“Speeds Up to Orbital”: A History of the William H. Avery Advanced Technology Development Laboratory

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During its 45 years of service, scientists and engineers at APL’s William H. Avery Advanced Technology Development Laboratory pioneered the field of hypersonic air-breathing propulsion systems, based on their post-World War II work on Bumblebee and Talos. Research, development, testing, and evaluation (RDT&E) efforts within the Avery Laboratory resulted in the development of cutting-edge Supersonic Combustion Ramjet Missile (SCRAM) and dual-combustor ramjet (DCR) engine technologies that became the basis for the military’s latest ramjet-powered vehicles. However, because of constantly shifting military RDT&E priorities, the laboratory was susceptible to budgetary pressures that ultimately resulted in its closure.

“THE FLIGHT OF THE BUMBLEBEE”

On 13 June 1945, while the battle for Okinawa raged and Japanese kamikaze and *Baka* bomb attacks battered the U.S. 5th Fleet, some 300 scientists from APL hunkered under makeshift observation shacks along a deserted stretch of coastline near Asbury Park, New Jersey. The APL group nervously watched as technicians mounted on a wooden launching rack a crude stovepipe-shaped missile, made from a P-47 Thunderbolt’s 6-inch exhaust pipe (see pp. 22–28 in Ref. 1).

After the technicians completed the final preparation, the countdown began. At zero, the strange missile roared off the launcher in a swirling cloud of flame, sand, and dust visible 3 miles away. The missile’s back blast was so powerful that it demolished a protective wooden wall and sandbags erected behind the launch rack for additional safety. Cheers rose from the observation shacks. Radar tracked the missile 10,000 yards down the beach before it descended and splashed into Barnegut Bay. Quick calculations showed that the missile had zoomed by at a speed of 1750 feet per second, or almost 1200 miles per hour. This maiden supersonic flight of the nation’s first successful ramjet-powered missile set the stage for future research and development of airbreathing military propulsion systems at APL (Fig. 1).

THE SUNDAY SUN

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Navy Reveals Supersonic Engine Exceeding 1,400 Miles An Hour

Ram Jet Weighs Only 70 Pounds Has No Moving Parts And Develops 2,000 Horsepower

Figure 1. APL flight-tested its first supersonic ramjet-powered vehicle on 13 June 1945. Conceived to counter Axis air-launched guided missiles, the Navy continued to support it after World War II because of the potential Soviet naval threat, and it became the basis for all future ramjet propulsion research at APL.

That work would culminate some years later in the creation of the William H. Avery Advanced Technology Development Laboratory.

The Avery Laboratory was one of the country's premier airbreathing propulsion test facilities from its 1961 creation until its closure in 2006. Its research and testing led to the development of advanced propulsion systems such as Supersonic Combustion Ramjet Missile (SCRAM) and dual-combustor ramjet (DCR) engines, laying the groundwork for advances in high-Mach ramjet-based technology. The laboratory not only supported its various military sponsors through its hypervelocity and high-temperature testing capabilities but also played a key role in the development of APL's cutting-edge aeronautics program, making it one of the country's leading laboratories in the fields of aerophysics, chemistry, and thermodynamics. The Avery Laboratory also applied its unique electrical arc-generation capabilities to the development of arc-fault detection systems that made U.S. warships much safer at sea.

As the Avery Laboratory grappled with the difficult science associated with hypervelocity airbreathing propulsion and associated technologies, it also contended with difficult military procurement economics. The latter overshadowed its operations and affected its most well-known projects, leading to repeated cancellations and ultimately outright closure of the laboratory itself. The laboratory's story therefore is alternately one of success and frustration. However, in the greater military research and development arena, its successes outweighed its disappointments, and during its heyday it stood as one of the country's dynamic contributors to the science of hypersonic propulsion.

THE DEVELOPMENT OF SUPERSONIC RAMJET MISSILES

The roots of the Avery Laboratory extend back to the latter half of World War II, when the U.S. Navy grew increasingly concerned with the Axis Powers' technological successes in air-launched guided missiles. Germany had already successfully deployed Henschel Hs 293 and FRITZ-X glide bombs in 1943, and the Japanese were then developing piloted, rocket-powered *Baka* bombs, which first struck the U.S. 5th Fleet off Okinawa in April 1945. Earlier, APL had developed the proximity fuze for the Navy, resulting in a major increase in the success of anti-aircraft kills in the Pacific. Nonetheless, the Navy's advanced anti-aircraft fire could not reliably engage the high-speed incoming missiles or their mother aircraft (see pp. 8–9 in Ref. 2).

So in July 1944, the Navy's Bureau of Ordnance again turned to APL, based on its growing reputation, to propose possible countermeasures against future long-range anti-ship missiles. The Avery Laboratory reported back in November that a supersonic, rocket-launched, ramjet-propelled, radar-guided surface-to-air missile might solve the Navy's problem. In January 1945, the Bureau of Ordnance tasked the laboratory to undertake a comprehensive, open-ended research, development, testing, and evaluation (RDT&E) program leading to a "useful" missile with performance characteristics to be defined as the work progressed. Called "Task F," this was the beginning of APL's 60+-year involvement in ramjet development and testing.

A ramjet consisted of an open pipe through which air could pass.

When the engine approached supersonic speed, an internal diffuser would slow the compressed air and a hydrocarbon fuel would be injected into the air stream and ignited. The mixture would then burn in the cylindrical combustion chamber, and the hot gas would discharge out the pipe's rear, pushing the missile forward. Ramjets were attractive to the Navy because they had no moving parts except regulator valves. Additionally, the use of air as an oxidizer for fuel combustion meant that ramjet engines required only one-fifth of the consumable weight of liquid-fueled rockets, which needed to carry both their fuel and oxidizers. However, one drawback was that a ramjet had to be boosted to almost supersonic speed before it began operating properly, and building the necessary boosters was almost as difficult as building the ramjet itself (see pp. 23–24 in Ref. 1).

Ramjet technology had been studied as early as 1908, when the French inventor René Lorin patented the first design. Others, such as Benjamin Charles Carter (1926), Albert Fono (1928), and René Leduc (1934), had improved and expanded Lorin's work in later years. However, ramjet engines had never been demonstrated before at the Mach 1-plus speeds required for intercepting high-speed incoming missiles. So APL focused its early efforts exclusively on reaching this key milestone (see pp. 24–27 in Ref. 1).[3,4]

The director of APL, Dr. Merle A. Tuve, strongly backed Task F but was keenly aware of its technological challenges. He accordingly suggested that "Bumblebee" would be an appropriate codename for the program, based on a quotation he had seen. It read: "The bumblebee cannot fly. According to recognized aerotechnical tests, the bumblebee cannot fly because of the shape and weight of his body in relation to the total wing area. BUT, the bumblebee doesn't know this, so he goes ahead and flies anyway" (see pp. 8–9 in Ref. 2).

Needing new facilities to make this particular Bumblebee fly, APL leased an obsolete Navy radio school located approximately 1 mile north of the laboratory on Georgia Avenue in Silver Spring, Maryland. This site became known as the Forest Grove Station. APL also added an engine testing laboratory called the Burner Laboratory (Fig. 2). In addition, a supersonic wind tunnel was needed for the work.

Figure 2. In February 1945, APL built the Burner Laboratory at its Forest Grove Station in Silver Spring, Maryland. It closed in 1962 after APL's new Propulsion Research Laboratory opened.

Bumblebee project leaders secured an abandoned Coast Guard Station at Island Beach, New Jersey, and a nearby beach in which to design, build, and test missiles. Working out of an open barn, the new Bumblebee Launch Group first investigated the theoretical principles of supersonic ramjet propulsion and then built their prototype "flying stovepipe," often using sledge hammers and sheer brute force to muscle its components together. By May 1945, the group, led by Richard Roberts, Wilbur Goss, and Kirk Dahlstrom, had achieved sustained ramjet thrust for the first time and had confirmed Lorin's early theories. Two weeks later, in June, the group launched the first missile at the Island Beach site. The test was a tremendous success, and APL had proven that a supersonic ramjet engine was indeed a practical concept (see pp. 26–27 in Ref. 1).

However, the war ended before the Bumblebee program entered its next design phase (called Cobra because of that variant's flared neck), which provided more room for telemetry equipment. Still, the Navy remained interested in supersonic ramjet technology because the Soviets were known to be transporting captured German missile components and scientists back to the U.S.S.R. for exploitation. With the new Soviet threat looming on the horizon, the Navy authorized the Bumblebee Launch Group to continue developing its supersonic ramjet-powered anti-aircraft missile, just in case the Soviets managed to build viable anti-ship missiles in the future.

In 1948, Dr. William H. Avery became the new supervisor of the Bumblebee Launch Group. Born in Fort Collins, Colorado, in 1912, Avery studied chemistry at Pomona College, earned advanced degrees in physical chemistry at Harvard in the late 1930s, and went to work for the Shell Oil Company. Avery's personality—he was a devotee of the arts, loved fine food and his family, and was honest to a fault—complemented his brilliance as a chemist and helped propel his rise within the scientific profession. Vannevar Bush brought Avery to the National Defense Research Committee in 1942 because of his expertise in fuels. There, Avery became an assistant to Dr. Ralph E. Gibson, the vice chairman of the National Defense Research Committee's Section H, which was developing solid-propellant-fueled rockets. While conducting tests at the Naval Powder Factory at Indian Head, Maryland, and at the Allegany Ballistic Laboratory near Cumberland, Maryland, Avery played a leading role in establishing the principles for making solid-propellant rockets more predictable and reliable.[5]

After the war, the Truman administration disbanded the National Defense Research Committee and turned its Allegany Ballistic Laboratory over to the U.S. Navy. Avery returned to the private sector to work for the Arthur D. Little Company but quickly grew dissatisfied. In 1946, APL recruited him to join his former National Defense Research Committee colleagues on the Bumblebee team (see pp. 37–38 and 59–60 in Ref. 1).[5]

As Launch Group supervisor, Avery supervised the design and test of two new Mach 2.4 ramjet missiles in the late 1940s. Avery's team also began working on what would ultimately become, after years of experimentation at the Ordnance Aerophysics Laboratory in Daingerfield, Texas, the U.S. Navy's Talos ramjet-powered surface-to-air missile (Fig. 3). Talos, in turn, led to APL's development of a higher-speed, long-range, ramjet-powered missile. Initially called Super Talos but renamed Typhon-LR, the long-range missile was smaller than Talos but had an increased range of 200 nautical miles and could fly at Mach 4. APL successfully tested prototype Typhon-LRs between March 1961 and September 1963, but the Navy cancelled the program in 1965 because of long-range targeting and tracking problems and the high costs of the missile's radar and fire control systems.[6–10]

Figure 3. First deployed to the fleet in 1955, the U.S. Navy's supersonic Talos surface-to-air missile was the operational end result of the Bumblebee program.

Concurrent with Talos, the Navy also asked APL to explore the potential for a Mach 3 intercontinental ramjet cruise missile capable of carrying a nuclear warhead 2000 nautical miles. The resulting design, called Triton, consisted of a bat-winged fuselage with two external ramjets slung underneath. Avery's Bumblebee team carried out numerous component tests for Triton's ramjet propulsion system before the Navy cancelled the missile in September 1957 in favor of Polaris. This choice also foreshadowed an often-repeated theme, where rockets were chosen over airbreathing propulsion systems for many weapon and aerospace systems. However, the Triton ramjet work would later pay dividends in the incremental ramjet technology advances of the 1960s and 1970s, particularly with SCRAM and DCR.

In 1956, Avery started APL's hypersonics program within the Bumblebee Group. Others had performed research into supersonic combustion before, but the phenomenon remained poorly understood. Avery was intrigued, particularly after his colleague James Keirsey, who had come to APL as a ramjet expert from the Navy's Ordnance Aerophysics Laboratory in 1951, did some preliminary calculations on potential hypersonic inlet performance that looked promising. So Avery organized a dedicated Hypersonic Propulsion Group in 1956 to begin RDT&E in the field. In January 1957, he hired Dr. Gordon Dugger, a chemical engineer and combustion specialist from the National Advisory Committee for Aeronautics' Lewis Flight Propulsion Research Laboratory in Cleveland, Ohio, and subsequently placed him in charge of the group.

A NEW PROPULSION RESEARCH LABORATORY

Ramjet experimental testing work had been carried out at APL's Burner Laboratory in Silver Spring. However, the site had been problematic from the outset. Late in 1945, the Burner Laboratory's neighbors began complaining about the loud noise emanating from the test sessions, and it had become a hot-button political issue. Consequently, APL and the Navy agreed to cease the laboratory's operations by the end of 1946. However, because the Burner Laboratory was critical to the Bumblebee program, APL bought some additional land in Prince George's County in anticipation of moving the laboratory there. The move fell through, however, after the owner of the Burner Laboratory site induced the Navy to renew its lease there and continue its operations at Forest Grove. So APL and the Navy remained at Forest Grove but constructed a soundproofing system that somewhat dampened the Burner Laboratory's noise (see pp. 23–24 in Ref. 2).

By the 1950s, ramjet missiles were using previously unavailable toxic, high-energy fuels. As a result, APL became concerned about the Burner Laboratory's hazards as new residences sprang up around the Silver Spring facility. In May 1953, Dr. Lowell Olsen from the Bumblebee Group proposed the construction of a new propulsion laboratory to Avery. Olsen and his colleagues argued that it had become too dangerous to use the new fuels in such a densely populated area. Avery supported the proposal.

Dr. Ralph Gibson, now director of APL, gave approval on 22 June 1955, to both move and modernize the Burner Laboratory. As a result, APL began making plans that summer to close the building on Georgia Avenue and relocate its equipment to its new Laurel campus in Howard County, which had opened in 1954. A new laboratory facility that could house the Burner Laboratory would be built on a 5-acre plot near the center of APL's 360-acre campus in a densely wooded area isolated from future residential encroachments. This was not only a much safer site, but its location would also keep Avery's hypersonic research staff and the new research facilities together on the laboratory's campus. Avery and Olsen estimated that the move would cost between $750,000 and $1,000,000 (see pp. 26–27 in Ref. 2).

The decision made, APL had to get the authorization and funding from Congress and the Navy. The Navy Bureau of Ordnance needed little convincing and agreed to support the plan. The bureau therefore requested $500,000 in the 1958 Public Works Authorization Bill, with the goal of beginning work on the new facility in 1957 and completing it by early 1958 (see pp. 26–27 in Ref. 2).

Congress hesitated. Not only did it dislike the price tag, but it also was concerned about a number of unresolved legal and policy questions about building a public facility on privately owned land. Undeterred, the Bureau of Ordnance kept the project on a high-priority track. In the fall of 1956, the Navy's Bureau of Yards and Docks hired the Blaw-Knox Company of Baltimore to provide a basis for a new line item in the next Military Construction Authorization Bill. The Bureau of Ordnance secured the backing of the Department of Defense as well as the Navy Department before submitting its new budget request for the newly projected cost of $1,452,000 (see pp. 26–27 in Ref. 2).

In late August 1957, Congress authorized the project but refused to fund it because military construction appropriations had been drastically curtailed. Then came the Sputnik launch in October 1957. In light of the apparent Soviet advances, both the Navy and APL hoped that Congress would provide the money in the Fiscal Year 1959 Appropriation Bill and hired the architectural firm McConathy, Hoffman, and Associates to prepare detailed engineering plans for the new laboratory site.

By November 1958, Congress still had not appropriated any money for transferring the Burner Laboratory to Howard County, citing the cost and APL's proposed 25-year lease. The Bureau of Ordnance nevertheless approved McConathy, Hoffman, and Associate's engineering study in April 1959 and made it the bureau's number one military construction project. The Bureau of Ordnance then asked the Chief of Naval Operations to reprogram money from other funded projects to build the new Burner Laboratory facilities. The Chief of Naval Operations, who rarely failed to support ship defense programs and had the money to spare, agreed to the request and sought permission from the House Appropriations Committee to transfer the necessary funds (see pp. 26–27 in Ref. 2).

APL's patience was wearing thin. Cost estimates for moving the Burner Laboratory to Howard County had soared to $4.6 million, and years had been lost in the budget battles. Current projections now pushed the relocation date back to 1962, a delay that would be disastrous from APL's perspective.

With Avery's blessing, Olsen and his colleague Howard F. "Bud" Kirk developed an alternative plan. They proposed leaving the Burner Laboratory where it was but then building a simple but adequate Hypersonic Propulsion Research Laboratory at APL's campus to handle the advanced RDT&E work that Forest Grove could no longer perform safely. The Burner Laboratory would be retained and used for low Mach experiments, but APL would relinquish it entirely once the new laboratory opened.

Olsen and Kirk proposed that the new laboratory would have an initial capacity for Mach 7 aerodynamic and propulsion experiments, with facilities to accommodate heaters and associated equipment to later extend the testing range up to Mach 10. They believed that the resulting facility would be adequate for the needs of the hypersonic program for many years to come and could begin operating by the fall of 1960. The cost would be $1,612,000 for first-stage construction, followed by an additional $1,013,000 for subsequent Mach 10 augmentation, approximately half the cost of the original plan. To pay for it, Olsen and Kirk wanted APL to contribute $300,000, while the Bureau of Ordnance would provide another $1,330,000.

On 19 May 1959, Gibson submitted Olsen and Kirk's proposal to the Bureau of Ordnance, which supported the plan and agreed to contribute its share of the money, subject to the approval of the Chief of Naval Material, the Navy Secretary, and the Defense Secretary. On 15 October, Gibson briefed APL's Trustees Executive Committee on the alternate plan and asked for both their authorization and the funds to build it. On 2 November, the Executive Committee approved the investment of $280,000 from university funds for the project. The Bureau of Ordnance, now reorganized into the Bureau of Naval Weapons as of 18 August 1959, reached a basic agreement with APL in late 1959 to help build the new propulsion laboratory. APL hoped that construction would begin in May 1960 and that the Hypersonic Propulsion Group could occupy the facility by February 1961.

APL hired the William T. Lyons Company of Baltimore in September 1960 to build the laboratory for $918,000. Soon afterward, the company's cranes and bulldozers began converting the 5 acres behind the main facility into the new Propulsion Research Laboratory. Midway through the project, however, the Lyons Company encountered financial difficulties and halted work, resulting in a significant delay. However, APL intervened and finished the job using its in-house maintenance personnel. The Propulsion Research Laboratory finally opened on 1 December 1961 (Fig. 4).[11–14]

APL had erected its new Propulsion Research Laboratory using inexpensive sheet metal "Butler" buildings rather than brick to save money, but it was superior to the old Burner Laboratory in every way. It included four test cells, each of which was built with 12-inch-thick reinforced concrete walls, along with lightweight doors and frangible roof safety panels, so that accidental fires or explosions could be safely isolated or redirected away from the main laboratory campus (see p. 566 in Ref. 15).[16]

Building on the Burner Laboratory's successful use of a small "blowdown" air supply system, in which energy and pressurized air were stored over a relatively long period of time and then discharged rapidly to produce required test conditions, the Propulsion Research Laboratory would operate a much more extensive blowdown system that would furnish optimum power for short periods of time. As Testing Operations Section chief Wallace Baker explained, "instead of pumping heated air through a test chamber and removing the exhaust gases with vacuum pumps continuously, as in earlier wind tunnels, we slowly accumulate high-pressure (up to 10,000 psi), heat (or electrical energy to produce heat at temperatures up to 8000°F), and steam to drive the vacuum system, and then discharge these energy sources rapidly to produce the required condition in the test chamber." This procedure was much more economical than a continuous run process and would enable testing at higher pressures and temperatures. Although the run times would be short, ranging from a few seconds to 5 minutes, they were acceptable considering the more advanced data-acquisition techniques used by military laboratories at that time. Olsen was especially pleased and said that "our operation is [now] capable of true simulation of flight environments up to a Mach number of 10, and it can simulate supersonic-combustion engine conditions by the 'connected-pipe method' for speeds up to orbital."

To generate the required 8000°F "stagnation temperatures," which hypersonic ramjets encountered between Mach 7 and Mach 10, Dr. Edgar A. Bunt supervised the design of special electric plasma arc jet heaters for the purpose. These heaters could deliver up to 8 million watts to energize the air over a period of 30 seconds or longer. To power the arc heaters, APL had acquired over 1200 surplus submarine batteries from the Navy. Capable of generating 2000 V and 30,000 A, these batteries had a maximum power output of 15 million watts and were housed inside a special "Battery Building" located behind the test cells (Fig. 5). Because the superheated air and gases produced during tests were extremely dangerous, a complex system of pipes, fed by a nearby 70,000-gallon "spray pond" reservoir, along with a two-stage steam ejector and a tower-mounted intercondenser, would bleed off excess heat.[17]

The Burner Laboratory had been manually operated, but as the temperatures and pressures increased with advancing ramjet propulsion technology, so did the dangers. In the interest of safety, therefore, the designers of the Propulsion Research Laboratory installed remote controls in a nearby building and shielded both it and the adjacent offices from the test cells with reinforced concrete. During tests, the entire

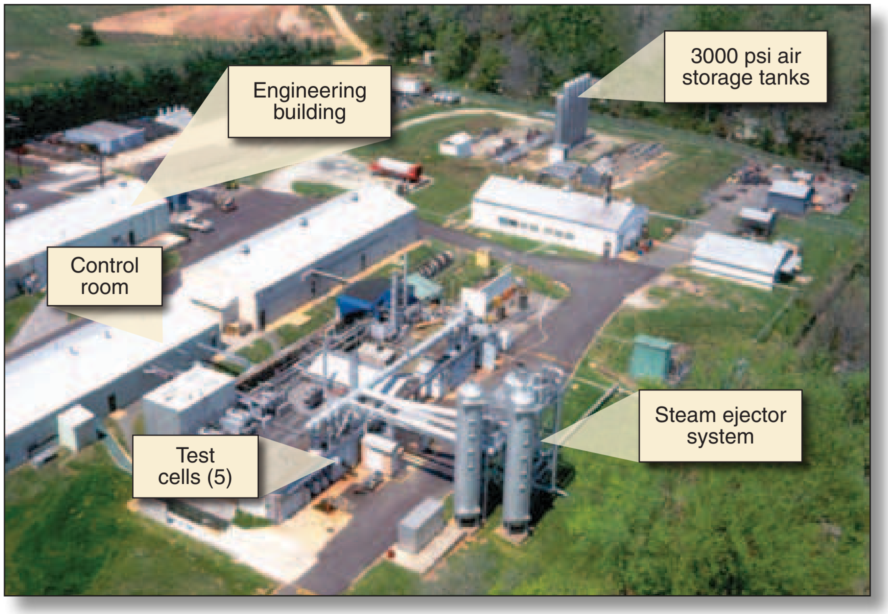

Figure 4. APL's Howard County Propulsion Research Laboratory, designed to conduct ramjet testing at simulated speeds of up to Mach 10, opened in late 1961.

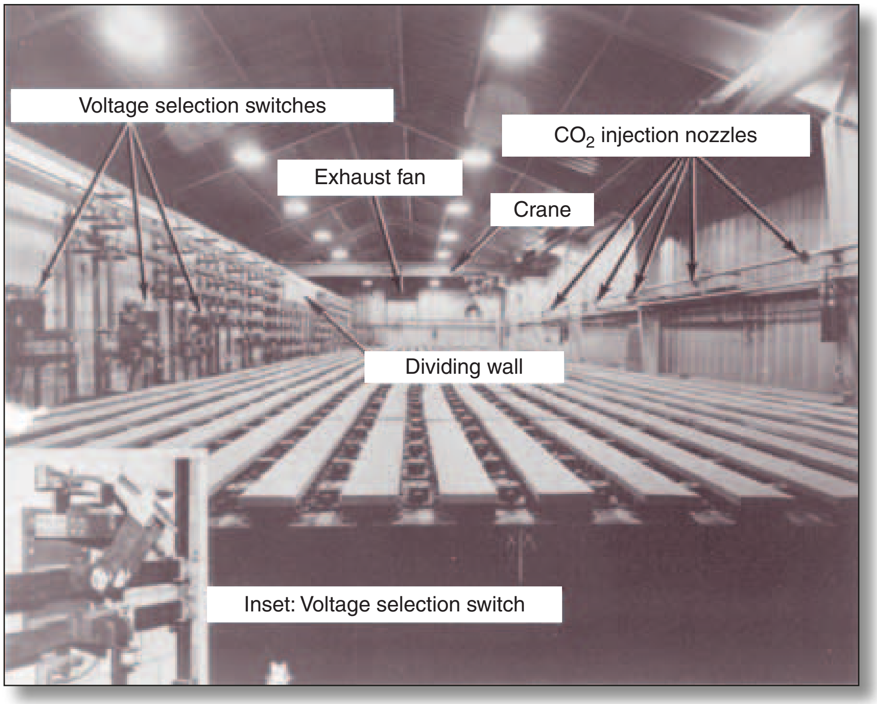

Figure 5. Some 1216 lead-acid submarine cells, housed in the Propulsion Research Laboratory's Battery Building, delivered over 10 MW of power during high-temperature hypersonic ramjet tests. Later, the Propulsion Research Laboratory used them to develop arc-fault detection systems for Navy warships.

area would be cleared, and data from the test instruments would be transmitted to the control room and recorded by closed-loop video systems, an oscillograph, strip chart recorders, and a high-speed data-acquisition system. At the time, this was state of the art (Fig. 6).

To administer the Propulsion Research Laboratory, APL consolidated the existing Aerodynamics, Engineering, Launching, and Propulsion Groups into a new Aeronautics Division in March 1961. APL did this to integrate the group's collective focus on design and development problems of airframe-engine combinations for guided missiles. In recognition of his Bumblebee leadership role and his behind-the-scenes efforts to get the Propulsion Research Laboratory built, Avery became the Aeronautics Division's first head, with Dugger serving as supervisor of APL's Hypersonic Propulsion Group and Olsen as Propulsion Research Laboratory facilities supervisor. Together, they would lead a staff of approximately 40 scientists and engineers as the Propulsion Research Laboratory began conducting its first hypersonic tests in early 1962. Meanwhile, the Burner Laboratory was abandoned in May 1962, and the Navy dismantled the entire Forest Grove Station in 1963 (see p. 24 in Ref. 2).

THE PROPULSION RESEARCH LABORATORY AND POLARIS

After the Navy ended Typhon-LR ramjet development in 1965, the Propulsion Research Laboratory refocused on the development of high-temperature, high-pressure plasma arc heaters for future hypersonic research and development. In addition, the laboratory found ample work in a variety of Polaris-related projects, including atmospheric gas detection instrumentation, contaminants, acoustic sensors, acoustic attenuation, and magnetic field measurements.

In April 1963, the Navy asked the Propulsion Research Laboratory to undertake a new hypersonic

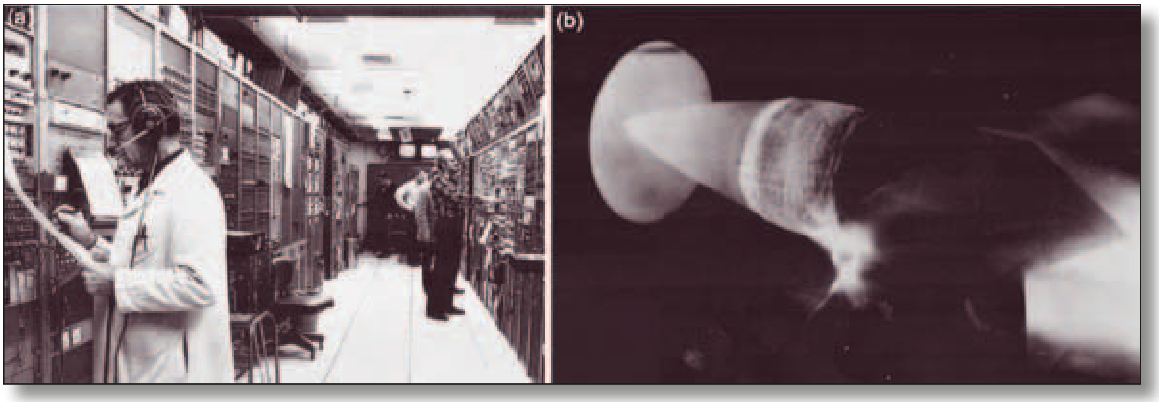

Figure 6. The Propulsion Research Laboratory's scientists and engineers monitored tests from a separate but fully automated control room (a) that was shielded from the test cells, protecting them from the extreme temperatures and pressures associated with hypersonic testing (b).

re-entry materials testing program for Polaris. Avery accepted the project, but because the laboratory's four test cells were already committed to other long-term projects, APL decided to build a fifth, larger test cell that would be devoted entirely to Polaris testing. To pay for the new cell, The Johns Hopkins University would provide $18,700 and the Navy would contribute $140,450, with additional monies available from the Polaris "Special Projects" budgets if needed.

APL built the fifth test cell, and to better focus its RDT&E effort on Polaris, APL also reorganized its Aeronautics Division on 1 May 1963. During this reorganization, APL established a wholly new Hypersonic Propulsion Group that consolidated the previous research teams concerned with propulsion, supersonic and hypersonic aerodynamics, arc tunnels and gun tunnels, aerodynamic design, and structural engineering. Forged to support the Propulsion Research Laboratory's hypervelocity mission, this administrative structure, established by Avery, remained unchanged for the next 35 years.

SUPERSONIC RAMJETS

The Propulsion Research Laboratory also embarked on a long series of supersonic ramjet engine and vehicle development projects during the 1960s, although the Navy cancelled most of them before flight testing. Among those that did get off the ground was the Augmented Thrust Propulsion program, undertaken with Martin Marietta/Denver and the Atlantic Research Corporation in 1965. The program's goal was to boost a Polaris rocket's engine by injecting air into its nozzle using a ramjet and a fuel-rich solid-gas generator system. The program achieved high combustion efficiencies of up to 90% by using solid fuels and different inlet types. The success of Augmented Thrust Propulsion Polaris rocket engines led the program to add a tactical missile, called the Thrust Augmented Rocket Surface-to-Air Missile. The Thrust Augmented Rocket Surface-to-Air Missile program ended as planned in 1971, but the Navy did not authorize follow-on flight tests in light of the more promising Integral Rocket Ramjets (see pp. 237–238 in Ref. 10).[18]

Integral Rocket Ramjets resulted from a breakthrough in the late 1950s by a private contractor, Experiment Incorporated, later Texaco Experiment Incorporated, during the Bumblebee program. The company's idea was to place the rocket booster propellant into the same chamber that was used as a ramjet's combustion chamber, hence an "integral rocket ramjet." This approach yielded more range or payload than the use of a separate rocket booster. The Bumblebee Group recognized the idea's value, and after completing the Typhon-LR engine work, the Propulsion Research Laboratory researched and tested several more efficient Integral Rocket Ramjet missile types. The Integral Rocket Ramjet surface-to-air missile prototype, developed between 1966 and 1970, was a medium-range missile capable of cruising at Mach 3.5. Research on an Integral Rocket Ramjet surface-to-surface missile, with a Mach 2.5 cruising speed, began in 1971, but the Navy's new AGM-84 Harpoon anti-ship missile system had proven itself more than capable of doing the same job, so further development stalled after 1974.

During the 1970s, the Soviet Union developed a startling series of standoff weapon systems that were designed to cripple the U.S. Navy, such as the *Slava* and *Kirov* class missile cruisers, backed by Badger and Backfire bombers armed with anti-ship cruise missiles. To counter these weapon systems, the U.S. Naval Sea Systems Command asked the Propulsion Research Laboratory in 1974 to begin exploratory development of an Advanced Surface-to-Air Ramjet that could defeat coordinated Soviet air- and sea-based missile attacks against U.S. Navy carrier task forces. Initial work took place between 1974 and 1978, with advanced development continuing from 1977 through 1981, which required modifications to Test Cell 5 to do the free-jet inlet testing. Avery's staff conducted trajectory tests at the Hercules Allegheny Ballistics Laboratory in Rocket Center, West Virginia, in 1980 and 1981. However, government interest in supersonic ramjet technology waned in the early 1980s in favor of the potentially more potent hypersonic ramjets that APL's Hypersonic Propulsion Group had been working on since before the Propulsion Research Laboratory's birth.[7]

SCRAM AND DCR

Avery's personal interest in developing hypersonic ramjet engines in the 1950s had been the initial catalyst behind the Propulsion Research Laboratory's creation. In 1957, Dugger led APL's first hypersonic propulsion research and development effort, called Project-53, which was focused on the external-burning ramjet. External-burning ramjets were intended as potential follow-on propulsion systems for the Navy's Triton ramjet-powered cruise missile, and Dugger hoped to prove that an "external ramjet," burning beneath a flat-topped, triangular airfoil, could produce both thrust and lift at Mach 5. It was a simple idea, and although Dugger did not expect the first external-burning ramjets to generate high thrust levels, he believed that they could ultimately cruise at Mach 8 once fully developed. During tests, Dugger's colleague James Keirsey added a short cowl to the design to capture and redirect the engine flow. The resulting external-expansion ramjet became the first of a new type of propulsion system called the Supersonic Combustion Ramjet Missile, or "SCRAM."[19]

At the same time, Dr. Frederick Billig, who had joined the Bumblebee Group in 1955, had just brought a Mach 5 wind tunnel online at Forest Grove in February 1959. That month, Dugger and Keirsey brought Billig an external-burning ramjet for testing at Forest Grove. Early experiments using hydrogen fuel failed, but on 5 March 1959, Billig successfully achieved stable supersonic combustion in the external-burning ramjet by using triethyl aluminum fuel in a Mach 5 airstream (Fig. 7). This was the first time that a hypersonic propulsion system had ever produced thrust. A follow-up experiment on Keirsey's cowled external-expansion ramjet proved equally successful, and further testing of this ducted SCRAM design continued through 1960. However, the external-burning ramjet program ended in 1961 when Navy support lagged after Triton's demise.[19]

Despite the setback, Navy interest in SCRAM technology continued through the 1960s and into the 1970s, with Avery's team designing and testing SCRAM components at Mach 3 to Mach 8 conditions. The Propulsion Research Laboratory's goal was to develop a tandem-boosted SCRAM propulsion system that could fly at Mach 4 with a powered range of 47 nautical miles at sea level, or a range of 350 nautical miles when flying at Mach 7.5 at an altitude of 100,000 feet, using liquid HiCal 3-D (ethyldecaborane) fuel. Dugger's team finally settled on a 10-inch-diameter, 3-foot-long, three-module SCRAM free-jet engine in 1968 as the most promising configuration for achieving the desired results. This SCRAM engine was the first to show positive thrust, and testing ran from 1968 to 1974 at speeds between Mach 5.2 and Mach 7.1 (see Fig. 8 and pp. 240–241 in Ref. 10).

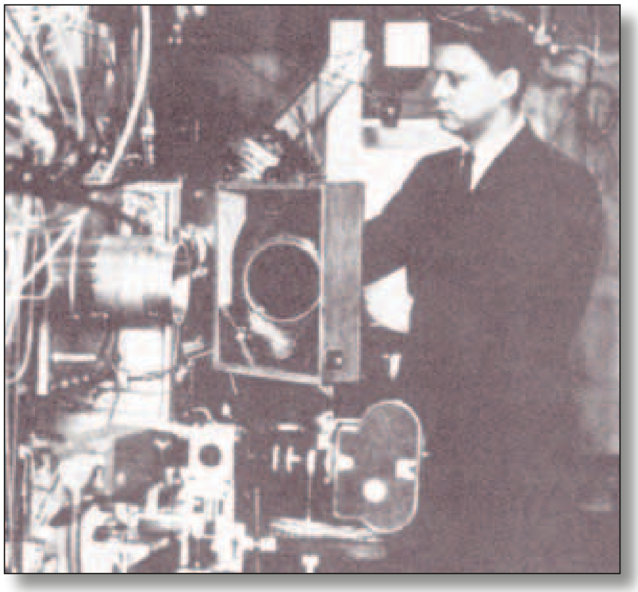

Figure 7. Fred Billig successfully demonstrated supersonic combustion in an external-burning ramjet for the first time on 5 March 1959, in the Forest Grove Burner Laboratory's Mach 5 wind tunnel.

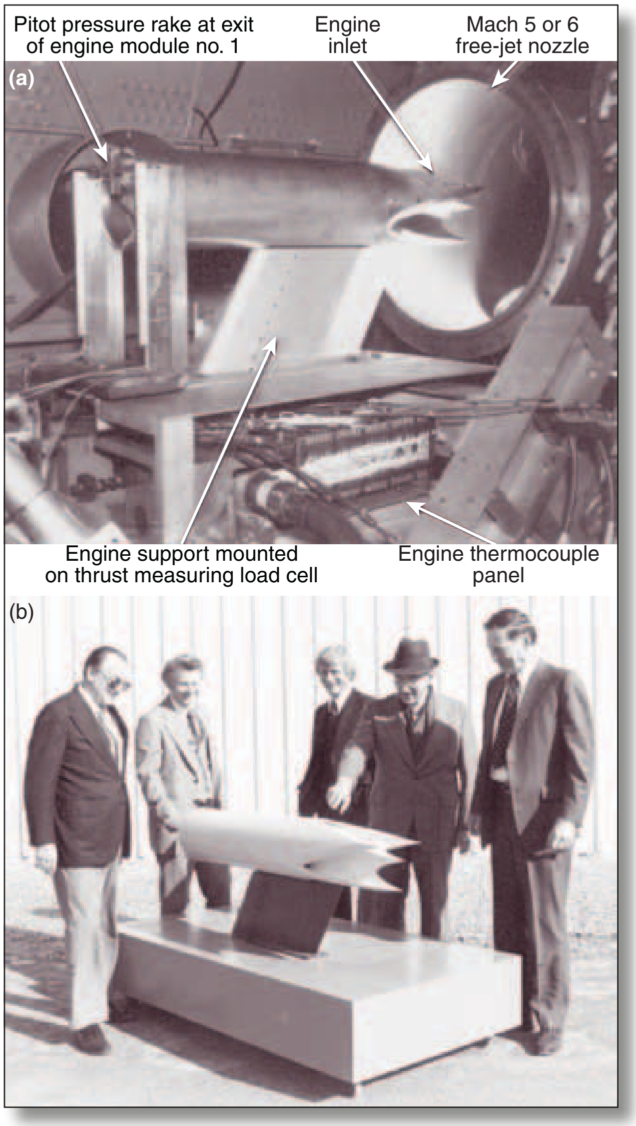

Figure 8. (a) Mach 5+ SCRAM research dominated the Propulsion Research Laboratory's operations during the 1960s and early 1970s. (b) R. Blevins, Fred Billig, Paul Waltrup, Gordon Dugger, and James Keirsey examine a heavyweight SCRAM engine model at the Propulsion Research Laboratory.

Despite the apparent successes, SCRAM suffered from several major faults that doomed it. First, SCRAM's use of volatile liquid fuels or blends could be devastating aboard ship in the event of an explosion or fire. Next, there was no room in the missile's fuselage for the large, active radio-frequency seeker that was needed to acquire and intercept incoming targets at long ranges. Finally, the Navy objected to the passive cooling requirements of the entire vehicle, which could conceivably make it prone to premature explosion during flight. Because any one of these failings alone could result in disaster for a warship, the Navy cancelled the SCRAM program in 1977 (see pp. 240–241 in Ref. 10).

Before SCRAM ended, however, Keirsey, who now headed the Propulsion Research Laboratory after Dugger succeeded Avery as Aeronautics Division chief in 1974, designed a new propulsion system that solved all three problems. Called the dual-combustor ramjet, or DCR, Keirsey's design used a subsonic pilot combustor to burn all of the fuel with only a fraction of the air needed for SCRAM. It blended the characteristics of a ramjet and scramjet and operated as a dual-mode engine capable of efficiently operating across a wide range of Mach speeds. DCRs permitted the use of conventional liquid hydrocarbon fuels and also left enough room for the required radio-frequency seeker in the nose. The DCR also was compatible with the Navy's need for a Wide-Area Defense Missile under the Surface-Launched Missile Technology Program. After Keirsey's initial success, he, along with Billig and Dugger, headed up a robust DCR testing regime at the Propulsion Research Laboratory in which a wide variety of fuels, components, and inlet configurations were investigated. Supplemental tests were done in the Vought (now Lockheed Martin) polysonic wind tunnel and in NASA's Mach 6 wind tunnel at the Langley Research Center. As with so many of the laboratory's prior projects, however, the program was terminated, this time by Congress in 1986. The laboratory never gave up on DCRs, and the technology would later reemerge as a potentially viable hypersonic propulsion system for a new class of missiles designed for the 21st-century U.S. military, specifically the HyFly hypersonic DCR-powered cruise missile (see pp. 240–241 in Ref. 10).

THE REFURBISHMENT STRUGGLE

By the 1980s, APL had upgraded the Propulsion Research Laboratory several times to reflect the changing technologies in Navy RDT&E. A sixth, smaller test cell had been added to allow small-scale nonhazardous testing of individual components, and a new Digital Data Acquisition and Control System had been installed in 1967 to provide computer control of the data-acquisition process, to be followed by computer control of the facility and testing operations themselves. In subsequent years, APL integrated newer, more advanced computers, such as the Intel 4004 and Texas Instruments 960A, into the laboratory's automated control system, giving it full digital capability in place of the old analog system.[20, 21]

Still, the wear and tear of hypersonic testing had begun to show on the Propulsion Research Laboratory (Fig. 9), which had shouldered all of the Navy's hypervelocity testing burden after its sister Ordnance Aerophysics Laboratory in Daingerfield, Texas, closed in 1968. In September 1983, the Navy learned about the Propulsion Research Laboratory's deterioration when Deputy Chief of Naval Material James E. Colvard established an ad hoc Ramjet Testing Facilities Committee to investigate the status of existing, government-supported ramjet test facilities and to evaluate their adequacy to support future Navy programs. The committee reported in May 1984 that the Navy depended almost exclusively on the laboratory, which it now treated as an in-house facility, to handle its hypersonic ramjet RDT&E. However, the Navy had neglected the laboratory's maintenance, and the Propulsion Research Laboratory had deteriorated as a result. Considering that the Navy would likely require advanced ramjet missiles in the future and would need the laboratory to undertake the necessary research, the committee recommended that the Naval Sea Systems Command quickly find money to refurbish it. The committee also recommended that APL make a formal statement of commitment to maintaining the Propulsion Research Laboratory.

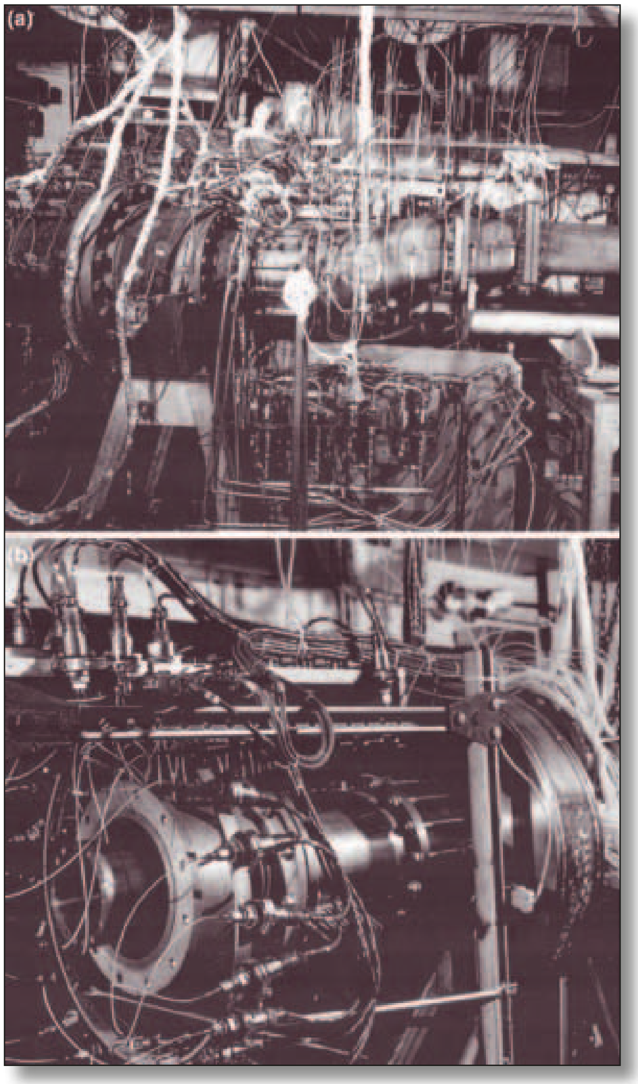

Figure 9. The Propulsion Research Laboratory's intricate electrical wiring (a) and arc-driven tunnel setups (b) required constant maintenance and periodic refurbishment as a result of the high stresses generated during hypersonic tests.

APL director Carl O. Bostrum quickly responded with a letter of reassurance to the Navy. He noted that the Propulsion Research Laboratory's maintenance funding had been a difficult problem because APL's overhead accounts had been the only source of repair money in recent years, the Navy's line item for the laboratory's maintenance having been terminated in 1975. The laboratory's annual overhead budget had averaged approximately $800,000 since 1982, which had allowed very little technical upgrade and no more than minimal maintenance. Nonetheless, APL had always believed in ramjets, and it believed that the technology remained important to the fleet's air defense capabilities, despite the Navy's neglect. Bostrum concluded that reliable long-term maintenance funding, along with the anticipated Naval Sea Systems Command funds, was necessary for restoration. Based on a preliminary engineering design and feasibility report previously commissioned in January 1984, APL believed that it would cost $7.5 million to renovate the Propulsion Research Laboratory.

APL found a powerful ally in the Naval Sea Systems Command's Deputy Commander for Weapons and Combat Systems, Rear Admiral Wayne E. Meyer, who had gained fame as the "father of the Aegis weapons system." In March 1985, Meyer submitted a memorandum to the Director of Research, Development, and Acquisition for the Chief of Naval Operations, Vice Admiral Albert J. Baciocco, asking for an immediate transfusion of funds for the refurbishment. Meyer noted that ramjet missiles currently played a key role in the Navy's strategy of layered defense and that the Navy heavily depended on the Propulsion Research Laboratory to do its ramjet testing.

Sympathetic, Baciocco supported the Propulsion Research Laboratory by making the upgrade his highest priority and recommending that $6.5 million be appropriated during the annual budget hearings. The Naval Sea Systems Command also informed the Chief of Naval Material and APL that the laboratory upgrade was its number one priority as well. But the Naval Sea Systems Command also advised that as an alternative, APL should break the $6.5 million into smaller amounts spread out over fiscal years 1986, 1987, and 1988. Because funding and sponsorship for the upgrade remained unclear at this point, APL solicited additional support from the Director of the Office of Naval Technology in August 1985.

Congress never appropriated the $6.5 million as requested. However, in successive years, as the Naval Sea Systems Command had suggested, the Propulsion Research Laboratory received enough funding in smaller increments from various Navy and APL sources to stay operational, to do the necessary repairs and maintenance, and to improve some of its capabilities.

By 1989, APL had finished most of the repairs on the Propulsion Research Laboratory. When Avery retired that year, APL dedicated the Propulsion Research Laboratory to him in recognition of his role in nurturing the laboratory and its hypersonic ramjet programs over the years. The ceremony was held on 2 October in front of the laboratory's administrative building, in which director Bostrum and Aeronautics Department head Dr. Richard Seuss unveiled a plaque designating the complex as the new Avery Propulsion Laboratory. The citation read:

> For over forty years, Dr. William H. Avery has served the Applied Physics Laboratory with great distinction. Dr. Avery is known for his pioneering work in combustion, solid rocket propellants, ramjet propulsion, design and testing of supersonic-combustion ramjets and hypersonic aircraft concepts. The Propulsion Research Laboratory (PRL) was established at APL under Dr. Avery's leadership in 1961. PRL was the first fully automated facility in the U.S. devoted to hypersonic propulsion. In recognition of Dr. Avery's outstanding contributions in the field of propulsion technology, the Propulsion Research Laboratory will bear his name.[5]

Other changes occurred at the laboratory in the late 1980s. Dugger died in 1987, and Keirsey retired that same year. Keirsey was succeeded by Dr. Paul J. Waltrup, who had been working at the laboratory since 1971.

THE X-30 NATIONAL AEROSPACE PLANE

Despite the refurbishment issue and management turnover, the Avery Laboratory maintained a continuity of operations that moved it forward into advanced space transportation during the late 1980s. The laboratory's most prominent role during this period was with the National Aerospace Plane project, conducted jointly with NASA, the Department of Defense, the U.S. Air Force, the U.S. Navy, and a host of other military and civilian research laboratories across the nation. The National Aerospace Plane had been conceptualized during the 1982–1985 Copper Canyon project by the Defense Advanced Research Projects Agency (DARPA) and NASA as a possible successor to the Space Shuttle.[22]

The National Aerospace Plane's specifications called for a hydrogen-powered aircraft capable of horizontal takeoff and landing that could fly at speeds between Mach 12 and Mach 25 at altitudes of between 100,000 and 350,000 feet. President Reagan, who had called for "a new Orient Express that could, by the end of the next decade, take off from Dulles Airport, accelerate up to 25 times the speed of sound, attaining low earth orbit or flying to Tokyo within two hours," hoped that the National Aerospace Plane could ultimately become a "global flight vehicle" or perhaps a long-range global air defense interceptor. If developed, it could significantly reduce payload-to-orbit transportation costs, and its dramatically reduced transit times on long-haul airline routes might reap significant economic benefits to the nation. While under development, the

National Aerospace Plane would be called the X-30 (Figure 10c).

The Avery Laboratory's part in the National Aerospace Plane program focused on engine development (Fig. 10b). Fred Billig spearheaded the development of a number of innovative inlet and component designs, including a generic engine with a rotating cowl and retractable fuel struts that he and colleague David Van Wie patented for APL in 1993. The laboratory also conducted direct-connect combustor tests at speeds simulating Mach 6 to Mach 8 conditions (Fig. 10a).

In 1989, the Air Force suddenly abandoned the program and switched its space transportation focus to its Advanced Launch System rockets, leaving the National Aerospace Plane program without the bulk of its promised funding from the Department of Defense. The move upset congressmen from key contractor districts, who convinced House budget writers to keep the National Aerospace Plane alive into the 1990s. But the Senate grew increasingly skeptical about its utility, especially after the Soviet Union collapsed in December 1991 and President George H. W. Bush began his "Peace Dividend" defense drawdown. In 1992, the Senate refused to back National Aerospace Plane funding increases from $250 million to approximately $500 million in 1996. This signaled the program's death knell, and Congress cancelled the program in November 1994. With the National Aerospace Plane now going the way of so many of the other ramjet projects, the Avery Laboratory was now without a major program.[23–25]

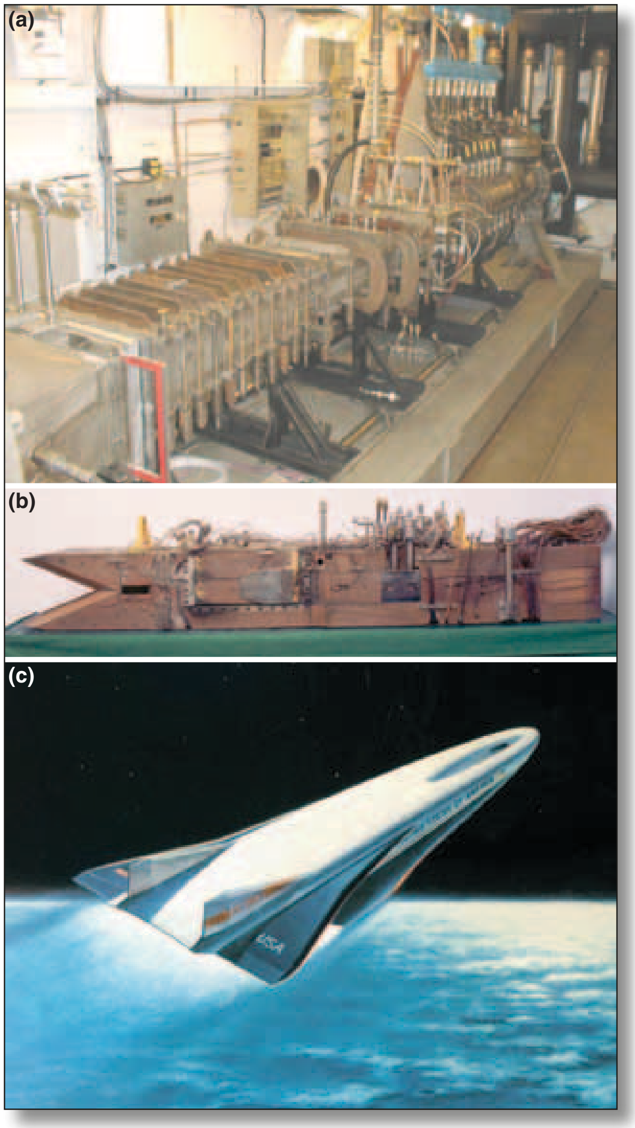

Figure 10. During the 1980s and early 1990s, the Propulsion Research Laboratory built the 2D direct-connect combustor (a) at APL to test Propulsion Research Laboratory-designed components such as the B1 engine (b) for the joint X-30 National Aerospace Plane program (c).

THE AVERY LABORATORY IN A POST-COLD WAR WORLD

The end of the Cold War and the cancellation of the National Aerospace Plane compelled the Avery Laboratory to diversify into other fields during the 1990s. One of its most successful endeavors was the continuing development of arc-fault protection technology for the U.S. Navy to protect submarine electrical systems. This work, led by the laboratory's instrumentation lead, Bruce Land, provided critical support to the laboratory and its staff for almost a decade. It also addressed a critical need in a completely new area of the Navy. Early work stemming from the Avery Laboratory's unique electrical arc-generation capabilities had been done in 1978, when the Naval Ship Engineering Center had commissioned the laboratory to investigate and mitigate the arcing, which could be catastrophic in a submarine. The laboratory successfully tackled the problem and developed arc-fault detection systems for the *Los Angeles* (SSN 688), *Seawolf* (SSN 21), and *Ohio* (SSBN 726) class submarines by 1993. By April 1996, arc-fault detection systems had been installed on all SSBN 726 class boats, one SSN 21, one SSN 637 (*Sturgeon*), and 52 SSN 688s, as well as at seven training centers. APL reported in 1997 that the Avery Laboratory's arc-fault detection systems had correctly detected and extinguished five electrical fires aboard submarines over a 2-year period and that the system had completed more than 100 ship years of operation without a reported failure.[26]

That same year, the Navy became concerned that its nine aircraft carriers were averaging three arcing faults per year. Avery Laboratory scientists joined a team that looked into the trouble. They found that the problem was the same as that aboard submarines and recommended the design of new arc-fault detection systems for the carrier force, a first for surface ships. In 2000, the laboratory also evaluated the Navy's new Integrated Power System for the next-generation DD(X) destroyers. The laboratory concluded that the system was just as susceptible as those aboard both submarines and carriers and recommended that the Navy write arc-fault detection into the Integrated Power System/DD(X) procurement specifications. Avery Laboratory personnel later investigated electrical fires aboard cruise liners and successfully extended the arc-fault detection technology for future application to the civilian sector in the early 2000s.

On another front, APL began establishing a number of "alliances" in 1997 with private companies that would enable them to contract directly with APL for testing services. This was a radical departure from its prior policy of not working directly for or competing with industry with respect to government contracts. The policy was intended to prevent any potential conflicts of interest and to avoid jeopardizing APL's role in providing unbiased support to the government.[27,28]

However, the downturn in military ramjet projects and the National Aerospace Plane's cancellation had left the Avery Laboratory periodically idle, with its staff often reassigned. Because private demand for the laboratory's services existed, APL finally decided, with the Navy's blessing, to make its facilities available to defense contractors under the Alliance for High-Speed Testing and its aerothermal capabilities available through the Alliance for High-Speed Aerothermal Sensor Testing. Membership was open to any agency or institution, private or academic, with a potential need or an interest in aerothermal or propulsion testing.[27,28]

HYPERSONIC RESEARCH AND DEVELOPMENT REDUX

Although APL had diversified the Avery Laboratory's operations into new areas after the National Aerospace Plane's cancellation, the Air Force contracted with APL in 1995 to perform new hypersonic research under its new Hypersonic Technology (HyTech) program. The renewed interest in hypersonic surface-to-air missiles was a direct response to the new threats posed by "rogue" nations such as Iraq and North Korea, which were fielding and proliferating nuclear-capable surface-to-surface missiles such as the SS-1 Scud. Iraq's indiscriminate use of Scud missiles against Israel, Saudi Arabia, and Bahrain during Operation Desert Storm in 1991 reinforced the urgency of new high-speed missile defense systems. Under HyTech, the Air Force specifically wanted the laboratory to revive James Keirsey's DCR research into a long-range, quick-reaction Mach 8 missile. Initial in-house funding was set at $500,000 (see p. 1 in Ref. 27).

The Avery Laboratory accordingly stepped up the tempo of its hypersonic studies through the rest of the 1990s in support of HyTech, as well as several other concurrent programs based on the DCR, including the Navy's Hypersonic Weapon Technology Program and DARPA's Affordable Rapid-Response Missile Demonstrator, both of which began in 1997. The use of tactical ballistic missiles by Iraq in the first Gulf War, and the subsequent proliferation of missile technology, made hypersonic ramjet research more attractive to the military because the United States needed new ways in which to strike time-critical, heavily defended, or buried targets from long distances. Punitive cruise-missile strikes against terrorist camps in Afghanistan made this point abundantly clear when subsonic Tomahawks repeatedly missed their intended Al Qaeda targets because their launch-to-impact flight time had been too great (see p. 1 in Ref. 27).

In 2002, DARPA and the U.S. Navy's Office of Naval Research started the HyFly program to develop and test a hypersonic Mach 6-plus, ramjet-powered cruise missile. Initial work progressed rapidly, and in May 2002, a team from the Avery Laboratory successfully tested the HyFly DCR engine in a wind tunnel at NASA's Langley Research Center at a simulated speed of Mach 6.5 (Fig. 11a). This was the first-ever ground test of a full-scale, fully integrated hypersonic cruise missile engine using conventional liquid hydrocarbon fuel. Additional engine tests were scheduled to be completed by March 2004, with eight flight tests planned later that year, in which the project team hoped that the HyFly missile would reach Mach 6 and achieve a maximum range of 400 nautical miles (see p. 1 in Ref. 27).[29]

TWILIGHT AT AVERY

The government's revived interest in DCR engine technology appeared to improve the Avery Laboratory's outlook for the future. Because of the expanded testing regime, APL began a major refurbishment of the laboratory's facilities in 1998 to keep abreast of the influx of hypersonic RDT&E programs. The final upgrade was completed in November 2003, allowing the laboratory to test engine materials at temperatures of up to 4500°F for as long as 14 minutes, thus simulating engine temperatures during a typical Mach 6 flight. The longer run times at higher temperatures were necessary to test HyFly engine components before missile construction and scheduled full-scale flight tests in 2004 (see pp. 4 in Ref. 27).

However, the Avery Laboratory had entered its twilight period. In October 1996, APL director Gary Smith radically reorganized the entire administrative structure to better align it with future Department of Defense and Navy priorities. As part of that effort, Smith disbanded the Aeronautics Department and in its place created an Aeronautical Science and Technology Group (RAS).

That group, led by Paul Waltrup, was placed within the Milton S. Eisenhower Research and Technology Development Center (RTDC). The Avery Propulsion Research Laboratory became the Avery Advanced Technology Development Laboratory and was then placed within RAS under Waltrup. Director Smith stated that the reorganization enhanced "our ability to do the kind of R&D and develop the systems that our sponsors need for the future. We have to be out there on the cutting edge."

In June 1997, citing the "special challenges in terms of safety, stability of its customer base, and recapitalization," RTDC's Director John Sommerer took the opportunity to revisit the overall organizational structure at the Avery Laboratory, as well as its integration with the rest of RAS and RTDC as a whole. He reassigned Waltrup's assistant RAS supervisor David Van Wie to become the Avery Laboratory Facility Manager, where he would supervise its RDT&E work, do its strategic planning and recapitalization, manage its increased integration into RAS and RTDC, and seek to diversify its sponsor base.

The overall reorganization at APL was unpopular with many at the Avery Laboratory. Some people also were concerned about APL's implied new emphasis on research and development at the expense of testing and evaluation. Waltrup's death in 2002 left Van Wie head of both the Avery Laboratory and the Aeronautics Group. He moved additional group staff to the laboratory and successfully expanded sponsorship of Avery Laboratory work with NASA. In addition, the HyFly program had taken off, which ironically enough had focused national attention on the laboratory through a 2 September 2002, cover story in *Aviation Week & Space Technology* (Fig. 11b).

In addition to management issues, the Avery Laboratory was vulnerable to Maryland's strict environmental laws because of APL's private status. Representatives from the Maryland Department of the Environment regularly performed thorough inspections at the site. Moreover, many of the same noise complaints that had plagued the old Forest Grove Burner Laboratory in the 1950s were now affecting the Avery Laboratory as Columbia's growing residential areas began encroaching on the APL campus. In November 2005, Ken Grossman of RTDC noted that to comply with local sound codes, the Avery Laboratory could operate in daytime hours only. He believed that further encroachment might make the laboratory's noise a further regulatory and political issue. Grossman also pointed out that the laboratory's spray pond had surfaced as a hot spot for inspectors and that APL had to recently defend its discharge permit from accusations of excessive surface erosion caused by the pond's discharge. The Avery Laboratory's 50-year-old boiler also was drawing unwanted attention from the state inspectors, and although it had been grandfathered into current regulations, Grossman believed it likely that the state would mandate a costly replacement in the near future.

Figure 11. The joint DARPA/Office of Naval Research HyFly missile, shown here at NASA's Langley Research Center (a), was based on James Keirsey's DCR research and brought national attention to the Avery Laboratory in 2002 (b).[31]

APL also was becoming increasingly concerned about the Avery Laboratory's aging physical plant.

Although some laboratory systems had just been upgraded, much of its equipment was still 40–60 years old. Its control system software was no longer supported, and the process gas system still ran on floppy disks and hardware that were no longer available from obsolete parts vendors. RTDC estimated that a "modest" upgrade would cost approximately $16 million, while a reasonable estimate for maintaining the Avery Laboratory's current capabilities ran between $1 million and $1.2 million, which was much more than the laboratory's annual $800,000 overhead budget could afford.

Government accounting rules, plus priorities set by Laboratory management to protect more widely used facilities such as the APL Engineering, Design, and Fabrication facilities, meant that the Avery Laboratory's overhead burden needed to be recovered on a small and diminishing business base. This drove costs up, which in turn made sponsorship more difficult to obtain. This cycle was known as a "rate death spiral."

The Avery Laboratory was now competing with private contractors, primarily Aerojet and Alliant Techsystems, along with the Department of Defense's Magnetohydrodynamics Accelerator Research Into Advanced Hypersonics II (MARIAH II) hypersonic tunnel in Butte, Montana. Repeated studies showed that the tunnel testing market was shrinking and that the laboratory was becoming noncompetitive because of its age and costs. Capturing a significant part of the shrinking market with old technology seemed unlikely at best to RTDC.

In the spring of 2005, RTDC formed a "Red Team" to study the Avery Laboratory's prospects for the future and to develop possible strategies for keeping it open. The team gave RTDC management four choices: (*i*) reduce the scope of operations; (*ii*) maintain current capabilities at a cost of $1 million to $1.2 million per year; (*iii*) undertake a "modest" upgrade at $16 million; or (*iv*) become a "fast-follower" of tunnel technology by making a major capital investment of tens of millions of dollars into brand new facilities that could simulate speeds up to Mach 15. RTDC Director Sommerer liked none of these options, and in summer 2005, he recommended that APL close the laboratory the following spring. One of the key factors in that decision was that RAS staff had shown increasing facility in using other, government-owned facilities to perform hypersonic testing.

Sommerer's recommendation was extremely polarizing and led to a prolonged search for alternatives, including other APL departments willing to assume responsibility for the facility. Critical analysis of the business case resulted in no takers. At the end of this process, it was decided that APL's best interests would be served by closing the Avery Laboratory (Fig. 12).

Sommerer, now APL's Director of Science and Technology, explained to the laboratory's community: "In one of the more painful decisions in recent memory, it was recently decided to close that aging facility because associated revenue streams, together with government and Applied Physics Laboratory cost-accounting policies, made it impossible to operate and recapitalize it. Further, retirements, deaths, and career changes by key technologists have thinned the ranks of human capital behind this technology area, making it less likely that the Applied Physics Laboratory will continue to maintain its preeminent role in the future."[30]

After consulting with current sponsors and transferring test articles still in use to other facilities, the Avery Laboratory conducted its final tests in May 2006, and APL closed it before the end of the month. That summer, bulldozers demolished the test cells and cooling apparatus. Some laboratory personnel took positions in other departments, while others continued with new work successfully initiated within RAS.

Although it ultimately succumbed to the harsh economic and administrative realities of modern defense laboratory management, the Avery Laboratory's legacy will continue on through the refinement of third- and fourth-generation technologies in the HyTech and HyFly programs. Its arc-fault detection technology likewise proved to be an important contribution to safety on the high seas by significantly diminishing the threat of catastrophic electrical fires aboard Navy ships. Despite its age and infirmities, the Avery Laboratory kept contributing to science and defense until the end.

Figure 12. From left to right: William Avery, Gordon Dugger, James Keirsey, Paul Waltrup, and David Van Wie successively led the Avery Laboratory from its creation in 1961 through the early 2000s, before its closure in 2006.

Avery Laboratory Timeline	
July 1944	The U.S. Navy's Bureau of Ordnance asks APL to perform preliminary analysis and propose possible countermeasures against future long-range anti-ship missiles.
November 1944	APL reports that supersonic, rocket-launched, ramjet-propelled, radar-guided surface-to-air missiles might counter the future anti-ship missile threat.
January 1945	The Bureau of Ordnance instructs APL to undertake a comprehensive, open-ended research, development, testing, and evaluation program leading to a "useful" missile with performance characteristics to be defined as work progresses.
February 1945	APL begins building a Burner Laboratory at the Forest Grove Station to handle supersonic ramjet propulsion testing.
June 1945	The Bumblebee Propulsion Group successfully tests the first supersonic ramjet-powered missile at Island Beach, New Jersey.
1948	Dr. William A. Avery becomes the supervisor of the Bumblebee Launch Group.
1951	Ramjet expert James Keirsey joins APL's Bumblebee Group from the Navy's Ordnance Aerophysics Laboratory.
May 1953	Dr. Lowell Olsen formally proposes the construction of a new propulsion research laboratory to Dr. Avery.
September 1954	APL opens its new campus in Laurel, Maryland.
June 1955	APL authorizes the Bumblebee Group to move the Burner Laboratory from Silver Spring to APL's Howard County campus.
1956	Dr. Avery starts the Hypersonics Program within the Bumblebee Launch Group.
January 1957	Dr. Gordon Dugger joins APL from the National Advisory Committee for Aeronautics' Lewis Laboratory, and APL's first hypersonic propulsion research and development project, called Project-53, focuses on external-burning ramjets.
1958	The Talos ramjet-powered surface-to-air missile enters Navy service.
March 1959	Fred Billig successfully achieves stable supersonic combustion in an external-burning ramjet at the Burner Laboratory. Keirsey subsequently adds a cowl to the design and creates the first SCRAM engine.
May 1959	APL director Dr. Ralph Gibson submits an alternate plan to the Navy to build a brand new but less costly propulsion research laboratory at APL.
1961	The external-burning ramjet program ends.
March 1961	APL consolidates the existing Aerodynamics, Engineering, Launching, and Propulsion Groups into a new Aeronautics Division.
December 1961	The Propulsion Research Laboratory opens with Dr. Avery heading it.
May 1962	APL abandons the Forest Grove Burner Laboratory.
April 1963	The Navy asks the Propulsion Research Laboratory to undertake a new hypersonic re-entry materials testing program for Polaris.
May 1963	APL reorganizes its Aeronautics Division and establishes a wholly new Hypersonic Propulsion Group.
1965	The Navy ends Typhon-LR ramjet development. The Propulsion Research Laboratory undertakes the Augmented Thrust Propulsion program with Martin Marietta/Denver and the Atlantic Research Corporation.
1966	The Propulsion Research Laboratory begins development of an Integral Rocket Ramjet surface-to-air missile prototype.
1967	APL installs a new Digital Data Acquisition and Control System at the Propulsion Research Laboratory to provide computer control of the data-acquisition process.
1968	The Navy closes its Ordnance Aerophysics Laboratory in Daingerfield, Texas, and shifts the testing to the Propulsion Research Laboratory.
1971	The Thrust Augmented Rocket Surface-to-Air Missile program ends, and research on an Integral Rocket Ramjet surface-to-surface missile begins.
1974	Development of the Integral Rocket Ramjet surface-to-surface missile stalls after the successful introduction of the Harpoon missile. Meanwhile, the U.S. Naval Sea Systems Command asks the Propulsion Research Laboratory to begin exploratory development of an Advanced Surface-to-Air Ramjet Missile engine. Also, Dugger succeeds Avery as Aeronautics Division chief, and Keirsey moves up to lead the Propulsion Research Laboratory.
1977	Keirsey invents DCR engines, but the Navy cancels the SCRAM program.

Avery Laboratory Timeline (continued)	
1978	The Propulsion Research Laboratory begins work on an arc-fault detection system for the Naval Ship Engineering Center.
1983	The Propulsion Research Laboratory begins engine research and development for the X-30 National Aerospace Plane program. The Aeronautics Division becomes the Aeronautics Department.
1986	Congress terminates the DCR program.
1987	Dugger passes away and Keirsey retires. Dr. Paul J. Waltrup becomes the new head of the Propulsion Research Laboratory.
1989	Dr. Avery retires from his official duties. APL dedicates the Propulsion Research Laboratory to Avery and renames it after him.
November 1994	Congress cancels the National Aerospace Plane project.
1995	The Air Force contracts with APL to perform hypersonic research under its new HyTech program.
October 1996	APL disbands the Aeronautics Department in favor of a new Aeronautical Science and Technology Group (RAS) under Waltrup's direction, to be managed within the Milton S. Eisenhower Research and Technology Development Center. APL changes the name of the Avery Propulsion Research Laboratory to the Avery Advanced Technology Development Laboratory.
1997	APL begins establishing "alliances" with private companies and nongovernment institutions that will enable them to contract directly with APL for testing services. Additionally, the Avery Laboratory begins performing research and development for the Navy's Hypersonic Weapon Technology program and DARPA's Affordable Rapid-Response Missile Demonstrator. Paul Waltrup steps down as head of the Avery Laboratory. Dr. David Van Wie becomes the Avery Laboratory Facility Manager.
1998	APL begins a major refurbishment of the Avery Laboratory.
11 September 2001	Al Qaeda launches near simultaneous attacks inside the United States, instigating the country's Global War on Terror.
2002	DARPA and the U.S. Navy's Office of Naval Research jointly begin the HyFly program to develop and test a hypersonic Mach 6+, ramjet-powered cruise missile. Waltrup passes away. Van Wie becomes head of the Avery Laboratory and the Aeronautics Group.
May 2002	The HyFly DCR engine is successfully tested in a wind tunnel at a simulated speed of Mach 6.5.
2003	Van Wie leaves the Avery Laboratory to take another position within the Research and Technology Development Center.
2004	Dr. Avery passes away.
March 2005	The Research and Technology Development Center establishes a Red Team to evaluate the Avery Laboratory's long-term prospects and to provide options for keeping it open.
January 2006	APL decides to close the Avery Laboratory.
May 2006	The Avery Laboratory concludes its final test sessions and closes.

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