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THE BEGINNING OF HYPERSONIC RAMJET RESEARCH AT APL

"If we wish to emulate Puck in *Midsummer's Night Dream* and put a girdle round about the world in forty minutes, then we shall probably use ramjets."

R. E. Gibson, APL Director
In an address to a joint meeting of the American Rocket Society and the Institute of Aeronautical Sciences, New York, 8 February 1948.

THE SURVIVAL OF THE FITTEST

Early in 1955, William H. Avery was asked by his friend Martin Summerfield, the Editor-in-Chief of *Jet Propulsion*, to review progress in ramjet development for a special issue commemorating the twenty-fifth anniversary of the American Rocket Society. "Twenty-Five Years of Ramjet Development,"[1] which was published later that year, traced the history of the ramjet from 1913 to the mid-1950s, starting with the ideas of the Europeans Albert Fono and René Lorin and ending with the latest U.S. development, the supersonic Bumblebee missile Talos (Fig. 1). In the article, Avery looked ahead to promising future applications for ramjet engines in air defense missiles, in long-range high-speed transports, and even in nuclear-powered aircraft capable of nearly unlimited supersonic flight near sea level.

The article also pointed to the presence of a thermal barrier, a major technical obstacle that, at the time, no one could see around. It would be encountered, Avery wrote, by any ramjet flying faster than about Mach 4, 4 times the speed of sound. As the barrier is approached, the air temperatures in and around the engine increase, and as a result, "material problems for aircraft and engine construction become severe," and "the thermal efficiency of the engine decreases because dissociation of the products of combustion limits the temperature rise that can be attained in the engine."[1]

Avery read his own words about the limits of high-speed flight with an inward eye. By 1955, the major research and development work for the Mach 2 Talos had been over for several years. Super Talos, a secret ramjet missile designed to fly to the edge of the thermal barrier, was on the drawing board. What was next? Or had the ramjet already reached the end of its development?

The questions had been on Avery's mind for some time. Ramjets were facing increasing competition from turbojet and rocket engines. In 1953, Avery returned from a National Advisory Committee for Aeronautics (NACA) symposium with news that the Air Force's Boeing/Marquardt (BOMARC) ramjet program was being curtailed, and that the long-range ramjet, Navaho, was threatened with cancellation. He confided to APL Director Ralph Gibson his worry that the Bumblebee group (headed by APL) was likely to emerge as the only group working seriously on ramjet propulsion.[2]

Many years earlier, Wilbur H. Goss (the manager of the Talos program and the leader of the APL team that had flown the world's first supersonic ramjet in 1947) had observed that biological systems and weapons systems adapt to change in the same way. "The same immutable law holds," he said, " . . . the survival of the fittest."[3] By the end of the 1950s, the ramjet would be showing unmistakable signs of extinction.

Avery was an expert in rocketry, but he understood the importance of the ramjet. He knew that for flight in the atmosphere over ranges greater than 100 miles and at speeds greater than Mach 3, a ramjet was the only practical choice. If ramjet propulsion were to have an open future, and particularly if sustained hypersonic flight over the Earth were to be possible, it was essential that a way around the thermal barrier be found. Within a few months of the publication of his *Jet Propulsion* article, Avery and his associates at APL took the first steps to push the development of ramjets into the regime where the flight speed is more than 5 times the speed of sound. Despite the inevitable ups and downs of government programs, the work has continued ever since. The latest effort supports the National AeroSpace Plane Program.

The following sections are the first part of a two-part history. Part I describes the events surrounding the two most significant achievements of APL's hypersonic propulsion work of the 1950s: (1) the successful testing of a unique hypersonic ramjet engine, and (2) the development of a concept for a ramjet-powered hypersonic airplane. Part II, to be published separately, will focus on the research carried out in the 1960s and 1970s on supersonic-combustion ramjets (Scramjets) and in particular on an APL invention called SCRAM, the first supersonic-combustion ramjet missile.

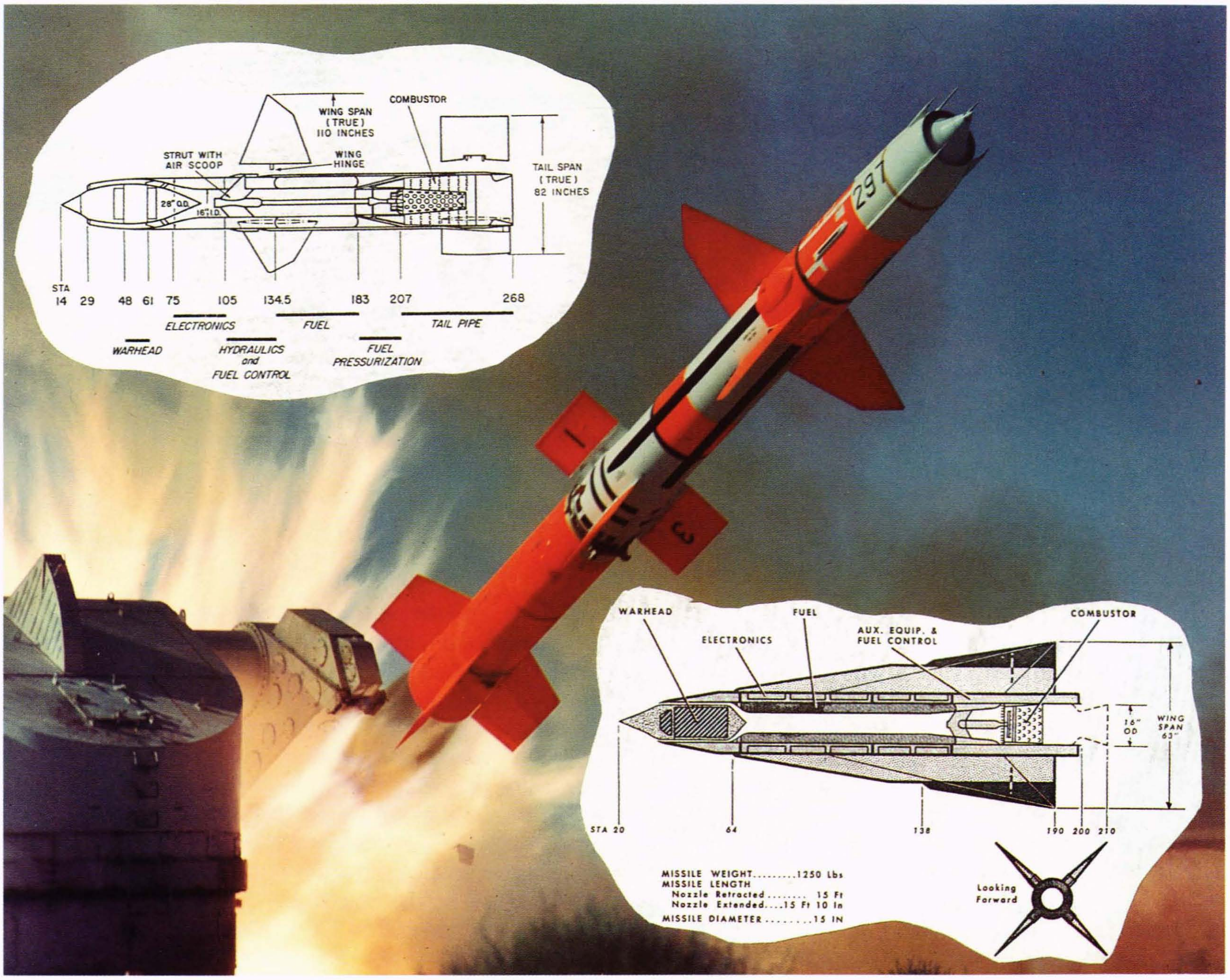


Figure 1. Talos was operational from 1958 to 1980. In one five-year period, 326 test flights were made without a failure, and (in 1965) each missile cost only about $75,000. The upper inset shows the general internal layout of Talos. Super Talos (lower inset) evolved into the long-range Typhon missile, which was successful in eight of nine test flights at Mach numbers up to 4.2. The Typhon program was canceled in 1962, due principally to the excessive cost and weight of the shipboard guidance and control equipment.

PROPULSION AT THE END OF THE POSTWAR DECADE

At the time he wrote his review article on ramjets, Avery was the supervisor of the Bumblebee Launch and Propulsion Group (BLP), which consisted of about 100 people (Fig. 2). He had come to APL eight years earlier at the age of thirty-five to rejoin his wartime colleagues, Ralph Gibson and Alexander Kossiakoff, among others, who had moved to APL from the old Section H of the National Research and Development Council (NRDC), an organization established in 1940 to carry out critical research and development projects during World War II. Section H ("H" for Clarence Hickman, its leader) had been largely responsible for developing solid-propellant weapons, including artillery rockets and the bazooka. (For his part in this work, Avery was later awarded a Presidential Citation, presented personally by Harry S. Truman.) The NRDC's Section T ("T" for Merle Tuve), the group that had developed the proximity fuze, became The Johns Hopkins University Applied Physics Laboratory.[4]

During the last months of the war, the fear that new types of guided weapons might be able to attack naval task forces caused the U.S. Navy's Bureau of Ordnance to ask APL to undertake the urgent development of "a guided jet-propelled anti-aircraft missile, preferably with supersonic speed."[5] Johns Hopkins officials decided to accept the assignment in December 1944.

The missile was to carry a 600-pound warhead over a range of ten miles to attack high-speed air targets at altitudes up to 30,000 feet. In those days, only a ramjet, boosted by a solid rocket, had the necessary acceleration, speed, and range to meet the specifications.[3] Developing Talos, named for the mythical defender of Crete, became Task F, code name Bumblebee. The first flight tests took place in February 1945.[6]

Soon after the war, the requirements for Talos were revised. The new goal was to extend the range of air defense to sixty miles. In addition, APL was to undertake the development of a supersonic surface-to-surface ramjet missile with a range of 2000 nautical miles, capable

Figure 2. William H. Avery started APL's work on hypersonic ramjets in 1956.

of being launched from a submarine. This missile, the second Bumblebee ramjet, was named Triton[7] (Fig. 3).

The first decade after World War II was a confusion of change in military theory and technology, especially in aviation. Many activities related to jet propulsion got under way at several organizations. A menagerie of rockets, rocket-boosted research airplanes and glide vehicles, turbojet missiles and aircraft, and several ramjets (BOMARC, Navaho, and the X-7 test vehicle) were under study or development in parallel with the APL Bumblebee program[8] (see the boxed insert entitled "The State of the Art, 1955"). By 1955, however, the lines between the technical options were becoming more clearly drawn: turbojets were favored to provide power to manned aircraft; solid-propellant rockets had the edge for short-range applications; and liquid rockets were the only option available for flight outside of the atmosphere. Ramjets vied with rockets for long-range, high-speed, surface-to-air and surface-to-surface missions.

The guidance of missiles was a major problem. The state of the art in the 1950s was such that surface-to-air ramjets could easily outfly the range of effective guidance and fire control. Without reliable long-range guidance, the air defense role would go to the shorter-range solid-propellant rocket, with its smaller volume, higher acceleration, and more attractive logistics. But even if improvements in guidance kept pace, so that the advantages of increased range and payload could be brought to bear, future surface-to-air ramjets would have to travel extremely fast to intercept retreating or feinting attackers, which one presumed would be moving at supersonic speeds a great distance away and at high altitude. Studies at APL suggested that a defensive missile might need to reach Mach 10.[9]

For long-range surface-to-surface missions, the liquid-rocket intercontinental ballistic missile (ICBM) seemed to offer complete invulnerability in contrast to its air-breathing counterparts. Cruise ramjets would have to fly much higher and much faster than they could in 1955 if they wanted to compete with long-range rockets. Although airbreathers held the theoretical edge for hypersonic near-Earth travel, the need for advanced guidance methods, exotic high-temperature materials, and new design and testing methods put them at a considerable disadvantage in hurried times.

LOOKING AT POSSIBILITIES

Avery was a busy man in 1955. Besides having the principal job of supervising BLP, he was a member of several national committees on propulsion technology, and he maintained an active professional career—writing and reviewing technical papers, and organizing and attending meetings. On top of all of these roles, he became the coordinator of the Bumblebee research and development (R&D) program in 1955. This program was concerned with more than propulsion technology. Some of the other topics under study were advanced guidance methods, countermeasures technology, and the application of transistors to missile systems.[10]

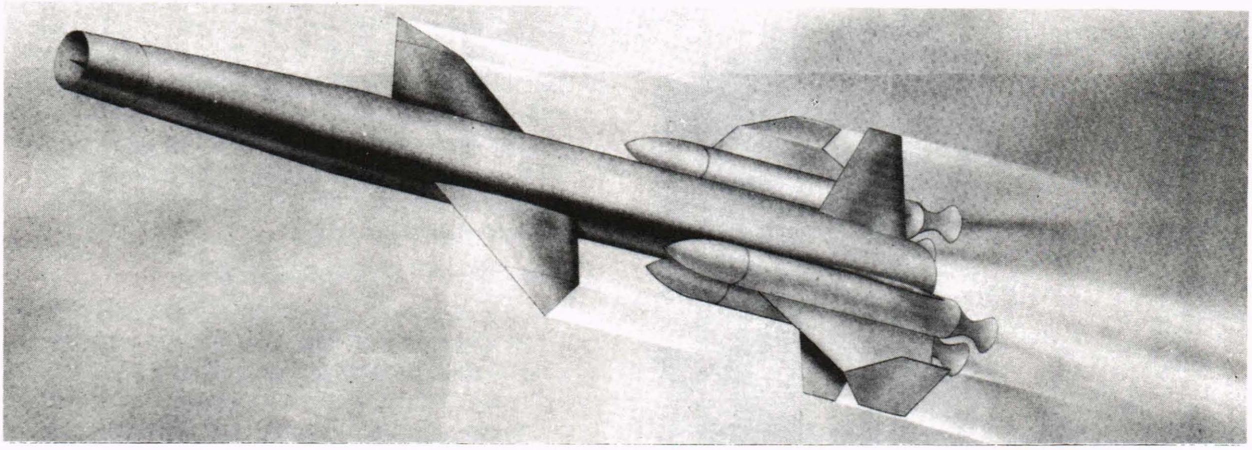
Early in 1956, several months after Avery took on his new R&D responsibilities, the Bureau of Ordnance decided to conduct its first long-range (twenty-year) planning exercise in response to the "rapid technological changes taking place in the Navy's weapons programs."[11] It fell to Avery to assemble APL's contribution to the plan. One of the technological areas to be included was advanced propulsion, and the subjects considered by Avery's planning team ranged from exotic high-energy fuels and nuclear ramjets to spaceflight.

Supersonic combustion was not a new subject in 1956 (see the boxed insert entitled "Other Pioneers"), but its role in helping ramjets break through the thermal barrier was largely unexplored. If fuel could be introduced, mixed, and burned efficiently in a supersonic stream, then the high temperatures and pressures that ordinarily resulted from the deceleration of air to subsonic speed in a ramjet engine intake could be avoided. The lower pressure would substantially reduce both the mechanical stresses and the rate of heat transfer in the engine, and the lower temperature would prevent, or at least diminish, the losses due to chemical dissociation.

At the time, however, the means for mixing and burning fuel in supersonic flow without producing massive shock waves seemed beyond reach. Besides, many people believed that there was no point in worrying about supersonic combustion at all because at hypersonic speeds the losses in the inlet would be too high to permit flight anyway.

As part of the planning work for the Bureau of Ordnance, Avery asked E. James Hargrave, the assistant supervisor of the Talos propulsion project in BLP, to look into the prospects for hypersonic ramjets, and in particular to concentrate on the inlet, since its expected poor performance might be insurmountable. The question was, "Given the expected high losses, are hypersonic ramjets feasible at all?"

Hargrave turned the job over to James Keirsey, a thirty-year-old engineer who had come to APL in 1951 from



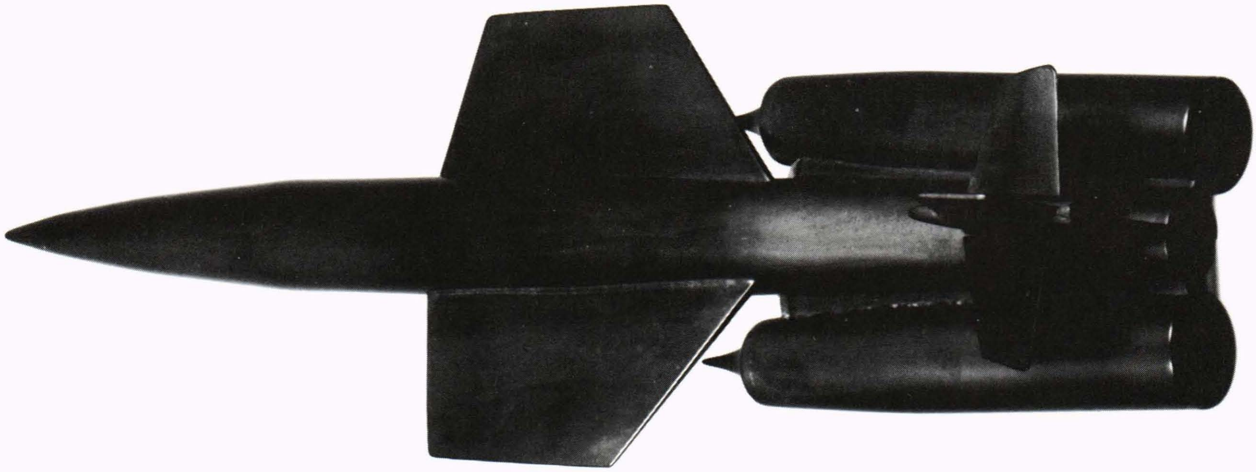


Figure 3. (Top) This 1951 drawing shows the early design concept of Triton, a very large missile intended for launching at sea. (Bottom) A wind-tunnel model of a later version, with its two ramjet engines mounted in the high-pressure region under the wings. The Triton program was canceled in 1958.

the Ordnance Aerophysics Laboratory in Dangerfield, Texas, where he had helped with the early testing of the Talos engine[12] (Fig. 4).

Answering Avery's simple question was not simple at all. The usefulness of a high-speed ramjet is determined by the small difference between two very large numbers: gross thrust and overall drag. Feasibility, therefore, hinges on achieving high efficiency in all engine components, with almost no margin for imperfection.

No wind-tunnel or flight test data at hypersonic Mach numbers were available to guide Keirsey's interpretation, so his conclusion about the feasibility of hypersonic ramjets was equivocal. But the notion seemed to him to be worth exploring. He wrote, "It is recommended, on the basis of these calculations, that ramjet diffusion R&D work be supported for determination of diffuser characteristics up to at least Mach 10, and that estimates be made of the drag of expected configurations . . ."[13] Others, including Hargrave, were more skeptical.[12]

"Maybe" was better than "No," however. Avery's group began to look for ways to close the gap between theory and technology. A ramjet that could operate between Mach 5 and Mach 10 became a new goal.

GETTING ORGANIZED

Avery was, by nature, interested in more than planning. He already had Arthur Westenberg and Robert Fristrom at work on the fundamentals of high-temperature chemical kinetics, and H. Lowell Olsen, the assistant supervisor of BLP, was beginning to lay the plans for a propulsion research facility that could be used to test engine components and materials at Mach numbers as high as 10. Working on hypersonic propulsion in this piecemeal fashion was not going to be enough, however. Avery needed to find someone to organize and lead a coherent project that would take an engine all the way from theory to hardware.

He first offered the job to his friend, D. B. Spalding, an internationally renowned combustion scientist from the Imperial College in London. Spalding found the offer a flattering suggestion, but he turned it down.[14]

A few months later, following a meeting of the NACA Subcommittee on Combustion, Avery was having dinner with Roland Breitweiser, the head of the Propulsion Section of NACA's Lewis Laboratory (Avery and Breitweiser were both committee members). Breitweiser had brought along a friend, Gordon Dugger, who had worked at the

THE STATE OF THE ART, 1955

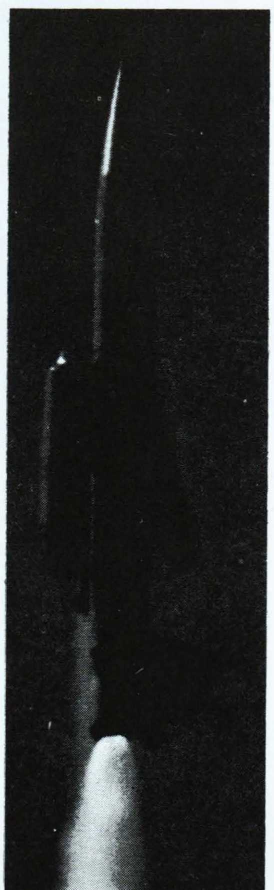
By 1955, the once ponderous and inefficient turbojet engine was well-entrenched as the power plant for manned jet aircraft. At low speeds, it was head and shoulders above any other jet-propelled device in fuel economy. In theory, high turbine temperatures limited its top speed to between 2 and 3 times the speed of sound, but although supersonic military jets were flying in 1955, Mach 3 airplanes were still years away. The appearance in 1955 of the J79 engine (the first lightweight high-compression-ratio engine in the United States with very low fuel consumption) opened a bright future for jet aircraft. The Boeing 707, derived from the B-47 and B-52 military designs, had taken its first test flight a year before, and the first long-range supersonic bomber, the B-58, was about to be rolled out. Work on the B-70, a Mach 3 intercontinental bomber, was in its early stages. Because developments in commercial aviation tended to follow those in military aviation, some people were already beginning to look ahead to airline travel at supersonic speeds.

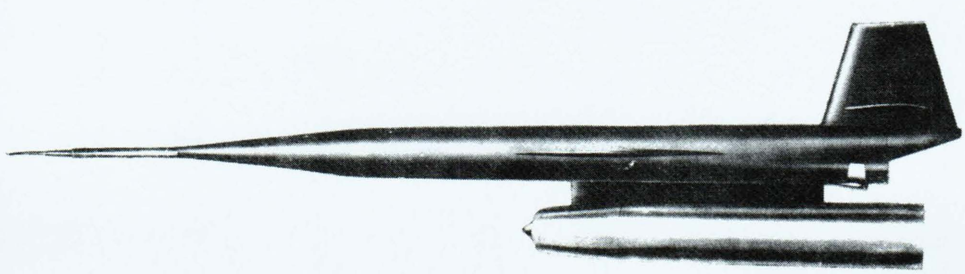
By virtue of their high acceleration but enormously high fuel consumption, solid-propellant rockets were relegated to quick-response short-range applications, such as close-in air defense or rocket-assisted takeoff. One of the solid-propellant test vehicles developed to carry out research for Talos became the first fleet defense missile—Terrier. The great advantage of solid-propellant rockets was that they could be stored in a ready-to-fire condition for long periods. In 1955, solid-propellant rocket motors could only be cast in relatively small diameters, and the burning of the grain was somewhat unpredictable and difficult to control.

Liquid-propellant rockets, complex and still unreliable, were the only option for long-range flight outside of the atmosphere since, like all rockets, they carried their own supply of oxygen. They were perhaps as much as 50% more efficient than solid rockets, and their thrust could be controlled precisely over a long duration. Long-range rockets avoided the aerodynamic heating that plagued high-speed airbreathers by traveling slowly in the dense part of the atmosphere during lift-off, and the heating problem associated with returning to Earth at high speed had turned out to be less difficult than first supposed. Combined with a dramatic reduction in the size of nuclear warheads, the solution of the reentry problem greatly improved the prospects for intercontinental ballistic missile (ICBM) weapons. In fact, development of the Atlas ICBM had been approved in June 1954. The Navy, anxious to enter the strategic missile arena, soon began experimenting with a version of the Jupiter liquid rocket to be based on ships and submarines.

Leaders of the exciting and successful X-airplane research program revealed the goal of extending their flights into the hypersonic regime, announcing in January 1955 the plan to develop a liquid-rocket-powered airplane, the X-15. On 29 July 1955, President Eisenhower unveiled the Vanguard program, to launch what everyone believed would be the world's first artificial Earth satellite.

The ramjet, the lightest and simplest of the jet propulsion engines, suffered from not being able to produce thrust unless boosted to high speed, usually by a solid-propellant rocket (see the accompanying figure). Nevertheless, it was still the power plant of choice for high-speed long-range flight in the atmosphere, and its reliability had proven to be exceptional. Above Mach 3, the ramjet was more efficient than the turbojet. In fact, theory predicted that, using hydrocarbon fuels, it did not reach peak efficiency until Mach 7. Ramjets were considered more accurate than ballistic missiles or solid-propellant rockets because they could fly under power all the way to the target, and they also had the potential of being able to return from long-range reconnaissance missions, or in more general terms, of being reused. In mid-1955, the first fully weaponized version of Talos was tested.





The Boeing/Marquardt ramjet is launched (left). The X-7 ramjet test vehicle is shown (right), fitted with a Navaho engine.

OTHER PIONEERS

The idea that fuel might be burned in a supersonic airstream to produce forces on bodies in flight appears to have arisen at several organizations near the end of World War II, motivated for the most part by attempts to increase the range of gun-launched projectiles (see the accompanying figure). Researchers at the Lewis Laboratory of the National Advisory Committee for Aeronautics (NACA) were more interested in augmenting lift, thrust, and maneuverability by injecting fuel directly under the wings of high-speed fighters. They centered their investigations on the use of pyrophoric fuels, the same category of hyperactive fuels used later at APL to power external-burning ramjets.

Some extensions of the wartime research were published openly in the early 1950s.[51-53] Critics later contended that these early experiments achieved combustion only in subsonic pockets of the flow; that is, they claimed that true supersonic combustion had not occurred. Researchers at NACA disputed this charge.[54] The controversy was significant at the time because, for primary propulsion applications at extreme flight velocities, the benefits of supersonic combustion revolved around avoiding the high temperatures and pressures that accompany the deceleration of the flow to subsonic speeds. Nevertheless, the work at the NACA Lewis Laboratory spawned theoretical studies that proved to be very helpful to Gordon Dugger, James H. Walker, and William H. Avery at APL in formulating the first integrated engine design for hypersonic flight.[18]

The Marquardt Corporation produced a subsonic-combustion ramjet engine for a manned airplane in 1944 and later developed the ramjet engine for the Boeing/Marquardt (BOMARC) missile. Marquardt may also have been the first company to study the internal supersonic-combustion ramjet engine. A 1962 memo written by Dugger sheds some light on this speculation and also adds some information about the origin of the term "Scramjet," which is commonly used to denote the internal supersonic-combustion ramjet engine: "Marquardt has, of course, been experimenting with ducted supersonic burning longer than anyone else (since 1957), and they have made many analyses of Scramjet performance. Incidentally, they did use "SCRAM" as an acronym over two years ago in reports, so they scooped us on what we thought was an original acronym for our naval air defense missile . . . "[55]

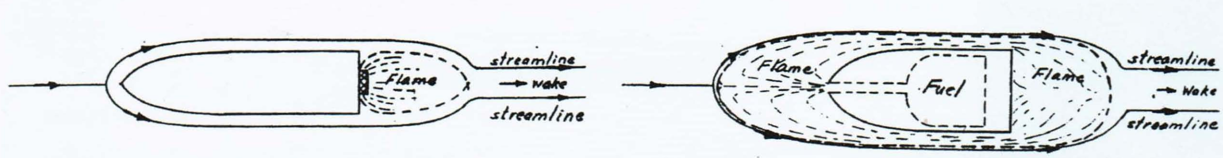
In the late 1950s, R. Dunlap and his co-workers at the University of Michigan and Robert Gross of Fairchild Aircraft Corporation promoted the concept of a detonation-wave hypersonic ramjet engine (see the boxed insert entitled "Hypersonic Ramjets").[56,57] The concept was later dismissed by the supersonic-combustion ramjet's chief proponent, Antonio Ferri, as impractical, and it was never seriously considered.[58] Nevertheless, interest in the approach persists today in several areas of application.[59]

In 1958, Richard Weber and John MacKay of the NACA Lewis Laboratory were the first to publish a complete analysis of the performance of supersonic-combustion ramjets. Although they found only small gains over conventional ramjets in the Mach number range from 4 to 7, they concluded that the trends developed indicated that the supersonic-combustion ramjet would provide superior performance at higher hypersonic flight speeds.[60]

The first person to envision a ramjet that could fly to orbital speeds and beyond seems to have been Roland Breitweiser, the head of the Propulsion Section at the NACA Lewis Laboratory. Around 1957 or 1958, Breitweiser held up the prospect of a hydrogen-fueled, fuel-rich, subsonic-combustion ramjet that might be able to achieve speeds up to 40,000 feet per second (using stored oxygen to make up gradually for the diminishing oxygen concentration at extreme altitudes).[61,62] Rich operation (supplying more fuel than is required for complete combustion in air) was proposed to lower the combustion temperature and thereby avoid the penalties of molecular dissociation at high speed.

Proposals to use a hydrogen-fueled supersonic-combustion ramjet engine to power an aircraft to orbital speed were published a few months apart by Ferri[63] and by D. L. Mordell and J. Swithenbank.[64] In the present context, it is particularly interesting to note than an important part of the research leading to Ferri's proposal was supported under an APL subcontract.[65] Ferri's principal ties, however, were to the U.S. Air Force through the Aero Systems Division at Wright Patterson Air Force Base. The first ground test of a complete hydrogen-fueled supersonic-combustion ramjet engine that could produce net thrust was performed in 1963 by Joseph Schetz, Ferri's erstwhile protégé at the General Applied Sciences Laboratory and an APL consultant since 1964.[66,67]

By the early 1960s, the allure of hypersonic ramjets had stirred nearly every organization in the propulsion business. Most major aviation companies in the world had active supersonic-combustion ramjet projects.[68] Interest at APL was focused on long-range liquid-fueled missiles for air defense.



These sketches are reproduced from *The External Ram Jet*, a 1950 report by Hebrank and Hicks.[51]

Figure 4. In 1956, James Keirsey carried out the first calculations at APL of the performance of hypersonic ramjets. In this photograph, taken in the early 1960s, Keirsey is shown holding an early model of a unique hypersonic inlet, which he invented for use on APL's supersonic-combustion ramjet missile (SCRAM).

Figure 5. Gordon Dugger, pictured in 1959, led APL's first hypersonic propulsion project. At the time of his death in 1987, he was head of the Aeronautics Department.

Lewis Laboratory for several years while studying for a Ph.D. degree in chemical engineering[15] (Fig. 5).

Dugger, although very quiet at dinner, appeared to be enthusiastic about high-speed propulsion, and he was also anxious to return from Florida, where he had moved after receiving his degree.[15] Avery had never met Dugger, but he had known about him since 1952, principally because that year Avery and Robert Hart had used Dugger's data on flame speeds in their widely acclaimed paper on the limits of ramjet combustor performance.[16] Dugger impressed Avery as being sharp, pragmatic, and thorough. He would be able to understand Avery's ideas and put them on a sound technical basis.[15]

Dugger joined APL in January 1957, and in November of that year he was appointed supervisor of Project D-53, the first hypersonic propulsion project in the Bumblebee program.[17]

For several months, Dugger and Avery discussed several propulsion options before finally deciding to focus their attention on the external-burning ramjet (ERJ), which offered several advantages over other hypersonic engine concepts (see the boxed insert entitled "Hypersonic Ramjets"). First and foremost, it was the simplest. The most rudimentary design was simply an inverted double wedge (later designated ERJ-1), in which fuel was injected just ahead of the knee. The absence of a cowl meant that all surfaces were free to radiate heat to the atmosphere, thereby lowering their temperatures considerably. This open "inside-out" engine design also allowed the basic processes involved in adding mass and heat to a supersonic flow to be seen directly, a feature that offered the potential of extending whatever was learned to other hypersonic engine concepts. A high degree of engine–airframe integration, a topic of longstanding importance to Avery, was inherent in the ERJ design.[15] The forces that produced thrust also produced lift, and Avery believed that the prospect of achieving a high lift-to-drag ratio (L/D) at hypersonic speeds made the ERJ a promising candidate for an advanced long-range vehicle, such as a follow-on to Triton. Not everyone at APL agreed that the concept was worth pursuing, notably James H. Walker, the head of the Bumblebee Preliminary Design Group. He and others thought that the ERJ's inherent propulsion efficiency was too low, and that the same improvement in L/D could be better achieved by simply flying at a slightly greater angle of attack.

The available theoretical models of external burning showed that an ERJ could not produce much thrust, but that once accelerated to cruise speed, its predicted performance should be comparable to that of a conventional ramjet at Mach numbers above about 8, with much-diminished thermal problems.[18] At the outset, Dugger worried that this model might be too simple and perhaps unrealistically optimistic about the amount of compressed air that could be captured for combustion, as well as about the rate at which combustion would occur over the rear wedge.[19] Keirsey suggested adding a very short cowl at the knee of the ERJ.[20] This alternative design allowed the appropriate quantity of air to be captured, provided time for ignition and combustion, and reduced the loss of thrust caused by the expansion of the flow around the knee. Most of the benefits of radiation cooling were preserved, except, of course, that parts of the cowl were now subject to high temperatures.

HYPERSONIC RAMJETS

In a classified report written in 1959, William H. Avery and Gordon Dugger explained the principles of operation of the various engine cycles then being considered for hypersonic power plants.[9] The report was later declassified, and major portions of it were published openly.[69] Excerpts of the text and figures from these references provide a clear description of the distinctions among the various types of hypersonic ramjets, as they were recognized at the end of the 1950s:

"The conventional ramjet engine [Fig. I(a)] operating in the Mach 2–4 range uses an inlet that compresses the air at first supersonically and then subsonically until the Mach number of the flow at the combustor inlet is reduced to about 0.2. Fuel is then injected and burned, the burned gases expand subsonically to the nozzle throat, and then supersonically to the exit. The latter part of the process is identical to what occurs in a rocket exhaust."

"As the flight speed goes up, less volume will be required for the combustion chamber due to higher inlet temperature and pressure, but the exhaust nozzle will necessarily become much larger [because of the higher expansion ratio] [Fig. I(b)]."

"In the conventional ramjet, the major part of the kinetic energy of the inlet air is converted to potential energy in the form of increased pressure (effectively, the stagnation pressure) before it enters the combustor. However, as speed is increased, such drastic air compression becomes inefficient, and the stagnation temperature becomes intolerably high, which causes losses due to energy absorption and the unwanted dissociation of reaction products. These two effects reduce the net thrust of the engine to zero at about Mach 10, depending on the fuel used and the engine design."

"As the hypersonic regime is entered, say $M > 5$, the CRJ [conventional ramjet] requires complex and expensive solutions to structural or cooling problems."

"An obvious path of evolution which would relieve the structural or cooling problem[s] significantly is one which seeks designs to take maximum advantage of thermal radiation. The ultimate in this regard would be the pure external ramjet of [Fig. I(d)] in which heat addition and expansion occur over the external surfaces of a body or airfoil . . . the overall efficiency expected for such an engine is only a small fraction of that obtainable with a CRJ, so that it would appear that the application of this engine would be limited to situations where the low efficiency is compensated by the simplicity of the system."

"A modification falling between the CRJ and the pure external engine is illustrated by [Fig. I(c)]. It comprises an external supersonic diffuser, a short subsonic duct in which fuel is added in such a way as to choke the exit, and an external or plug-type nozzle. Analysis and experience with plug-type nozzles have shown that such an engine could be designed to give an overall efficiency comparable to the CRJ. In addition to the thermal radiation advantages offered by the external nozzle, a bonus in lift can be ob-

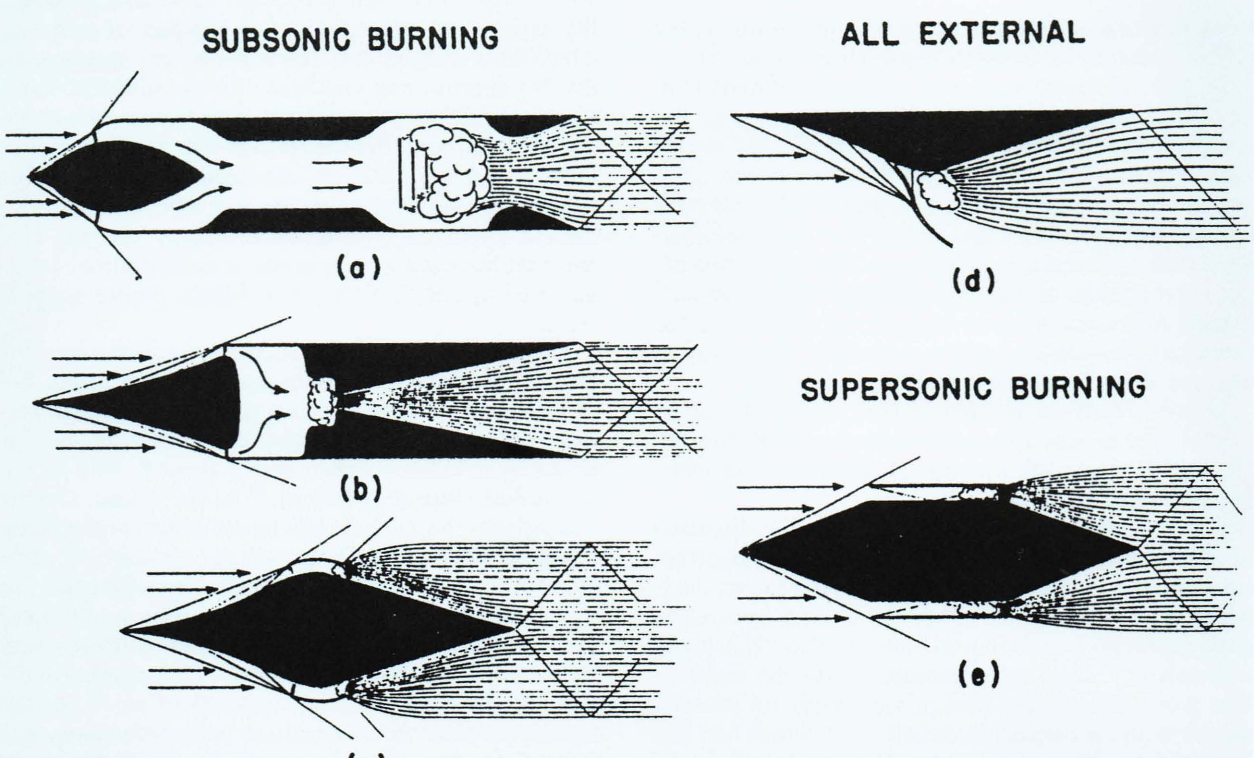


Figure I. Possible paths of evolution for the hypersonic ramjet. (a) Conventional ramjet engine. (b) High-speed subsonic-combustion ramjet. (c) External expansion ramjet. (d) Pure external ramjet. (e) Supersonic-combustion ramjet.

tained with very little loss in thrust or efficiency by cutting the engine in half longitudinally or making it in a flat-top, two-dimensional configuration."

"Another engine of considerable theoretical interest is the supersonic-combustion ramjet, or SCRJ, illustrated in [Fig. I(e)]. In this engine, the airflow is decelerated only to Mach 2 or 3 before fuel is added . . . The SCRJ would have structural advantages over the CRJ due to lower internal pressures. It is not likely that it would have a lower cooling requirement, because its lower heat transfer rate per unit area would probably be outweighed by the greater length and hence area required to complete mixing and reaction in supersonic flow. The practical problem of achieving fuel injection without large shock losses and then completing the mixing and reaction in a few tenths of a millisecond is a formidable one."

"A modification to the SCRJ which would permit a decrease in combustor length at the expense of a total pressure loss is the standing-wave engine, or SWRJ [Fig. II] . . . An oblique detonation wave is stabilized on a wedge; the wave angle varies with flight Mach number and fuel–air ratio. Reaction time is reduced to practically zero, but the problem of fuel injection and mixing in supersonic flow ahead of the wave remains."

"This discussion of expected performances for high-speed engines may be summed up as follows [Fig. III]: The conventional ramjet would give the highest overall thrust efficiency and best fuel economy in the Mach 4 to 7 range. The modified, two-dimensional, external expansion ramjet . . . would have a slightly lower thrust efficiency but would permit an increase in range by virtue of a net increase in the [product of specific impulse and lift-to-drag ratio]. Either of these engines . . . would have to be boosted to supersonic speed by another power plant. For missiles, a rocket booster would probably be used; for transport aircraft, a turboramjet with Mach 4 capability is a likely choice. For hypersonic speeds above Mach 7 or 8, either a supersonic heat-addition engine or a standing-wave engine would be superior to a subsonic combustion engine, provided that the formidable problems related to fuel injection and mixing could be solved. The external asymmetric expansion feature of the [external expansion ramjet] should be sought in any case. Airbreathing engines will have superior fuel economy—a governing factor for a reusable vehicle—compared to rockets for speeds to at least Mach 10 and possibly much higher if either the supersonic heat-addition or standing-wave principle proves feasible."

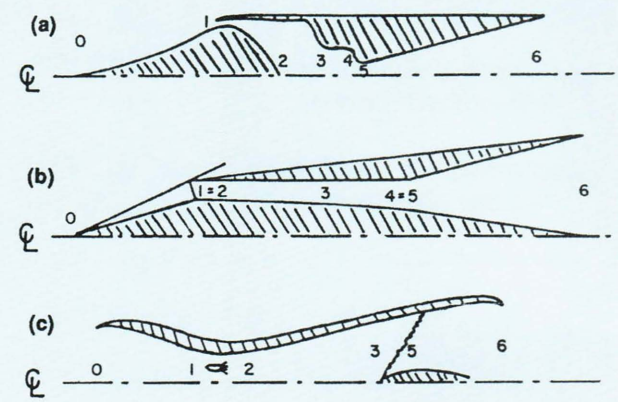


Figure II. Hypersonic ramjet forms. (a) Conventional ramjet. (b) Supersonic-combustion ramjet. (c) Standing-wave ramjet.

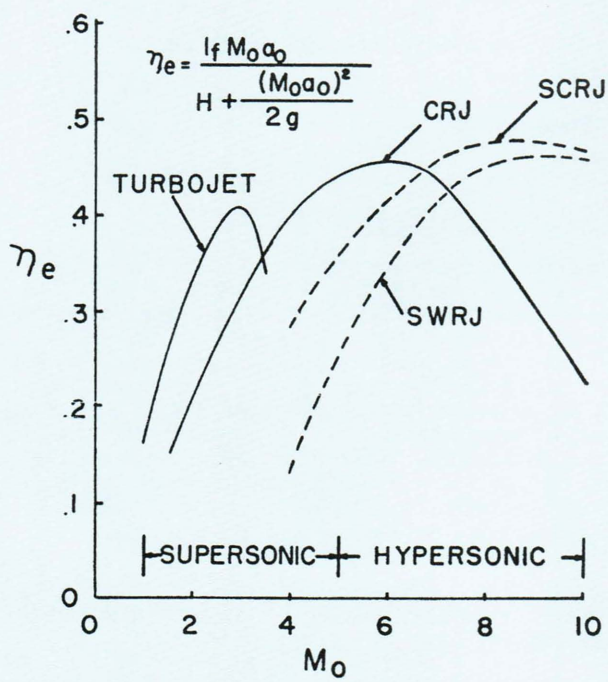


Figure III. Efficiencies for airbreathing engines. CRJ = conventional ramjet, SCRJ = supersonic-combustion ramjet, SWRJ = standing-wave ramjet.

Nevertheless, it was envisioned that the velocity of the flow in the short combustor would be high (but generally subsonic), and that transverse fuel injection and spontaneous combustion could be made to occur very near the duct exit, minimizing the total heating load. The concept came to be called the external expansion ramjet (EERJ) and was designated ERJ-2. Technically speaking, it was not a true external-burning ramjet (Fig. 6).

The two designs, ERJ-1 and ERJ-2, were the central test pieces of Project D-53. In his first APL memo, Dugger said that the principal question to be answered was, "Can a positive net thrust be obtained by external burning near the surface of a body in supersonic flight?"[21] Louis Monchick soon joined the research group to extend and apply the theory of external-burning ramjets, and Sidney Spencer was assigned the job of designing a new 6 in. × 7 in. Mach 5 wind tunnel.[22,23] The tunnel would simulate flight at altitudes up to 90,000 feet at temperatures between 1200 and 1800°F, and the schedule called for its completion by October 1957.

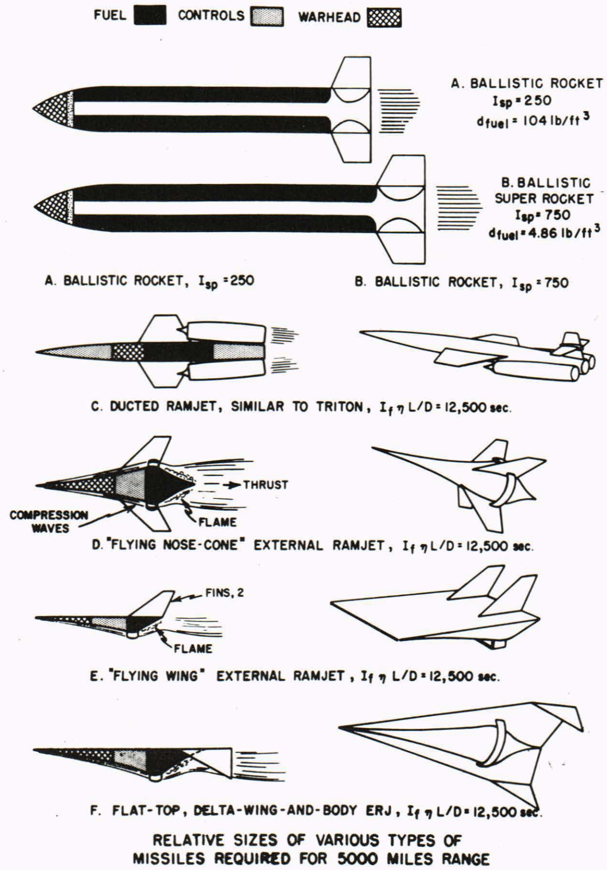


Figure 6. This figure is reproduced from Gordon Dugger's first APL technical memorandum. The sketches compare various types of missiles, showing the size advantage of hypersonic ramjets. The presence of a short cowl on the ramjet missiles indicates that the external expansion ramjet was considered as an option from the beginning. In the memorandum, however, Dugger doubts that an external expansion ramjet could be used at speeds above Mach 5. The term "super rocket," appearing in the upper part of the figure, designates a rocket that might use fuel laced with atomic hydrogen. So-called free-radical propellants were a major topic of interest in the 1950s.

Numerous problems caused this target to be missed by more than a year.

THE FIRST ENGINE

Although Dugger did not realize it at the time, the fate of the ERJ project would be sealed before the first test could be conducted in the new tunnel. The Triton program, upon which much of the justification for ERJ research was based, was canceled, the victim of a rocket-powered missile named Polaris. As a consequence, interest in long-range airbreathers soon faded, and with it the funding for Project D-53.

One of the few benefits of the Triton cancellation was the entrance into Project D-53 of a young experimentalist who would later become a key figure in hypersonic propulsion research. Frederick Billig, who had been assigned to the Triton program, was recommended to Dugger as someone who had a knack for getting things done[12] (Fig. 7). Billig was weary of the ups and downs of Triton,

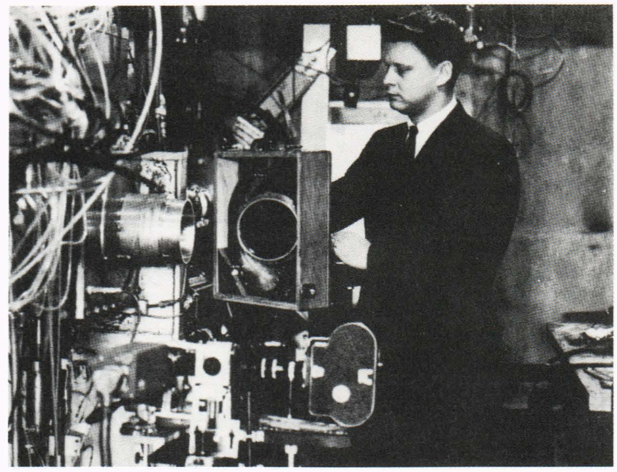


Figure 7. Frederick Billig stands beside the Mach 5 wind tunnel in which he conducted the first successful test of an external-burning ramjet model.

and since he was studying part-time for a Ph.D. degree in engineering, he was anxious to find work more oriented toward research.[12] Dugger asked him if he would be interested in getting the Mach 5 wind tunnel up and running and then taking charge of the external-burning experiments.[24]

Hypersonic tunnels are not easy to build, and the task was especially difficult in the 1950s. In July 1958, when Billig joined Project D-53, he found the Mach 5 tunnel beset by leaks and makeshift repairs. When, after considerable work, extended test runs were finally possible, the thermal stresses that arose were very large. The diffuser section of the tunnel glowed white-hot and had to be supported from the ceiling with straps.[25] Nevertheless, by February 1959, Billig had the tunnel ready for the first tests with the ERJ-1 engine model.[26]

The plan was to use hydrogen as the fuel for the initial trials.[27] For nearly a month, Billig tried time and again to carry out the work Dugger had outlined, but in the tunnel's low-pressure environment, the hydrogen just would not ignite. Dugger had foreseen this possibility. In an early memo, he noted that it might be necessary to develop an ignition system based on electric spark heating, pyrotechnic flares, or high-energy fuels (HEF's).[21] In the mid-1950s, the subject of HEF's was near the top of the list of high-priority propulsion topics. Project ZIP was established to develop special fuels, principally mixtures of borohydrides, for the B-70 long-range bomber (canceled in 1959). Developers of other airbreathers, including APL, were interested in special fuels, too, since the possible increases in range were substantial. With the same fuel load, Triton's range might be nearly doubled. One of the foremost experts in this area was Walter Berl, who led the HEF effort at APL.[28] He had accumulated and tested a wide variety of exotic fuels, and a ready supply was on hand.

Electrical ignition had not worked. Billig generated gigantic arcs at the ERJ-1 injection station, but to no avail. He felt that, at this rate, nothing was going to be learned, so he reluctantly resorted to rummaging through

Berl's collection of fuels. He decided to try triethyl aluminum, a pyrophoric liquid—a liquid that reacts spontaneously (and violently) on contact with air.[25]

The results of the tests on 5 March 1959 were dramatic. A vigorous white flame erupted over the rear of ERJ-1 the instant the triethyl aluminum fuel entered the tunnel, jolting the model against its support.[25] The pressures measured on the rear surface jumped upward. Calculations soon showed that, for the first time, a hypersonic propulsion device had actually produced net thrust[27] (Fig. 8).

For Billig, it was a mixed victory. Scarcely eight months after he had joined the project, the tunnel was working, and the prime experimental objective had already been achieved. But the need to resort to pyrophoric fuels was dissatisfying, and he was worried that the research had fallen short. Somewhat to Billig's surprise, Avery and Dugger were extraordinarily pleased.[26]

The thrust produced in the first successful ERJ test was small—less than one pound—and the overall thermal efficiency was very low.[29] But, as Dugger reported, such results with a small-scale device were "not surprising because from visual observation it appeared that the major part of the combustion occurred downstream of the model where the pressure rise was of no benefit."[30] Nevertheless, a large amount of lift had been generated, making the ERJ very interesting as an effective lift-enhancement device. Later testing showed that a substantial amount of the combustion occurred in supersonic regions of the flow, so the experiment represented the first test of a thrust-producing supersonic-combustion ramjet engine.[25]

The ERJ work produced a fairly complete understanding of external-burning ramjets, and the work was eventually extended to the testing of larger-scale devices at the Ordnance Aerophysics Laboratory.[31] The EERJ model (ERJ-2) was built but could not be made to operate as intended.[20] Billig and Edward Seaquist had designed a sophisticated model, made of molybdenum and fitted with internal cooling jackets, a flexible fuel-injection system, and provisions for geometric compensation (needed to correct for the changes in shape due to heating) (Fig. 9). But the test data, obtained with hydrogen fuel, showed that the flow through the model was supersonic, instead of subsonic. Billig remains convinced that these tests constitute the first demonstration of a ducted supersonic-combustion engine, although the results were never published.[25]

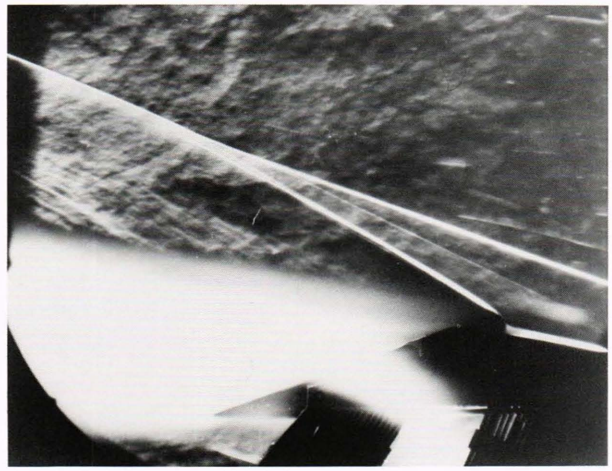


Figure 8. Supersonic combustion at the rear of an external-burning ramjet model is shown in this schlieren photograph taken in a Mach 5 flow. The double wedge model is upside-down, with its knee pointing upward, and the air flows from right to left. The first shock wave is produced by the model's leading edge (out of view). The second shock is caused by the injection of fuel. The bright region is due to the emission of light from the flame.

Nothing could change the fact that an ERJ was only useful as a sustainer engine for hypersonic cruise within the atmosphere, or perhaps as a lift-augmentation device. It showed no promise at all as a primary power plant. Without the impetus of Triton, the Navy saw no future

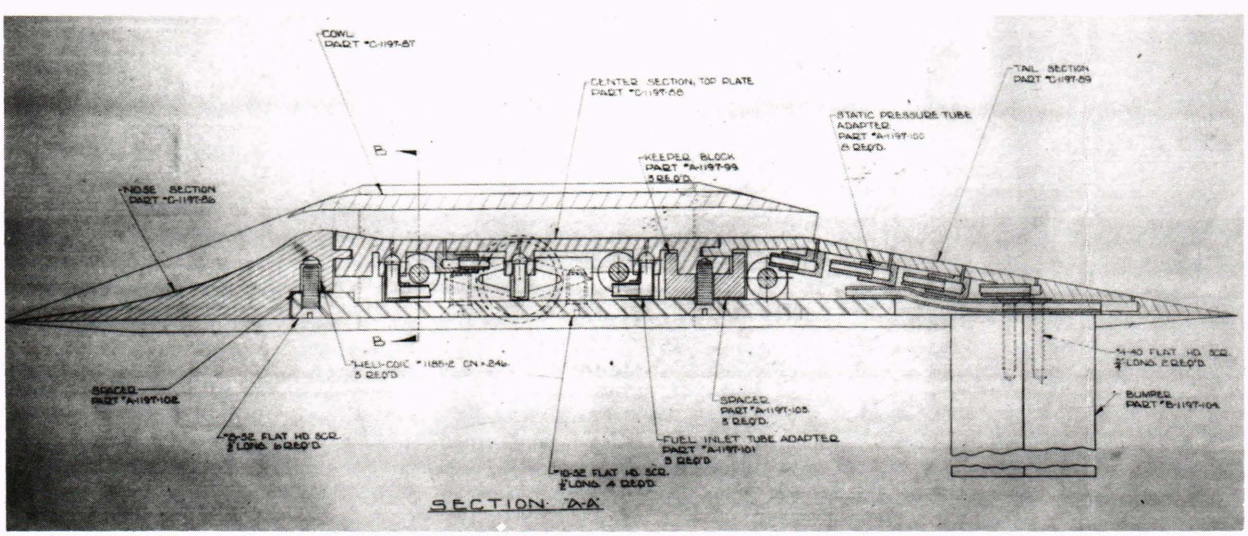


Figure 9. The external expansion ramjet (ERJ-2) model.

in the ERJ concept and little value in the research. The work became difficult to justify, and in 1959, there were few friends in the Navy for hypersonic airbreathers.[32] Polaris was, by far, the highest-priority program, and, under Eisenhower, defense funding for everything else was scarce. The final report on Project D-53 was issued in 1961.[20]

Dugger and Billig, with the help of a key consultant from the University of Illinois, Robert McCloy, turned their attention to a different hypersonic engine concept, the internal supersonic-combustion ramjet, which theory said could produce a great deal of thrust at high Mach numbers[33] (Fig. 10).

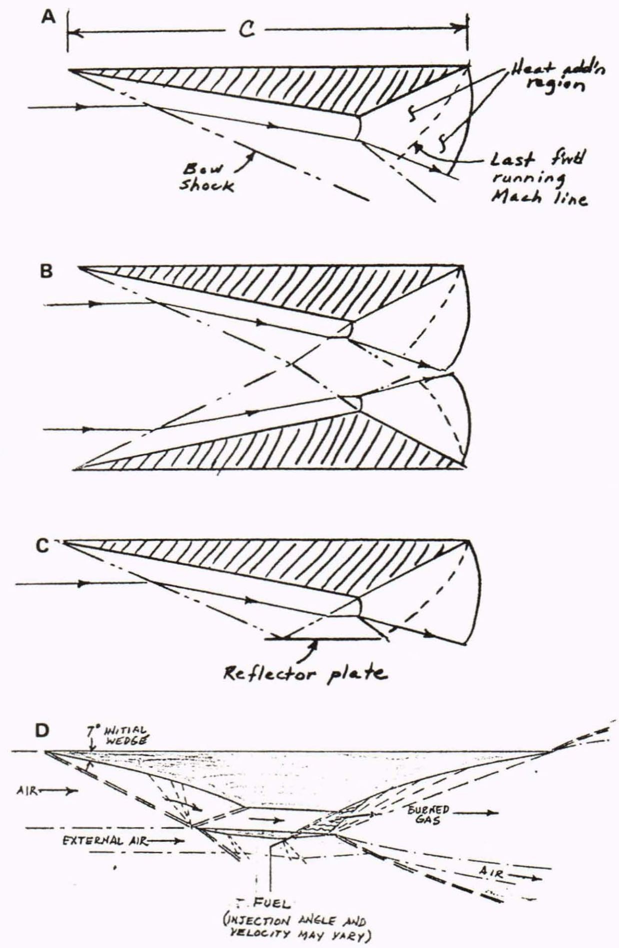


Figure 10. This series of sketches drawn by Gordon Dugger in 1959 shows how the simple external-burning ramjet evolved into the early design of a supersonic-combustion ramjet. **A.** Basic external-burning ramjet. **B.** Concept suggested by Robert McCloy of two external-burning ramjets placed belly-to-belly. **C.** McCloy's modification of the design shown in part B. **D.** The supersonic-combustion ramjet design (drawn later) that Dugger and his group studied in the early 1960s, which is a close relative of the design shown in part C.

POLARIS

Until 1956, Triton had appeared to be an important option in the Navy's plan for long-range surface-to-surface weapons. The Navy had been interested in breaking into the glamorous ballistic rocket business for a long time, and a sea-based intermediate-range ballistic missile (IRBM) force had received high-level support from the Pentagon. Nevertheless, few seamen were entirely happy with the vision of Jupiter missiles, over fifty feet high and full of liquid oxygen and gasoline, going to sea aboard ships and submarines. The logistical and operational problems would be enormous, not to mention the consequences of a launch failure at sea. Admiral William "Red" Raborn, the head of the Special Projects Office created to develop a sea-going missile system, succinctly called the liquid rocket "big and ornery."[34]

Dramatic progress in solid-propellant rocketry changed the picture in 1956.[35] New propellant formulations gave the solid-propellant rocket a level of performance comparable to the liquid rocket. Coupled with improvements in fabrication methods, which allowed large-diameter grains to be cast, this development meant that solid-propellant rockets might be capable of intercontinental ranges. If the Navy researchers dropped the work on Jupiter and devoted their full energy to a new solid-propellant missile, they could end up with a much smaller, and much more seaworthy, weapon. The gamble would be a major one, however.

Because he was an expert in solid propellants, Avery played an important role in the decision to develop Polaris in the first place (Fig. 11). He was a member of the Polaris Ad Hoc Group, chaired by Kossiakoff. This group had been appointed by C. Furnas, the Assistant Secretary of Defense for Research and Development, at the request of Admiral Raborn, to review the critical technical problems involved in developing a solid-propellant version of the Navy Jupiter missile.[36] Avery spent a large portion of his time in 1957 in conscientious consideration of the many technical risks that the Navy Special Projects Office would have to face.

At first, Avery had serious personal reservations about Polaris. He said, "On technical grounds, we can demonstrate that Triton would be more accurate, lighter in weight, and more flexible in use." He also believed strongly that firing inaccurate nuclear missiles would be both wrong and ineffective.[37]

Major problems with accuracy were later ameliorated by the development of the Ship Inertial Navigation System (SINS) and the incorporation of the guidance system from Navaho (Navaho was canceled in 1958, a victim of Atlas). But Avery's feelings about Polaris persisted. Early in 1958, at a time when the American public was particularly interested in missilery, Avery was featured on a nationwide telecast on the ABC Color Television Network in a program called "Progress on Propulsion." The program explained and compared various propulsion options, and it pointedly noted the advantage of airbreathers over rockets for long-range missions[38] (Fig. 12). In 1958, the argument was lost on Avery that a missile flying thirty miles high, at a speed of two miles per second, was somehow vulnerable to projected air defense systems (Fig. 13). Ironically, despite Avery's battles, the Polaris program turned out to be crucial to the survival of the early hypersonic propulsion research at APL, al-

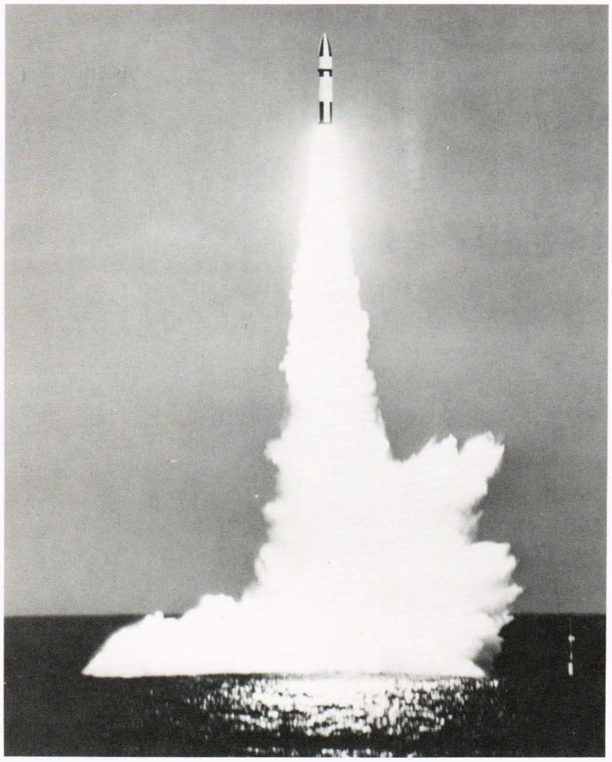


Figure 11. A breakthrough in propellant formulation in 1956 made Polaris a high-priority project. A few years later, Triton was canceled, and the Navy's work on hypersonic ramjets nearly ended.

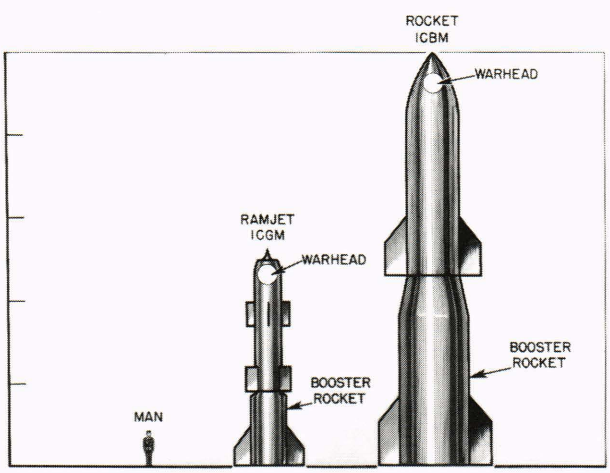


Figure 12. This drawing was used by William H. Avery in his nationwide television appearance early in 1958. Airbreathing missiles were shown to have several major advantages over rockets.

though the event that caused this unlikely alliance was not expected by anyone.

THE SPACE AGE

On 4 October 1957, one month before Dugger was appointed supervisor of Project D-53, the Soviet Union launched Sputnik I (Fig. 14). The impact of this event is perhaps difficult to gauge today, but at the time it

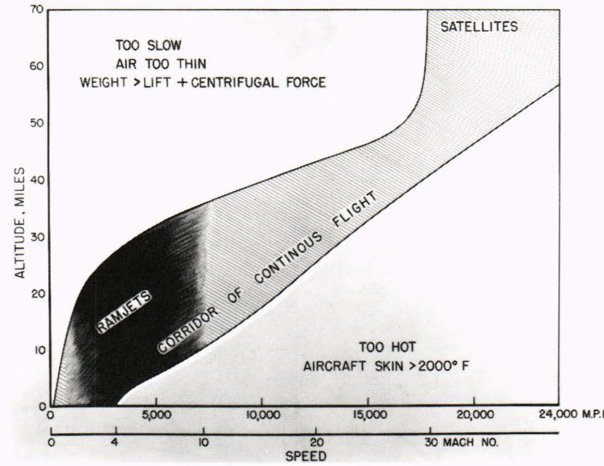


Figure 13. William H. Avery's televised talk suggested that ramjets would be able to fly more than thirty miles high at 10 times the speed of sound.

was devastating to the self-esteem of the United States and extremely worrisome to the U.S. military.

The obvious military implications of the Sputnik launch greatly influenced the Polaris program. Instead of aiming for an initial operational capability in 1963, the program was accelerated so that the first missiles could go to sea by 1960. This bold action required certain technical compromises, particularly in propellant formulation. The net effect was to reduce the intended maximum range from 1500 to 1200 nautical miles.[34]

The Navy Special Projects Office was understandably anxious to recover the lost range as soon as possible. One option, suggested by APL consultant McCloy, was to augment the thrust of the engines by injecting fuel directly into the nozzle flow in a manner akin to the method used in turbojet afterburners. The similarity of this system to the ERJ concept was not coincidental. Moreover, adapting the ERJ configuration to a missile nose cone might provide control during reentry, possibly improving accuracy. Further, the facilities being developed at APL for hypersonic propulsion research could be used to address some of the questions of reentry aerothermodynamics. The upshot of these possibilities was that, as hypersonic propulsion funding at APL evaporated, funding for related work in the Polaris program grew, dollar for dollar.[39]

The launch of Sputnik had another major effect. At a meeting of the NACA Subcommittee on Propulsion during the first week in April 1958, Avery learned that a new agency, the National Aeronautics and Space Administration (NASA), would supersede NACA on 1 October 1958.[40]

Avery was disturbed to hear at the meeting that NASA's intention was (in Avery's words) "to terminate as rapidly as possible all work on airbreathing systems" and to concentrate instead on the problems of space propulsion. He stood up and objected to what he believed was an abandonment of the unexplored potential of high-speed airbreathing engines.[40]

80th Year ... No. 304 .. Phone RE. 7-1234 SATURDAY, OCTOBER 5, 1957 WTOP Radio (1500) TV (Ch. 9) FIVE CENTS

Space Satellite Launched by Russians, Circling Earth at 18,000 Miles an Hour; Is Tracked Near Washington by Navy

Hoffa Wins, Faces New Challenge

Senators Subpena Teamster Records On Credentials

By Bernard D. Nossiter

MIAMI BEACH, Oct. 4 James Riddle Hoffa today rolled up an easy 3-1 victory for the presidency of the Teamsters Union and promptly bumped into a challenge from Senate investigators.

The Select Committee on union, employer misdeeds subpenaed the records of the Teamsters' Credentials Committee which approved the

Mrs. James Hoffa joined her husband on the rostrum in

Police Clubs Fail to Halt Polish Riots

Students Taunt Foes, Shouting 'Gestapo, Gestapo'

By Colin Frost

WARSAW, Oct. 4 (AP) Combined forces of Polish Red police, security troops and militia men from worker ranks fought a new student uprising for freedom here tonight.

The students, still apparently untamed, taunted the anti-riot forces with shouts of: "Gestapo, Gestapo."

(Poland was one of the first and worst sufferers at the

This global projection illustrates the orbit of the earth satellite launched by Russia yesterday.

22-Inch Artificial Moon In Orbit 560 Miles Up; Signals Heard in U.S.

By Henry Shapiro

MOSCOW, Oct. 4 (U.P.)—Russia tonight announced the first launching of an earth satellite. Soviet scientists hurled the satellite into space earlier today and sent it spinning around the earth at a speed of 18,000 miles an hour and at an altitude of 560 miles, the announcement said.

The sphere-shaped, man-made "moon" was equipped with a radio transmitter sending signals to earth stations.

(Within a few hours, American networks in New York and the British Broadcasting Corp. in London picked up tiny pulsating signals.

(Shortly before midnight, the Naval Research Laboratory in Washington announced that its tracking equipment had recorded three passes of the satellite over the United States. One seemed to be near Washington while the

setting sun through binoculars and telescopes.

Completing its announcement, the Tass agency said, "artificial earth satellites will pave the way for space travel."

At dawn Saturday, the Soviet satellite will be visible to watchers in Russia using only binoculars or small telescopes, the Russian announcement said.

The dispatch did not disclose the launching site.

No advance announcement had been made of the launching plan. It was apparent that the Soviet Academy of Sci-

Figure 14. The launch of Sputnik was the most significant technical event of the late 1950s. The Polaris program was accelerated, and as a result, the work at APL on hypersonics was kept active.

The day after the meeting, Avery became even more troubled by a phone conversation with C. C. Sorgen, an official in the Department of Defense (DoD).[41] Sorgen confirmed the NASA decision against further support of research on airbreathers, and he agreed with NASA's intention to emphasize rockets and space travel. The feeling in the military, he added, was that ballistic missile programs should receive top priority. Funds were not available to develop both rocket-powered missiles and high-speed ramjets.

Two weeks later, Avery and Gibson met with Hugh Dryden, the Administrator of NACA, who was slated to become the Deputy Administrator of NASA. In the back of Avery's mind was the idea that, if APL volunteered to continue the NACA airbreathing program, NASA might be willing to sponsor the undertaking, given that APL was a nonprofit public service organization and a major player in the airbreathing propulsion business.[42]

Dryden, however, was not receptive to the idea, pointing out that NASA was already set to reduce the effort at the Lewis Laboratory by 70%. This attitude, he said, was influenced by the prevailing feeling in DoD that no further development of military airbreathing engines was warranted. Thus, according to Dryden, NASA was not justified in spending a substantial amount of money in the field.

THE HYPERSONIC TRANSPORT

Through years of service on NACA subcommittees and other national panels, Avery had developed a broad interest in U.S. aviation, and he was sure that the abandonment of high-speed airbreathers was a major mistake. To illustrate the endangered potential, he had developed the concept of a hypersonic transport, powered by turbojets to a Mach number of 3 and by ramjets from Mach 3 to Mach 7.[38] The plane would be able to connect Washington and Los Angeles in thirty minutes. During the summer of 1958, in the midst of the Sputnik reaction, he asked Walker to look into the concept in more detail. Walker and Raymond H. Cramer developed some basic configurations that integrated an airframe with turbojets and EERJ engines[43] (Fig. 15).

By the end of the year, Walker had five or six people assigned to the work on a part-time basis.[44] In particular, Gene Pietrangeli was developing a composite design for a 600,000-pound, 130-passenger transport with a range of 5000 to 6000 nautical miles. The plane was to be able to fly nonstop between 80% of the principal cities in the world in less than five hours, using current runways. Other workers were considering the use of hypersonic airbreathing engines to launch vehicles on spaceflight missions. In his spare time, Avery was working personally on a concept for protecting hypersonic structures by covering them with insulating shingles, similar in approach to the tiles used today on the space shuttle.[45]

Pietrangeli's analysis clearly showed the importance of integrating the engine and airframe to minimize weight, drag, and center of pressure movement, and to take advantage of favorable aerodynamic interference effects. The study also considered various fuel schedules and climb trajectories (including sonic boom limits), as well as the effects of component efficiencies, cooling requirements, etc.[9]

The final design succeeded in achieving a little more than half of the original range objective.[46] Excessive fuel consumption during climb and the weight penalty of the cooling and insulation equipment were identified as major problems, but overall, this early work heightened the feeling that hypersonic transportation was technically feasible.[47] Nevertheless, many technical and practical problems, some profound, were recognized by

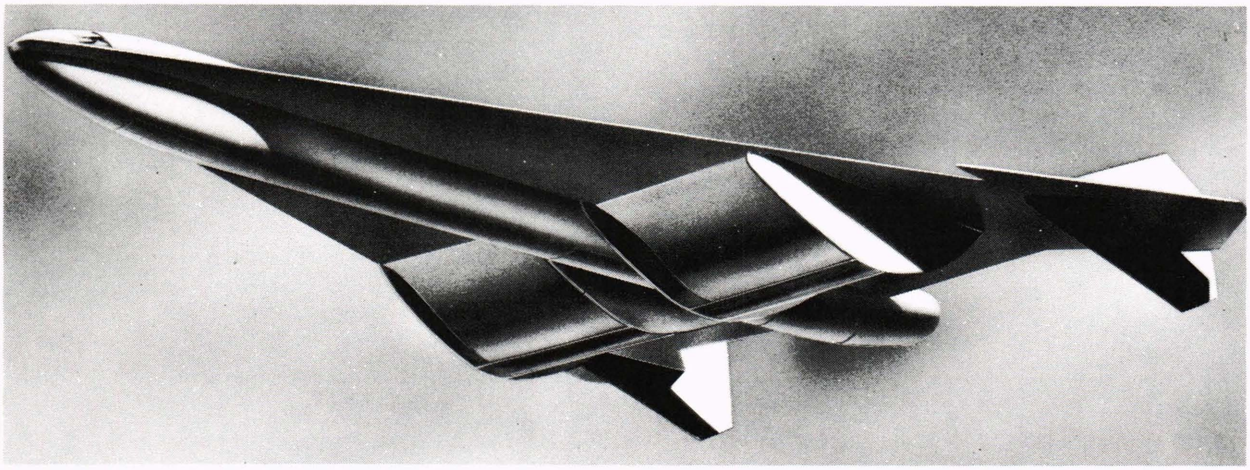


Figure 15. The principal configuration of the APL hypersonic transport was a 175-foot-long delta-winged aircraft with a wing span of 102 feet. It used turbojet engines to accelerate to Mach 3.6 and external expansion ramjets for propulsion at higher speeds, up to a cruise Mach number of 7. In the lower-speed range, the inlet ramps of the ramjet engine retracted to provide an opening for airflow to the turbojets.

APL engineers, so the degree of optimism felt by people who had actually built and flown ramjets can be overstated.

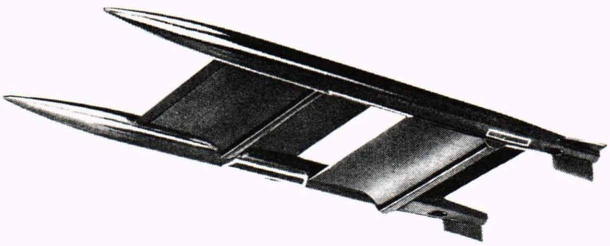
Several other configurations were examined, some of which were intriguing (Fig. 16). For example, in a 1959 report, Avery, Dugger, and Walker stated, ". . . the use of staging for long flights would be attractive. The large boost airplane might well be used for shorter-range transport. Thus, a flight from Cleveland to Manila could be accelerated to Mach 3 by a supersonic booster plane flying to Los Angeles."[9]

Analyses of spaceflight missions suggested that an airbreathing first-stage vehicle would reduce fuel cost to a few percent of that required by rocket launching. The conclusion was that a recoverable airbreathing first stage, as opposed to a recoverable rocket-powered first stage, would soon pay for its development costs through fuel savings alone.[9]

All of this work was taking place during the early days of the space age, but also during the time that the U.S. public was becoming acquainted with the glamour and convenience of high-speed commercial air travel. The Boeing 707 took it first commercial flight in 1958, followed closely by the DC-8 and Convair 880—all subsonic jets. People began looking ahead to the next generation of transport aircraft. Everyone assumed that those planes would be supersonic.

Writing in the April 1959 issue of *Astronautics*, Dugger commented, "The bolder forecasters suggest that [the] moderate supersonic era be leapfrogged in favor of the introduction of Mach 3 to 5 aircraft in 1970 . . . The writer would go even further and suggest that the optimum flight speed for intercontinental carriers will be near Mach 7, that much of the know-how for building such aircraft already exists, and that if planning were to begin now, it would be entirely possible to have Mach 7 transports by 1970."[48]

Airline executives were not as effusive about high-speed transportation. William Littlewood, a vice president of American Airlines, thought that hypersonic airplanes had no commercial value for flights less than 3000 miles, which eliminated the profitable New York to Chicago routes.[49] In any case, the industry was in no position to finance the introduction of such a plane. The capacity of subsonic transports was projected in the late 1950s to exceed demand for many years. Littlewood's viewpoint about the useful range for hypersonic travel was shared at APL. A hypersonic transport would take a long time to accelerate and a long time to slow down, and as Dugger knew, any advantages would probably be found only in intercontinental applications.



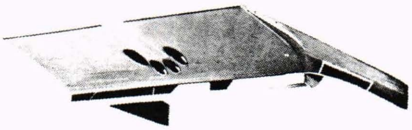


Figure 16. The hypersonic transport configuration shown in the upper part of this figure employed a highly staggered biplane design to control the movement of the center of pressure during large changes in speed, and to allow a high degree of engine/wing integration. The configuration in the lower part of the figure is a flying-wing (or a flying-engine), with passengers seated within the wing itself. Pectoral flaps extended from the sides for takeoff and landing.

THE VIEW AT THE END OF THE 1950s

Most of the scientists and engineers who were working in aviation at the time Avery wrote his review article in 1955 probably thought that technical progress would continue to occur in a series of orderly steps. Experimental aircraft would travel higher and faster, gradually pushing back the limits of flight. The new technology would be applied first to military planes and later to commercial airliners. Supersonic air travel would be widespread by the 1970s.

Similarly, space travel would begin by placing Vanguard's small payload into Earth orbit, and then, after a long series of careful advances, perhaps a human being would venture into space sometime in the twenty-first century. The wildest fanatic could not have imagined a person on the Moon by 1969.

The arms race, the space race, and economic reality combined to distort orderly development in the second half of the decade. At the end of the 1950s, the U.S. space and ICBM programs commanded overriding priority, as a matter of national prestige and security. Flight in the atmosphere at speeds greater than Mach 3 or 4 was generally believed to be technically feasible, but those who controlled funding were convinced that the cost of developing aircraft or missiles capable of such speeds would outweigh any foreseeable advantages for either military or civilian use.

The major technical obstacle was the thermal barrier. Since the X-15 program was already addressing the problems of high-temperature materials and cooling techniques, further research on hypersonic airbreathing engines could wait until feasible solutions to the problem were demonstrated. Out of the $100 million NASA budget for R&D in 1960, only $700K was earmarked for research on airbreathers, and APL's related research funding from the Navy was cut. Although the ramjet engine was still a topic of interest in 1959, the future was beginning to darken.

Avery and Dugger remained determined and optimistic, however. In the Air Propulsion Section of the 1959 edition of the *Bureau of Ordnance Long-Range Plan for Research and Development,* they wrote: "In the period from 1968 to 1978, it is expected that ramjets, with internal supersonic burning or external burning, will be operating in the Mach number range from 5 to 15."[50] Their determination and optimism were to be rewarded in the 1960s, at least for a while.

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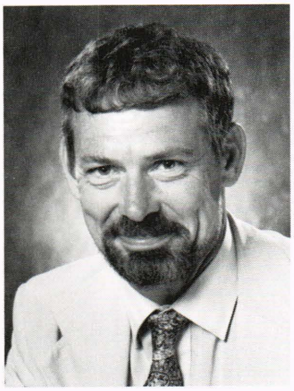

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