Hypersonic Weapons Come of Age

By Mark J. Lewis

Will the US—or some other nation—be first to field these game-changing weapons?

An experimental hypersonic scramjet—aboard a sounding rocket—launches at the Pacific Missile Range Facility in Hawaii. Hypersonic weapons could compress the shooter-to-target timeline.

Air Force Research Laboratory photo

"17 September 2035 … The enemy did not detect the approaching hypersonic missiles until it was too late. … The enemy [integrated air defense system], saturated by the formation of decoy-jammers, had missed the one fleeting opportunity to target the high-speed munitions. Now in the terminal phase, the hypersonic missiles streaked into their targets."

The vignette above was taken from "Air Force Future Operating Concept: A View of the Air Force in 2035," a paper released by USAF at AFA's 2015 Air & Space Conference. Endorsed by both the Secretary of the Air Force and the Chief of Staff, the document presents a view of the service two decades hence. Though fictional for now, the vignette captures the great promise of nearly unstoppable high-speed weapons that could strike quickly at targets deep within an enemy's territory—weapons that today are rapidly accelerating toward reality.

This most recent document is just one in a series of USAF publications that have highlighted the utility of such high-speed weapons. A year earlier, USAF released "America's Air Force: A Call to the Future." In it, Chief of Staff Gen. Mark A. Welsh III urged the service to "continue to adapt and respond faster than our potential adversaries." Hypersonics was one of five key game-changing technologies the report identified, the others being nanotechnology, unmanned systems, autonomy, and directed energy.

Hypersonics generally refers to flight in excess of about five times the speed of sound, or above Mach 5. "A Call to the Future" noted that the "leap" to hypersonics will have a revolutionary effect on how USAF approaches its core missions, "from investments, to force posture, to tactics, techniques, and procedures." The paper said that the catchphrase "speed is life" is often true, and while "we may not always desire to operate at the fastest possible speed, the ability to do so creates a significant advantage."

Coincident with the release of "A Call to the Future," the Air Force Scientific Advisory Board completed a classified technology readiness study.

Former Air Force Historian Richard P. Hallion and retired Maj. Gen. Curtis M.

Bedke have also recently written about the utility of hypersonic weapons for AFA's Mitchell Institute for Aerospace Studies, in "Hypersonic Weapons and US National Security: A 21st Century Breakthrough." Hallion and Bedke highlighted the main advantage of this technology: that it can counter the so-called "tyranny of distance" associated with global reach. Such weapons would compress the shooter-to-target timeline, allowing for the prosecution of fleeting targets or providing more decision time before engagement. Hypersonic weapons, they wrote, would enhance joint operations, would be able to address a variety of targets, and would be deployable from a variety of platforms.

To accomplish this, Hallion and Bedke call for a national strategy that includes continued research and development, maintenance, and support for testing infrastructure. They also call for new investments in a future workforce.

The credibility of these various reports has been enhanced by recent successful flight efforts, especially the Air Force's X-51 program and the series of Hypersonic International Flight Research Experimentation (HIFiRE) trials conducted jointly with Australia. Taken with other well-publicized activities around the world, there is a renewed sense that hypersonic weapons are not only plausible but seemingly inevitable.

A B-52 carries the X-51 under its wing before its first flight in May 2010 at Edwards AFB, Calif. On the program's last flight three years later, the Waverider reached Mach 5.1, demonstrating the feasibility of air-breathing scramjet propulsion.

PROGRESS AND SETBACKS

The idea of a hypersonic weapon is not new. In fact, high-speed military systems have been a dream of technologists since at least the 1930s, when German engineer Eugen Sänger and his wife, Irene Bredt, did studies of vehicle concepts capable of ocean-spanning flights using skipping trajectories. The earliest man-made self-propelled hypersonic object was the two-stage American "Bumper" rocket, assembled from a captured German V-2 with a US Army WAC Corporal sounding rocket as an upper stage, which reached a speed of 2.3 kilometers per second (5,145 mph) on Feb. 24, 1949.

After those early steps came some more successes but also a long list of failed hypersonic programs and unrealized promises.

In the early 1960s, USAF began a project to build a hypersonic vehicle called the Aerospace Plane, canceled after the Air Force Scientific Advisory Board identified "many clearly infeasible factors" in the program.

The roster of abandoned hypersonic programs has grown since, including the 1980s X-30 National Aerospace Plane (NASP), the Navy's HyFly test program (discontinued after three failed tests), and the Defense Advanced Research Project Agency's HTV-2 hypersonic glider (canceled after two flights).

Even ongoing hypersonic efforts have had setbacks. The August 2015 HIFiRE flight test of a new hypersonic engine design suffered a frustrating loss of flight telemetry. Similarly, the US Army's Advanced Hypersonic Weapon, an unpowered hypersonic glide vehicle, had a successful flight in the Pacific Missile Range Facility in 2011, followed by a launch failure three years later.

Some of these setbacks, such as HyFly and the AHW, had nothing to do with the soundness of the hypersonic technologies being studied. Other failures, such as the DARPA flights, yielded increased understanding of aerodynamics and materials. Despite this, even some enthusiastic supporters of high-speed technology have quipped, "Hypersonics is the future—and always will be."

That view is now changing, due not only to tangible flight successes and concrete investments, but also to a shift of ambitions from expensive vehicle concepts to more practical military systems. A key milestone among these was the Air Force's X-51 program, led by the Air Force Research Laboratory in concert with the Air Force Test Center and industry partners. The first X-51 vehicle flew on May 26, 2010, and the last on May 1, 2013. Though neither the second nor third flights achieved program objectives, the first achieved nearly all of its objectives and the fourth flight was a complete success.

Launched from beneath the wing of a B-52 bomber, each Boeing-built X-51 was initially powered by a solid rocket motor derived from an Army Tactical Missile System (ATACMS) booster, intended to carry the test vehicle to 4.8 times the speed of sound, then separate and allow the X-51's main engine to take over. On its last flight, the X-51's hypersonic "scramjet" engine, built by Rocketdyne, accelerated the craft for 210 seconds, to a final speed of Mach 5.1 before its fuel was exhausted and the vehicle coasted to a planned crash into the Pacific.

In addition to proving the propulsion technology, the X-51 flights represented a triumph of Air Force-led research and design where numerical simulation, using the latest in computational codes for design and analysis, was combined with state-of-the-art ground test and real-world flight experience.

RAMJETS TO SCRAMJETS

Hypersonic scramjets were almost six decades in the making. In the late 1950s, Richard J. Weber and John S. MacKay wrote their landmark National Advisory Committee for Aeronautics (NACA) Technical Note 4386 exploring a concept for a new type of aircraft engine—one that could burn fuel in air moving at high Mach numbers. Working at the Lewis Flight Propulsion Laboratory (the precursor to today's NASA John H. Glenn Research Center at Lewis Field in Cleveland) Weber and MacKay looked at ways to increase the flight speed of a conventional ramjet engine. Though the NACA researchers didn't know it at the time, engineers in the Soviet Union were working on the same problems.

entering the engine, the air decelerates to low relative velocity, resulting in a corresponding rise in pressure and temperature. That hot compressed air moves into a combustor where fuel is injected and mixed. The combination ignites and adds heat energy, resulting in hot gas accelerating through a nozzle to create net thrust. Because the air is compressed by the ramming effect of the engine's motion, a ramjet doesn't require a mechanical compressor ahead of the combustor. Without a compressor, there's no need for turbines, so a ramjet has no primary moving parts.

Because of their dependence on their own motion through the air, ramjets work poorly at low speeds and can't produce any thrust at all when standing

USAF photo by Greg L. Davis

The scramjets that powered the X-51 represent an attractive alternative to rockets, the current propulsion choice for air-to-air or intercontinental missiles. Rockets produce high thrust and can fly outside the atmosphere, but because they must carry all of their fuel and oxidizer with them, they're ill-suited for high-speed cruise within the atmosphere. For long-range, high-speed cruise within the atmosphere, it makes more sense that the engine be an "air-breather"—gathering oxygen as it flies to burn with the carried fuel. It's the same principle used by all modern jet engines, which gather oxygen through the inlet.

A ramjet is the mechanically simplest type of jet engine. The development of the modern ramjet dates from the 1920s, though the basic concept was proposed over 100 years ago by the Frenchman René Lorin. By the late 1940s prototype ramjet engines were being tested and flown in Europe and the United States and were later used to power the Soviet Union's Burya cruise missile, the US Navy's Gorgon IV missile, and USAF's Bomarc interceptor.

The ramjet derives its name from the basic operating principle where air is forced into an inlet by the engine's own motion through the air. On

still. As a result, ramjets are generally reserved for supersonic flight, beyond Mach 1, the speed of sound. That means they must be accelerated to operational speed by another kind of engine, such as a rocket motor (in the case of the Bomarc missile) or a gas turbine engine.

Ramjets also perform poorly at very *high* speeds, above about Mach 4, although the exact limits depend on a number of factors. There are two primary reasons for this performance loss. First, any craft flying faster than the speed of sound generates shock waves—sudden increases in local temperature and pressure that create the well-known sonic boom. Shock waves waste energy, adding drag on an airplane but also causing a loss of energy in the ramjet inlet that ultimately reduces thrust. This energy loss becomes increasingly severe at higher speeds.

Another problem has to do with the temperatures associated with the ram compression effect. At extremely high speeds the temperature of the air as it slows down in the inlet can be so high that it's above the temperature at which fuel burns. When that happens, combustion stops and there can be no energy addition inside the engine—hence, no thrust.

Weber and MacKay asked a simple question: What would happen if the air that enters a ramjet at high Mach number doesn't slow down much but instead continues to move at high speeds through the entire engine flow path? By keeping the air moving at supersonic speeds, inside the engine, thrust could be produced all the way up the Mach scale. The resulting engine type has the appropriate name of supersonic combustion ramjet, or "scramjet."

Such an engine makes a whole new realm of atmospheric flight possible, with a corresponding list of possible missions and vehicle applications. However, actually building a practical scramjet proved quite difficult. For example, trying to burn fuel in a supersonic stream has been likened to lighting a match in a hurricane. There is precious little time to inject the fuel, mix it with the air, and burn it to completion.

In a reasonably sized scramjet, the air entering the front of the engine would spend only one or two thousandths of a second in the combustor before exiting through the nozzle. Even if combustion were possible, the very process of adding heat to fast-moving air results in significant energy losses as compared to ramjets.

Despite efforts beginning in the 1960s, including the construction of various scramjet test articles (notably, the pioneering work of Antonio Ferri), these challenges and others delayed the practical development of a scramjet-powered vehicle for more than 45 years. The HyShot research team at Australia's University of Queensland flew what is generally credited as the first scramjet in July 2002 on the nose of a sounding rocket, though its thrust was less than the overall drag. HyShot was soon followed by two successful flights of NASA's highly sophisticated X-43 vehicle, proving once and for all that scramjet thrust could be greater than vehicle drag.

A hypersonic cruise missile engine used in a ground test as part of HyFly.

Photo courtesy of DARPA/ONR/NASA Langley Research Center

Though impressive accomplishments and important steps along the way, both the Queensland work and NASA's X-43 were powered by scramjets that burned hydrogen and could only operate for a few seconds.

The Air Force's X-51 took scramjets further by burning a more easily handled jet fuel for almost 3.5 minutes in flight, albeit at a more moderate flight speed. It was the defining breakthrough that may lead the way to practical hypersonic missiles.

USAF continues to invest in hypersonics, including activities at the Air

Force Research Laboratory and at wind tunnel facilities at the Arnold Engineering Development Complex at Arnold AFB, Tenn. There is significant work being done—on increased thrust, better mixing, ignition, and fuels—to explore ways to improve scramjet performance. In combination with industry partners, USAF researchers are also looking to combine scramjets with other engine types for an expanded flight envelope.

Lessons learned on the X-51 are being applied to solving operational and scaling issues. At the same time, the Air Force Office of Scientific Research sponsors ongoing university programs to expand the fundamental understanding of high-speed aerodynamics, develop new modeling and simulation techniques, and invent new high-temperature materials and instrumentation.

Working with the Department of Defense Test Resource Management Center and AEDC, the Office of Scientific Research has also been developing programs that allow undergraduate and graduate students to participate in hypersonic testing, with the goal of replenishing the workforce that specializes in hypersonics.

The Air Force is partnering with NASA, too. Historically, the civilian space agency has been an important contributor and developed many aspects of scramjet propulsion. NASA engineers played a key role in programs such as X-51, HIFiRE, and took the lead in X-43 and the HyBoLt—Hypersonic Boundary Layer Transition—aerodynamics experiment. Although hypersonics funding at NASA has been decreasing in the last few years, the agency recently committed to expanding its research efforts for fundamental science and to providing ongoing test and modeling support.

Despite these successes, there's a long way to go to achieving fully operational weapons systems. Advanced guidance systems, sensors, and warheads will be required to make practical weapons. Figuring out how to integrate these weapons with existing or future platforms will be a challenge.

Two DARPA programs, funded in part with USAF dollars, are attempting to demonstrate technologies for a realistic weapon, but critics note that at their current pace the first planned flights won't occur until the end of this decade, years after the X-51.

Of particular note is the DARPA Tactical Boost Glide program. Instead of using scramjets, TBG is an unpowered hypersonic glider that will be rocket-boosted to a high Mach number. TBG builds on lessons learned from DARPA's HTV-2 and may offer an attractive alternative concept for a hypersonic missile.

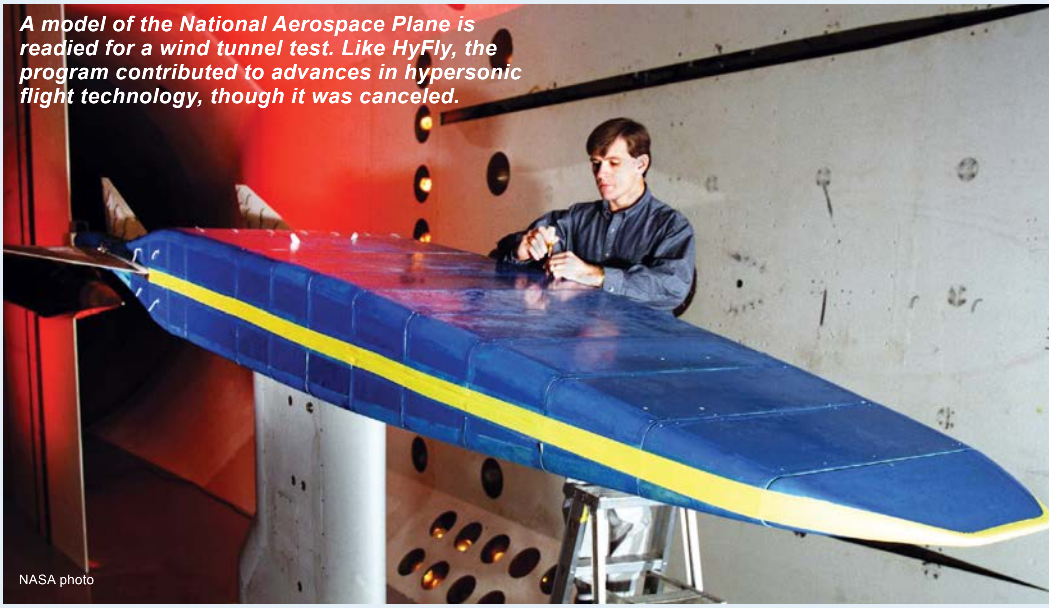
The US is hardly alone in developing hypersonic systems. Russia, India, and China have been active in the field. China's People's Liberation Army has boasted of a rocket-powered hypersonic missile apparently designed to attack aircraft carriers. Russian leaders, including Deputy Prime Minister Dmitry Rogozin, have voiced strong support for continued hypersonics development, and Russia has announced a joint program with India to develop a hypersonic successor to the BrahMos supersonic cruise missile.

The push for practical hypersonic weapons has been construed by some as a new arms race, focused on speed. As Hallion and Bedke have warned, hypersonic weapon technology is "ripe for exploitation as a theater and global strike game changer" but it's not yet clear "whether America will own that advantage first." Though the US is investing in hypersonics and their maturation, "it is not on a guaranteed path to near-term success." As the authors noted, there's still no firm national commitment to a disciplined plan tackling the remaining hypersonic challenges, let alone a plan to develop and acquire high-speed weapons even if planned demonstrations are successful.

The US has clearly established itself as the early leader in the hypersonics field, but it remains to be seen whether the first practical hypersonic weapons will bear the markings of the US or the insignia of some other nation. ✪

US Air Force Flight Test Center Public Affairs photo

The X-51 at Edwards before its first flight. The idea of hypersonic weapons goes back to at least the 1930s.



A model of the National Aerospace Plane is readied for a wind tunnel test. Like HyFly, the program contributed to advances in hypersonic flight technology, though it was canceled.

NASA photo

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