Hypersonics: Past, Present, and Potential Future

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ABSTRACT

Hypersonic technologies have been investigated for more than six decades, and important operational capabilities exist in the form of reentry, space lift, and interceptor systems. Today, new classes of hypersonic weapons capabilities are emerging throughout the world. This article provides a brief overview of the history, today's state of the art, and the future potential for hypersonics.

THE BASICS

Although hypersonic technologies and systems have existed for more than 60 years, national and international interest in them has varied. At times these technologies are viewed as critically important, and at other times they receive little to no interest beyond a small research community. Today, in 2021, hypersonics receive tremendous attention as geopolitical forces return nations to a great-power competition.[1] This article briefly summarizes APL's contributions to the field, assesses the current state of technology, and makes some projections for the future of hypersonics at the time of APL's centennial celebration.

It is important to review what "hypersonics" entails. Both *super*- and *hyper*-, derived from root words in Latin and Greek, respectively, mean "more than," so supersonic and hypersonic mean more than sonic, another way of saying faster than the speed of sound. Using the similarity parameter Mach number, defined as the ratio of speed to the local sound speed, supersonic flight refers to vehicles flying faster than Mach 1. For supersonic flight, aerodynamic phenomena are strongly impacted by Mach number.

As flight speeds and associated energy levels increase, additional physical phenomena become important, and the term *hypersonics* was introduced to refer to these speeds. Regarding aerodynamics, important energy exchange mechanisms in the fluid occur due to excitation of vibration and electronic energy levels, dissociation of air molecules and their attendant chemical reactions, and ionization of the gas to create plasma. At sufficiently high speeds and altitudes, the boundary layer (i.e., the gas layer near any solid surface where dissipative friction and heat transfer dominate) can grow quickly enough to have a significant impact on the entire flowfield. As these phenomena become more important, Mach number loses much of its significance as the aerodynamic phenomena become much more complex.

While historically the term *hypersonics* was used to describe conditions where these energy exchange mechanisms become important to aerodynamics, today a much simpler definition is used, where a hypersonic flight is defined as a vehicle flying faster than Mach 5. Also, the term *hypersonics* is now used to describe all aspects of vehicles flying at these speeds. Thus, the term *hypersonic materials* refers to materials with potential application to hypersonic vehicles. Among others, important technologies include aerodynamics; propulsion; high-temperature materials and structures; thermal protection systems; and guidance, navigation, and control.

HISTORICAL PERSPECTIVE AND EMERGING NEW CAPABILITIES

Hypersonics has been investigated for many decades, and both experimental and operational systems have been developed. Today, new capabilities are emerging (Figure 1). Any ballistic missile with a range greater than 400 km operates at hypersonic speeds, so hypersonic systems have flown since the use of V-2 rockets during World War II.

It is useful to put today's hypersonics activities in the context of engineering advancements that have already occurred. Some examples include the following:

- The three X-15 research aircraft flew 199 flights between 1959 and 1968 at speeds up to 2 km/s, providing great knowledge of hypersonic aerodynamics, thermal protection, and reusable aircraft structures.
- The Apollo reentry capsules, 19 of which launched between 1966 and 1975, achieved reentry speeds of 11 km/s, demonstrating an ability to withstand very high aerothermal loads.
- The Space Shuttle program, which built five reusable vehicles, launched a total of 135 times, achieved reentry speeds of 8 km/s, demonstrating knowledge of hypersonic aerodynamics and reusable thermal protection.
- Many of today's interceptor missiles fly in the hypersonic domain at 2–5 km/s, demonstrating advanced guidance, navigation, and control algorithms.
- The SpaceX Falcon 9 launch system stage separation routinely occurs at ~2 km/s, with the recovery of the first stage demonstrating routine reusable hypersonic flight.

Today, new classes of hypersonic capabilities are being developed and explored—capabilities associated with hypersonic cruise missiles, boost-glide systems, interceptor missiles, reusable aircraft, space launch vehicles, and gun-launched projectiles. APL has investigated the underlying technologies enabling these new capabilities for more than six decades.

APL has made significant contributions to the development of the scramjet engine, which is an essential element of most propelled hypersonic systems. The scramjet engine is conceptually a simple fixed-geometry

Figure 1. Examples of past, current, and potential hypersonic capabilities. (a) Apollo reentry capsule and ballistic reentry vehicles. (b) X-15 reusable research aircraft. (c) X-37B reusable spaceplane. (d) Space Shuttle and Falcon 9 first stage. (e) Standard Missile-3 interceptor missile. (f) HyFLY, X-51A, and Hypersonic Air-breathing Weapon Concept (HAWC). (g) Tactical Boost Glide concept vehicles and DF-17 missiles. (h) X-43A, Skylon, and Falcon concepts. (i) Sänger and National AeroSpace Plane Program (NASP) concepts. (j) Electromagnetically launched railgun projectile. (See acknowledgments for image credits.)

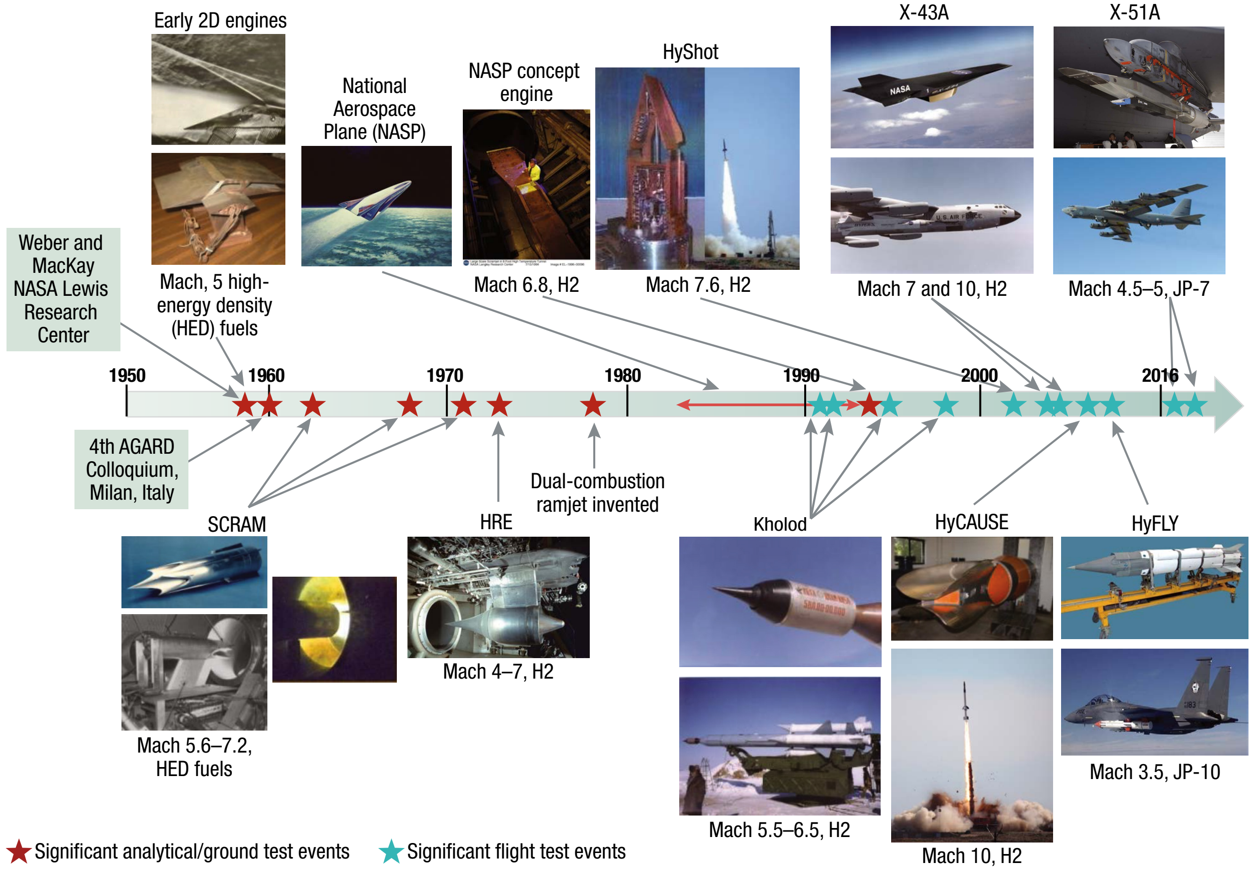

Figure 2. Timeline showing major milestones for scramjet development. Red stars indicate significant analytical and ground test milestones. Blue stars indicate significant flight test milestones. The top portion shows the development of planer engine technology. The lower portion shows axisymmetric and 3-D configurations. (See acknowledgments for image credits.)

device that operates at hypersonic speeds by capturing and compressing airflow for processing in a combustor, where fuel is injected and burned, before the combustion products are exhausted through a nozzle.[2] Detailed descriptions of APL's contributions to scramjets are provided by Gilreath[3] and Van Wie.[4]

Milestones from scramjet engine development are shown in Figure 2. The first analytical descriptions of supersonic combustion systems were provided by Weber and MacKay,[5] before a complete community presentation of concepts was provided at the 4th AGARD Colloquium in 1960, including a paper by Dugger.[6] Billig conducted many of the first demonstrations of scramjet combustion in primitive two-dimensional engines as part of APL's long history of contributions in scramjet development that included the SCRAM missile concept,[7] NASP,[8] dual-combustor ramjet,[9] HyCAUSE (Hypersonic Collaborative Australia/United States Experiment),[10] and HyFLY.[11] Additional noteworthy milestones that occurred in parallel include the ground test of the NASA Hypersonic Research Engine (HRE),[12] the first flight test of a hydrogen-fueled scramjet on the Russian Kholod vehicle,[13] the Australian HyShot flight of a Mach 7.6 supersonic combustion experiment,[14] the NASA X-43A flight demonstration of a scaled aircraft configuration,[15] and the US Air Force X-51A flight demonstration.[16]

Frederick Billig is now recognized as a pioneer in the development of the scramjet engine. He championed APL's efforts for more than 40 years while continually leading the nation forward. Billig retired from APL in 1996 but continued consulting with the hypersonic community until he died in 2006. A tribute to the magnitude of his and APL's contributions is shown on the X-51A flight vehicle (Figure 3). The X-51A vehicle contained a fully integrated hydrocarbon-fueled scramjet engine designed to operate at speeds above Mach 6. May 26, 2010, marks the date of the first X-51A flight. Just before the flight, the X-51A program manager, Charles Brink, wrote the words seen scribbled down the side of the scramjet engine in the photo: "THIS ONE'S FOR FRED BILLIG."

STATE OF THE ART IN HYPERSONICS

As of this writing in 2021, we find hypersonic systems in routine use in many fields, but we are also seeing the emergence of entirely new classes of hypersonic systems,

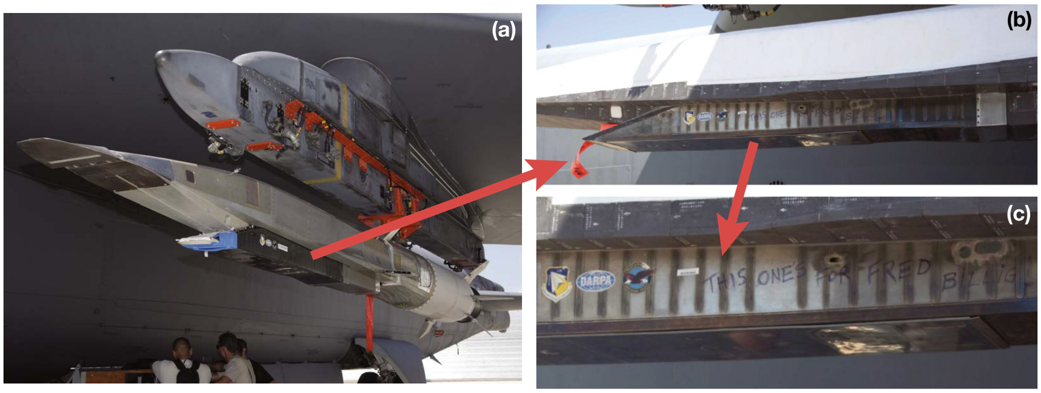

Figure 3. X-51A tribute to Dr. Frederick Billig, a pioneer in the development of the scramjet engine. (a) X-51A first flight vehicle mounted on the pylon of the B-52 test aircraft. (b) Close-up view of the hydrocarbon-fuel-cooled metallic scramjet engine. (c) Further close-up view of the scramjet engine with the words "THIS ONE'S FOR FRED BILLIG" written on it. (See acknowledgments for image credits.)

principally in the realm of offensive hypersonic strike systems. When discussing these capabilities, it is useful to categorize the weapons by range using the terminology developed for ballistic missiles: short range (<1,000 km), medium range (1,000–3,000 km), intermediate range (3,000–5,500 km) and intercontinental (>5,500 km).

These new weapon systems can also be broadly classified into powered cruise missiles and hypersonic boost-glide systems. Powered cruise missiles are multistage vehicles that use solid rocket propulsion to accelerate from launch to a speed enabling a scramjet-powered sustainer stage to take over powering the remaining portion of a mission. Hypersonic boost-glide systems operate using multiple stages typically powered by solid rockets to accelerate a glide vehicle to hypersonic speeds; the vehicle then glides unpowered when completing its mission.

Hypersonic strike systems can be discussed in terms of their inherent energy state, as illustrated in Figure 4, where the system's specific kinetic energy at the end of boost is shown as a function of maximum flight speed. For boost-glide systems, the maximum missile range is principally influenced by the lift-to-drag ratio of the glide vehicle and the maximum end-of-boost speed. For achievable ranges of vehicle lift-to-drag ratio, range classes of boost-glide vehicles can be approximated by their end-of-boost speed. Further, if the weapon is assumed to impact the target at a nominal speed of 1 km/s, the energy dissipated between the end-of-boost state and ground impact is known. It is this energy that is available for achieving range extension and maneuvers.

A principal challenge with the development of hypersonic boost-glide systems is accommodating the energy dissipation during flight. Since the glide vehicles must be slender to achieve their needed high lift-to-drag ratio for efficient long-range flight, much of the energy dissipation occurs through aerodynamic friction, which translates to vehicle heating. This situation can be contrasted to Apollo-like blunt capsules, where much of the energy dissipation during reentry goes directly into air heating. All aerodynamic heating must then be accommodated through re-radiation from high-temperature surfaces, absorbed into an ablative aeroshell, or transferred to the vehicle's internal structure. The development of a thermal protection system is critical for a robust system design emphasizing sharp, low-drag leading edges; affordable, lightweight, high-temperature carbon-carbon or ceramic-matrix composite aeroshells; and volume-efficient internal insulation. As shown, the challenges associated with this energy management double when going from a medium-range weapon to an intermediate-range weapon and increase more than 50% again for an intercontinental-range weapon.

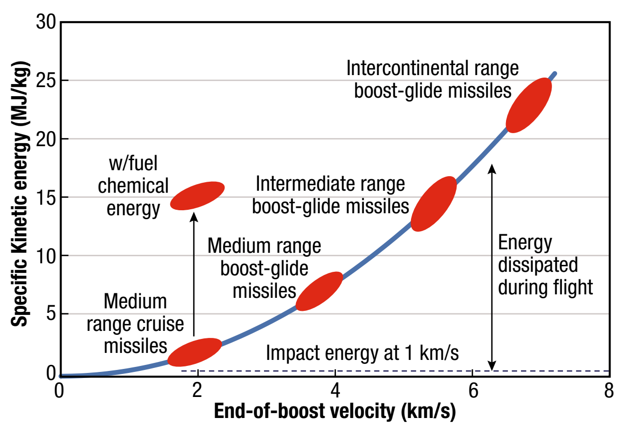

Figure 4. The specific kinetic energy state of hypersonic weapons at the end-of-boost condition. The graph shows the impact of increasing energy state with increasing range, increasing needed energy dissipation with speed and range (assuming terminal impact at 1 km/s), and chemical energy potential for powered cruise missiles (assuming 10% fuel fraction for cruise vehicle). Note: Specific potential energy is neglected in this figure; it would add 0.3–0.5 MJ/Kg to the available energy at the end-of-boost condition.

As illustrated in Figure 4, hypersonic cruise missiles typically operate near 2 km/s, providing a medium-range capability. For a powered cruise missile, the energy state at the end of boost also needs to include the chemical energy of fuel carried onboard. As indicated, with the assumption of a 10% onboard fuel fraction, the energy state of a cruise missile can approach that of an intermediate-range system while operating at a much slower speed. This has important implications for thermal management, seeker integration, and overall weapon system size.

A principal technical challenge with the powered cruise missile is the development of the scramjet engine and its associated thermal management. Since scramjets involve ducted flow, radiative cooling from internal surfaces is impossible, resulting in a more complex thermal management problem than external surfaces. Today in 2021, scramjet engines are highly developed for Mach 6 class vehicles and are being developed for applications in many countries, although dates for initial operating capabilities are not openly published.

According to the Congressional Research Service,[17] hypersonic strike weapons are in development for applications from short to intercontinental ranges. Reportedly, Russia has fielded an intercontinental-range system called Avangard, as well as Kinzhal, which is an air-launched ballistic missile. Russia is also developing Tsirkon, a ship-launched hypersonic system capable of attacking land and naval targets. China has publicly displayed its medium-range DF-17 hypersonic boost-glide system, and reports of significant testing of its DF-ZF are widespread.

In the United States, development is underway for medium- and intermediate-range hypersonic strike weapons.[17] These include the Conventional Prompt Strike (CPS), Long-Range Hypersonic Weapon (LRHW), AGM-183 Air-launched Rapid Response Weapon (ARRW), Tactical Boost Glide (TBG), and Hypersonic Air-breathing Weapon Concept (HAWC).

HYPERSONICS AT APL'S CENTENNIAL CELEBRATION

In 1959, Dugger[18] wrote, "Already the aircraft companies are looking forward to supersonic transports. Predictions of hypersonic airbreathing aircraft appear frequently, and ramjet propulsion will undoubtedly be used in such aircraft." The intervening 60 years did not lead to this envisioned future, so projecting a future for hypersonics is risky. Notwithstanding this risk and looking forward to APL's centennial celebration in 2042, it is worthwhile to express a vision for the future of this technology in which, likely, we are still much closer to its beginning than its end.

In the realm of hypersonic weapons, offensive weapons will likely continue development as an essential element in the great-power competition, providing rapid-response strike capabilities at standoff ranges. Technology advancements in aerodynamics, propulsion, materials, component miniaturization, sensors, and warheads will enable effective weapons at smaller and more affordable scales, leading to much larger inventories.

In parallel with the emergence of offensive strike systems, significant hypersonic defense capabilities are likely to emerge, with the United States leveraging the starting advantages of its global ballistic missile defensive systems. Initial integrated defense systems are likely to emerge, providing effective midcourse and terminal defense against hypersonic strikes. As time advances, affordability initiatives will likely result in smaller, more effective interceptors and fully integrated nonkinetic capabilities.

By 2042, conventional hypersonic strike weapons are expected to be widely proliferated throughout the world, with the continual development of new offensive and defensive capabilities providing a rich background for technology improvements in the areas of propulsion, materials, sensors, and autonomous operations of coordinating salvos of weapons. Although hypersonics will have widely proliferated, only the most advanced countries will have the ability to integrate offensive and defense capabilities at scale using the needed underlying

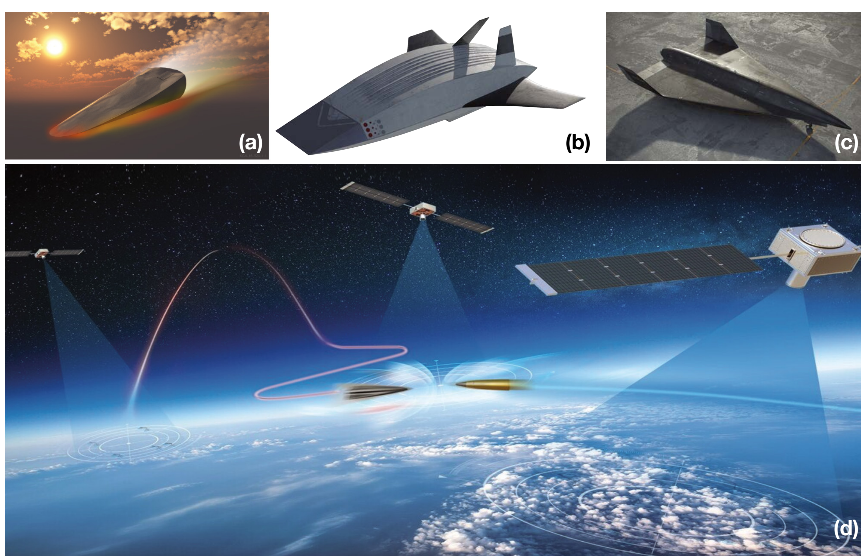

Figure 5. Future envisioned hypersonic capabilities. (a) Small, highly effective strike weapons. (b) Reusable point-to-point transportation or space-access system. (c) High-altitude, hypersonic unmanned aerial vehicles. (d) A large-scale, highly integrated battlespace with an evolving offensive–defense competition.

capabilities of distributed intelligence, surveillance, reconnaissance, and targeting and distributed command and control driven by autonomous decision aids. Thus, this future for hypersonic weapons is tied to the broadening trajectory for warfare where future conflict may occur with much faster timescales across theater and global battlespaces.

In parallel with the development of new military weapon capabilities, reusable hypersonic systems are also envisioned to emerge for both military and commercial applications, as illustrated in Figure 5.

As Dugger projected in 1959, reusable hypersonic aircraft are envisioned to be developed for routine flight at hypersonic speeds within the atmosphere as high-altitude, high-speed sensor platforms or point-to-point delivery systems. These vehicles will operate with high vehicle autonomy levels and will require advancements in today's ability to predict multidisciplinary interactions between aerodynamics, propulsion, structures, thermal management, and guidance and control. This coupling of technologies in vehicle design and operation will be strong for hypersonic flight vehicles, as contrasted with subsonic or supersonic aircraft, and will represent a critical challenge to be overcome.

Hypersonic technology also offers the potential for revolutionizing access to space. In 1964, Avery and Dugger[19] wrote:

> Chemical rockets have now advanced to the stage where the hard-fought battle for a few extra points in specific impulse become more and more expensive and show smaller relative returns. . . . Present and planned chemical rocket programs will provide propulsion Earth-to-Orbit propulsion requirements, as well as lower-stage requirements for direct-flight modes, for our space missions into the mid-1970s. However, the cost of developing these chemical systems is enormous and the projected cost of launching space missions escalates every year. This is causing rocket engineers and their government sponsors to search very hard for (a) practical schemes for recovery and reuse of launch systems, and (b) alternate, more economical propulsion system.

With the advantage of hindsight now in 2021, we now know the reusability attempts with the Space Shuttle advanced technologies but never realized the projected cost savings. Instead, it was the development of the SpaceX Falcon 9—using a hybrid launch system with a reusable first stage and expendable second stage—where the economic advantages of reusability and scaled production of propulsion systems were first realized.

Avery and Dugger's identification of the need for more efficient chemical propulsion systems remains today. Research continues for advances in novel and combined cycle propulsion for both hybrid and fully reusable launch systems, and scramjet engines often serve as a key element of these concepts. Airbreathing propulsion systems, with their 300–1,000% improvement in propulsion specific impulse performance compared with rockets, are projected to result in smaller launch systems that offer significant reliability and safety increases compared with rocket-propelled vehicles. These safety improvements will ultimately lead to launch vehicles operating from conventional spaceports in the continental United States, compared with the large coastal launch complexes used today.

SUMMARY

More than six decades of hypersonic history have resulted in important operational capabilities and a basis for developing new classes of hypersonic capabilities. Today, an international great-power competition is underway, with new classes of hypersonic strike weapons emerging. Defense capabilities to counter these offensive systems are in development, and it is projected that a continuous interplay of offensive and defensive capabilities will occur over the coming decades. In parallel with the development of weapons, the potential exists for development of both reusable hypersonic aircraft and fully reusable space-access vehicles. These new system capabilities will be driven by needed advancements in the underlying technologies of aerodynamics, propulsion, materials, thermal management, and guidance and control.

IMAGE CREDITS: **Figure 1**—(a) left, Smithsonian Institute; right, Wilson44691, via Wikimedia Commons. (b) NASA. (c) US Air Force. (d) left, NASA; right, SpaceX. (e) MDA. (f) left, Office of Naval Research (ONR); middle, US Air Force; right, DARPA. (g) left, DARPA; middle, DARPA; right, taken during a PLA parade. (h) left, NASA; middle, Reaction Engines Limited (REL); right, DARPA. (i) left, Palatinatian, via Wikimedia Commons; right, James Schultz, via Wikimedia Commons. (j) US Navy. **Figure 2** (clockwise from top left)—early 2D engines, APL. NASP, James Schultz, via Wikimedia Commons. NASP CDE, NASA Glenn Research Center. HyShot, University of Queensland. X-43A, NASA. X-51A, US Air Force. HyFly, ONR. HyCAUSE, DARPA. Kholod, AIAA. HRE, US National Archives. SCRAM, APL. **Figure 3**—(a) US Air Force. **Figure 4**—APL. **Figure 5**—APL.

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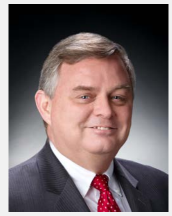

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