History of Ramjet and Scramjet Propulsion Development for U.S. Navy Missiles

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A history of high-speed airbreathing propulsion ramjet engines and their respective vehicle and weapon systems developed under the support of the U.S. Navy is presented. These include surface- and air-launched subsonic combustion ramjets, supersonic combustion ramjets (scramjets), and mixed-cycle ramjet/scramjet/rocket engines intended primarily for missile applications for flight speeds from Mach 2 to Mach 8.
(Keywords: Missiles, Propulsion, Ramjets, Scramjets.)

INTRODUCTION

The intent of this article is to summarize the evolution and development of ramjet engines (and variants thereof) as propulsion systems for missiles flying at supersonic (or faster) flight speeds that have been supported by the U.S. Navy since World War II. Reference 1 provides a discussion on the details of the types of engines under discussion, along with their limitations, and a historical perspective on the evolutionary timescale of ramjets, scramjets, and mixed-cycle engines. Reference 2 presents a similar discussion for U.S. Air Force–developed systems.

In this article we summarize programs to develop surface-launched and air-launched subsonic combustion ramjets and scramjets. Table 1 shows the evolutionary history of all of the ramjet and scramjet engine and vehicle concepts and systems included in these discussions. The names, engine types, dates, performance, system constraints, etc., for each are presented. (Some information is not given for reasons of security.)

The U.S. Navy has supported and developed a substantial technology base, including a variety of ramjets. This technology base, however, is not nearly as substantial for scramjets and their derivatives. A number of these ramjet engines and ramjet-powered weapon concepts have been flight tested, but none at hypersonic speeds. Only one U.S. Navy ramjet system has ever become operational (the Talos), and it is still being used as a target today (Vandal).

SURFACE-LAUNCHED RAMJET DEVELOPMENT

The history of surface-launched supersonic ramjet-propelled vehicles began in 1944 at APL at the behest of the U.S. Navy's Bureau of Ordnance.[3] The Navy needed (1) an antiair weapon that could defeat aircraft threats using the lessons being learned in the Pacific theater and (2) projections of the future availability of

Table 1. U.S. Navy ramjet evolution.

Engine/vehicle	Engine type	Dates (year)	Cruise Mach no.	Cruise altitude (ft × 1000)	Powered range (nmi)	Launcher	Total length (in.)	Sustainer length (in.)	Diameter (in.)	Total weight (lbm)	State of development
Ramjets											
Cobra	LFRJ	1945–46	2.0	20	—	Rail	—	—	6	240	Flight demonstration
BTV	LFRJ	1947–48	2.4	30	10	Rail	—	—	18	—	Flight demonstration
RTV	LFRJ	1949–50	2.4	30	25	Rail	—	—	24	—	Flight demonstration
Talos	LFRJ	1950–80	2.7	70	120	Rail	386	254	28	7720	Operational
Triton/SSGM	LFRJ	1951–58	3.0	70	>2000	Rail/sub.	—	—	—	—	Component tests
RARE	SFIRR	1955–60	2.3	—	—	Rail	120	120	5	153	Flight tests
Typhon	LFRJ	1957–65	4.1	100	200	Rail	333	185	16.75	6160	Flight tests
CROW	SFIRR	1956–64	3.0	50	97	Air	127	127	8	370	Flight tests
ATP/TARSAM-ER	ADR	1965–71	3.8	50–70	160	Rail	348	186	13.5	6420	Component tests
ATP/TARSAM-MR	ADR-IRR	1965–71	3.8	50–70	80	Rail	200	200	13.5	1750	Component tests
IRR-SAM	LFIRR	1966–70	3.3	80	—	Rail	220	220	14.75	2200	Component tests
ALVRJ	LFIRR	1968–79	3.0	30	100	Air	179	179	15	1480	Flight tests
IRR-SSM	LFIRR	1971–74	2.5	50	—	Rail	200	200	14.75	2000	Free-jet tests
ASAR	LFIRR	1972–81	3.8	80	—	VLS	220	220	16	2650	Semi-free-jet tests
GORJE	LFIRR	1972–76	2.6	0	35	Air	168	168	12	750	Semi-free-jet tests
MRE	LFIRR	1973–77	3.0	30–70	150	Air	168	168	15	1500	Free-jet tests
IRR-TTV/TTM	LFIRR	1974–85	3.0	60	—	Submarine	246	246	21	3930	Component tests
SOFRAM	SFIRR	1976–81	>3.0	—	150	Air	144	144	8	650	Free-jet tests
LIFRAM	LFIRR	1976–80	>3.0	—	150	Air	144	144	8	650	Semi-free-jet tests
ACIMD	LFIRR	1981–84	—	—	—	Air	144	144	9	—	Component tests
Vandal (Talos)	LFRJ	1983–present	2.2	0	43.5	Rail	434	302	28	8210	Operational
SFIRR	SFIRR	1984–89	2.5	0	50	Air	168	168	18	—	Component tests
SLAT	LFIRR	1986–92	2.5	0	50	Air	216	216	21	—	Flight tests
LDRJ	LFIRR	1995–present	4.0	—	—	Air	—	—	21	—	Planned flight tests
Scramjets											
External burn	ERJ	1957–62	5–7	—	—	—	—	—	—	—	Combustion tests
SCRAM	LFSJ	1962–77	7.5	100	350	Rail	288	158	26.2	5470	Free-jet tests
WADM	DCR	1977–86	4–6	80–100	—	VLS	256	183	21	3750	Component tests
Counterforce	DCR	1995–present	4–6	80–100	—	VLS	256	183	21	3750	Component tests

ACIMD = Advanced Common Interceptor Missile Demonstrator; ADR = air-ducted rocket; ALVRJ = Advanced Low-Volume Ramjet; ASAR = Advanced Surface-to-Air Ramjet; ATP = Augmented Thrust Propulsion; BTV = Burner Test Vehicle; CROW = Creative Research on Weapons; RTV = Ramjet Test Vehicle; DCR = dual combustor ramjet; ER = extended range; ERJ = external ramjet; GORJE = Generic Ordnance Ramjet Engine; IRR = integral rocket ramjet; IRR-SAM = IRR Surface-to-Air Missile; IRR-SSM = IRR Surface-to-Surface Missile; IRR-TTV/TTM = IRR Torpedo Tube Vehicle/Torpedo Tube Missile; LDRJ = Low-Drag Ramjet; LFIRR = liquid-fueled IRR; LIFRAM = liquid-fueled ramjet; LFRJ = liquid-fueled ramjet; MR = medium range; MRE = Modern Ramjet Engine; RARE = Ram Air Rocket Engine; SCRAM = Supersonic Combustion Ramjet Missile; SFIRR = solid-fueled IRR; SLAT = Supersonic Low Altitude Target; SOFRAM = solid-fueled ramjet; SSGM = Surface-to-Surface Guided Missile; TARSAM = Thrust Augmented Rocket Surface-to-Air Missile; WADM = Wide-Area Defense Missile.

small, high-speed, radar-guided antisurface missiles. This request led to the Bumblebee program and a succession of rocket- and ramjet-powered flight vehicles, culminating in a triad of surface-launched missiles: Terrier, Tartar, and Talos. Terrier evolved into what is now the Navy's Standard Missile (SM) weapon system.

For the ramjet, the desire was to field a radar-beam–riding antiair weapon that could deliver a 600-lbm warhead to ranges in excess of 100 nmi. To do this, a progressive ramjet development program was devised that included a succession of ramjet-powered flights in which size, range, and cruise altitude were increased.

The first of these was the Cobra ramjet: a 6-in.-dia., ramjet flight test vehicle that cruised at Mach 2 at an altitude of 20,000 ft. In June 1945, Cobra was the first successful demonstration of a ramjet in supersonic flight. These initial tests were followed by tests in 1948 of an 18-in.-dia. ramjet called the Burner Test Vehicle, a scaled-up version of the Cobra with a higher flight speed (Mach 2.4) and cruise altitude (30,000 ft), and tests in 1950 of the Ramjet Test Vehicle, a 24-in.-dia. vehicle that demonstrated a 25-nmi powered range cruising at Mach 2.4 at 30,000 ft.

As a result of these successes, the next 5 years were spent developing a ramjet-powered system that met the requirements of a beam-riding weapon with a 600-lbm warhead and a powered range of more than 100 nmi. The resulting Talos missile was powered by a ramjet engine and could cruise at Mach 2.7 at altitudes up to 70,000 ft after tandem boost to Mach 2.2. Talos was manufactured by the Bendix Corp. and was first introduced into the Fleet in 1955 (Fig. 1). Talos was quite large (see Table 1) and was capable of a powered range in excess of 120 nmi. It was the first (and last, in 1980) ramjet weapon in the U.S. Navy's inventory.

This does not end the Talos story. After the last heavy cruiser was decommissioned (USS *Boston,* which deployed the Talos missile in 1980), there was (and still is) a need for a supersonic target to simulate hostile antiship missiles known to be in other nations' inventories. The solution was to make the Talos capable of Mach 2.2 flight at sea level with a powered range in excess of 40 nmi. The requisite modifications—including an inlet designed for a lower Mach number (2.2), additional fuel, and a selectable, autonomous guidance system—were made. The resulting vehicle, known as the Vandal, is 48 in. longer and 490 lbm heavier than the Talos system (Table 1), and it is the only U.S. ramjet operational today.

Subsequent to the Talos, the Navy in the early 1950s was addressing ways to deliver strategic ordnance at long range. Consequently, the second Bumblebee task undertaken by APL was to develop a ramjet-powered surface-to-surface cruise missile capable of traveling 2000 nmi at Mach 3 flying at an altitude of 70,000 ft, designated the Triton missile.[4] Several configurations were investigated; the final version was capable of launch from an SSBN/Polaris launch tube. Although engine component tests were successfully conducted and the vehicle concepts met the established mission requirements, the Triton/SSGM (Surface-to-Surface Guided Missile) program was canceled in 1958 in favor of the Polaris solid-rocket ballistic missile.

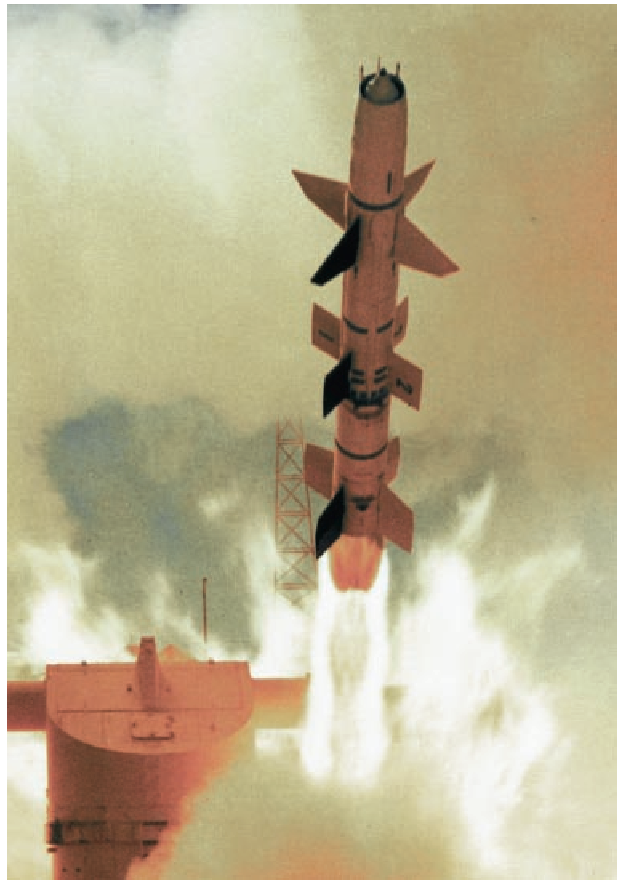

Figure 1. The Talos missile (ca. 1958).

The success of the Talos antiair missile led to the Navy's decision to pursue a follow-on version. The Typhon missile program, or super-Talos as it was called then, was initiated in 1957, again under the direction of APL, as its third Bumblebee ramjet task.[5–7] The resulting tandem-boosted missile, shown in Fig. 2, was developed over the next 7 years along with its shipboard guidance system.

The Typhon missile was much smaller than its Talos predecessor (Table 1), but was capable of flying 200 nmi while cruising at Mach 4.1 at an altitude of 80,000–100,000 ft after tandem boost to Mach 2.7. Relative to Talos, Typhon carried a smaller (250 lbm in contrast to 600 lbm) warhead and had a more efficient ramjet propulsion system, and its subsystems and structure were more compact and weighed less.

The Typhon missile was successfully flight tested nine times in the period 1961–63. However, the Typhon weapon system ultimately was not introduced

Figure 2. The Typhon long-range missile on an early launcher (ca. 1960).

into the Fleet because the missile could outfly and outperform its radar, guidance, control, and battlespace coverage; it was technologically ahead of its time. Consequently, in late 1965, the program was canceled; however, the infrastructure developed and envisioned for the Typhon weapon system became the cornerstone of the Aegis weapon system 10 years later.

In 1965, the Navy initiated an advanced development program to determine the performance of air-ducted rocket propelled missiles. Thus began the Augmented Thómst Propulsion program[7] conducted at APL with its two subcontractors, Martin Marietta/Denver and the Atlantic Research Corp. The objectives of the Augmented Thrust Propulsion program were to develop the propulsion (APL), fuels (Atlantic Research Corp.), and missile configuration (Martin Marietta/Denver) for an antiair alternative to the then-existing SM (Terrier, SM-I) and Talos missile systems. The emerging integral rocket ramjet (IRR) technology was also to be investigated. The propulsion and solid-fuel technology programs were successfully carried out in a collaborative effort between APL and the Atlantic Research Corp. High ramjet combustion efficiency (up to 90%) with up to 60% boron-loaded solid fuels was demonstrated, as were high-efficiency axisymmetric and half-axisymmetric conical inlet designs. Two-dimensional flush-mounted (during boost), pop-out inlets were also demonstrated to perform adequately.

Two basic tactical missile configurations that also evolved were designated Thrust Augmented Rocket Surface-to-Air Missiles (TARSAMs). Both configurations were 13.5 in. in diameter and were designed to cruise at Mach 3.8 after boost to Mach 2.7. The medium-range version had a predicted powered range on the order of 80 nmi, and the extended-range configuration (TARSAM-ER) had a powered range of around 160 nmi. This program was concluded as planned in 1971, but the proposed follow-on flight tests were not funded.

Concurrent with air-ducted rocket development efforts, liquid-fueled ramjet-powered missile concepts were developed. The first of these was an IRR air defense concept denoted the IRR Surface-to-Air Missile (IRR-SAM), which was explored between 1966 and 1970. Its mission was as an intermediate-range air defense weapon. It cruised at Mach 3.3 at an altitude of 80,000 ft after boost to Mach 2.5. Inlet and combustor tests were conducted on this engine/missile concept. The IRR-SAM configuration was redesigned as a surface-to-surface (strike) weapon, and component development continued through 1974, culminating in free-jet engine testing. The IRR-SSM (Fig. 3) was capable of cruising at Mach 2.5 at 50,000 ft on up-and-over trajectories, or could cruise at sea level at Mach 2.2. Although the IRR-SSM met its performance objectives, the Harpoon antiship missile was deemed adequate at that time and no further development was pursued.

In 1974, a ramjet-powered version of a cruise missile for underwater launch was conceived and became known as the IRR Torpedo Tube Vehicle or Missile (IRR-TTV or -TTM) (Fig. 4). It was nominally boosted to Mach 2.2 but could cruise at Mach 2 at sea level or up to Mach 3 at altitudes up to 60,000 ft. Development of the IRR-TTV database was initiated in 1975 and continued at a low level through completion of the exploratory development database in 1985.

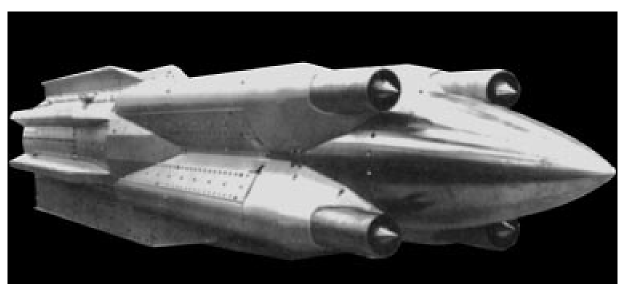

Figure 3. The integral rocket ramjet surface-to-surface missile free-jet battleship model (ca. 1973).

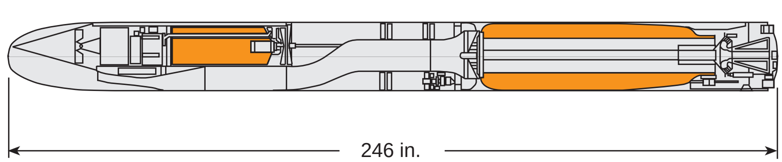

Figure 4. The integral rocket ramjet Torpedo Tube Missile concept (ca. 1978).

Throughout the 1970s and early-to-mid 1980s, a concerted effort (and documented need) was also under way to develop a long-range air defense system that could negate the tactics and increasing ranges and speeds of the Soviet Union's air threat to the Fleet. To satisfy these requirements, the Navy chose to conduct exploratory development on the Advanced Surface-to-Air Ramjet[7] (ASAR). ASAR component exploratory development continued on this engine from 1972 through 1978, and advanced development occurred from 1977 through 1981. These efforts culminated in an integral boost/ramjet transition/semi-free-jet ramjet engine trajectory test series in 1980–81. Figure 5 shows a schematic of the ASAR missile concept, which cruised at Mach 3.8 at an altitude of 80,000 ft after boost to Mach 2.7. Later versions of this configuration, such as the Stand-Off Jammer Suppresser, were somewhat larger, but the technology employed was developed using the ASAR configuration.

AIR-LAUNCHED RAMJET DEVELOPMENT

Almost all of the U.S. Navy's air-launched ramjet work was conducted at or directed by what is now the Naval Air Warfare Center, Weapons Division at China Lake (NAWC/CL). Ramjet development at NAWC/CL (previously NWC or NOTS) goes back to the mid-1950s,[8,9] when the solid-fueled Ram Air Rocket Engine (RARE) system was developed and flight tested from 1955 through 1960. The RARE system was a 5-in.-dia., 120-in.-long missile designed to provide much improved range capability for an air-to-air missile system such as Sidewinder. Three flight tests of the RARE vehicle were successfully conducted at Mach 2.3 between 1959 and 1960.

Subsequent to RARE, the Creative Research on Weapons (CROW) was developed by NAWC at Point Mugu (formerly the Naval Missile Center [NMC], Point Mugu) beginning in 1956. The initial goal of this effort was to demonstrate the feasibility of an integral solid-fueled rocket ramjet for delivering a payload from aircraft launch to a desired destination. It was an axisymmetric IRR that was characterized by a solid-fueled ramjet sustainer with an integral solid booster packaged within the ramjet combustor (Fig. 6). The CROW was designed for air launch at 50,000 ft at speeds of Mach 1.1 to 1.4, rocket boost to Mach 3, and then ramjet sustain at Mach 3 for 3.4 min. to a range of 97 nmi.[10] Ground tests demonstrated that the CROW system could operate from Mach 2.5 at an altitude of 45,000 ft to Mach 3.3 at 65,000 ft.

Six flight tests were conducted with the CROW system with excellent results. Two ballistic flight test vehicles were flown in November 1962, and four controlled vehicles (with a horizon-scanning autopilot and bang-bang controls) were subsequently flown between 1963 and 1964. The CROW system performed as planned, and its full operational potential was established and validated. The CROW concept was briefly considered by the Bureau of Naval Weapons (now the Naval Air Systems Command) for use as an air-to-air missile system and as a high-speed aerial target, but never became operational.

The Navy's entry into aft-mounted side inlets on a liquid-fueled IRR (LFIRR) occurred in the mid-1960s with the initiation of the Advanced Low-Volume Ramjet (ALVRJ) program (Fig. 7). The ALVRJ[11,12] was an IRR characterized by cruciform side-mounted inlets, a liquid-fueled ramjet sustainer, and an integral solid-rocket booster with an ejectable nozzle, a concept originally devised and planned by APL. The program was conducted as a joint effort between government and industry, the latter developing and producing the ramjet, airframe, and flight system and NAWC/CL developing and producing the integral booster, insulation system, and ejectable nozzle. The exploratory development phase of the program successfully demonstrated rocket booster, transition, and ramjet sustainer operation in connected pipe tests and simulated flight operation of the ramjet sustainer in free-jet tests. ALVRJ was approved for advanced development in 1967.

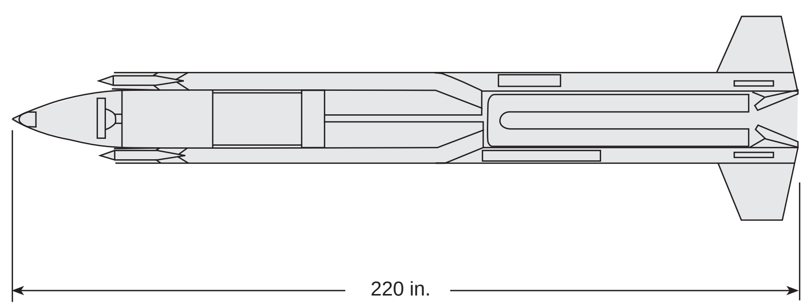

Figure 5. Advanced Surface-to-Air Ramjet missile concept (ca. 1976).

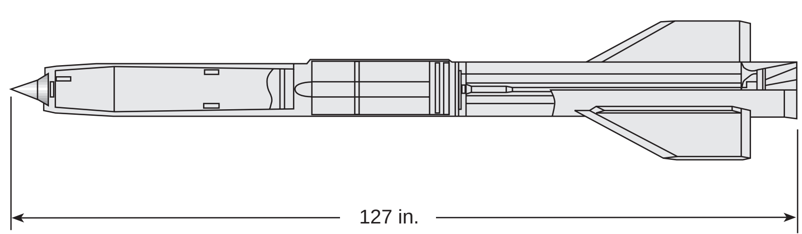

Figure 6. Creative Research on Weapons vehicle (ca. 1963).

Figure 7. Advanced Low-Volume Ramjet flight test vehicle (ca. 1975).

Seven flight vehicles were built in the course of the program, six of which were flown between 1975 and 1979. The flight tests were conducted at NMC/PtMugu in the Pacific Missile Range. All components and subsystems as well as the overall system were successfully demonstrated in free flight. All goals, objectives, and specified data points were substantially achieved. Demonstrated ranges, launch to splashdown, were 28 nmi at Mach 2.5 and sea level and 108 nmi at Mach 3.0 and 30,000 ft. The seventh vehicle, never flown, remains in storage at NAWC/CL.

A number of other advanced development efforts to round out the technology base for a Supersonic Tactical Missile (STM) were conducted in parallel with the ALVRJ effort. Successful programs were conducted in the areas of terminal guidance, midcourse guidance, and warheads, several of which subsequently matured into other beneficial applications. Applications and weapon systems studies culminating in a conceptual STM system were also conducted.

An STM concept resulting from the foregoing activities and directed toward tactical land targets was approved by the U.S. Congress in 1979, and funds for a new start for engineering development of the STM were appropriated in Fiscal Year 1980. Approval to proceed was withheld by the Office of the Secretary of the Navy, however, pending a further review of tactical needs and requirements. Subsequent delays in initiating the development effort resulted in cancellation of the STM by Congress.

In the early 1970s, the Generic Ordnance Ramjet Engine system was developed through engine testing at NAWC/CL. As envisioned, it would provide an air-breathing propulsion system for the High-Speed Anti-Radiation Missile (HARM). The configuration chosen was a parallel rocket, annular ramjet.

After developmental testing, the ramjet engine was eventually integrated with the booster, and semi-free-jet propulsion tests were conducted during which a critical combustor oscillation and instability problem was highlighted. Even though most of the pressure oscillations were accommodated by the inlet pressure recovery margin, some unanticipated higher-frequency instabilities unstarted the inlets. Subsequently, the combustor and inlets were subjected to additional connected pipe and semi-free-jet testing. These tests characterized all the combustor-inlet pressure oscillations, and methods were developed and incorporated to mitigate and contain them. The planned flight tests of this system were never conducted because of a lack of funds, and the program was concluded in 1976.

In 1973, there was a perceived need to extend the range of the Phoenix missile because of enhanced threat capabilities. The Modern Ramjet Engine (MRE) was developed. The MRE employed an IRR engine and, since it would require maneuvering for the antiair mission, it incorporated two cheek-mounted two-dimensional inlets and had bank-to-turn controls, the same as an airplane. The MRE concept used an integral rocket booster for vehicle acceleration to the ramjet takeover speed. Work on the MRE was performed under exploratory development funding for NAWC/CL. The engine was successfully developed, then free-jet tested in 1976–77.

In the mid-1970s, a number of propulsion systems and vehicle concepts were being investigated for a long-range antiair missile. Consequently, both solid-fueled ramjet and liquid-fueled ramjet engine development and demonstration programs were initiated at NAWC/CL. The performance goals for both were to fly 150 nmi at a cruise speed of more than Mach 3. In the early 1980s, following successful semi-freejet engine tests of these missiles, a second-generation integral rocket, liquid-fueled ramjet long-range air-to-air missile was developed for the Advanced Air-to-Air Missile (AAAM) system. The resulting Advanced Common Interceptor Missile Demonstrator engine (Fig. 8) employed a high-performance aluminized solid-rocket booster and JP-10 fuel for the ramjet. The Advanced Common Interceptor Missile Demonstrator program involved extensive component, engine, and vehicle performance analyses as well as installed inlet and direct-connect combustor tests. A fuel management system was also developed, including a turbopump fuel control valve and fuel tank bladder design and demonstration. A flight demonstration vehicle was designed and fabricated. However, the AAAM program was canceled in 1984 before flight testing.

Another solid-fueled IRR propulsion system was designed and developed from 1984 through 1989. It was intended to be a high-speed propulsion system that could fly at Mach 2.5 at sea level for a range of about 50 nmi and carry a penetration or other warhead of similar size. This solid-fueled IRR employed a chin inlet with air introduced into the engine at two locations, in a bypass concept, at the front of the combustor and just aft of the fuel grain. The combustor was developed

Figure 8. Advanced Common Interceptor Missile Demonstrator (ca. 1983).

through connected-pipe testing in full scale at nominal as well as extreme operating conditions ranging from –45°F to +145°F. The inlet was designed and developed through installed inlet wind tunnel testing. The booster used a high-performance, reduced-smoke solid propellant and was developed through static firings at the temperature extremes as well as at ambient conditions. Boost-to-ramjet operation with transition testing remained to be accomplished but was not believed to present any problems and, thus, was not considered to be critical when this program was concluded in 1989.

As mentioned previously, the Navy has used the Vandal (modified Talos) missile as a low-altitude supersonic target since the mid-1980s. Because of decreasing inventories, the Navy began to develop the Supersonic Low-Altitude Target (SLAT) (Fig. 9) in 1986 using an LFIRR engine. SLAT was intended to fly at Mach 2.5 at sea level for 50 nmi and to replace Vandal. It was developed by the Martin Marietta Corp. under contract to the Naval Air Systems Command. NAWC/CL provided technical support for the missile propulsion components. The engine design was based on the LFIRR engine technology demonstrated in the ASALM program several years earlier.[2] Five SLAT flight tests were conducted. During two of those flights, the engine performed satisfactorily and its operation was demonstrated successfully. The other flights never reached the point of transition to ramjet operation. These failures were caused by a number of airframe, system integration, and range interface problems. As a result, the program was canceled in 1992.

Currently, only one active ramjet development program is supported by the U.S. Navy, designated the Low-Drag Ramjet but sometimes referred to as the Cheapshot ramjet. This ramjet is a high-performance LFIRR system that is intended to cruise at speeds up to Mach 4. It incorporates a low-drag airframe with a fixed-geometry axisymmetric nose inlet and bending airframe thrust vector control system; therefore, there are no wings or other surfaces for control. Plans call for a flight test demonstration of the Low-Drag Ramjet under a FY97–FY99 Advanced Technology Demonstration.

SCRAMJET ENGINE DEVELOPMENT

Research on supersonic combustion ramjet (scramjet) engines and their derivatives started in the 1950s in the NASA centers. The Navy's support of hypersonic propulsion began shortly thereafter (in the mid-1950s) at APL in the form of the External Ramjet program.[4,13] The intent of this effort was to demonstrate that both lift and thrust could be produced from the burning of fuels on the underside of wings when flying at supersonic or hypersonic speeds. In 1958, this support paid off in the form of the first demonstration of supersonic combustion providing net positive thrust on a double wedge in a Mach 5 airstream. A Schlieren photograph of that experiment, which used a pyrophoric (triethylaluminum) liquid fuel, is shown in Fig. 10. This project continued through 1961, when it was successfully concluded.

Following these early successes, the Navy began supporting an exploratory program to develop and demonstrate the technology necessary to prepare for the flight of an internally ducted scramjet-powered missile. This missile and its engine were to become known as the Supersonic Combustion Ramjet Missile, or SCRAM[14] (Fig. 11).

SCRAM was tandem boosted to Mach 4 and was predicted to have a powered range of 350 nmi when flying at Mach 7.5 at an altitude of 100,000 ft or a range of 47 nmi flying at Mach 4 at sea level using liquid HiCal 3-D (ethyldecaborane) fuel.

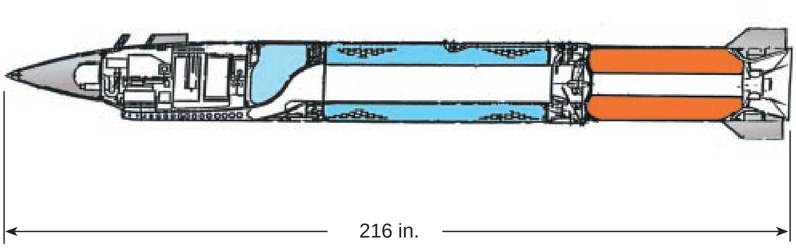

Figure 9. Supersonic Low-Altitude Target propulsion system (ca. 1991).

The SCRAM engine and its components underwent considerable development work from the early 1960s through its termination in 1977. A large number of inlets, isolators, fuel injectors, liquid and gaseous fuels, ignition aids, and combustors were tested[15] between Mach 3 and 8. A 10-in.-diameter 360-in.-long, three-module SCRAM

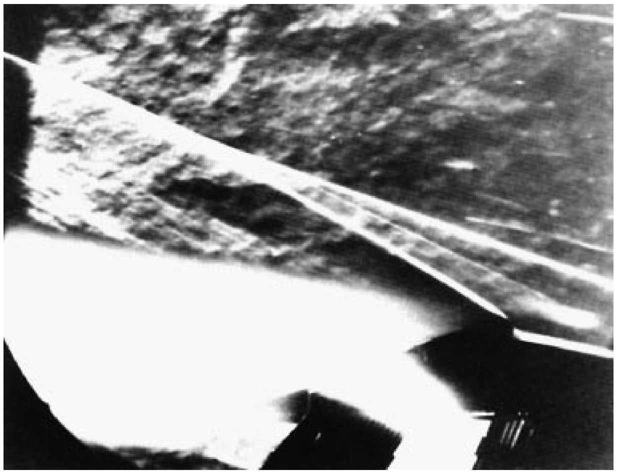

Figure 10. Supersonic combustion at rear of an externally burning ramjet (ca. 1958).

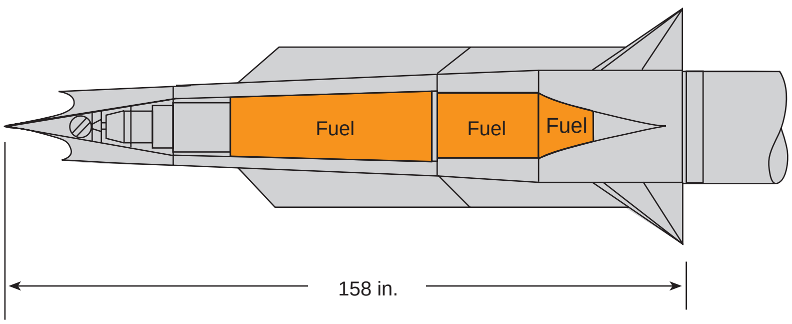

Figure 11. Supersonic Combustion Ramjet Missile system concept (ca. 1975).

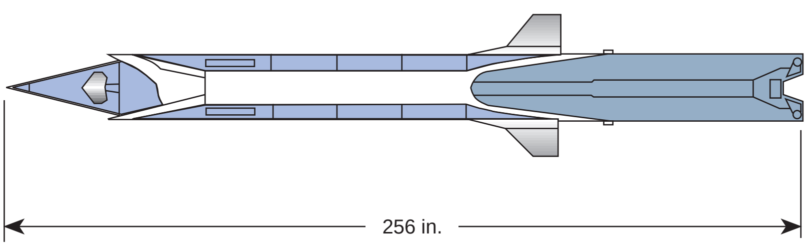

Figure 12. Dual combustor ramjet-powered Wide-Area Defense Missile concept (ca. 1983).

free-jet engine was tested in 1968–74 from Mach 5.2 to 7.1[16] using liquid borane or mixtures of liquid hydrocarbon/borane fuels. This engine was the first to demonstrate net positive thrust in a scramjet engine.

Although the SCRAM program successfully demonstrated the technology necessary to proceed into flight testing, it had three unacceptable shortcomings for a surface-to-air missile: (1) the requirement for the use of logistically unsuitable pyrophoric and toxic liquid fuels or fuel blends, (2) the absence of sufficient room in the forebody to house a large (>10-in.-dia.) active RF seeker, and (3) passive cooling requirements for the entire vehicle. A large active seeker was necessary to acquire and intercept targets autonomously at long ranges.

Thus, in 1977, the SCRAM program was terminated, but not before a successor concept was devised by J. L. Keirsey of APL. His engine concept, the dual combustor ramjet, overcame all three of the preceding objections by using a subsonic pilot combustor to burn all of the fuel with only a small portion of air.[7,13,17] It allowed the use of conventional liquid hydrocarbon fuels in a scramjet-type engine and permitted a large active RF (or other type) seeker to be housed in the nose of the vehicle. It was incorporated into a missile concept that was predicted to be capable of meeting the long-range wide-area defense mission requirements of the late 1970s through the mid-1980s. The missile was capable of cruise flight speeds of more than Mach 6, using passively cooled materials. It was also capable of increasing its range by about 50% by cruising at Mach 4 rather than Mach 6.

One version of a dual-combustor-ramjet–powered missile, called the Wide-Area Defense Missile (WADM) or Hypersonic WADM (HyWADM), is shown in an artist's rendition in Fig. 12. Considerable exploratory development was conducted on this engine and missile concept through the Surface-Launched Missile Technology program. Not only were engine components such as inlets, isolator ducts, fuel injectors, fuel supply and control, and combustors investigated, but materials, structures, guidance, control, aerodynamics, ordnance, boosters, power, and most other subsystems were also studied. Unfortunately, this program was terminated in 1986 by Congress. However, because it was such a successful and useful concept, it is now being evaluated for a counterforce and strike weapon.

CONCLUSION

We hope that this presentation of ramjet history over the past 50 years has given the reader an appreciation for the depth and extent of U.S. Navy support of supersonic and hypersonic ramjet-engine–powered vehicles. Indeed, the Navy's experience reflects the full scope and depth of ramjet and scramjet development experience accrued since World War II. It should also illustrate the substantive reductions in support for these types of vehicles in recent times, even as other nations (e.g., France, Russia, Germany, Japan) continue to vigorously pursue the development and deployment of such vehicles and weapon systems. There appears, however, to be a rekindled interest in these systems by the Navy over the past year, but only time will determine if and when another ramjet-powered system is deployed.

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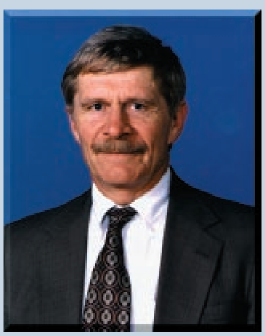

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