outyear budgets at the level described above, and for one additional year (FY02) at approximately $20M. Second, I will continue to encourage science and technology investments in other technologies that contribute to the hypersonics technology base. Third, in my discussions with warfighters and with other Air Force and congressional decision makers, I will encourage the appropriate transition of hypersonic technologies. Fourth, I will assist in the rapid approval of the acquisition plan required for HyTech's primary scramjet development contract(s).

4. As Mr. James Mattice (SAF/AQ) testified to Congress on 15 Mar 94, "Hypersonic technology, which yields an optimum combination of speed, range, precision, lethality, and flexibility, is one of the three highest priority technologies to enable future warfighting capabilities identified by senior Air Force leadership." Similarly, in its 15 Dec 95 New World Vistas report, the Scientific Advisory Board recommended the Air Force develop the scramjet and materials technologies required for hypersonic airbreathing flight. Given the recognized potential of hypersonics, and the corresponding foundational requirements for a US capability to build operational scramjet engines, I expect Wright Laboratory to lead the nation in the development of a hypersonic technology base. Please let me know if I can provide further assistance in meeting the objectives outlined in this letter.

[Signed by Richard R. Paul]
RICHARD R. PAUL
Major General, USAF
Director, Science and Technology

cc:
SAF/AQR
ASC/XR

ATTACHMENT 2

Programmatic History of the Hypersonics Technology (HyTech) Program January 1995–December 1996

Richard M. Moore, Lt Col, USAF
(Chief, HyTech Program, May 1995–Jul 1996)

Background: For nearly a decade this nation's investment in hypersonics was focused on the National Aero-Space Plane (NASP) Program. NASP was expected to produce two single stage to orbit experimental vehicles. The technical challenges of this joint Air Force - NASA program were enormous. The high temperature materials, the hybrid propulsion system that could take off from a dead stop and efficiently produce thrust up to Mach 25, the very restrictive structural weight fraction limits, and many more challenges made the X-30 seem impossible to all but a few visionary people. Unfortunately, the political challenges proved to be even greater. In FY94 the program was de-scoped to a flight test program named the Hypersonic Systems Technology Program, HySTP. Then, in response to FY95 Congressional language, the Secretary of the Air Force canceled HySTP on 3 Jan 1995.

However, not wanting to kill the technology, the Secretary turned to Wright Laboratory to initiate a new, more conservative hypersonic technology program. Specifically, it was to be a $20M per year program to develop a technology base to enable future hypersonic weapon systems. The new program was to have more reasonable technical goals and it was expected to succeed. Wright Laboratory named the new effort the Hypersonic Technology (HyTech) Program. HyTech continued to use the HySTP program element, PE62269F.

In the meantime, NASA Langley Research Center's (LaRC) hypersonics community was regrouping after the Air Force's withdrawal from NASP. NASA chose to develop a smaller unmanned hydrogen-fueled hypersonic X-plane. They were also struggling through the quagmire of enormous budget and personnel cuts, along with reorganizations. These administrative hurdles kept LaRC from developing their X-plane plans as quickly as HyTech was planned.

Program Development: Many of the challenges facing HyTech were similar to those that most new programs face. The organization, goals, processes, networks, etc. had to be established. In addition, as of 3 Jan 95, this program had not even been conceptualized, thirty percent of the fiscal year was already gone, and HyTech was expected to spend an unspecified amount of FY95 funds on a well planned technology program, with funds to arrive after program approval by SAF/AQ in late February. Also, the industry stakeholders were more numerous than the HyTech Program could support, yet with NASA's delays, if HyTech didn't support them they could be gone within the calendar year. Further, once the NASA program was in place it would have to be complementary to HyTech, rather than duplicative, if both were to survive Congress' scrutiny. These issues, compounded by the pessimistic attitude that some Congressmen and concerned Pentagon personnel had regarding NASP, left HyTech with an uphill battle from the start.

Wright Laboratory built a team consisting of Air Force engineers, managers and financial personnel, together with a Navy technical manager and a NASA representative. With half of these people having been assigned to the NASP program, the team expected to transition some NASP technology as appropriate, but would also have fresh perspectives, precluding a simple NASP continuation. The vision of the new program was to "Enable Sustained Hypersonic Flight." Unlike NASP, HyTech adopted a stepping stone approach by focusing initially on technologies required for expendable (unmanned and single use) missiles, with the understanding that they could spin-off these relatively low cost and low risk applications soon after the turn of the century and extend the US technology base to higher Mach, reusable and/or manned vehicles.

Through an exhaustive process the HyTech team and colleagues throughout Wright Lab and across the nation reached a solid consensus that the technical long poles in the tent were the air breathing propulsion system and the engine's materials and structures. On a smaller scale, other potential technical show-stoppers included the airframe materials and structures, sensor windows and radio antennas that could survive and operate in the severe hypersonic flight environment. Because the propulsion development is the most important and expensive technology, and the projected funding would only allow an acceptable rate of progress in this area if the vast majority of the funds were directed there, Wright Laboratory chose to focus on a supersonic combustion ramjet (scramjet) engine development, combined with relatively small related efforts in engine materials, airframe design and structures, and hypersonic wind tunnel concepts. Fortunately, NASA's Marshall Space Flight Center (MSFC) was initiating the X-33 and X-34 programs to demonstrate advanced space launch technologies. These programs would not develop the airbreathing propulsion technologies or some of the materials and structures specifically required for hypersonic missiles, but their investment in technology development for airframe materials and structures, avionics antennas and sensor windows would keep the industry alive and progressing in these areas. HyTech briefed the program strategy and plan to the AFMC chain of command, the Air Force Scientific Advisory Board, SAF/AQ, DDR&E's staff, and the Senate staffer responsible for this portion of the defense budget, Mr. John Young. All reviews were very well received.

Program Approval and Funding History: Initially, the FY95 funding level was expected to be between $l0M and $30M, with the following years funded at a level $20M per year. In Feb 95, the FY95 funding level was definitized at $10M. This was in addition to $8M to be used for NASP and HySTP termination. Unfortunately, $5M of these termination funds became, and are still tied up in litigation, keeping the FY95 expenditure rate for HyTech's PE very low. The briefing, coordination and approval process described above was originally scheduled for Feb 95, but scheduling conflicts with these busy executive's schedules stretched the briefing schedule through late Spring. When some of these schedule delays became apparent in March, SAF/AQT determined HyTech would not be able to spend all $10M in FY95 so they reduced the planned FY95 funding to $3M. Therefore, the HyTech team restructured the program to accommodate this reduction and prepared the contractual mechanisms for rapid initiation.

At the end of the briefing to Mr. Young, he asked many questions and then stated that he "would like nothing better than to see this program go!" Mr. Young asked why the Air Staff had moved $7M of FY95 funds from this program. He reminded them that the law states that they can move up to $4M without Congressional approval, but no more. Unfortunately, the ensuing dialog regarding this subject lasted three months, so it was not until Aug 95 that SAF/AQ informed the HyTech Program office that the FY95 funds were available and that HyTech *would receive the full $10M*! Under some circumstances, additional funding is good; however, in this case it was very late in the fiscal year and HyTech had prepared to spend only $3M in FY95. Nevertheless, HyTech rapidly re-expanded the structure of the program and began to obligate the funds as rapidly as possible.

During the early days of planning and advocacy, a new organization called the Air Force Revolutionary Planning Office (RPO), located within AF/XOM at the Pentagon, was chartered to find leapfrog approaches to warfighting. RPO took notice of HyTech's missile concept and proposed a hypersonic missile ACTD to the Air Force four-star generals at their semi-annual 'Corona' meeting on 28 Feb 95. AF/CC said the concept looked interesting and asked the office to study it and report back at the next Corona meeting on 30 Aug 95. Through the Spring and Summer, HyTech provided technical consultation to the RPO. Then, during the month of August, in preparation for the upcoming Corona meeting, AFMC/CC, ACC/CC, and AFMC/ST requested several point papers and white papers to help them understand hypersonics and potential missile applications. While this effort provided excellent visibility for HyTech, it also compounded the busyness created by the change in FY95 funding described above. At the August Corona meeting, AF/CC concurred that the concept offered high payoff, but wouldn't consent to a fast paced ACTD due to the $330+M price tag and the lack of the propulsion system technology maturity. Nevertheless, the visibility afforded the concept left very favorable impressions in the minds of many Air Force generals. In addition, AFMC/CC and AFMC/ST came away intending to insure that Wright Laboratory was indeed developing the needed propulsion technologies. Therefore, just after the FY95 funds arrived, AFMC/ST (Maj Gen Paul) asked HyTech to put the program execution on hold until he could review it. That review cycle was completed 21 Dec 95 with AFMC/ST's formal go-ahead and direction to focus exclusively on propulsion and related materials technologies, dropping the airframe and wind tunnel technology activities. These decisions were documented in a 1 Feb 96 letter from AFMC/ST.

Unfortunately, the AFMC/ST review processes delayed HyTech's full implementation and funds obligation until well past the end of the fiscal year. Therefore, based on HyTech's 30 Sep 95 obligation statistics, the DoD comptroller stated his intention to cut PE62269F's funds. Since the Pentagon was working the FY97 POM at that time. making FY97 funds the easiest to change; since the FY95 funds couldn't be withdrawn without Congressional approval; and because the FY95 funds were already somewhat stale, the DoD removed $9M of HyTech's FY97 funds via PBD-203. In the PBD language, the comptroller stated that HyTech would spend its FY95 funds in FY96 and a similar amount of FY96 funds in FY97, and therefore HyTech's funding bow wave would fill-in this new FY97 deficit. This set HyTech on a path that could keep it behind in obligation and expenditure rates for two years - a very dangerous position! At this point HyTech restructured the program, yet again, and prepared for the meeting with AFMC/ST which was described above.

Once AFMC/ST approved the program plan, rapid funds obligation began. Since the program is a technology base program with many elements, it could not be accomplished on a single contract. In fact, over fifty FY95 and FY96 obligation actions were required to initiate the program. In order to obligate funds on all of these efforts rapidly, the vast majority were accomplished through modifications to existing contracts or by establishing new tasks on existing task order contracts. HyTech obligated nearly 100 percent of FY95 funds, including recording them on the DoD comptroller's data base, during the months of Jan through Mar 95. Then the team obligated most FY96 funds between March and June. Thus, after six months, nearly two years of funds were obligated and, for both years, the program was ahead of AFMC and OSD obligation rate goals. In addition, FY95 expenditures were beginning to roll in.

The cornerstone of HyTech is a $62M contracted engine development effort consisting of a competitive first phase, with a downselect to one contractor for the second and third phases which consist of a full engine development and freejet ground demonstration. Because of its funding level, this effort required an approved acquisition plan and a new contract for each of the two prime contractors. Unfortunately, the acquisition plan approval process couldn't be initiated until AFMC/ST approved the new program structure in Dec 95. Despite the administrative delay, the HyTech team set an aggressive goal to have the contracting actions completed, the funds obligated and the engine developments initiated by 30 Aug 96, one month prior to the end of the fiscal year. After program go-ahead, this goal allowed only half the time normally required for a solicitation and source selection of this magnitude. Final acquisition plan approval arrived in Apr 96 and the HyTech office promptly released the scramjet engine development solicitation in the Commerce Business Daily. After receiving the proposals in June, the source selection team completed their efforts in July and handed the results to Wright Laboratory's contracting personnel. The contracting team also moved out at full speed and the contracts were awarded four days ahead of the goal! This was only possible because every individual involved took ownership of the process and worked together creatively and enthusiastically.

HyTech took another major step to preclude additional cuts. Wright Laboratory's PE62203F is the home of the Integrated High Performance Turbine Engine Technology (IHPTET) program, which needed $3M as soon as possible for an important task but was waiting for FY97 funds. With the help of the Air Force Comptroller and AFMC/STX, Wright Laboratory transferred $3M of HyTech's FY96 funds to IHPTET and is currently in the process of transferring $3M of IHPTET's FY97 funds to HyTech. This resulted in the IHPTET achieving results sooner, HyTech's funding profile being more appropriate for the work planned, and led to better HyTech execution statistics in both FY96 and FY97. The effort was formally initiated through a 4 Apr 96 meeting involving SAF/AQT, AFMC/STX, WL/XP and HyTech personnel. Then the FY96 funds were moved on 16 July 96 and the FY97 payback will be completed in early Jan 97. *(Note from HyTech, 15 Aug 97: This was completed and the funding is included in the FY97 total for PE62229F).*

Despite excellent programmatic recovery from a very difficult situation and expressed support for hypersonics technology development at all levels in the Air Force and DoD, HyTech's FY96-FY03 budgets were cut repeatedly and extensively. In FY96 the Air Force cut HyTech's budget 13 times for a total of $4M. Six of these cuts were to provide funds for the US's peacekeeping effort in Bosnia. The remainder of the cuts were for a variety of other needs. As described above, in late CY95, PBD-203 removed $9M from HyTech's FY97 budget based upon poor FY95 obligation rates, leaving $7.5M in the PE for that year. Fortunately, the zero-sum reprogramming swap with IHPTET described above moved $3M from HyTech's FY96 budget, precluding some further cuts, and will increase the FY97 budget back to $10.5M. During the FY96 POM/BES process, HyTech's budget over the FYDP (FY98-03) was adjusted downward from the original $20M per year. Then, based on the combined FY95-96 expenditure rates, the Air Force and the DoD Comptrollers cut the FY98 budget by $12.6M; however, the DoD Comptroller agreed to restore $4M of those funds because the Air Force has no control over the speed with which the NASP/HySTP termination litigation is being conducted. This left HyTech with only $9.9M in FY98. Then, in Nov 96, AFMC/ST was required to cut another $210M from its FYDP budget. AFMC/ST directed approximately 22 percent of that budget cut to HyTech's PE! Specifically, HyTech was cut another $3.6M in FY98, leaving the FY98 total at $6.3M and cutting the following years to an even $10M per year!

On 5 Dec 96, Gen Paul called Dr. Curran to request WL/PO provide a hypersonics briefing to the Air Force Science and Technology Board (AFSTB) on Monday, 9 Dec 96. Gen Paul stated that the program should be briefed at the *1 Feb 96 budget level* (as Gen Paul committed to on 21 Dec 95) and that he would be restoring the budget to that level. On 9 Dec 96, Lt Gen Muellner (SAF/AQ) briefed the AFSTB on the Air Force's modernization plans and acquisition reform, Maj Gen Paul briefed them on the Air Force S&T program and Lt Col Moore briefed HyTech and other hypersonics activities at DARPA, NASA and internationally. The AFSTB was very receptive and is initiating the study. The AFMC/ST staff informed all four AF Laboratory XP directorates that Gen Paul had been "asked to" restore HyTech's funding and that they were to use other sources for the major budget cut. In the table below, the 1 Feb 96 budget is contrasted to the 4 Dec 96 and the 20 Dec 96 budgets. Obviously, as of 20 Dec 96, the budget has not been *fully* restored to the 1 Feb 96 level. The AFMC/ST staff has agreed to restore the FY99-FY03 funding levels to the 1 Feb 96 budget levels during the APOM update in the Spring of 1997. However, HyTech's major concern is the FY98 funding level which is about to be incorporated into the President's Budget and submitted to Congress. Once that is done, the Air Force cannot request additional funds until after congressional appropriation, and then with near zero probability of receiving the extra funds. Therefore, HyTech is appealing to AFMC/ST for assistance to raise the FY98 budget to at least $15M prior to incorporation into the President's Budget. With DARPA expecting scramjet technology from HyTech, the current FY98 budget level will make HyTech unresponsive. In addition, the FY98 to FY99 funding ramp will be viewed unfavorably by the Air Force and DoD Comptrollers, who will probably flatten it in the out-years, with the result that the HyTech budget for the remainder of the current FYDP will likely return to a level similar to the 4 Dec 96 level shown in the table.

PE62269F Budget: FY95-03

	FY95	FY96	FY97	FY98	FY99	FY00	FY01	FY02	FY03
1 Feb 96	$10.5M	$20M	$7.6M	$19.2M	$17.4M	$17.5M	$18.9M	$20M	
4 Dec 96	$10.5M	$12.6M*	$10.3M*	$6.3M	$10M	$10M	$10M	$10M	$10M
21 Dec 95	$10.5M	$12.6M*	$10.3M*	$9.9M	$16.1M	$16.1M	$17M	$16M	$16.1M

*Includes $3M reprogrammed from FY96 to FY97 to alleviate bow wave.

Lessons Learned: The HyTech team learned many lessons during this adventure, including the following:

1. Receiving significantly more money than a program is prepared to spend and receiving it late in the fiscal year can hurt a program much more than it helps.
2. Good communications between the program management, financial and contracting personnel; and insuring they each take ownership in the program can make a seemingly impossible requirement achievable, as was the case for HyTech.
3. Even when the comptroller states that a program will forward finance its funds, it doesn't mean he is going to let the program get away with it.
4. Keeping a program as simple as possible can make reaction times quicker. HyTech's 50+ tasks took months to obligate, even though the skids were greased. However, not all programs can be technically effective if over-simplified.
5. If a program has a dedicated PE, as opposed to being part of a "basket PE," it will gain more visibility and it will be safe from its funds being easily transferred to other related programs. If the program is healthy or needs assistance this can be very good. However, the same visibility will bring obligation or expenditure rate problems to the attention of headquarters personnel and the lack of flexibility will restrict the program manager's options for resolving these problems at the local level.
6. Never give-up. Sometimes budgets are restored when the leadership recognizes the potential in revolutionary technology, even during periods of major budget reductions.

APPENDIX
C

Vulnerability of a Hypersonic Missile to Surface-to-Air Defensive Missiles

The committee performed a first-order analysis of the vulnerability of a hypersonic missile to surface-to-air defensive missiles. The analysis is one of several types of mission analyses the Air Force should conduct to make decisions about an operational requirement for a hypersonic missile system. The committee has included this analysis in the report because in the course of this study the committee was told that one of the advantages of hypersonic flight was that a hypersonic missile would be less vulnerable to surface-based air defense systems. Specifically, the committee was told that a missile with a speed of Mach 8 (approximately 1.3 nautical miles per second) would have a significant advantage over a missile with a speed of Mach 6.5 (approximately 1.1 nautical miles per second). The committee found that the marginally higher vulnerability of the Mach 6.5 missile compared to the Mach 8 missile can be offset with a moderate reduction in the radar cross section of the Mach 6.5 missile.

ANALYTICAL APPROACH, ASSUMPTIONS, AND RESULTS

The analysis was based on a simple model estimating the time to the detection and interception of a hypersonic missile. The analysis was performed by varying the radar cross section of the hypersonic missile and using typical modern surface-to-air missile system parameters. The analysis is based on the description of a simple one-on-one engagement model for a surface-based air defense system (Macfadzean, 1992). The performance of the interceptor is based on a model for miss distance that embodies the assumption of a command-guided, proportional navigation intercept (Alpert, 1988).

Characteristics of a Surface-to-Air Missile System

The characteristics of modern surface-to-air missile systems can be estimated from information in the open literature (Zaloga, 1993; Barton, 1995; Lemansky and Nenartovich, 1995; Yefremov, 1996; Bunkin and Svetov, 1997; Zaloga, 1997a; Zaloga, 1997b). A hypothetical, near future, command-guided, surface-to-air missile system was considered with the characteristics shown in Table C-1.

TABLE C-1 Hypothetical Command-Guided, Surface-to-Air Missile System

Parameter	Value of Parameter
Reference radar range	160 nautical miles
Radar beamwidth	0.7 degrees
Radar measurement rate	10 Hertz
Maximum target altitude	120,000 feet
Maximum target speed	Mach 10
Reaction time	8 seconds
Warhead weight	330 pounds
Missile time constant	1.5 seconds
Average missile speed	Mach 5

Limitations of Surface-to-Air Missile Fly-out

The limit of the interception range of a modern surface-to-air missile system can be easily estimated. Given the radar performance parameter, R_0, which is the maximum range for initial detection of a target with a radar cross section of one square meter, the detection range for a target with a radar cross section, σ, is:

$$R_{det(\sigma)} = R_0 \cdot \sigma^{1/4}$$

After initial detection, there is a time delay or reaction time during which a firm track is established, the target is identified, and the missile is launched. The time dependence of the target range, as measured from the radar, is:

$$R_{target}(t) = \left[\left[\left[R_{det}^2(\sigma) - altitude^2\right]^{1/2} - V_{target} \cdot t\right]^2 + altitude^2\right]^{1/2}$$

where:
$altitude$ = target missile altitude
V_{target} = target missile speed

The time dependence of the range of the intercepting surface-to-air missile, as measured from the radar, is:

$$R_{SAM}(t) = V_{SAM} \cdot (t - \tau_{delay})$$

where:

V_{SAM} = surface-to-air missile average speed
t_{delay} = time delay or reaction time

By setting these two equations equal, $R_{SAM}(t) = R_{target}(t)$, the maximum potential interception range, as limited by surface-to-air missile fly-out, can then be calculated as a function of several variables.

The performance of the hypothetical defensive system was estimated parametrically by varying the target missile's speed [Mach 4 (supersonic), Mach 6.5 (hypersonic), and Mach 8 (hypersonic)], altitude (85,000 feet for the Mach 4 missile, 107,000 feet for the Mach 6.5 missile, and 115,000 feet for the Mach 8 missile), and radar cross section (from 0.01 to 1 square meter). For purposes of comparison, the missiles were assumed to have the same size and shape. It is not unreasonable to assume that a lower speed missile might be smaller than a higher speed missile and may also have a lower radar cross section.

The maximum potential interception distance of the defensive system using a fire control radar with an R_0 of 160 nautical miles was analyzed and plotted in Figure C-1 as a function of missile radar cross section for three missile speeds. (The curves in Figure C-1 plot the fly-out limitation of the surface-to-air missile as driven by radar sensitivity, system reaction time, and average speed of the interceptor. They do not indicate the actual effectiveness of the surface-to-air missile system.) The maximum potential interception range for a target radar cross section of one square meter is approximately 55 nautical miles or more against any of the

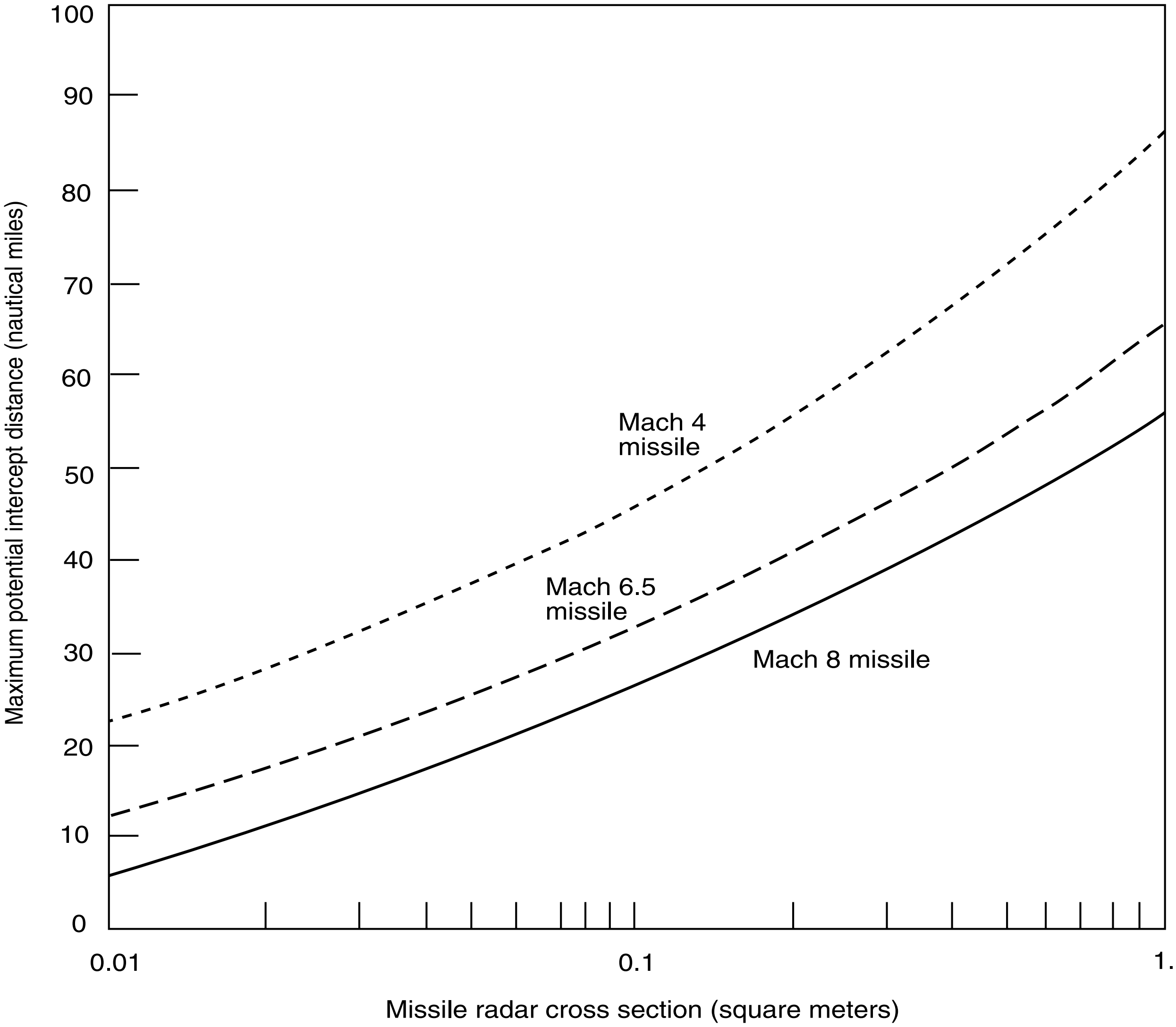

FIGURE C-1 Maximum potential interception range as a function of the target's radar cross section.

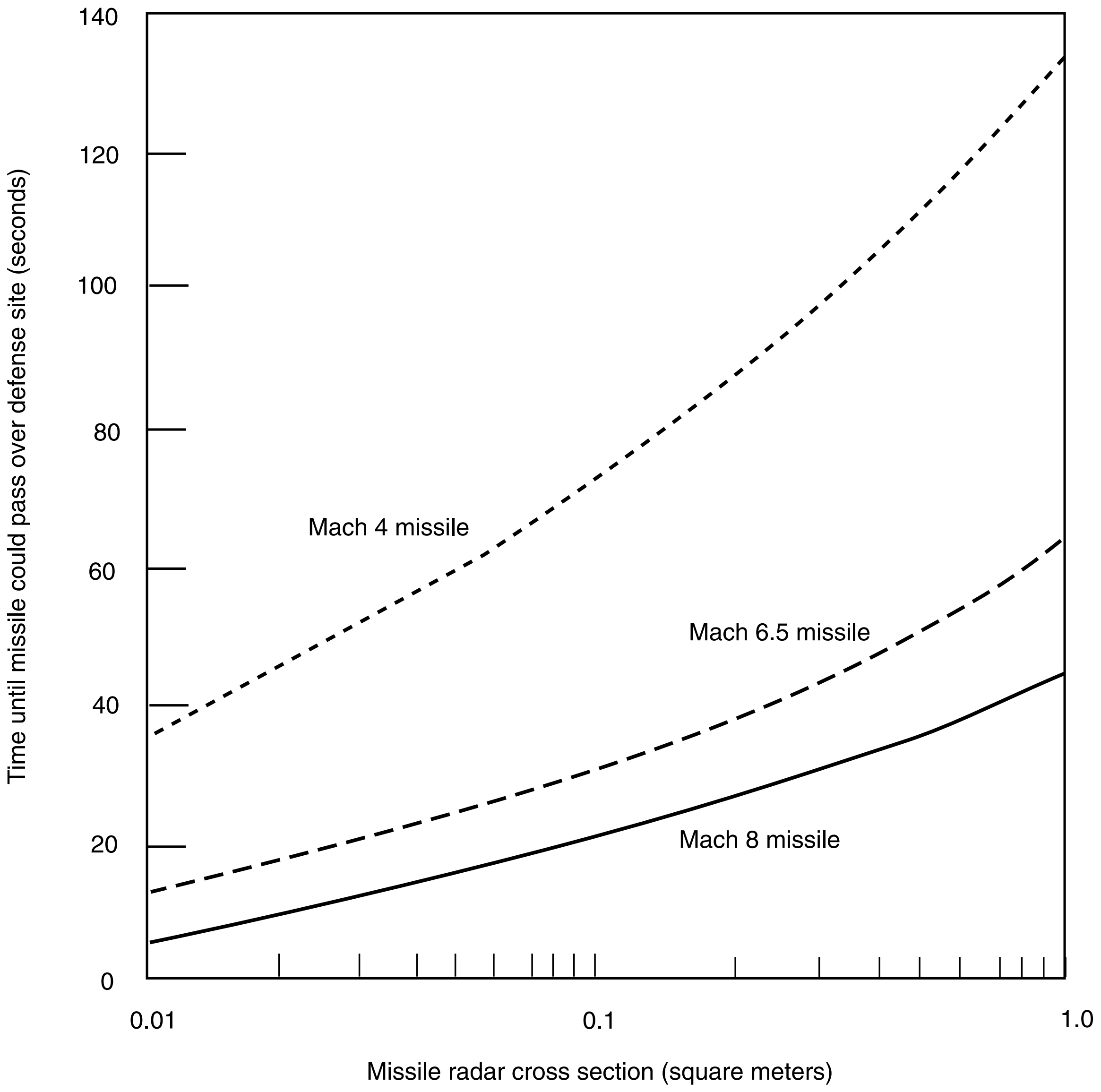

FIGURE C-2 Time from maximum intercept point until missile could pass over defense site, as a function of radar cross section.

three missiles. When the radar cross section is reduced to 0.01 square meter, the maximum interception range drops to about 22 nautical miles for the Mach 4 missile, 12 nautical miles for the Mach 6.5 missile, and 6 nautical miles for the Mach 8 missile. The difference in maximum potential interception range between the Mach 6.5 hypersonic missile and the Mach 8 hypersonic missile varies from about 6 nautical miles for a radar cross section of 0.01 square meter to about 10 nautical miles for a radar cross section of one square meter.

Figure C-2 displays similar information as a function of time rather than distance. This figure illustrates the time it would take for each missile to fly from the maximum intercept point to directly over the defense site. These times give an indication of the timeliness of the intercept as a function of radar cross section and missile speed. Figure C-2 shows again the strong dependence on radar cross section and the lesser effect on timeliness for speeds of Mach 6.5 to Mach 8 than for speeds of Mach 4 to Mach 6.5.

Lethality of a Surface-to-Air Missile

To complete the estimate of the performance of this hypothetical surface-to-air missile system, several additional performance parameters had to be estimated. The first of these is the lethal radius of the interceptor's warhead. Lethality can be extrapolated from the estimates given in Table C-2.

When a linear curve is fit to the data in Table C-2, the estimated warhead lethal radius is approximately 100 feet for the hypothetical interceptor with a warhead of

TABLE C-2 Estimates of the Lethal Radius of Surface-to-Air Missiles from the Open Literature

Missile System	Warhead Weight (pounds)	Lethal Radius (feet)
SA-3	130	40
SA-8	40	15
SA-9	15	5
SA-11	175	55

Source: Zaloga, 1989.

330 pounds. Although the lethality of the warhead may be a function of interception altitude, this analysis assumes a constant lethal radius.

An adjoint analysis of the miss distance of a command-guided missile described in the open literature (Alpert, 1988) was used to estimate the miss distance of the hypothetical surface-to-air missile system. Radar antenna beamwidth, radar measurement rate, missile time constant, target speed, target radar cross section, and target maneuvers were the inputs to this part of the analysis. In this scenario, the command-guided surface-to-air missile miss distance has three components: miss due to range-independent angle noise; miss due to range-dependent angle noise; and miss due to target maneuver. If the target missile is in nonmaneuvering, level flight, the range-independent noise dominates the miss distance.

The miss distance was calculated as a function of missile speed (Mach 4, Mach 6.5 and Mach 8) and missile cross section (0.01 to 1 square meter). The maximum lethal range—defined as the distance on the ground from the surface-to-air missile site to the projected point of intercept—was determined by comparing the total miss distance to the lethal radius of the surface-to-air missile.

The results of the analysis show that the hypothetical defensive system is capable of engaging all three missiles. Figure C-3 summarizes the results for nonmaneuvering missiles. It should be noted that these ranges only apply to the forward sector of the surface-to-air missile radar because the radar is unlikely to be able to track and engage the missile after it has passed over the site.

On the basis of this analysis, the committee concluded that the vulnerability of hypersonic missiles may be loosely related to speed (in the range Mach 6.5 to Mach 8). By

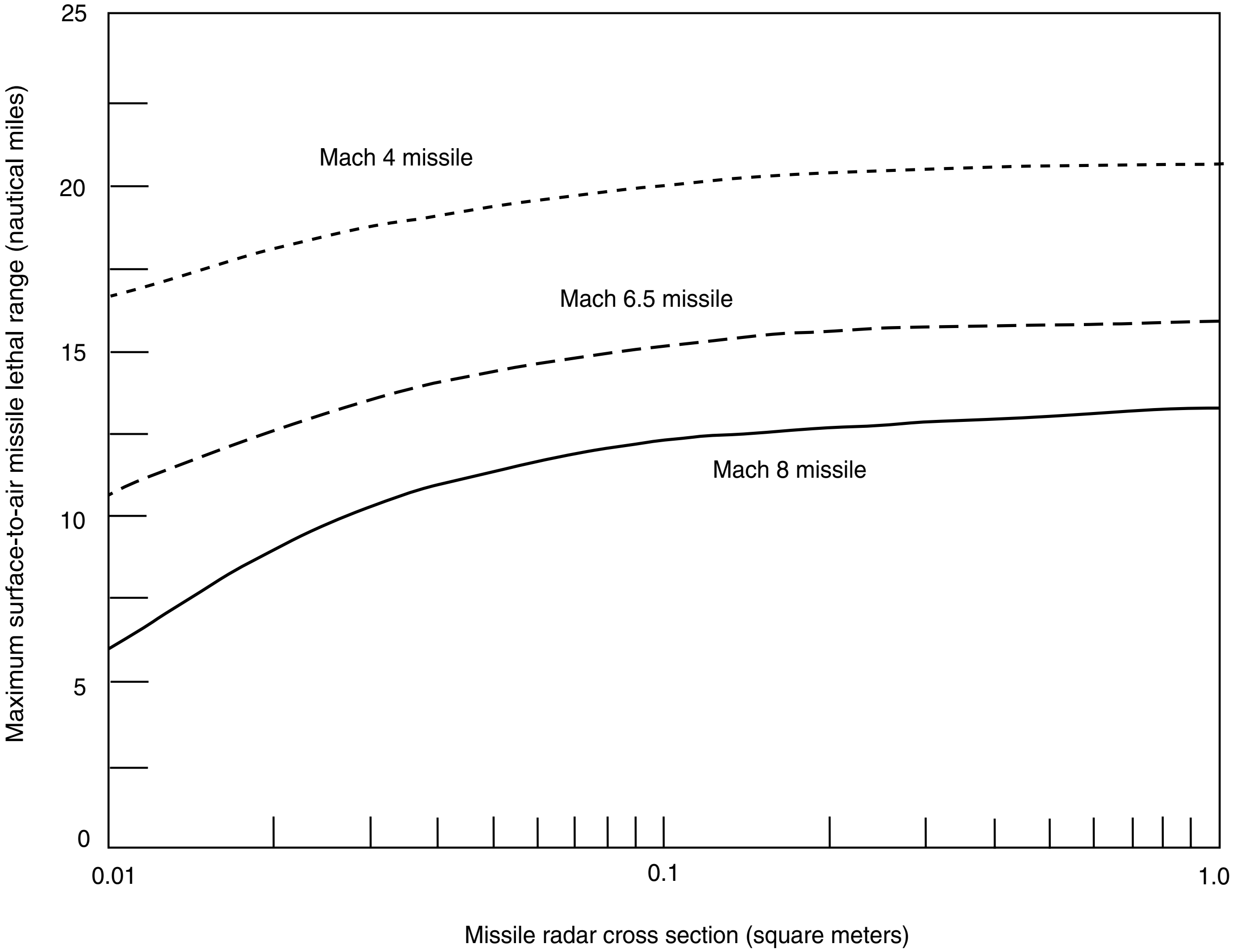

FIGURE C-3 Maximum lethal range of a hypothetical surface-to-air missile system against a nonmaneuvering missile.

continuing to reduce the radar cross section below 0.1 square meter, the performance level of the defensive system continues to fall; the system's effectiveness is limited eventually by radar sensitivity and interceptor fly-out. The useful defended area is minimal for a combination of hypersonic missile speed of Mach 8 and a radar cross section of 0.01 square meter. This analysis suggests that reducing a hypersonic missile's radar cross section is a meaningful way of reducing its vulnerability.

SUMMARY OF WORK TO DATE

Hypersonic missiles are within the design envelopes of several modern air defense systems that have been designed to defend against tactical ballistic missiles with hypersonic terminal velocities. For the hypothetical defensive system considered above, and for a radar cross section of greater than 0.1 square meter, there is relatively little difference in the lethal range for hypersonic missile speeds between Mach 6.5 and Mach 8. However, the vulnerability of a hypersonic missile to surface-to-air missiles can be reduced through combined reductions in radar cross section and in-flight maneuvering, and, to some extent, an increase in speed. The lethality of command-guided, surface-to-air missiles is markedly reduced for targets with a radar cross section less than 0.1 square meter. Overall, the most important factor in hypersonic missile survivability is the size of radar cross section.

ADDITIONAL COMMENTS

Although the committee analyzed the vulnerability of a hypersonic missile to a hypothetical, command-guided, surface-to-air missile system, more advanced surface-to-air missile systems are being developed to counter the threat of tactical ballistic missiles, such as the U.S. Theater High Altitude Area Defense and the Naval Area Defense. These systems are designed with high performance radars and interceptors. For example, the radar has a much larger antenna aperture and can make much better angular measurements to guide an interceptor at longer ranges; also, the interceptor will probably have a higher average speed and will be more maneuverable than the hypothetical interceptor assumed in this analysis. The advanced systems could also use a terminal infrared homing seeker for accurate hit-to-kill against ballistic missiles. Therefore, by the time a hypersonic missile could be fielded (e.g., in 2015), it could potentially face a much more lethal threat from surface-to-air missiles.

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Glossary[1]

advanced concept technology demonstrations: U.S. Department of Defense programs that demonstrate the use of technology in a weapon system concept; the demonstration establishes a residual, usable military capability.

adjoint analysis: a method of computation based on the reciprocal relation between a system of ordinary linear differential equations and the adjoint system; the matrix of the adjoint system is the conjugate transpose of the matrix of the original system.

aerothermodynamic environment: the flight environment in which a high-speed vehicle's aerodynamic properties are coupled with the thermodynamic properties, including heat transfer, of the constituent gases through which the vehicle is moving.

avionics: electronic systems, subsystems, and components used in aeronautical or astronautical systems; usually refers to the flight computer and associated sensors and control devices used in the flight control system of an air or space vehicle.

Castor IVB class booster: a launch vehicle capable of boosting an experimental test vehicle weighing 3,000 to 5,000 pounds to hypersonic speeds.

catalyst: a solid substance, usually placed on the passage walls of a propulsion system, that causes the rapid endothermic decomposition of hydrocarbon fuels into desired compounds prior to combustion.

circular error probable: the radius of a circle centered on the target, within which approximately half of a large number of shots at the target will fall.

combined-cycle propulsion: a system capable of more than one mode of propulsion (e.g., the turboramjet, which provides turbojet propulsion at low speeds and ramjet propulsion at higher speeds).

combustor: the portion of a propulsion device in which fuel is injected, mixed with air, and burned.

concept exploration and definition: the earliest phase of the U.S. Department of Defense's process for acquiring weapon systems, during which alternative concepts are evaluated and the most promising concept is determined.

control effectors: devices used in a feedback control system to cause changes in the variable being controlled; in an air vehicle, effectors typically are the surfaces (e.g., fins, ailerons, and rudders) that can be moved to apply forces to the vehicle and cause it to change its trajectory.

cracking (of fuel): the process of heating a hydrocarbon fuel in the presence of a catalyst, which causes one or more of the hydrocarbon bonds to break resulting in the production of lighter hydrocarbons.

dehydrogenation (of fuel): the process of heating a hydrocarbon fuel in the presence of a catalyst, which frees hydrogen atoms.

demonstration and validation: an early phase of the U.S. Department of Defense's process for acquiring weapon systems, during which a system is designed and its critical technologies are demonstrated in early prototypes.

dual-mode scramjet: a propulsion device that can operate with either subsonic combustion (i.e., as a ramjet) or supersonic combustion (i.e., as a scramjet).

dynamic pressure: an aerodynamic quantity used as the reference value for lift and drag forces on a vehicle (i.e., the pressure of air on a flight vehicle); it is defined as one-half of density times speed squared.

endothermic fuel (and endothermics): fuels that undergo chemical transformations when heated in the presence of a catalyst; of interest for hypersonic vehicles because of their large heat sink capacity.

engineering and manufacturing development: a major, and expensive, phase of the U.S. Department of Defense's process for acquiring weapon systems, during which the design is matured, manufacturing and production processes are validated, and the system is tested and evaluated.

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[1] The definitions in the glossary are simplified to assist readers who do not use these terms regularly to understand the text.

flame-holding mechanism: the device or process in an engine that allows combustion to occur continuously after ignition; usually contains a small recirculation region in the engine where the residence time of a fuel-air mixture is sufficient for combustion to occur.

flow field: the distributed portion of the flow around a vehicle.

free-jet wind tunnel: a special purpose wind tunnel for testing integrated airframe-engine components (e.g., airframe forebody, air intake engine, exhaust system, and airframe aftbody); allows the entire test article to be immersed in an unconfined jet of air (or other test gases) flowing from an appropriately sized nozzle at the desired simulated Mach number.

hydrocarbon-based propulsion (hydrocarbon-fueled): air-breathing propulsion system that uses hydrocarbon fuels.

hypersonic speeds: generally defined as speeds greater than five times the speed of sound (Mach 5); the more slender a vehicle is, the higher the Mach number at which hypersonic effects are in evidence; inside the engine, the term hypersonic refers to stagnation temperatures at which chemical reactions become important and simple models of gas behavior break down.

initial operational capability: the point at which a newly acquired weapon system is ready to perform a military mission.

initial operational test and evaluation: tests conducted during the engineering and manufacturing development phase of the U.S. Department of Defense's acquisition process to ensure operational suitability.

inlet contraction: the geometric degree to which the air stream captured by the engine is compressed.

inlet relaminarization: under some flight conditions, the cooling of the boundary layer by the walls of the air inlet causes the turbulent boundary layer to return to a laminar state, which greatly increases its displacement thickness; this can also happen in the nozzle, although the cause is primarily rapid acceleration rather than cooling of the wall.

launch offset: ability of a vehicle to acquire an orbital plane different from the plane of the launch site.

launch window: exactly defined period within which the earth and other bodies (in orbit or interplanetary) are in the proper relationship for vehicle launch and optimum interception.

liquid hydrocarbon: carbon-hydrogen compound with sufficiently low molecular weight that it is liquid at ambient temperatures but sufficiently high molecular weight that it is not a gas under the same conditions.

Mach number: the ratio of the speed of a body to the speed of sound in the fluid through which the body is moving.

milestone dates: the major decision points in the U.S. Department of Defense's process for acquiring weapon systems; for example, Milestone 0 is the approval to begin concept exploration and definition; Milestone I is the approval to begin demonstration and validation; Milestone II is the approval to begin engineering and manufacturing development; and Milestone III is the approval to begin production and deployment.

mission need: a deficiency in current capabilities or an opportunity to provide new capabilities (or enhance existing capabilities) through new technologies.

multistage space launch: orbit-capable launch vehicles consisting of two or more stages, each having a propulsion system.

nozzle recombination loss: losses of efficiency that result when the expansion is too fast for the chemistry to remain in equilibrium.

operational requirements: a system capability or characteristic required to accomplish approved mission needs; usually performance parameters, but may also be derived from cost and schedule; for each parameter, an objective and threshold value must also be established.

piloting the combustion (or combustor) process: a technique in which the combustion process of the flowing gases is supported by providing an adjacent region of high temperature, low velocity, combustion products (e.g., in a dual-combustion scramjet, a small fraction of the air is decelerated to achieve combustion, the products of which then promote the burning of, or "pilot," the larger supersonic stream).

production and deployment: a phase of the U.S. Department of Defense's process for acquiring weapon systems, during which a system is produced, fielded, and supported, and its performance is monitored.

pseudo-air: a mixture of gases that has the same volumetric concentration of oxygen as standard air (i.e., 21 molar percent), but the quantities of the other 79 percent of gases, such as nitrogen, carbon dioxide, carbon monoxide, water vapor, hydrogen, nitric oxide, and hydroxyl, are substantially different from the quantities present in standard air.

pyrolyzed fuel: fuel that is chemically decomposed by heating in the presence of a catalyst, i.e., dehydrogenation or cracking.

ramjet: a propulsion device that replaces the mechanical compressor of the turbojet engine with the natural compression of the incoming "ram" air; combustion occurs at subsonic speeds, and the device can operate effectively in the Mach 1 to Mach 6 range.

refractory metals: metals having extremely high melting points (in the broad sense, metals having melting points above the range exhibited by iron, cobalt, and nickel); oxidation-resistant coatings are typically required for high-temperature use.

scramjet: a supersonic combustion ramjet; above about Mach 5 or 6, it becomes impractical to decelerate the air flowing into the engine to subsonic speeds prior to combustion, and supersonic combustion is required to generate thrust.

specific impulse: a basic propulsion performance parameter measured in seconds (also, thrust per unit weight of fuel flow per second, which is measured in seconds); the higher the specific impulse, the better the performance of the stored propellant, which is generally only fuel for air-breathing engines and fuel plus oxidizer for rockets.

speed of sound: in air at sea level and at a temperature of 59°F, sound travels approximately 1,116 feet per second; as the temperature diminishes, the speed of sound decreases (e.g., at the temperature associated with an altitude of 100,000 feet, the speed of sound is approximately 990 feet per second).

subsonic: less than the speed of sound (i.e., < Mach 1).

supersonic speeds: generally considered between approximately Mach 1 and Mach 5.

supersonic diffuser: the contracting duct or compressing part of an engine inlet.

system design integration: the complex, multidisciplinary engineering task that includes selecting technologies, performing design trade-off studies, and generating a balanced system design that meets requirements and can be implemented.

technology maturity levels: the degree to which a technology has been developed, ranging from level one for basic principles observed and reported, to level six for system or subsystem model demonstration in a relevant environment, to level nine for an actual system that has been flight-proven in mission operations.

transitions: changes from one scramjet operating mode to another without disrupting the overall process (e.g., the change from subsonic combustion to supersonic combustion while maintaining continuous thrust output).

wooden round: a term indicating that a weapon can be stored for long periods of time with little checking or maintenance and can be employed on short notice when taken out of storage.