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HYPERSONIC POWER PROJECTION

By Richard P. Hallion

Mitchell Paper 6

Brig. Gen. Billy Mitchell

On September 12, 1918 at St. Mihiel in France, Col. William Mitchell became the first person ever to command a major force of allied aircraft in a combined-arms operation. This battle was the debut of the US Army fighting under a single American commander on European soil. Under Mitchell's control, more than 1,100 allied aircraft worked in unison with ground forces in a broad offensive—one encompassing not only the advance of ground troops but also direct air attacks on enemy strategic targets, aircraft, communications, logistics, and forces beyond the front lines.

Mitchell was promoted to Brigadier General by order of Gen. John J. Pershing, commander of the American Expeditionary Force, in recognition of his command accomplishments during the St. Mihiel offensive and the subsequent Meuse-Argonne offensive.

After World War I, General Mitchell served in Washington and then became Commander, First Provisional Air Brigade, in 1921. That summer, he led joint Army and Navy demonstration attacks as bombs delivered from aircraft sank several captured German vessels, including the SS *Ostfriesland*.

His determination to speak the truth about airpower and its importance to America led to a court-martial trial in 1925. Mitchell was convicted, and resigned from the service in February 1926.

Mitchell, through personal example and through his writing, inspired and encouraged a cadre of younger airmen. These included future General of the Air Force Henry H. Arnold, who led the two million-man Army Air Forces in World War II; Gen. Ira Eaker, who commanded the first bomber forces in Europe in 1942; and Gen. Carl Spaatz, who became the first Chief of Staff of the United States Air Force upon its charter of independence in 1947.

Mitchell died in 1936. One of the pallbearers at his funeral in Wisconsin was George Catlett Marshall, who was the chief ground-force planner for the St. Mihiel offensive.

ABOUT THE MITCHELL INSTITUTE: The General Billy Mitchell Institute for Airpower Studies, founded by the Air Force Association, seeks to honor the leadership of Brig. Gen. William Mitchell through timely and high-quality research and writing on airpower and its role in the security of this nation.

ABOUT THE AUTHOR: Dr. Richard P. Hallion is an aerospace historian who served 11 years as the Chief Air Force Historian and has written widely on aerospace technology and airpower topics.

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PREFACE

"Hypersonic flight at levels of Mach 6 was first raised as a possibility in the 1920s and 1930s. Promising research programs in the 1960s made it seem as though routine hypersonic flight was just around the corner. That promise was not fulfilled.

Today, a casual observer could be excused for thinking that very little progress has been made. There's no sleek fleet ferrying passengers from New York to Tokyo in two hours, as has at times been postulated. The quest for a practical, operational, air-breathing hypersonic aircraft feels like aviation's unrequited dream.

With this paper, Dr. Richard P. Hallion, a former Chief Historian of the Air Force, takes readers on a tour of the milestones in the history of hypersonics and makes a compelling case for his belief that recent developments bode well for continued work toward Mach 6 and beyond.

As soon as airmen developed high-speed flight, they itched to break the sound barrier, and did, in October 1947. Next up was supersonic flight at multiple Mach numbers. As Hallion points out, it didn't take long for development of the X-15 to push past that barrier. SR-71 Blackbird crews made Mach 2 and Mach 3 a routine occurrence. "In October 1967, not quite two decades after Yeager's pioneering flight, Maj. William "Pete" Knight reached Mach 6.70," Hallion writes.

Nearly half a century later, however, the trajectory of hypersonics remains uncertain, and its difficulties perplexing.

Of course, there are several hundred Americans for whom hypersonic speed became quite routine. Astronauts on moon trips or shuttle missions experienced acceleration at speeds of Mach 24. Those craft used rockets with huge tanks mixing in liquid oxygen to achieve their velocity.

Yet the current quest for hypersonics is both more modest and more complex. It centers on building an engine that can be housed in an aerospace craft with multiple uses. Given the aerospace prowess of the United States, it is odd that this dream has not yet come to fruition. The question is, why?

In this paper, Hallion tackles this issue square on. His first point is that hypersonics remains an important national security capability. As he writes: “Modern hypersonics technology offers clear opportunities for joint service power projection in general and for United States Air Force power projection in particular.”

Research here and abroad remains active. “Hypersonics is a mature and weaponizable technology, being actively pursued not only in the United States but also in quite a few nations. Russia, China, Iran, France, Germany, Australia, India, and Japan all have robust programs in hypersonic missile, and missile-related, activities,” notes Hallion.

However, Hallion does not shrink from acknowledging that hypersonics sometimes has suffered from a bad reputation. One common quip says that hypersonics is the future of airpower … and always will be. Hypersonics have been just 10 to 20 years away from fulfillment for so long that the act of budgeting for research has turned into a leap of faith.

As Hallion puts it: “The hope of hypersonics … became inextricably caught up in what might be termed a hypersonic hype. This led, over time, to a cycle of fits and starts that has largely worked to discredit the potential of the field and taint it with an image of waste and futility. Typically, a program has begun with great fanfare and promise, increased in complexity, and when realistic performance, schedule, and cost estimates are derived, its appeal quickly fades.”

To Hallion, who has long observed test programs, the reasons for underwhelming progress to date in hypersonics range from a lack of focus to the specific tribulations of various “X” programs. He traces the fortunes of programs such as Dyna-Soar and the National Aerospace Plane, along with earlier experiments. Hallion also revisits the Air Force’s stewardship of hypersonics and the gradual build up of doubt about the value of the technology. At a low point in 2000, USAF established a special study to debate whether “hypersonics actually constituted a worthwhile investment area for continued Air Force research and development.”

The answer was yes, but it took several low-key efforts over the past decade to bring hypersonics research back to the mainstream. Now, the fortunes of hypersonic technology may be about to change.

A case in point is the recent, successful beginning of flight tests with the X-51 WaveRider. The sustained engine burn with a mix of JP7 fuel and supersonic compressed air—the elusive scramjet—achieved important goals in a truly practical demonstration. “This engine can be considered the next step in aviation," commented the Air Force Research Lab's X-51 program manager shortly after the first flight test on May 26, 2010.

Another promising path may be the development of hypersonic missiles. "The engine technology exists today to produce an air-, surface-, and/or sub-surface launched hypersonic missile that could reach out to 1,000 miles or beyond," concludes Hallion.

Above it all is the continued operational value of hypersonics in the application of airpower. Hallion cites the "tyranny of time" as well as enemy defenses as a limiting factor for conventional airpower. "The United States faces a future in which a troubling synergy of distance to target, weapon time of flight, and defense strength all combine to frustrate the intent of theater commanders and national command authorities, preventing the achievement of American security objectives in a timely and 'least cost' fashion," Hallion says.

Those geopolitical realities make hypersonics more compelling than ever. The relatively modest investment in research opens the possibility of an economical new way to wield the power of Mach.

"Hypersonics is a game-changer, and the price of it being in hostile hands is the loss of air dominance and the ability of our various joint task forces to operate on the surface," Hallion concludes. As a result, he says: "Hypersonics should be one race the United States does not lose."

Rebecca Grant, Director
Mitchell Institute for Airpower Studies
June 2010

I. THE PROMISE

Modern hypersonics technology offers clear opportunities for joint service power projection in general and for United States Air Force power projection in particular. This is somewhat ironic, given that hypersonics initially began as a necessary aspect of ballistic missile development and became associated with increasingly large and complex air-and-spacecraft systems, from the X-15 and X-20 to the space shuttle and National Aero-Space Plane. Now, hypersonics more and more is focused upon application to remotely piloted aircraft and missiles.

The term "hypersonic" generally refers to flight ranging from Mach 5 to orbital velocity.[1] Thought and study in this field has traditionally focused on "big ticket" concepts such as ready space access by fully reusable or nearly fully reusable launch vehicles (RLVs) and concepts for global-ranging hypersonic cruisers. There always were smaller and far more achievable concepts. The X-20 boost-glider and the proposed SV-5 and M-2 lifting reentry manned spacecraft all could have used a modified Titan booster for orbital insertion. In the mid-1980s, there emerged various small "Transatmospheric Vehicle" concepts; they could have been launched from modified carrier aircraft such as the Boeing 747. The imaginative Black Horse concept appeared in the 1990s. All, however, failed to win support.

Fortunately, as hypersonics has gotten smaller, so to speak, so too has its actual military application become more achievable and desirable, evidenced by growing interest in small specialized hypersonic reentry systems. These include small winged craft such as the Boeing X-37B, launched from Cape Canaveral AFS, Fla., on April 22, 2010, by an Atlas V, and possibly missile systems such as the Boeing X-51 WaveRider, which made its first flight on May 26, 2010, via a B-52 flying out of Edwards AFB, Calif.

What, in fact, does a hypersonic missile offer? In 2000, an official Air Force study concluded that "[an] Airborne Hypersonic Missile would open a new regime in the battlespace (range, speed, etc.) that provides the commander increased options."[2] In 2007, a Committee on Future Air Force Needs for Survivability, formed by the Air Force Studies Board of the National Research Council (NRC) at the request of HQ Air Force, recommended that the Air Force increase its investment in hypersonic missile technologies.

The latter study contained this double-edge commentary: "It is not clear ... whether a hypersonic cruise aircraft ... designed for long-range flight and recovery offers unique capability and operational utility. ... [I]t is unlikely that such an air-breathing hypersonic platform, other than a missile, will be available in the near term." However, it went on, "Hypersonic missiles with ranges comparable to those of current missiles could increase targeting timeliness and flexibility and thus increase operational utility in the 2018 time frame."[3]

A hypersonic missile enables the seizure of opportunity against distant and perhaps fleeting targets. In one minute, at Mach 6.5, a hypersonic missile flies approximately 73 miles, roughly eight times further than a conventional subsonic cruise missile. Thus, in 10 minutes, it can engage and destroy a target at a distance in excess of 700 miles from its launch point—yet, in that same period, a conventional cruise missile may not yet have made it to hostile airspace.

The specific advantages of a hypersonic missile are many, a fact this paper will develop at some length. However, we may summarize these advantages by saying that such a missile:

- Overcomes the constraints of distance, time, and defense that already limit conventional aerospace power projection.

- Shortens the shooter-to-target loop, compressing it and thereby redefining "time-sensitive target" and "actionable intelligence."

- Holds hostage multiple types of target sets that are key to winning in regional wars.

- Supports and makes possible successful joint operations through its ability to diminish enemy power persistently, from afar.

This could presage a revolution in mobility. The United States entered the 19th century at the speed of an animal-pulled vehicle, the 20th at the speed of a steam locomotive, and the 21st at the speed of an intercontinental jetliner: 6-60-600 miles per hour.

Just over four decades after the invention of the practical reusable airplane—the Wright 1905 Flyer—winged human flight passed beyond the subsonic era. On Oct. 14, 1947, Air Force Capt. Charles E. "Chuck" Yeager exceeded Mach 1, the speed of sound, in the Bell XS-1, ushering in the supersonic era. Within a decade, piloted flight had progressed beyond Mach 3, though at the cost of Air Force test pilot Capt. Milburn "Mel" Apt, lost in the crash of the Bell X-2 in September 1956. Then, in the 1960s, the X-15 took it into the hypersonic arena, as Air Force Maj. Robert M. White became the first pilot to exceed Mach 4, 5, and 6. In October 1967, not quite two decades after Yeager's pioneering flight, Maj. William "Pete" Knight reached Mach 6.70. Uninhabited hypersonic lifting reentry systems such as the ASV-3 ASSET and SV-5D PRIME returned to Earth at ever-higher hypersonic velocities. Piloted hypersonic reentry vehicles, typified by the Mercury, Gemini, and

Apollo blunt-body spacecraft, took Americans into space and to the moon, returning them safely to Earth. When the space shuttle roared into orbit in 1981, piloted by astronauts John Young and Robert Crippen, it represented fulfillment of an international dream of reusable space access dating to the earliest pioneers of aeronautics and astronautics.

Such was the technical progression of high-speed flight.

For the foreseeable future, the United States will be required—and must be able—to project power globally, swiftly, and decisively, sufficient to overcome regional actors who have only to be concerned about their own geographical "neighborhood." This mission traditionally has fallen to the Air Force. However, the shrinkage of the long-range bomber fleet, recent retirements of systems such as the F-117, reductions to others such as the F-22, and delays with projected systems such as the F-35 have further widened the gap between the current and projected joint-force airpower construct and the global threat environment that it must be prepared to face.

That danger is expanding year by year. America's global responsibilities are growing, not shrinking. America's ability to project decisive global power is shrinking, not growing. The range and nature of threats to deployed forces is expanding, not reducing, as is their lethality against older forms of power projection.

What is to be done? Specifically, what is to be done when access into crisis regions and an enemy's heartland might be contested by combat systems and forces at least as strong and technologically capable as the deployed American and perhaps coalition forces that they face?

One possible answer is reliance on hypersonic weapons. There exists the potential for the United States to introduce new long-range hypersonic offensive and defensive systems to fulfill future needs and confront future threats. More importantly, it is likely this could be achieved, from onset to initial operational capability, within the next decade.

II. HYPERSONICS: AN OVERVIEW

Unlike Mach 1—the speed of sound—hypersonic speed has no clearly defined physical phenomenon demarcating its boundaries. Instead, it is generally held to begin where aerodynamic heating considerations become at least as significant as concerns over aerodynamic design and structural design. The Mach 5 point, then, is largely a reference of convenience.

Hypersonic speed is achievable through the power of either rocket or air-breathing propulsion. One almost-hypersonic rocket was Nazi Germany's infamous V-2. In the Gulf War, Patriot missiles encountered Scuds moving at near-hypersonic velocities. In 2004, for the first time, a hypersonic vehicle, the X-43, flew with an air-breathing supersonic combustion ramjet (scramjet) engine, a means of propulsion postulated a half-century previously.

Hypersonics is consistent with the evolution of Air Force long-range engagement capabilities. Because of the innate speed of the vehicle, hypersonics inherently involves achieving long-range as well. A small scramjet engine can propel a cruise-missile-sized hypersonic missile at speeds of up to 60 miles per minute, enabling it to hold hostage within a few minutes at most targets across an entire theater.

The US Army Air Forces, and successor USAF, was spurred to develop this field by its Chief of Staff, Gen. H. H. Arnold, and, its technological leader, Theodore von Karman. Under them, the service undertook the development of game-changing jets, rockets, and missiles in the post-World War II era. Their successors, in the post-Vietnam era, pushed this record of innovation to include stealth aircraft, electronic combat, Global Positioning System (GPS) navigation and location, and increasingly precise and far-reaching air-delivered munitions.

We could one day look back and realize that hypersonics was the logical next step in that progression. To understand the context from which operational hypersonics emerges, it is necessary to review some of its history.[4]

Hypersonics was, in effect, an afterthought, a necessary attribute, of flight beyond the speed of sound and into space, particularly the flight of rockets and missiles. In the earliest scientifically rooted (as opposed to fanciful) visions of spaceflight, astronautics pioneers such as Konstantin Tsiolkovskiy, and Robert H. Goddard conceptualized rockets flying out into space, necessitating their transitioning the hypersonic regime.[5] Others, such as rocket enthusiast Max Valier, envisioned a different sort of ascent, one by winged rocket-powered airplanes rising through the atmosphere into space, and then returning to Earth.[6] These two strains—ballistic versus winged ascent and reentry—would subsequently come to characterize subsequent space-launch endeavors.

Of the two, the ballistic space-transiting rocket appeared first, in 1943. The advent of the large liquid-fuel rocket, essentially coincident with the advent of atomic weapons, generated the specter of intercontinental rocket bombardment. Rocketry went to the forefront of weapons research. The USAAF-sponsored von Karman study team concluded long-range ballistic missile research was "vital to the future defense of our nation."[7] Within months, the AAF Air Materiel Command issued a study contract to the Douglas Aircraft Company for a report on the feasibility of Earth-orbiting satellites. In May 1946, the Douglas team—the genesis of the RAND Corporation—submitted an impressively detailed analysis on the prospects and requirements of a "World-Circling Spaceship," predicting the value of the satellite for reconnaissance and communications, ruminated on prospects for human spaceflight, and concluded:

"Technology and experience have now reached the point where it is possible to design and construct craft which can penetrate the atmosphere and achieve sufficient velocity to become satellites of the Earth."[8]

While artillerists and ballisticians waxed enthusiastic about parabolic rockets, the more seductive concept of an advanced airplane taking off and flying out into space, then returning safely to Earth, was one that inherently appealed to airmen. The scientific and technological roots of such winged hypersonic vehicles were soon to be put down in 1920s Germany.

In 1923, Hermann Oberth published the first great scientific exposition of spaceflight, a practical exercise in rocket design.[9] The next year, enthusiast Max Valier proposed extrapolative development of commercial intercontinental passenger-carrying "ether planes" using rocket power to boost into the upper reaches of the atmosphere, beginning with derivations of German commercial airliners such as the Junkers G23 trimotor.[10] In 1925, the German civil engineer Walter Hohmann extended Oberth's work to address the problems of orbital insertion and transfer between orbits, reentry heating, and aerodynamic braking devices.[11]

In the early 1930s, Austrian engineer Eugen Sanger undertook a comprehensive technical analysis of the requirements and necessary characteristics of rocket-powered aircraft, including considerations of rocket-powered fighters and bombers.[12] Sanger, working with mathematician Irene Bredt (who subsequently married him), next undertook conceptual studies for a large single-stage-to-orbit (SSTO), sled-launched, rocket-powered, winged boost-glider. This design, the Silbervogel (Silver Bird) of 1938, was intended as a space logistical supply craft. During World War II, however, its purpose was changed as a means to secure further research funding support. Sanger and Bredt changed its rationale to that of a possible "antipodal bomber." Following boost into space, it would follow a skip-reentry profile, each skip of shorter length and height, until it finally entered a terminal supersonic glide down to landing. Though impracticable for many individual reasons and abandoned in 1944, the Sanger-Bredt Silbervogel nevertheless was an extraordinarily significant design study which strongly stimulated postwar hypersonic research efforts.[13]

However, the complex flows and long-duration exposures of a winged vehicle, or a tailored lifting body, proved difficult to address. While a low-lift and high-drag ballistic warhead plunges through the atmosphere very quickly, minimally exposing itself to the furnace-like temperatures of reentry, a relatively high-lift and low-drag winged hypersonic vehicle experiences a prolonged heating and soaking exposure lasting for many minutes. So severe is this aerodynamic heating environment that, as late as 1987 (and despite 30 years' experience with ballistic missile reentry and over half a decade with the space shuttle), one expert still acknowledged it as a daunting "constraint to flight at hypersonic speeds."[14]

This vexing multidisciplinary problem taxed aerodynamics, materials, and structures technology, and forced development of new configuration, structural, and thermal protection concepts; many specialized test methods and facilities; and a variety of analytical and simulation tools. Among them:

■ Flight research with the piloted Mach 6+ North American X-15, added vital data points and experience on a variety of issues such as human factors, a pilot's ability to precisely control a winged spacecraft during acceleration into the upper atmosphere and then during reentry from space, thermally induced structural loads and deformations, and flight control and aerodynamic load interactions.[15]

■ Specialized reentry experiments and maneuverable reentry vehicle (MARV) studies furnished insight into the magnitude and problems of reentry heating and maneuvering entry, particularly boundary-layer transition from laminar to turbulent flow, an issue of critical (and lasting) significance to reentry vehicle design. These probes included NASA's FIRE I and II, and Reentry-F; the Air Force's Boost-Glide Reentry Vehicle (BGRV), the Navy's Mk 500 reentry vehicle, and the Sandia Winged Energetic Reentry Vehicle Experiment (SWERVE).[16]

■ The six-year Boeing X-20 Dyna-Soar development effort was of immense importance. Though cancelled by Secretary of Defense Robert S. McNamara in 1963, it offered vital practical experience in hypersonic design and vehicle-booster systems integration. Dyna-Soar (for Dynamic-Soaring, a reference to its Sanger-Bredt-like skip-reentry profile) constituted the first attempt to build an orbital winged hypersonic piloted vehicle, and, in retrospect, was a program that should have been completed, not cancelled.

■ The McDonnell ASV-3 ASSET (for Aerothermodynamic/elastic Structural Systems Environmental Tests), an X-20-like half-cone and flat-bottom delta that flew to Mach 15+, contributing much useful knowledge on issues such as hypersonic behavior of radiative-cooled structures and leeside heating.[17]

■ Low-supersonic and high-hypersonic tests explored facets of a new category of flight vehicles—tailored lifting bodies that avoided the challenges of protecting a conventionally winged reentry vehicle by employing a modified semi-ogival half-cone, fattened delta, or flat-bottom slender delta body shape. Lifting bodies achieved modest lift-to-drag ratios and, hence, reasonable reentry cross-ranges and low-speed performance permitting runway landings. Tests of the NASA M2-F1/2/3 and HL-10, and the Air Force X-24A and X-24B demonstrated that pilots could fly such craft from Mach 2 down to precision landings.[18] The unmanned Mach 27 Martin SV-5D PRIME (Precision Recovery Including Maneuvering Entry) lifting body (X-24A body shape), lofted over the Pacific Test Range by a modified Atlas booster, earned distinction as the first lifting reentry vehicle to complete a maneuvering reentry from space from orbital velocity.[19]

These efforts furnished a satisfactory data base for design of the world's first operational lifting reentry logistical spacecraft, the NASA-Rockwell space shuttle, which first flew in 1981, fulfilling the dreams (if not, alas, fully meeting the expectations) of advocates who had championed achieving such a capability for nearly a century. In eight decades of flight, the aerospace community—and primarily American aerospace community, at that—had refined hypersonic design approaches for missiles and air- and spacecraft, mapped the hypersonic regime from Mach 5 to beyond Mach 27, and achieved notable milestones, including true "transatmospheric" operations.

III. RISK AND HYPE, FITS AND STARTS

All was not well, however, in this field of hypersonics. Any attractive and potentially revolutionary technology is prey to over-optimistic expectations. In the case of hypersonics, the pace of aeronautical progress over the first half of the 20th century, coupled with the commonly held perception that the airplane would itself evolve into a winged spacecraft, caused many to exaggerate the state of available technology, minimize the technical challenges involved in achieving hypersonic flight, and greatly underestimate how difficult it would be to develop and fly such craft.

The hope of hypersonics thus became inextricably caught up in what might be termed a hypersonic hype. This led, over time, to a cycle of fits and starts that has largely worked to discredit the potential of the field, and taint it with an image of waste and futility. Typically, a program has begun with great fanfare and promise, increased in complexity, and when realistic performance, schedule, and cost estimates are derived, its appeal quickly fades.

In the 1950s, the Air Force began both the Dyna-Soar and Aerospaceplane programs. The Dyna-Soar, a lofted slender-delta orbital boost-glider, represented a reasonable and practical successor to the "Round One" supersonic research aircraft (the X-1, X-2, X-3, and D-558-2), and the "Round Two" hypersonic X-15 that followed, but it had few friends and was cancelled in 1963, about two years before its scheduled first flight.

In contrast, the Aerospaceplane was a wildly impracticable attempt to design and build a fully recoverable winged booster using a complex air-extraction propulsion system to give it the ability to take-off like a conventional airplane and then boost into space. Shortly before its cancellation, the Air

Force Scientific Advisory Board recommended that the Air Force ensure in the future "that no new program achieves such a difficult position."[20]

Large-scale hypersonic studies continued under the aegis of the DOD-NASA Aeronautics and Astronautics Coordinating Board (AACB), within the Air Force Flight Dynamics Laboratory, and within NASA (looking toward its post-Apollo future).[21] However, until the first flight of the space shuttle in April 1981 (itself an effort in which proponents optimistically overestimated anticipated launch rates and utilization, while underestimating its turn-around time, supportability, sustainability, and, worse, operational flight safety issues), no large hypersonic winged vehicle took to the air after the retirement of the X-15 in December 1968.

In the 1970s, government and industry geared up to initiate a modest Mach 6+ hypersonic follow-on to the X-15, using a derivative of the X-24 body shape. This craft, the X-24C, also known as the National Hypersonic Flight Research Facility, subsequently fell from favor as its anticipated costs rose, at a time when dollars were needed for more pressing programs, including the space shuttle and military force restructuring in the post-Vietnam era.

In the 1980s, the X-30 National Aero-Space Plane (NASP) represented an attempt to reinvent the Aerospaceplane concept of the 1960s. It was supported strongly by President Ronald Reagan. Despite this, NASP also collapsed, falling apart in the early 1990s, though it stimulated a needed reinvestment in research and testing facilities, and promoted much useful related research on materials, structures, propulsion, and analytical methods such as computational fluid dynamics.

A number of hypersonic development efforts were undertaken after this time, and some resulting aircraft (like X-43) actually flew, though many others—X-33, X-34, X-38 being notable examples—were either cancelled outright or truncated early in their testing process. The X-33 and X-34 were initiated as efforts to reduce launch costs. The former was a lifting body using an experimental and unproven external-burning engine concept, and the latter was a winged Mach 8 rocket-boosted demonstrator capable of autonomous operation.[22] The X-38 was a demonstrator for a proposed space rescue system, based on the proven SV-5D body shape of the 1960s.

Aside from the much heralded but quietly buried X-33, the best known of these failed efforts was the Defense Advanced Research Project Agency (DARPA) Blackswift, itself the subject of much confusion as to its purpose and capabilities. Often alluded to as a "next generation SR-71" global-ranging hypersonic system capable of being operated as a conventional aircraft while furnishing rapid and responsive intelligence, surveillance, and reconnaissance (ISR) and strike, it was, in reality, a strictly experimental system, capable of only achieving Mach 6 speeds for a maximum of 60 seconds. When its limitations and potential cost became widely apparent, it lost support within the Air Force and was cancelled. Hype had again raised expectations, only to dash them.[23]

Indeed, looking at these and a variety of other, smaller efforts and paper studies, it is evident that 75 years' worth of effort has produced much frustration and discouragement. Nor has this been all within the United States. Large-scale foreign hypersonics has experienced a similar history, affirmed by cancelled development efforts such as France's Hermes, Japan's Hope, Britain's HOTOL, Germany's Sanger II, and Russia's Buran.

What has been the problem? Common threads running through the American experience have included:

■ Little consistency or persistence. Generally speaking, the "fits and starts" research and development history prevented any consistent effort to take a particular program from drawing board to flight test, and then on to exploitation for broader national security needs. Some potentially useful efforts—the Boeing X-37B Orbital Test Vehicle (OTV), for example—experienced a fortuitous "handing off" from one party to another (in its case, from NASA to DARPA and thence to the Air Force Rapid Capabilities Office), saving them from early extinction.

■ Complex and unsustainable proposals. Operational systems using exotic propulsion and fuels, requiring space shuttle-like post-flight logistics and sustainability requirements simply did not have any meaningful or lasting military appeal. When, in any case, their research and development proved woefully more complicated and demanding than originally thought (Aerospaceplane and NASP offer two telling examples), interest quickly cooled.

■ Primarily space-driven. Hypersonics has been closely associated with concepts for Single-Stage-to-Orbit (SSTO) or Two-Stage-to-Orbit (TSTO) launch systems, access to space issues, and on-orbit operations. As a result, potential hypersonic applications in missions other than space have been generally minimized.

■ Unrealistic vehicle concepts. Most large hypersonic systems feature configurations and design concepts—SSTO, TSTO, Vertical Takeoff-Horizontal Landing, Horizontal Takeoff and Landing—that guarantee very large size, for example, fuselage lengths in excess of 300 feet and wingspans in excess of 100 feet, and high liftoff weights—more than one million pounds. Their size—well beyond that of the immense XB-70A Mach 3+ experimental bomber of the 1960s—and supportability requirements make them unattractive as operationally reliable systems.

■ No real connection to warfighter needs: Aside from often vague reference to missions such as “global strike,” “global ISR,” and “space access,” concepts for large piloted hypersonic vehicles have not specifically addressed defined Air Force or joint requirements, and sometimes, again with their exotic propulsion and logistical support requirements, seem distinctly at odds with the needs of an expeditionary Air Force. Large piloted hypersonic systems will likely continue to face at best a lukewarm reception among planners and warfighters alike.

IV. USAF’S HYPERSONICS EFFORT

Given this history, it is understandable that, overall, hypersonics has been a controversial subject within the United States Air Force. However, despite frustration and disappointment accompanying the service’s nearly seven-decade involvement with hypersonics, the field has repeatedly received consistent endorsement from a variety of senior-level review boards and bodies, reflecting the conceptual legacy of the von Karman era, which implicitly tied the future of the service to possession of fast, globe-ranging aircraft and missiles.[24]

Reviewing the Air Force’s benchmarking efforts on hypersonics from the late 1980s onward offers a significant means to assess the potentialities of successful hypersonic weapon development and its capabilities. These efforts provided a glimpse at the enduring questions, issues, and conclusions regarding the value to be gained by pursuing development of operational hypersonic systems and weapons.

Oddly enough, impetus was generated by one of the nation’s most successful conventional operations—the 1991 Persian Gulf War.

In Desert Storm, a range of advanced military capabilities had proved invaluable, from space-based navigation with GPS to precision-guided smart bombs dropped from stealth fighters. Even so, the war had taxed military forces, and some aspects of the campaign, such as the counter-Scud theater ballistic missile effort, had shown shortcomings in ISR, in closing the sensor-to-shooter loop, and in having appropriate rapid-response weapons that could intervene quickly and decisively against the foe. The Scud threat in particular had highlighted how a hypersonic or near-hypersonic enemy ballistic missile required a sophisticated layered response of the sort that hypersonic weapons—surface-to-air (SAM), air-to-surface, and air-to-air—could furnish when integrated with warning, cueing, and command and control architectures.

Thus, in the wake of the Gulf War, hypersonics retained and perhaps expanded its appeal. This appeal was further buttressed by three important hypersonic benchmarking studies. These were “Spacecast 2020” (1994), “New World Vistas” (1995), and “Why and Whither Hypersonics Research in the US Air Force?” (2000). Each came at critical times, the first two as the NASP effort passed into oblivion, the last in the confused wake of the late 1990s when hypersonics was competing with many other Air Force development efforts for increasingly scarce investment funds.

The post-Gulf War Air Force’s emphasis on speed and range implicitly endorsed the kind of qualities inherent in hypersonic power projection systems (which then Secretary of the Air Force Donald B. Rice personally followed with interest). At the time of the study’s release, the long-suffering NASP program, begun with so much enthusiasm just a half-decade previously, was already deficient in meeting its performance, schedule, and cost goals, largely all reflecting the unrealistic expectation underlying the program: developing an air-breathing SSTO that could operate all the way from takeoff to orbit. NASP would shortly collapse, its difficulties unfortunately obscuring the very great and significant accomplishments the NASP team achieved in critical hypersonic technological areas such as structures, materials, and propulsion, and which, ironically, both enabled the successful development of follow-on systems such as the X-43 and encouraged further investment in hypersonic technology and programs.[25]

In this climate, the Air Force might have turned away from hypersonics. The fact that it did not stemmed from its experience in the Gulf and from Spacecast 2020, an Air University study mandated by Gen. Merrill A. McPeak, USAF Chief of Staff (1990-94). The study’s participants advocated developing alternatives to the shuttle and large expendable launch vehicles, favoring rapid and responsive space lift using a squadron composed of a small hypersonic F-16-sized spaceplane—the Black Horse. Capable of inserting payloads of up to 5,000 pounds into low Earth orbit, Black Horse was neither as complex nor as capable as the shuttle, but it was more versatile. Its proponents considered it the “C-130 of space,” to the shuttle’s huge and lumbering C-5.[26]

Sheila E. Widnall, Secretary of the Air Force (1993-97), and Gen. Ronald R. Fogleman, USAF Chief of Staff (1994-97), the successors to Rice and McPeak, continued and extended high-level support for the service’s investment in robust science and technology efforts. Most notable was their formulation and launch of the most comprehensive and sweeping science and technology assessment and forecasting effort undertaken within the Air Force since its creation as an independent service.

“New World Vistas: Air and Space Power for the 21st Century,” was undertaken by the Scientific Advisory Board in 1995. Using a series of expert panels, New World Vistas assessed the science and technology capabilities, needs, challenges, and opportunities of the Air Force, including hypersonics. Its summary volume tellingly noted:

"Time is now, always has been, and even more so in the information age future will be, of the essence in military operations, especially those of the Air Force. All distances on the Earth are fixed. If the Air Force is to execute faster than an enemy in the 21st century, then, to reduce time, the only alternative is to go faster. Hypersonic air-breathing flight is as natural as supersonic flight. Advanced cycle, dual-mode ramjet/scramjet engines and high temperature, lighter weight materials which allow for long-range, long-endurance, high-altitude supercruise are the enabling technologies."[27]

"New World Vistas" assessed a wide range of technological choices and options for Air Force investment, and none received a stronger endorsement than hypersonics. The study concluded that the majority of critical enabling technologies—systems integration, aerodynamics, air-breathing propulsion, structures, vehicle control, and aircraft subsystems—were already in hand, or would be within 15 years. (Subsequent technical experience has generally confirmed the judgments made by the SAB's Aircraft and Propulsion Panel).[28]

In 2000, following on the pronouncements of the New World Vistas study and some related work by the National Research Council and the Air Force Research Laboratory (AFRL), the Air Force Scientific Advisory Board was tasked by Secretary of the Air Force F. Whitten Peters (1997-2001) and Gen. Michael E. Ryan, the Chief of Staff (1997-2001), to assess the state of hypersonics and its potential applicability to the Air Force.

This study—"Why and Whither Hypersonics Research in the US Air Force"—marked a critical passage in the service's approach to hypersonics. Besides New World Vistas, several other catalysts served to trigger the study.

Two years earlier, the National Research Council, at the Air Force's request, had undertaken a hypersonics study, concluding that Air Force efforts at that time were inadequate to support the rapid introduction into service of a Mach 8 hydrocarbon-fueled air-breathing (scramjet) missile. As well, AFRL had established a technology roadmap supporting Mach 3+ propulsion that could be applied to a missile, an air vehicle, and to space access. The AFRL study also identified requisite infrastructure investment needs. Then, there was a perception of rapid foreign advancement, particularly in Russia, which was testing small-scale scramjet engine components and forecasting radical new propulsion that would take advantage of magnetohydrodynamics, using weakly ionized gas to "steer" the flow-field of the vehicle to reduce drag, achieve greater propulsion efficiencies, and generate power to drive onboard systems and perhaps even weapons.[29]

At the time of this study, there was no consensus that hypersonics actually constituted a worthwhile investment area for continued Air Force research and development. The potential of hypersonics to fulfill Air Force mission areas was at best unclear. The study structure reflected the uncertainty attending hypersonics, and, as well, the desire that the product be thoroughly vetted, reasonable and tested in its conclusions, and a baseline from which the service leadership could determine whether further investment in the hypersonics field was warranted.

To this end, the study had three panels. An operational concepts panel was tasked to develop operational concepts, demonstrating why hypersonic speed was needed and why conventional platforms could not meet national security mission requirements. An investment panel was charged with developing a time-phased investment plan based upon operational need and the availability of requisite technology. Then, a "red team" panel was built into the study—a SAB "first"—to argue the position that hypersonics lacked military utility, given costs and alternatives.[30]

The Why and Whither study effort concluded that the Air Force already had amassed much experience with hypersonic systems such as ballistic missiles and maneuvering reentry warheads, that both rocket and air-breathing hypersonics could be applied to space access and global attack missions, and that there was "great opportunity to leverage NASA's investment" in hypersonics, noting, "It's time to make the Vision a reality."[31]

Beyond this, panel members concluded that:

■ A hypersonic TSTO RLV was more feasible than an SSTO RLV (a direct refutation of Aerospaceplane/NASP-type approaches).

■ Hypersonic speed made vehicles more survivable, but should also be joined with other supporting technologies such as penetration aids, signature reduction, and terminal area maneuvering.

■ Hypersonic air-breathing RLVs could fulfill dual roles as space launch systems and global Continental US-based attack systems.

■ Hypersonic air-breathing aircraft and missiles could address such challenges as time-critical mobile targets, hard or deeply buried targets, suppression of enemy air defenses (SEAD), counter air, counter ballistic missiles, global strike/recce, survivable directed energy or airborne laser platform missions, rapid global resupply, routine space launch, maintenance of critical satellite constellations, anti-ASAT (anti-satellite) friendly satellite protection, and space denial via ASAT and satellite capture or disabling.

■ Deployment of an operational hypersonic air-breathing missile was achievable within 15 years (2015), and an RLV in 20 years (2020), if investment began immediately.

■ Research into hypersonics was at the same relative position as was supersonic research a half-century before, with an inadequate Federal organizational structure, serious ground test facility shortfalls, inherent risk and design uncertainties, subscale substitutes for full-size test systems, controversial test aircraft (X-1 then, X-43 in 2000), disadvantageous economic circumstances, and no obvious operational requirement. Yet, it asked tellingly, "Would a reasonable person today say we made a mistake supporting supersonic research and development?"[32]

■ Outside of the US, "significant foreign activities" were already underway in hypersonics, including research programs in Russia, France, Japan, Germany, China, and India. In the hands of a hostile power, hypersonics could threaten US space access and conventional military operations.[33]

The Why and Whither report concluded, "Hypersonics and hypersonic related technologies offer the potential for revolutionizing aerospace warfare."[34] It is clear that, within the Air Force, the Why and Whither report worked to preserve an active interest and research effort supporting hypersonics.

Briefed to the Secretary and the Chief of Staff, the study led to their cautious endorsement of continued modest investment in hypersonics programs and infrastructure. In the corporate Air Force environment of the period, such results constituted an unambiguous achievement for hypersonic partisans, again at a time when hypersonics, nationally, was in danger of waning.

It was NASA, surprisingly, that turned most dramatically away from hypersonics, in part because of its budgetary problems supporting the shuttle and space station, both extremely costly programs. NASA cancelled development of the X-33 in 2001 following serious developmental problems. The agency cancelled the X-34 and a lifting reentry demonstrator for a proposed space "lifeboat," the X-38, though both were making satisfactory progress. The X-43, a small scramjet testbed accelerated to hypersonic velocity by a modified Pegasus booster, eventually flew to nearly Mach 10 in November 2004, effectively marking the end of NASA efforts to build further scramjet powered test vehicles.

NASA also abandoned the X-37 to DARPA, which, in turn, gave it up to the Air Force, which pursued its development under the aegis of its Rapid Capabilities Office. This long-lived program at last produced a working vehicle, which was successfully launched in April 2010. The next to do so was the Boeing X-51, which made its first flight in May 2010.

V. GROWING THREATS AND CHALLENGES

In current US military strategy, an important element concerns fighting and prevailing against a hostile regional power. The United States, as a global superpower, must be able to project decisive combat force into a crisis region, there to win against a regional actor who only has to be concerned about his back yard. It is not as simple a matter as it at first might seem. In 1982, during the Falklands War, the inability of Britain to secure a swift and overwhelming victory over Argentina exposed British naval forces to prolonged air and missile attacks that brought serious losses and risked loss of the war. Writing in 1997, analysts Daniel Goure and Stephen A. Cambone noted in an Air Force-directed Center for Strategic & International Studies (CSIS)-VII, Inc. report (using words that now ring with a special resonance):

"Potential US adversaries are not standing still. They are taking advantage of opportunities presented in the international arms market. [We] need to prepare to meet the threat of robust regional adversaries early in the next century and the prospect of heavily armed, theater-level 'peer' competitors or major power [sic] by approximately the year 2014. Regional or theater-peer competitors need not build military forces symmetrical to those of the United States to mount a significant challenge. In many cases, they need only to focus on denying or minimizing the US forward presence and the ability of the United States to intervene in their region."[35]

Even before the CSIS report, US defense planners already had identified the possibility of what now, more than a decade later, have become "normative" threat capabilities possessed by many potential adversaries. They include:

- Interest in (perhaps possession of) nuclear weapons and other types of weapons of mass destruction.

- Information warfare systems and capabilities.

- Precision bombs and missiles.

- GPS or equivalent technology.

- Remotely piloted aircraft for ISR and strike.

- Integrated defense tying together radars, fighters, SAMs, and anti-aircraft guns.

- Redundant command and control.

- Hardened and deeply buried underground facilities.

This array of attributes is already a reality found in nations around the globe, some of which possess all of these, and many others of whom possess substantial numbers of them. As later SAMs and fighters replace those of earlier eras, and as Moore's Law of computational power marches onward unimpeded by the passage of time, the dangers this kind of adversary poses to American attack forces already seriously constrained by shrinking size and growing age will steadily grow.[36]

As the threat of rising regional powers that may be hostile to the United States and its allies steadily increases—exemplified by the introduction of advanced fourth-plus generation fighters, SA-10-and-higher SAMs, theater ballistic missiles, and anti-access specialized long-range surface-to-surface and air-to-surface weapons into the service of various totalitarian and bellicose states—the deficiencies of America's joint service airpower projection forces increasingly will constrain the decision-making options of the national command authorities.

One serious challenge is the tyranny of distance. Since 1989, the robust basing of the Cold War has been replaced by dependence upon a few far-flung regional power-projection centers that are themselves often far removed from regions of actual or potential conflict. Diego Garcia, for example, is roughly 2,500 miles from Afghanistan; Guam is 2,000 miles from North Korea, and more than 1,500 miles from the Taiwan straits. "Rapid power projection," commonly thought of in terms of Mach 0.8 cruising aircraft and 30-knot naval vessels armed with subsonic cruise missiles, is not sufficiently timely to meet the growing challenges of 21st century rogue states and irresponsible actors who have access to advanced weaponry and a willingness to use it against America and its friends. Here is where the addition of hypersonic weapons to such platforms can reduce arguably the most important loop of all—the shooter to the target.

There is also the tyranny of time. The long fly-out times of conventional subsonic cruise missiles (launched from aircraft, ships, and submarines) risk missed opportunities against even moderately distant targets, and the fly-out times of conventional aircraft are likewise insufficient. Intelligence may detect a fleeting target at, say, a distance of 500 to 600 nautical miles, but the technological limitations of current attack systems generally ensures that it cannot be acted upon, unless, by very good fortune, strike forces are already present and within effective range of it. This creates a set of "are we there yet?" zones for targets offering an aggressor effective sanctuary from the routine worry of air attack.

Finally, there is the nature of modern air defenses. For the sophisticated opponent, the readily available capabilities of a modern integrated air defense system (IADS)—command, control, communications, and computer (C4)

ISR architectures, SAMs, radars, aircraft, antiaircraft artillery, skilled training and maintaining personnel—can all be had for a price, the individual pieces observable at the world's defense trade shows. Already, for some scenarios, aircraft such as the F-15, F-16, and F/A-18 are denied access, except at prohibitive risk of loss. Thus, we may posit that, for the future, American power projection forces as currently constituted, and even reflecting planned acquisition of systems such as the F-35, will operate within an environment in which:

■ Traditional intrusive "fly-over" force-package attack scenarios, are constrained by networked fourth- and fifth-generation fighters, advanced double-digit SAMs, more efficient command and control, all working against aging performance-limited legacy attack systems. While stealthy attackers will continue to possess significant survivability over non-stealthy conventional and legacy attackers, even they will not operate risk-free as the lethality of air defenses grow and the radius and area of threat-rings (and, consequently, the area of endangered coverage) steadily expand.

■ Stand-off platform-launched options are constrained by the increasing vulnerability and slow transit speeds of conventional cruise missiles; the short attack ranges of other air-to-surface systems (which risk placing the launching aircraft or platform well within the threat rings of contemporary and anticipated air defense networks; and the increasing limitations and vulnerability of aging platform aircraft themselves.

In sum, then, the United States faces a future in which a troubling synergy of distance to target, weapon time of flight, and defense strength all combine to frustrate the intent of theater commanders and national command authorities, preventing the achievement of American security objectives in a timely and "least cost" fashion.

VI. HYPERSONIC ADVANTAGE

These three problems are not going away anytime soon. Given the impact on US military strategy, the value of hypersonic systems becomes readily apparent.

■ First, hypersonics overcomes the constraints of distance, time, and defense that already limit conventional aerospace power projection. It affords inherent rapid reach simply by the nature of its propulsion system. By definition, a hypersonic weapon moves at a minimum of about a mile per second, 60 miles per minute. Already, flight-worthy scramjet engine modules have functioned in excess of 50 seconds, equivalent to more than 50 miles range, constrained not by their performance, but, rather, from the amount of air that could be furnished to them in the high temperature tunnel in which they were being tested.[37]

The engine technology exists today to produce an air-, surface-, and/or sub-surface launched hypersonic missile that could reach out to 1,000 miles or beyond. This quality of rapid reach works to furnish two important military advantages for the theater commander: (1) virtually immediate target access—only a "Mach-a-million" laser weapon is faster—across a theater of operations, and (2) imposition of "4th Dimension" and associated dislocating effects upon an opponent, getting inside the opponent's decision-making loop, seizing initiative, and negating response.

Indeed, in the time that an opponent begins shaping a response to a hypersonic attacker, the attacker can be already exploiting the effects of the first attack and moving on to other target sets. An historical example may be instructive: during the Second World War, a German general exposed to conventional air attack compared himself to a chess player who could make only one move to an opponent's three.[38] What caused his consternation were propeller-driven fighter-bombers flying at six miles per minute, dropping dumb bombs with about a 360-foot circular error probable (CEP). The effect of multiple hypersonic weapons striking at least 10 times more precisely and 10 times faster offsets any of the communication and decision-making advantages enjoyed by the adversary.

■ Second, hypersonics compresses the shooter-to-target loop, offering the theater commander important command advantages. Hypersonics redefines both what constitutes a "time sensitive target" and what constitutes "actionable intelligence." It permits the seizure of fleeting opportunity, and increases the warfighter's decision-making options. In August 1998, the Clinton Administration undertook conventional cruise missile attacks against Osama Bin Laden training camps in Afghanistan that "probably missed Bin Laden by a few hours."[39]

It is worth noting that the 80-minute fly-out time of the conventional cruise missiles used in the attack would have been cut to just over 12 minutes if a Mach 6 hypersonic missile system had been available. While it must be emphasized that one cannot say with certainty that a hypersonic missile attack would have had any greater luck, under circumstances where minutes count, the advantage of striking at hypersonic, as opposed to subsonic, velocities is self-evident.

Because of its ability to strike quickly, it redefines both what can be hit and what constitutes actionable intelligence. Information that might have elicited a "too bad we can't do anything about this" response is transformed by the availability of hypersonic strike systems into "let's act on this." Conversely, if commanders need greater time to assess a potential target, the rapid closure speed of a hypersonic weapon affords them the ability to wait before making the launch decision.

■ Third, hypersonics can hold hostage multiple target sets. Hypersonic weapons, like other weapons before them such as precision-guided bombs and subsonic cruise missiles, are suited for various kinds of tasks. These include SEAD, where a hypersonic weapon could react rapidly to a "pop-up" threat such as a radar or a SAM launch system before it can engage a friendly aircraft. With its speed and inherently higher degree of survivability than other forms of attack, the hypersonic missile is an ideal asymmetric counter to the growth of sophisticated integrated air defense networks that buttress anti-access strategies aimed against the United States. Examples of other target types that can be addressed by a hypersonic weapon are high-leverage targets such as command, control, and communications (C3), leadership, key infrastructure, aircraft, cruise missile, and maritime threats.

If planners learned of a meeting of key terrorist principals, such a meeting could be readily targeted by a hypersonic weapon within minutes, even, depending on the range of the weapon, at a distance well in excess of 1,000 nautical miles from the launch point. A maritime patrol aircraft on counter-piracy patrol could engage and sink a pirate craft endangering commercial traffic with the confidence that the hypersonic weapon would reach the vessel before it closed with the ship under attack, something not possible with traditional subsonic antishipping weapons. A dual-use hypersonic missile could have a "dial" update feature enabling it to be used in the air-to-air role against vital airborne targets, such as long-range fighters threatening air lines of communication, maritime patrol bombers endangering naval forces, cruise-missile launchers (or the cruise missiles themselves), or seized aircraft used for terrorist attacks.

High-threat time-critical targets—for example mobile theater ballistic missiles (TBM) being readied for launch—represent an ideal target for hypersonic intervention. In one notional example, the SAB Why and Whither team concluded a circa-2020 C4ISR system could detect a mobile TBM target at more than 400 miles within two minutes of its moving out of concealment (minutes 0 to 2). Within another two minutes it could identify it as a TBM on the move (minutes 2 to 4). A cued hypersonic air launched missile could launch a minute after target identification (minute 5), track the TBM as it moved, stopped, and entered the erection and launch preparation phase, destroying it after a seven-minute flight (minutes 5 to 12), approximately three minutes before it could, at the earliest, be fired.[40]

Because of its high-impact velocity, a hypersonic weapon is ideally suited for attacking hardened critical targets such as command bunkers. However, faster than very high supersonics-low hypersonics is not necessarily better, thanks to the strange properties of materials. Up to an impact speed of approximately 4,500 feet per second (Mach 4 at sea level), a steel penetrator retains great strength; beyond this point it begins to lose strength rapidly. Therefore, the hypersonic weapon plunging from high altitude, perhaps undertaking terminal maneuvering to evade any potential chance of interception by enemy terminal defenses, should impact a target at about Mach 4 for maximum penetrative effect. This is, of course, separate from the issue of whether it carries within it an explosive warhead.[41]

■ Fourth, hypersonics is an enabler of successful joint operations. It permits a persistent air presence and combat punch from well beyond an enemy's IADS threat rings, and its ability to cover and protect joint forces enhances a theater commander's operations against a variety of targets across the spectrum of conflict. In particular, hypersonic missiles deployed from air, surface, and subsurface launch systems can serve to increase both the survivability and the power-projection options of naval forces, particularly naval carrier battle groups and surface action groups.

Whether in naval or other service, the hypersonic missile can eliminate air and surface threats endangering naval forces in both littoral and deep water operations. Indeed, the ability of the hypersonic missile to operate in a SEAD and counter-TBM mode can work to ensure both the "feet wet to feet dry" survivability of carrier air groups equipped largely with legacy aircraft and the survivability of the carriers from where they fly. In concert with the advanced SAM defenses of the ships themselves—and the Navy has its own hypersonic missile programs underway for fleet defense—hypersonic missiles maintained by surface and air forces constitute a genuine "joint warfare" asset, and one worthy of joint service exploitation and adaptation.

VII. OPTIONS, CHOICES, CHALLENGES

What, it may be asked, constitute hypersonic options for military power projection? The answer is a range of systems, of which some are more likely and achievable than others.

The most readily achievable is the rocket-boosted hypersonic missile (effectively a rocket-boosted dart that can be either a simple projectile form or a complex lifting shape such as a hypersonic waverider). If fueled by a highly energetic propellant, it can accelerate to hypersonic velocity, though it begins to decelerate as soon as it exhausts its propellant burn, and so has inherently shorter range than a missile with sustaining propulsion, such as an air-breathing scramjet engine.

The air-breathing scramjet-boosted missile has much greater range, but also a more complex operating cycle. It must be rocket-boosted to the point where its scramjet engine can ignite (typically, in the vicinity of Mach 4.5 at 65,000 feet), requiring that the launch booster (or boosters) be powerful enough to ensure that it can be dropped at a reasonable operational launch altitude—say, 35,000 to 40,000 feet—and then reach the predetermined ignition envelope for the system, yet, at the same time, be compact enough so that it can be carried within the weapon bay of a launch aircraft. During the transition from rocket-lofting to scramjet ignition, "capturing" the airflow for proper internal flow, fuel-mixing, and ignition is complex, requiring a highly efficient flight control and propulsion system. The X-43 demonstrated that such is readily possible, and the X-51 will take this further during its own test program, which is just beginning.

Likely the most useful scramjet-boosted missiles will be low-drag and high hypersonic lift "waveriders," looking somewhat like hypersonic surfboards, with two-dimensional scramjet engine modules, such as with the X-51. The extreme density of these craft (often with dense tungsten nose caps) assist their value as penetrators of hardened targets, while their high fineness ratios make them suitable for tube or rotary rack launch from air, surface, and subsurface vehicles. While a range of fuels can furnish high performance—for example, liquid hydrogen, anhydrous ammonia, and methane—the most practicable fuel is a hydrocarbon such as JP-8, which being itself a dense and energetic fuel, enables production of smaller weapons of greater range than if a fuel requiring larger volume—such as liquid hydrogen—is used. Finally, exotic fuels have little attraction for expeditionary forces, already taxed by their logistical requirements. Anything offering commonality with conventional systems is to be welcomed.[42]

The high cost of space lift has always drawn a great deal of hypersonic interest, whether by TSTO fully reusable concepts, or by semi-expendable concepts such as the shuttle with its "stage and a half" approach to orbit. The search for suitable rocket-lofted and lifting reentry space lift systems has been a generally unhappy one, with cancelled programs such as X-20, the X-33, and X-34 littering the historical landscape.

However, one project that holds great promise is the Air Force's X-37B OTV. Itself the product of a tortuous development program, this small V-tailed double-delta vehicle (reminiscent of—in size and manner of launch—earlier reentry test vehicles such as ASSET and PRIME) is, in fact, the possible progenitor of a whole family of vehicles able to be launched, "parked" and maneuvered in space as needed—carrying a range of payloads to meet national

X-51 May Be Vanguard of Weaponizable Hypersonic Technology

The X-51 WaveRider crossed an important threshold in May 2010 by achieving successful engine ignition and a flight time of 200 seconds at approximately Mach 5. Previously, the longest scramjet engine burn in flight was about 10 seconds in NASA's X-43 Hyper-X in 2004.

Working with prime contractor Boeing, Pratt & Whitney Rocketdyne developed the X-51's revolutionary SJY61 engine, the focus of the test program, which is spearheaded by the Air Force Research Laboratory (AFRL) at Wright-Patterson AFB, Ohio.

"This engine can be considered the next step in aviation," said AFRL program manager Charlie Brink. Ramjet engines feed air through an intake but decelerate it before mixing it with fuel to ignite. Scramjet theory is to mix air at supersonic speeds for combustion. Previous scramjet tests used hydrogen as a fuel for fast but brief flights.

The X-51 achieved two major new goals: use of JP7, a hydrocarbon fuel once used by the SR-71; and the length of engine burn.

The Pacific Test Range off Point Mugu, Calif., was the scene for the first test. Five Navy P-3s systematically cleared the ocean and airspace. A specially modified B-52 flying out of Edwards AFB, Calif., carried the X-51 aloft to 49,000 feet and a speed of .78 Mach. After separation, the booster accelerated the X-51 to achieve supersonic airflow. The engine was then started on an ethylene mixture and transitioned to burning JP7.

The X-51 accelerated and flew under full flight control with a slight deceleration in the final seconds. After 200 seconds, controllers lost the telemetry link with the X-51 and agreed to terminate the flight to ensure the fast-moving vehicle stayed within boundaries on the range. In all, the test yielded between 140 and 170 seconds of engine run data.

For "the DOD S&T community to see that a scramjet actually flew for multiple minutes and powered a vehicle … to have the slew of data we have, everybody is extremely happy," Brink said.

security needs—and then brought back to reenter the atmosphere and land on conventional runways: in short, making space access operations more aircraft-like rather than support-intensive as is the shuttle.
Time will tell if the X-37B does for military space operations what the Remotely Piloted Aircraft (RPA) has done for atmospheric air combat. If so, historians may well mark 2010 as the point where the old style of support-intensive space was retired with the shuttle, and a new era of responsive rapid-turnaround space access began with the X-37B.

What is the prospect of the oft-heralded global-ranging piloted hypersonic cruiser? The answer, at least to this author, seems to be that its need has not yet been defined sufficiently as to warrant its development. A system such as Spacecast 2020’s Black Horse may well make some sense: small, readily maintained, able to be swiftly employed. The RPA revolution, however, has gone so far that even this mission may well be more suitable to the kind of vehicle represented by the X-37B than by an X-20-style crewed approach. Larger global systems seem miscast for their intended roles. Further, operational considerations in almost all cases indicate that a global ranging hypersonic system, operating from the continental United States, would require air-refueling to return unless, from the outset, it was operating from orbit, as an orbital spacecraft. Again, for the present, the RPA approach—smaller, more focused, more tied to identifiable and achievable warfighting needs—seems best, perhaps blending the advantages of waverider design with a turbine-based combined cycle (TBCC) system transitioning to scramjet operation for sustained hypersonic cruise.

There are many other options involving hypersonic military applications and weapons, ranging from use as nuclear weaponized systems to use across the range of conventional warfighting scenarios. It is entirely likely that a "generic" hypersonic missile could be carried within the weapons bay of a maritime Boeing P-8 Poseidon aircraft, an Air Force B-2 loitering hundreds of miles from a target of interest, a large Global Hawk-type UAV, a modified high-capacity airlifter such as an Airbus or Boeing 747-787 derivative, or launched from a special-purpose battlefield rocket system such as an ATACMS-2 (Army Tactical Missile System-2) or a littoral warship or an Aegis cruiser.

VIII. TOWARD TOMORROW

Hypersonics is a mature and weaponizable technology, being actively pursued not only in the United States but also in quite a few nations. Russia, China, Iran, France, Germany, Australia, India, and Japan all have robust programs in hypersonic missile and missile-related, activities.

Though not cheap, hypersonics is far from prohibitively expensive. In July 2002, for example, Australia's Centre for Hypersonics at the University of Queensland flew HyShot, a small scramjet combustor test article to Mach 7.6, a "world's first," for a total cost of just $1.4 million.[43] The ubiquitous access afforded by keystroke-accessed international technical data bases (such as the NASA Technical Report Server, NTRS, or those of leading aerospace professional organizations such as the American Institute of Aeronautics and Astronautics and the Royal Aeronautical Society), the rapid advance of computational-based modeling and simulation tools for aerodynamic, structural, propulsion, and performance prediction, and the practical expertise afforded by the example of successful design approaches already taken, all means that individuals interested in pursuing hypersonic design have a rich vein of material readily available for their contemplation and exploitation.[44] Thus, whether its national and service leadership appreciates it or not, the United States is in a global hypersonic race.

In early times, protected and lulled into complacency by the broad expanse of two oceans and robust military forces, the United States repeatedly missed key technical developments, even ones that it should have pioneered. For example, despite all the great strength of American industry and the underpinnings of national aeronautical research and development policy, American engineers, research administrators, and military officials in the interwar years and afterward missed opportunities to invent the turbojet engine, the jet fighter, liquid-fueled rockets, ballistic and cruise missiles, precision air weapons, radar, swept wings, and satellites.

Hypersonics is a game-changer, and the price of it being in hostile hands is the loss of air dominance and the ability of our various joint task forces to operate on the surface. Today, as regional and international threats proliferate and as rogue states acquire systems capable of denying American access into crisis regions and freedom of movement more generally and develop missile capabilities endangering not only their neighbors but countries on continents far removed from them, hypersonics should be one race the United States does not lose. ■

END NOTES

1. Richard D. Neumann, "Defining the Aerothermodynamic Methodology," in John J. Bertin, Roland Glowinski, and Jacques Periaux, eds., *Hypersonics: Vol. 1: Defining the Hypersonic Environment* (Boston: Birkhauser, 1989), 127.

2. Ronald P. Fuchs, et al, "Report on Why and Whither Hypersonics Research in the US Air Force," SAB-TR-00-03 (Washington: Scientific Advisory Board, December 2000), 47.

3. Lt. Gen. Leslie F. Kenne, USAF (Ret.), et al, "Future Air Force Needs for Survivability" (Washington: The National Academies Press, 2006), 70.

4. See the author's "The History of Hypersonics: or, 'Back to the Future—Again and Again,'" American Institute of Aeronautics and Astronautics (AIAA) Paper 2005-0329 (2005) for a more comprehensive review of this history.

5. A. A. Blagonravov, ed., *Collected Works of K. E. Tsiolkovskiy, Vol. 2: Reactive Flying Machines,* NASA TT-F-237 (Washington: NASA, 1965), 528-530; and Robert H. Goddard, "A Method of Reaching Extreme Altitudes," in Esther C. Goddard and G. Edward Pendray, eds., *The Papers of Robert H. Goddard, Vol. 1: 1898-1924* (New York: McGraw-Hill Book Company, 1970), 337-406.

6. I. Essers, *Max Valier: A Pioneer of Space Travel,* TT-F-664 (Washington: NASA, 1976), 81-97, 130-135, and 248.

7. Hugh L. Dryden, "Present State of the Guided Missile Art," p. 1, in the Technical Intelligence Supplement to Theodore von Karman, et al, "Where We Stand: First Report to General of the Army H. H. Arnold on Long-Range Research Problems of the AIR FORCES with a Review of German Plans and Developments (22 Aug. 1945)," in Papers of General Henry H. Arnold, Microfilm Reel 194, Manuscript Division, Library of Congress, Washington, D.C.

8. Francis H. Clauser, et al, "Preliminary Design of an Experimental World-Circling Spaceship," Report No. SM-11827 (Santa Monica: Douglas Aircraft Company, Inc., Santa Monica Plant Engineering Division, 2 May 1946), 1, 9-16; see also RAND, *The RAND Corporation: The First Fifteen Years* (Santa Monica: RAND, 1963), 9.

9. Herman Oberth, "Die Rakete zu den Planetenräumen" [trans. "The Rocket into Interplanetary Space"] (Munich: Verlag von R. Oldenbourg, 1923), 36-39, 49-51, 57-58, 63-64.

10. Essers, 81-97, 130-135, 248; in 1930, Valier was killed by shrapnel when a rocket engine exploded.

11. Walter Hohmann, *Die Erreichbarkeit der Himmelskörper* (Munich: Verlag von R. Oldenbourg, 1925) translated by NASA as *The Attainment of Heavenly Bodies,* NASA TT F-44 (1960), 16-17, 33, 45-48.

12. Eugen Sanger, *Raketenflugtechnik* (Munich: Verlag von R. Oldenbourg, 1933) translated by NASA as *Rocket Flight Engineering,* NASA TT F-223 (1965); for his earlier military conceptions, see Eugen Sanger, "Neuere Ergebnisse der Raketenflugtechnik," Flug: Zeitschrift für das gesamte Gebiet der Luftfahrt, Vol. 1 (December 1934), esp. 11-16, 19-22.

13. Their later work is detailed in Irene Sanger-Bredt, "The Silver Bird Story: A Memoir," in R. Cargill Hall, ed., *Essays of the History of Rocketry and Astronautics: Proceedings of the Third Through the Sixth History Symposia of the International Academy of Astronautics, Vol. 1* (Washington.: NASA, 1977), 195-228; for the wartime conceptualization of this "antipodal aircraft," see Eugen Sanger and Irene Bredt, Übereinen Raketenantrieb für Fernbomber, Bericht UM-538 (Ainring: Deutsche Forschungsanstalt für Segelflug, August 1944), translated by the Technical Information Branch, US Navy Bureau of Aeronautics, and published as *A Rocket Drive for Long-Range Bombers,* Translation CGD-32 (Washington: Department of the Navy, 1952); for its influence, see John V. Becker, "The X-15 Program in Retrospect," Third Eugen Sanger Memorial Lecture, Deutsche Gesellschaft für Luft-und Raumfahrt (DGLR), Bonn, Germany, Dec. 4-5, 1968. Becker is father to the X-15.

14. Richard D. Neumann, "Defining the Aerothermodynamic Methodology," in Bertin, Glowinski, and Periaux, eds., *Hypersonics,* 125.

15. Wendell H. Stillwell, "X-15 Research Results," NASA SP-60 (Washington: NASA, 1965); Joseph Weil, "Review of the X-15 Program," NASA TN D-1278 (Washington: NASA, 1962); Johnny G. Armstrong, "Flight Planning and Conduct of the X-15A-2 Envelope Expansion Program," AFFTC-TD-69-4 (Edwards AFB, CA: Air Force Flight Test Center, 1969); and Richard E. Day, "Energy Management of Manned Boost-Glide Vehicles: A Historical Perspective," NASA TP-2004-212037 (Edwards AFB: NASA Dryden Flight Research Center, May 2004).

16. Dona L. Cauchon, "Project FIRE Flight 1 Radiative Heating Experiment," NASA TM-X-1222 (1966); Elden S. Cornette, "Forebody Temperatures and Calorimeter Heating Rates Measured During Project FIRE II Reentry at 11.35 Kilometers Per Second," NASA TM-X-1305 (1966); Lt. Col. C. Duke Sherin, USAF, BGRV Fact Sheet, AF SAMSO Information Office, Nov. 17, 1972, in BGRV files, US Air Force Museum Archives, Wright-Patterson AFB, OH; P. Calvin Stainback, Charles B. Johnson, Lillian R. Boney, and Kathleen C. Wicker, "A Comparison of Theoretical Predictions and Heat-Transfer Measurements for a Flight Experiment at Mach 20 (Reentry F)," NASA TM-X-2560 (1972); W. A. Wood, C. J. Riley, and F. M. Cheatwood, "Reentry-F Flowfield Solutions at 80,000 ft.," NASA TM-112856

(1997); Kenneth W. Iliff and Mary F. Shafer, "A Comparison of Hypersonic Flight and Prediction Results," NASA TM-104313 (1995); Steven P. Schneider, "Hypersonic Boundary Layer Transition on Reusable Launch Vehicles," presented at the RLV/SOV Airframe Technology Review, NASA Langley Research Center, Hampton, VA, Nov. 19-22, 2002; and Maj. Stephen L. Davis, "Speed Kills: Implications of Prompt Global Strike," Student Thesis (Maxwell AFB: Air University, School of Advanced Air and Space Studies, 2003), Table 1, 14.

17. Air Force Flight Dynamics Laboratory, ASSET Final Briefing, Report 65FD-850 (Wright-Patterson AFB, OH: AFFDL, 1965); and M. H. Shirk, ASSET: Aerothermoelastic Vehicles (AEV) Results and Conclusions, Report 65FD-1197 (Wright-Patterson AFB, OH: AFFDL, 1965).

18. R. Dale Reed, *Wingless Flight: The Lifting Body Story,* NASA SP-4220 (Washington: NASA, 1997); Alfred C. Draper, Melvin L. Buck, and David R. Selegan, "Aerospace Technology Demonstrators: Research and Operational Options," in Norman C. Baullinger, ed., *Aircraft Prototype and Technology Demonstrator Symposium,* March 23-24, 1983 (Dayton: AIAA Dayton-Cincinnati Section and the US Air Force Museum, 1983), 89-102; Milton O. Thompson and Curtis Peebles, *Flight Without Wings: NASA Lifting Bodies and the Birth of the Space Shuttle* (Washington: Smithsonian Institution Press, 1999), 57-62;and Johnny G. Armstrong, *Flight Planning and Conduct of the X-24B Research Aircraft Flight Test Program,* AFFTC-TR-76-11 (Edwards AFB: AFFTC, 1977), 12-14, 89-97.

19. John L. Vitelli and Richard P. Hallion, "Project PRIME: Hypersonic Reentry from Space," in Richard P. Hallion, ed., *The Hypersonic Revolution: Case Studies in the History of Hypersonic Technology, Vol. 1: From Max Valier to Project PRIME (1924-1967)* (Bolling AFB: Air Force History and Museums Program, 1998 ed.), 529-745.

20. SAB, "Memo-Report of the USAF SAB Aerospace Vehicles/Propulsion Panels on Aerospaceplane, VTOL and Strategic Manned Aircraft," Oct. 24, 1963, 3, copy in the office files of the AF SAB, HQ USAF, Pentagon.

21. DOD-NASA Aeronautics and Astronautics Coordinating Board, *Report of the Ad Hoc Sub-panel on Reusable Launch Vehicle Technology* (Washington, D.C.: NASA, Sept. 14, 1966), NASA Johnson Space Center archives.

22. Statement of Richard S. Christiansen, Acting Assoc. Administrator for Aeronautics & Space Transportation Technology, NASA, before the US House of Representatives Subcommittee on Space and Aeronautics, Committee on Science, Feb. 12, 1998, at http://www.house.gov/science/christiansen_02-12.htm, accessed Aug. 5, 1998.

23. The author was present at a DARPA Blackswift briefing to a senior Air Force leader who, at the conclusion of the meeting, exclaimed ‘This wasn’t at all what I was led to believe.’

24. Evident in von Karman’s judgment that “speed is imperative for effective action [and] safety against enemy countermeasures,” in his “Science: The Key to Air Supremacy,” part of the multi-volume *Toward New Horizons: A Report to General of the Army H. H. Arnold* (Army Air Forces Report, 1946).

25. NASP’s unhappy history led to a search for less-ambitious but more readily achievable alternatives, many of which were unpiloted systems. Within NASA, for example, partisans proposed developing HALO, a small piloted scramjet research testbed that could be air-launched from an SR-71 at Mach 3, accelerate with rocket boost to Mach 12 at 110,000 feet, and then run an experimental scramjet for two minutes before making an unpowered descent to land at Edwards AFB, Calif., though it was not subsequently pursued. This was briefed to the author in June 1992 by Milton O. Thompson, chief engineer of the then-Dryden Flight Research Facility (notes in author’s possession). More broadly, NASP’s problems, and the attractiveness of hypersonics for military and space access purposes, simulated many other programs as well, such as the Hyper-X (the X-43), the X-33, X-34, X-37, and X-40, and the DARPA AARMD (Affordable Rapid Response Missile Demonstrator, which led, circuitously, to the X-51).

26. Lt. Gen. Jay W. Kelley, USAF, et al, “Spacecast 2020,” Vol. 1 (Maxwell AFB: Air University Press, June 1994), H-1 to H-31.

27. Gene H. McCall and Maj. Gen. John A. Corder, USAF (Ret.), “New World Vistas: Air and Space Power for the 21st Century,” (Washington: USAF Scientific Advisory Board, 1995), Summary Volume, 60; see also Richard G. Bradley, et al, “Aircraft and Propulsion” volume, “New World Vistas” (1995), 28-31.

28. The panelists were Dr Richard Bradley of Lockheed Martin (chair); Dr. William Heiser, USAF Academy; Dr. James Lang, McDonnell Douglas; Prof. Terrence Weisshaar, Purdue University; Dr. James Mitchell, Micro-Craft; Prof. Eugene Covert, MIT (advisor); Dr. Keith Richey, Air Force Wright Laboratory; Dr. Douglas Dwoyer, NASA Langley Research Center; and Mr. William King, Office of Naval Research. As well, the panel had two executive officers and a technical editor. See Bradley, et al, “Aircraft and Propulsion,” Appendix B.

29. This system was called AYAKS and subsequently proved less achievable than anticipated. See Fuchs, et al, 18-20. For AYAKS influence in the US, see R. L. Chase, R. Boyd, P. Czysz, H. D. Froning Jr., Mark Lewis, and L. E. McKinney, “An AJAX Technology Advanced SSTO Design Concept,” AIAA Paper 98-5527(1998).

30. Fuchs, et al, H-2. For the record, the author was a member of the Operational Concepts panel.

31. Fuchs, et al, H-1.

32. Fuchs, et al, H-5. This portion of the report was written by the author.

33. Fuchs, et al, H-7.

34. Fuchs, et al, H-21.

35. Daniel Goure and Stephen A. Cambone, "The Coming of Age of Air and Space Power," in Daniel Goure and Christopher M. Szara, eds., *Air and Space Power in the New Millennium* (Washington: The Center for Strategic & International Studies in association with VII, Inc., 1997), 4-5.

36. As the author recalls from briefing notes taken at the second working group meeting of the Air and Space Superiority Panel for the Air Force-mandated CSIS-VII Inc. study *Air and Space Power in the New Millennium.*

37. Data from tests of the X-51 scramjet engine module in the NASA Langley eight-foot High Temperature Tunnel.

38. Maj. Gen. Frido von Senger und Etterlin, *Neither Fear Nor Hope* (New York: Dutton, 1964), 224; the exact quote is "a chess player who for three moves of his opponent has the right to make only one."

39. Thomas H. Kean, et al, *The 9-11 Commission Report* (Washington: National Commission on Terrorist Attacks Upon the United States, 2004), 117.

40. Fuchs, et al, Fig. 25, 46.

41. Fuchs, et al, G-1 through G-7.

42. As early as 2007, the X-51 scramjet engine test program spawned interest in a more operationally focused derivative experimental system that could lead to introduction of an operational "Gen 1" hypersonic scramjet missile. As of this essay, the Air Force Research Lab is exploring options for a system tentatively called RIPTide (Rapid Identification and Prosecution of Targets in Denied Environments) that could explore operationally related aspects of a scramjet missile, including launch, fly-out to a target, acquisition, and terminal maneuvering and engagement. In 2007 and 2008, Dr. Mark Lewis (then Air Force Chief Scientist) and the author (then Senior Advisor for Air and Space Issues within the Secretary of the Air Force Directorate for Security and Special Programs, SAF/AAZ), vigorously promoted X-51 derivatives in discussions with Air Combat Command and AFRL. The author

proposed an X-51-follow-on experimental system, HOTFOOT (for Hypersonic Operational Test of Follow-On Optimized Technologies), which, if pursued, could have led to development of two follow-on “Gen 1” and “Gen 2” missiles called Surfer and Scorcher. AFRL has a deserved reputation for vigorous hypersonic advocacy, and out of the mutually beneficial and synergistic climate has sprung RIPTiDE. I acknowledge with gratitude information from Dr. Lewis.

43. A. Paull, H. Alesi, and S. Anderson, “HyShot flight Program and How It Was Developed,” AIAA 02-4939, September 2002.

44. For example, readers are invited to access the NASA Technical Report Server at http://ntrs.nasa.gov/search.jsp and type in the keyword “hypersonic,” which opens access to almost 5,000 publicly available technical reports covering aerodynamics, structures, propulsion, materials, fuels, controls, design, computational analysis, test methodologies, lessons learned, etc.

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