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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. A summary of the development of the joint DoD/NASA-sponsored National AeroSpace Plane is also presented. (Author)

HISTORY OF U.S. NAVY RAMJET, SCRAMJET, AND MIXED-CYCLE PROPULSION DEVELOPMENT

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Abstract

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. A summary of the development of the joint DoD/NASA-sponsored National AeroSpace Plane is also presented.

Nomenclature and Glossary

A	Area
ER	Fuel–air equivalence ratio
M	Mach number
R_p	Powered range

Subscripts

0	Free stream
1–6	Engine stations (see Fig. 1)
f	Fuel

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Abbreviations

ADR	Air-ducted rocket
ATRJ	Air-turbo ramjet
CRJ	Conventional ramjet
DCR	Dual combustor ramjet
ERJ	Ejector ramjet
ESJ	Ejector scramjet
GFRJ	Gaseous-fueled ramjet
IRR	Integral rocket ramjet
LFRJ	Liquid-fueled ramjet
LFSJ	Liquid-fueled scramjet
LFIRR	Liquid-fueled integral rocket ramjet
SFRJ	Solid-fueled ramjet
SFIRR	Solid-fueled integral rocket ramjet

Introduction

The intent of this paper is to summarize the evolution and development of ramjet engines (and variants thereof) as propulsion systems for air vehicles flying at supersonic (or faster) flight speeds that have been supported by the U.S. Navy. Also discussed are the systems into which these engines were integrated, including surface- and air-launched missiles as well as air vehicles for weapons delivery, surveillance, and orbital insertion.

Before going into the details of these systems, however, it is useful to (1) define the types of engines under discussion, along with their limitations, and (2) put some historical perspective on the evolutionary timescale of ramjets, scramjets, and mixed-cycle engines. Figure 1[1] depicts the types of subsonic combustion ramjets considered. For reference, the subsonic combustion ramjet typically operates in the Mach 2 to 4.5 speed regime (although some can operate at a subsonic speed), whereas the supersonic combustion ramjet typically operates at speeds above Mach 4 (and cannot operate at subsonic speeds). Orbital speeds (Mach 26) are theoretically possible with scramjets, but a more practical upper bound may be near Mach 20.

In Fig. 1(a), a traditional can-type liquid- or gaseous-fueled ramjet (LFRJ, GFRJ) is depicted with a tandem booster attached. A tandem booster is required to provide static and low-speed thrust, which pure ramjets alone cannot provide. Here, $M_0 > M_1 > 1$, but the air is diffused to a subsonic speed through a normal shock system before reaching station 4. Fuel is then injected and burned with the air at low subsonic speeds before reacceleration

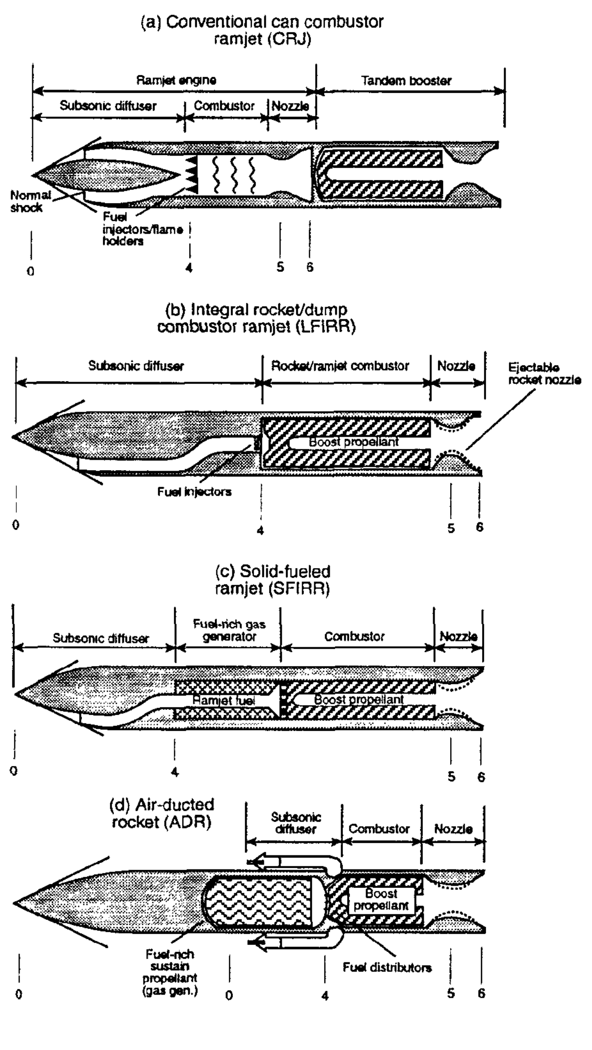

Fig. 1 Schematics of generic ramjet engines.

through a geometric throat ($M_5 = 1$) and exit nozzle ($M_6 > 1$). The position of the normal shock system in this and all subsonic combustion ramjets is determined by the flight speed, air captured, total pressure losses up to the inlet's terminal normal shock, amount of heat addition, and exit nozzle throat size.

A more recent alternative to this concept is to use a common combustion chamber, commonly referred to as an integral rocket ramjet (IRR), for both the boost and sustain phases of flight. This generally requires a dump-type rather than a can-type combustor, but the cycle operation of the ramjet remains the same. Figure 1(b) illustrates this concept for a liquid-fueled IRR (LFIRR), and Fig. 1(c) depicts it for a solid-fueled version (SFIRR). Solid-fueled ramjets (SFRJs) are generally preferred over LFRJs or GFRJs because of the simplicity of the fuel supply, but only when fuel throttling requirements are minimal. The air-ducted rocket (ADR), shown in its IRR form in Fig. 1(d), is another ramjet variant. Here, a fuel-rich monopropellant is used to generate a low-to-moderate-pressure gaseous fuel supply for the subsonic combustor. The choice of an ADR is generally based upon a compromise between the fuel supply simplicity of the SFIRR and the unlimited throttleability of the LFRJ or GFRJ. An ADR is generally used when the total fuel impulse does not adversely impact powered range (R_p). Remember, however, that of the four variants shown, the liquid- or gaseous-fueled systems always exhibit superior performance to the other concepts.

Again, none of the ramjet systems shown in Fig. 1 can produce net positive static thrust. To overcome this deficiency, three hybrid or mixed-cycle ramjet engines have been investigated and are illustrated in Fig. 2. The first, shown in Fig. 2(a), embeds a turbojet within the main ramjet engine, is usually liquid fueled, and is called an air-turbo ramjet (ATRJ). In this cycle, the turbojet produces the required static and low-speed thrust for takeoff (and landing if required) that may or may not be isolated from the main ramjet engine flow at supersonic speeds. The second hybrid, Fig. 2(b), is the air-turbo rocket (ATR), in which a low-to-moderate-pressure rocket motor is used to drive a turbine as it provides a gaseous fuel to the ramjet combustor. The turbine, in turn, is used to drive a compressor which, in combination with the ramjet combustor, will produce net positive static thrust. At supersonic speeds, the compressor may, again, be isolated from the main ramjet flow and the turbine idled so that the engine cycle operates as an ADR.

The third variant is the ejector ramjet (ERJ) as shown in Fig. 2(c). Here, a rocket motor, gas generator, or alternate fuel system produces a high-pressure, generally fuel-rich, supersonic primary (or ejector) flow, which induces secondary air to flow through the engine, even at static conditions. The ejector effluent and air then mix and burn

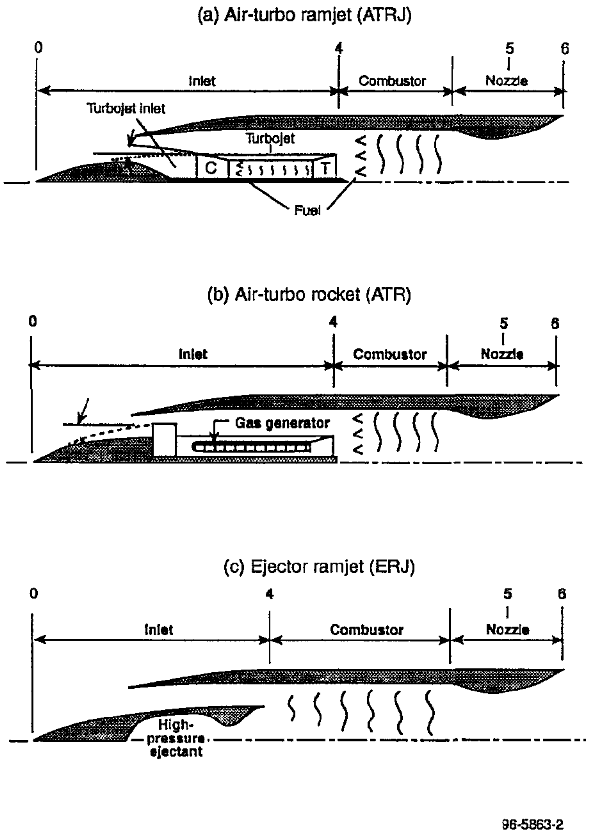

Fig. 2 Schematics of generic hybrid ramjet engines which produce static thrust.

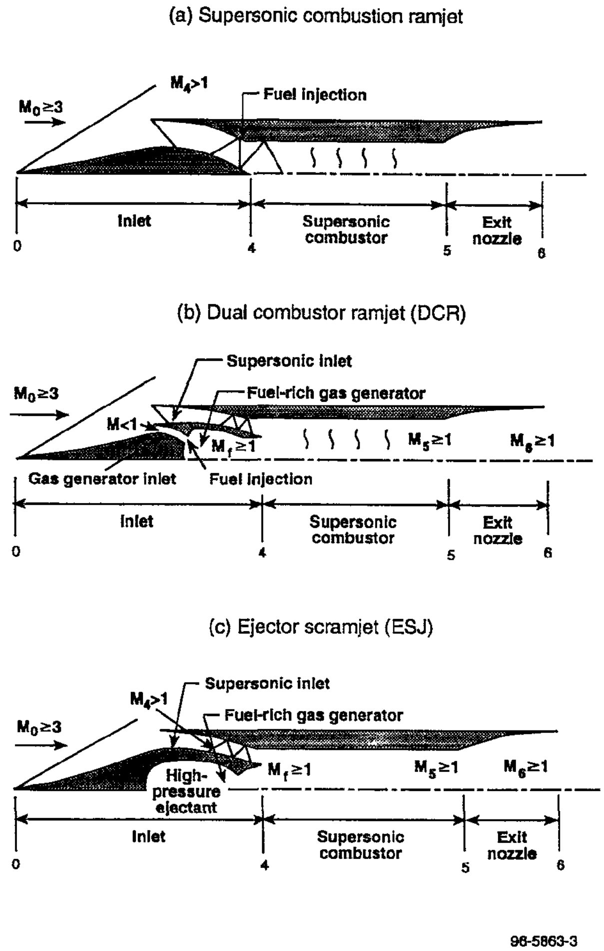

Fig. 3 Schematics of generic supersonic combustion engines.

at subsonic speeds in the combustor before exiting through the convergent–divergent exit nozzle, producing net positive thrust, even at static conditions. Once the flight speed is such that the ramjet by itself can provide sustain thrust ($M_0 > 2$–3), the ejector flow is no longer necessary, and operation is as a conventional ramjet. Other variants of these three cycles, such as "cryo-cooled," "cryo-expander," "turbo-expander," "air liquefaction," etc., are not included here for brevity and because they are specialized subsets of these three mixed-cycle ramjet engines.

Turning now to supersonic combustion engines, Fig. 3 illustrates a generic scramjet engine and two hybrid variants thereof. Figure 3(a) depicts the traditional scramjet engine wherein air at supersonic or hypersonic speeds is diffused to a lower, albeit still supersonic, speed at station 4. Fuel (either a liquid or gas) is then injected from the walls (holes, slots, cavities, pilots, etc.) and/or in-stream protuberances (struts, tubes, pylons, etc.), where it mixes and burns with the air in a generally diverging area combustor. Unlike the subsonic combustion ramjet's terminal normal shock system, the combined effects of heat addition and diverging area in the scramjet's combustor, plus the absence of a geometric exit nozzle throat, generate a shock train located at and upstream of the combustor entrance, which may vary in strength between the equivalent of a normal shock and no shock. The strength of this shock system depends on the flight conditions, inlet compression or inlet exit Mach number (M_4), overall engine fuel–air equivalence ratio (ER_0), and supersonic combustor area ratio (A_5/A_4).

The unique combination of heat addition in a diverging area combustor and the absence of a nozzle throat permits a fixed-geometry scramjet to operate effectively over a wider flight Mach number range ($\Delta M_0 = 4$) than a conventional ramjet ($\Delta M_0 = 2$). At low flight Mach numbers (3–5+) and high ERs, it operates as a nozzleless subsonic combustion ramjet, i.e., the combustion begins in a subsonic flow generated by the precombustion shock system, but accelerates through a thermal throat before exiting the combustor with $M_5 \geq 1$. At higher flight speeds or lower ERs, the strength of the precombustion shock system decreases, and combustion takes place at entirely supersonic speeds. This is commonly referred to as dual-mode combustion and permits efficient operation from Mach 3 to Mach 8+ with storable liquid fuels and up to orbital speeds with gaseous diatomic fuels such as hydrogen.

Although the scramjet offers these unique attributes, they do not come easily, especially in the required fuel preconditioning for efficient combustion at flight speeds below approximately Mach 7. At these speeds, the combination of a "low" air static temperature and short combustor residence time (<1 ms) requires the use of storable liquid (generally hydrocarbon) fuels containing highly reactive additives (such as an alkylated borane) or use of a highly reactive pilot (such as chlorine trifluoride or silane) to achieve the requisite performance. Gaseous fuels require preheating and/or the addition of a pilot. In either case, the additive and/or pilot are usually environmentally and logistically unsuitable.

To overcome this deficiency, several alternate mixed-cycle engine concepts have been invented with varying degrees of development behind them. The most developed of these concepts is the dual combustor ramjet (DCR) shown schematically in Fig. 3(b). The DCR has all the features of the scramjet except that a portion of the air is diverted to a small, embedded subsonic dump combustor into which all of the liquid hydrocarbon fuel is injected. By judicious distribution of the fuel, a near-stoichiometric flame can be maintained, the energy from which heats and cracks the remaining fuel into combustible products when they enter the supersonic combustor, even at Mach 3 flight speeds. This concept is similar in principle to the ADR in Fig. 1(d) and permits the use of liquid heavy hydrocarbon fuels without resorting to any combination of fuel preconditioning, reactive fuel additives, or reactive pilots. The penalty for this, if it can be called that, is that a nontrivial amount of volume and weight is used for the gas generator.

Another variant is to combine the fuel preheating and subsonic dump combustor pilot attributes into a scramjet engine to effect acceptable performance at the lower flight speeds.[2] In this case, the fuel is an endothermic liquid hydrocarbon, and the pilots are half-axisymmetric dump combustor ramjets with conical forebodies mounted on the scramjet forebody wall at the combustor entrance. Here, 15 to 20% of the captured air is ingested by the pilots which, in turn, burn endothermic or gaseous hydrocarbon fuel stoichiometrically. The remainder of the fuel is endothermically cracked to a gas and injected from the outer walls of the pilots, between and in the wake of the pilots, and at other downstream locations when staged injection is required. The potential drawbacks of this concept are the stability of the pilots when ingesting the variable (with flight conditions) wall boundary layer, pilot drag, starting the endothermic process at the end-of-boost flight speed, and maintaining the requisite energy balance between vehicle cooling requirements and endothermic conversion of the fuel to a gas over the entire flight regime.

As in the case of the ramjets shown in Fig. 1, the pure scramjet, DCR, and engine cycle discussed above require an auxiliary propulsion system to provide a static through end-of-boost velocity increment, generally in the form of a solid rocket booster. Unfortunately, unlike the integrally boosted versions of the ramjet, scramjet combustors are not amenable to integral boost designs because of their much smaller volumes and irregular shapes. Consequently, vehicles powered by these engines are generally tandem-boosted to flight speeds on the order of Mach 3 to 4.

The final supersonic combustion cycle, which is an extension of the gas generator–type cycle, is the ejector scramjet shown schematically in Fig. 3(c). Unlike other supersonic combustion engine cycles, it can produce static thrust using axial injectors fed by a high-pressure supersonic gaseous fuel or fuel/oxidizer (e.g., fuel-rich rocket motor) supply. This high-pressure/velocity fuel-rich ejector action pumps air into the supersonic combustor where combustion takes place, producing static thrust. Since there is no exit nozzle throat, combustion at the lower speeds takes place in a mixed subsonic/supersonic flow and passes through a thermal throat before exiting the combustor, i.e., it operates as a dual-mode scramjet, with air entrainment created by the ejector pumping action. Once the engine is capable of ingesting sufficient air to produce net positive thrust without the ejector action, generally between Mach 2.5 and 3.5, it then operates as a more conventional dual-mode scramjet. If properly designed, such an engine is capable of static-to-high hypersonic speed flight. Again, variants of these engines (e.g., so-called cryo, air liquefaction, etc., cycles) are not included because they are subsets of these three main types of scramjet engines.

With the ramjet engine cycles thus defined, we now turn to a brief review (see Ref. 1), through WW II, of ramjets before discussing ramjet and scramjet development supported by the U.S. Navy. Historically, ramjet concepts have been around since the early 1900s, but actual testing did not begin for another 30 years. The first patent of a ramjet cycle device, which actually was an ejector ramjet, was issued to Lake (USA) in 1909, and the first treatise on ramjets was written by Lorin (France) in 1913, both for subsonic flight. The first practical device (for enhancing the range of artillery shells) was patented by Carter (GB) in 1926, and the first recognizable conical-nosed liquid-fueled ramjet patent was given to Fono (Hungary) in 1928.

Actual construction and testing did not occur until the mid-1930s in France, Germany, and Russia. In 1935, Leduc (France) ground tested a conical ramjet up to Mach

0.9. By 1938, work on a full-scale ramjet-powered aircraft had begun, with component ground tests conducted up to Mach 2.35 in 1939. These tests were halted thereafter owing to the onset of WW II. In Germany, Trommsdorff led a successful effort that began in 1935 to develop artillery shells powered by multiple-shock, conical-inlet, liquid-fueled ramjets. These shells actually accelerated from Mach 2.9 to 4.2 in trials in the early 1940s. The Germans (Sanger et al.) also had designs for an aircraft-launched ramjet-powered cruise missile but never constructed or tested one. They did, however, field the first operational ramjet-powered missile in the form of the V1 "buzzbomb" powered by a subsonic flight speed pulsejet engine. Strechkin in Russia also began ground testing of ramjet components at speeds up to Mach 2 in the mid-1930s and successfully flight tested a tandem-boosted ADR using magnesium/aluminum solid fuel in 1939 under the direction of Merkulov. These were subsequently supplanted by the desire to augment the thrust of existing aircraft using wing-mounted ramjet pods, again under Merkulov's direction, but the attempt was thwarted, after initial flight testing in 1940, by the events of WW II.

Reid (USA) and Marquardt (GB) joined the ramjet development effort in the early 1940s in the form of aerial-guided projectiles and aircraft performance augmenters, respectively. These efforts continued after WW II and resulted in weapon systems such as the BOMARC (USAF), Talos (USN), and Bloodhound (GB) anti-air missiles, as well as numerous basic and applied experiments at national research centers in both countries. The next section describes those efforts supported by the U.S. Navy from WW II through the present, and Ref. 3 describes those supported by the U.S. Air Force and the National Aeronautics and Space Administration during this same time span. The reader is referred to Ref. 1 for foreign ramjet development efforts during this period.

The history of scramjets[1] is more compact, although still 40+ years old. The initial theoretical and experimental feasibility studies on combustion in a supersonic flow were not done until 1952–1953 by Pinkel, Smith, and Davis (USA) on a flat plate. These were followed by several theoretical studies on the utility of external burning on supersonic airfoils to reduce drag and/or produce thrust and an experimental demonstration of net positive thrust on a double wedge in 1958 by Dugger and Billig (USA).

Interest in scramjet engines as we know them today, (i.e., in internally ducted flows with supersonic heat addition) began in the late 1950s and early 1960s. A plethora of theoretical studies were done in the United States, Canada, Great Britain, France, Germany, and Russia during this period, demonstrating the potential for large performance gains with scramjet engines over all other known propulsion systems at flight speeds above Mach 5. These and their follow-on studies, including basic experiments and component and engine tests, are documented in Ref. 1 up through 1987.

U.S. Navy Ramjet Development

Our intent for the remainder of this paper is to describe, in chronological order, the development of ramjets and scramjets supported by the U.S. Navy since WW II. For convenience, descriptions are divided into surface-launched and air-launched subsections for subsonic combustion ramjets, but combined for scramjet engine development. For reference, 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.)

In addition, these same data have been incorporated on a histogram (Fig. 4) to show not only the time span but the type and extent of development done on each. Here, the type of development includes fundamental R&D studies, exploratory component development studies and ground tests, free-jet engine ground tests, flight tests, and operational deployment. For clarity, only the highest category is used for a given concept. From Fig. 4, several observations can be made. First, the U.S. Navy has supported and developed a substantial, although not complete, technology base on a variety of ramjets. This technology base, however, is not nearly as substantial for scramjets and their derivatives. Second, a number of these ramjet engines and ramjet-powered weapon concepts have been flight tested, but none at hypersonic speeds. Third, only one ramjet system has ever become operational (the Talos), and it is still being used as a target today (Vandal). Finally, the level of support has and continues to cycle with time, with evidence of a very low ebb in support today.

Surface-Launched Ramjet Development

The history of surface-launched supersonic ramjet-propelled vehicles began in 1944 at The Johns Hopkins University Applied Physics Laboratory (JHU/APL) at the behest of the U.S. Navy's Bureau of Ordnance.[4] The Navy's surface fleet was very much interested in (1) an anti-air weapon that could defeat aircraft threats in response to the lessons being learned, especially in the Pacific theater, and (2) projections of the future availability of small, high-speed, radar-guided anti-surface missiles. This request led to the initiation of the "Bumblebee" program for the Navy 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.

Table 1: U.S. Navy ramjet evolution.[a]

Engine/Vehicle	Engine Type	Dates (year)	Cruise Mach No.	Cruise Altitude (K ft)	Powered Range (nmi)	Launcher	Total Length (in.)	Sustainer Length (in.)	Diameter (in.)	Total Weight (lbm)	State of Devel.
Ramjets											
Cobra	LFRJ	1945–46	2.0	20	—	Rail	—	—	6	240	Flight demo.
BTV	LFRJ	1947–48	2.4	30	10	Rail	—	—	18	—	Flight demo.
RTV	LFRJ	1949–50	2.4	30	25	Rail	—	—	24	—	Flight demo.
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
/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
NASP	MCSJ[b]	1985–94	0–26	0–orbit	Orbital	Runway	—	—	—	500K	Free-jet tests (M7)
Counterforce	DCR	1995–present	4–6	80–100	—	VLS	256	183	21	3750	Component tests

[a]Abbreviations defined throughout the paper unless otherwise noted.
[b]Mixed-cycle scramjet.

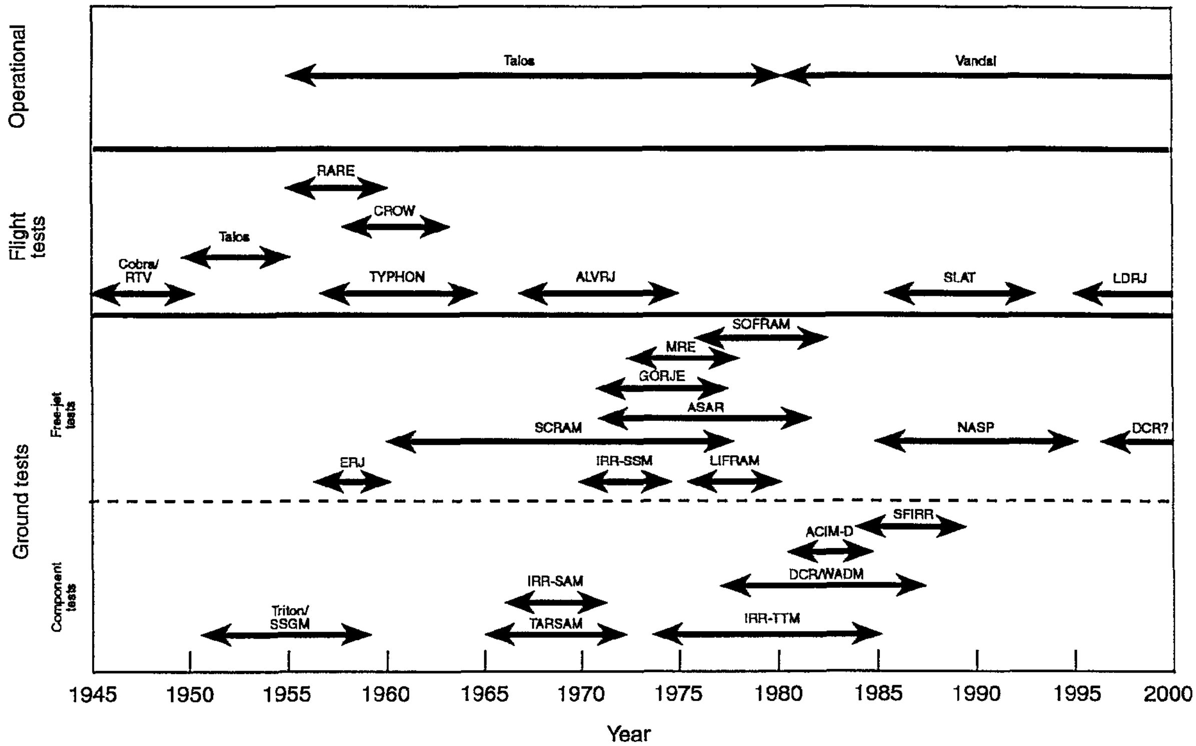

Fig. 4 Navy ramjet/scramjet development.

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For the ramjet, the desire was to field a radar–beam-riding anti-air weapon capable of delivering a 600-lbm warhead to ranges in excess of 100 nmi. To do this, a progressive ramjet development program was devised (remember that there was essentially no experience in the development of supersonic ramjets in 1944). This program comprised a succession of ramjet-powered flights in which size, range, and cruise altitude were increased.

The first of these was the Cobra ramjet (Fig. 5). The Cobra was a 6-in.-dia., normal shock inlet, tandem-boosted (to Mach 2), liquid propylene oxide– fueled ramjet flight test vehicle which cruised at Mach 2 at a 20K-ft altitude. Its purpose was to demonstrate that a ramjet could produce the requisite thrust to cruise at supersonic speeds, which it did in June 1945 while flying off of the New Jersey coast. This was the first-ever 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 (BTV). The BTV was just a scaled-up version of the Cobra with a higher flight speed (Mach 2.4) and cruise altitude (30K ft) using kerosene fuel. It also demonstrated the throttleability and accelerative and cruise range capabilities of a ramjet, accelerating from its end-of-boost flight speed (Mach 2) to Mach 2.4, and then cruising for 10 nmi. A third normal shock inlet ramjet-powered demonstration vehicle, denoted the Ramjet Test Vehicle (RTV), followed the BTV, with increased diameter and powered range. In these tests, conducted in 1950, a 24-in.-dia. vehicle demonstrated a 25-nmi powered range cruising at Mach 2.4 at 30K ft.

Based on these successes, the next 5 years were spent developing a ramjet-powered system that met the beam-riding, 600-lbm-warhead, 100+ nmi powered range weapon requirements. The resulting ramjet engine evolved to where it no longer used a normal shock inlet; rather, it employed an annular inlet with a conical centerbody which directed air into a liquid hydrocarbon–fueled can combustor and could cruise at Mach 2.7 at altitudes up to 70K ft after tandem boost to Mach 2.2. The result was the Talos fleet air defense missile,[4] which was manufactured by the Bendix Corp. and first introduced into the fleet in 1955 (Fig. 6). Talos was quite large (see Table 1) in that it weighed 7720 lbm at launch and was 386-in. long with a 28-in. diameter. The sustainer portion itself was 254 in. long, weighed 3360 lbm, and was capable of a powered range in excess of 120 nmi after boost to Mach 2.2. It was the first (and last, in 1980) operational ramjet in the U.S. Navy's inventory (the U.S. Air Force had BOMARC as an operational system).

THE SUNDAY SUN

BALTIMORE, SUNDAY, JUNE 9, 1946

Navy Reveals Supersonic Engine Exceeding 1,400 Miles An Hour

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Fig. 5 *The Baltimore Sun* reported in June 1946 on the development of a supersonic ramjet engine. (© 1946, *The Baltimore Sun.* Photo courtesy of World Wide Photos.)

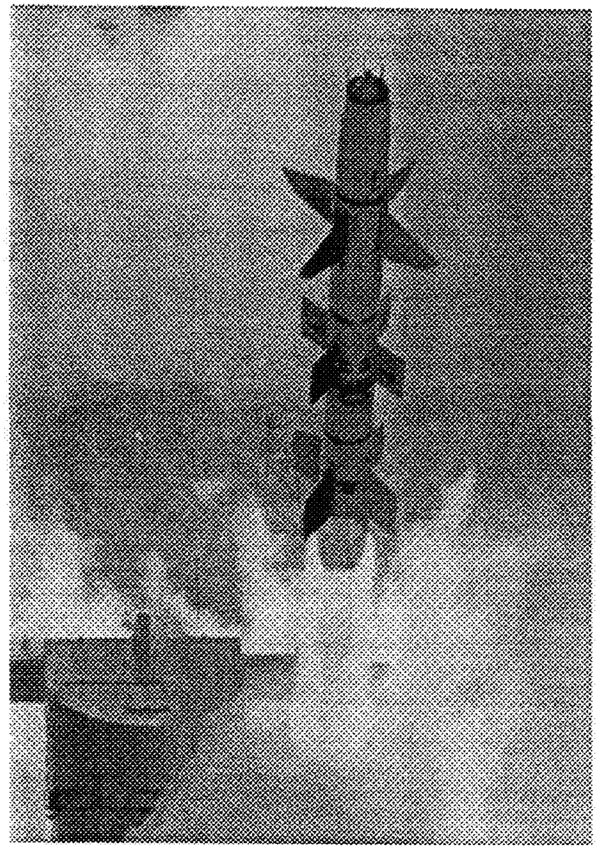

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Fig. 6 The Talos missile (ca. 1958).

This does not end the Talos story. After decommissioning of the last heavy cruiser (USS *Boston,* which deployed the Talos missile in 1980), there was (and still is) a need for a supersonic target to simulate hostile anti-ship missiles known to be in other nations' inventories. The solution? 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 a lower inlet design 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.

Returning now to the history of surface-launched ramjets subsequent to the Talos, the Navy in the early 1950s was addressing ways to deliver strategic ordnance at ranges in excess of 2000 nmi. At that time, solid-rocket propulsion was considered appropriate only for short-range flights because of its very high fuel consumption and difficulty in casting large-diameter motors. In addition, the reliability and safety of liquid rocket propulsion had not evolved to the point of confidence, especially for shipboard use. Consequently, the second Bumblebee task undertaken by JHU/APL was to develop a ramjet-powered surface-to-surface cruise (or strike) missile capable of traveling 2000 nmi at Mach 3 flying at a 70K-ft altitude, designated the Triton missile.[5] Several configurations were investigated, with the final version capable of launch from an SSBN/Polaris launch tube. Such a configuration is shown in Fig. 7. This particular configuration is powered by two underslung, conical-inlet, liquid-fueled ramjet engines.

Although component tests were successfully conducted on these engines and the vehicle concepts met the established mission requirements, very-long-range ramjets needed (and still need) to fly within the atmosphere and be reliably guided to their intended target(s). Both requirements presented problems in the mid-to-late 1950s. The active, autonomous guidance systems tended to be very

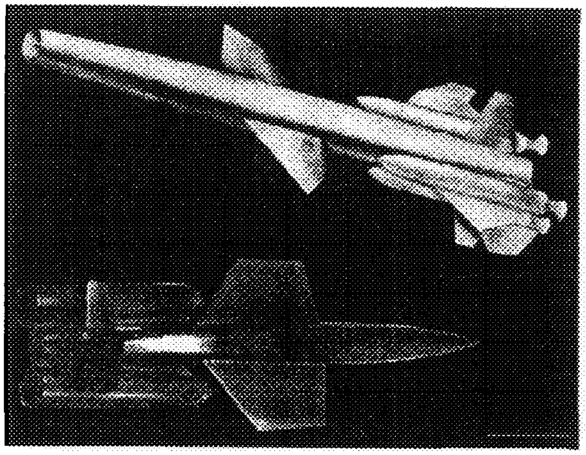

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Fig. 7 (Top) Early design concept (ca. 1951) of Triton, a very large missile intended for sea launch. (Bottom) Wind tunnel model of later Triton version. Twin ramjet engines were mounted in the high-pressure region under the wings.

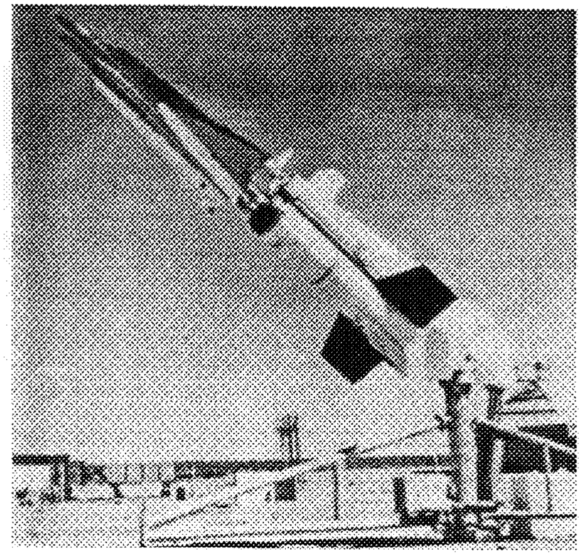

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Fig. 8 The Typhon long-range missile on an early launcher (ca. 1960).

large and heavy and exhibit questionable accuracy. Also, special materials were needed for the heating encountered in the atmosphere during these long flights. On the other hand, large strides were made in both liquid- and solid-rocket motors by the late 1950s. The safety and reliability of liquid rockets had dramatically improved, and solid-rocket propellants were being reliably cast in large-diameter motors, along with an increase in specific impulse. In addition, inertial guidance systems were much smaller and lighter than their active counterparts, and most of the re-entry heating problems had been resolved. As a result, rockets were chosen over their airbreathing counterparts for long-range strike applications, and the Triton/SSGM (Surface-to-Surface Guided Missile) program was canceled in 1958 in favor of the Polaris solid-rocket ballistic missile.

Although interest in strike applications of missiles powered by ramjets waned in the late 1950s, the success of the Talos anti-air missile led to the Navy's decision to pursue a follow-on version whose range was double that of Talos and whose flight speed was increased from Mach 2.7 to 4, while recognizing the need for an advanced beam-riding (semi-active) detection, guidance, and control system. The Typhon missile program, or super-Talos as it was called then, was initiated in 1957, again under the direction of JHU/APL, as its third Bumblebee ramjet task.[6–8] And, once more, industrial participation and prototype fabrication were provided by the Bendix Corp. The resulting tandem-boosted missile, shown in Fig. 8, was developed over the next 7 years along with its shipboard guidance system.

The Typhon missile was much smaller than its Talos predecessor, but was capable of flying 200 nmi while cruising at Mach 4.1 at an 80 to 100K-ft altitude after tandem boost to Mach 2.7. The Typhon was 16.75 in. in diameter and weighed 6160 lbm at launch (using the Talos booster) and 1800 lbm at end of boost compared with Talos's 28 in., 7720 lbm, and 3360 lbm, respectively (see Table 1). One reason for these decreases was that Typhon carried a smaller (250 lbm vs. 600 lbm) warhead, but its conical-inlet can-combustor ramjet propulsion system was also more efficient, and its subsystems and structure were more compact and weighed less.

The Typhon missile was successfully flight tested nine times in the period 1961–1963. However, the Typhon weapon system ultimately was not introduced into the fleet because the shipboard acquisition and tracking radar systems were not reliable, the software to operate the then newly introduced shipboard computers was difficult to operate and change, and the detection range performance was inadequate for single or multiple targets. In other words, the Typhon missile could outfly/outperform its radar/guidance/control/battle space coverage; it was technologically ahead of its time. Consequently, in late 1965, the program was canceled. However, the lessons learned and technology developed and envisioned for the Typhon weapon system were to become the cornerstones of the Aegis weapon system 10 years later.

About the time of the cancellation of Typhon in 1965, the Navy expressed interest in and initiated an advanced development program to determine the performance of air-ducted rocket-propelled missiles. Why air-ducted rockets? Because of the simplicity of the fuel supply/control system and the belief that solid propellants could be "shelved" for very long periods without maintenance, unlike liquid-fueled ramjets. (This notion was to be disproved via the Talos and other operational ramjet systems in subsequent years.) Thus began the Augmented Thrust Propulsion (ATP) program[8] conducted at JHU/APL with its two subcontractors, Martin Marietta/Denver (MMD) and the Atlantic Research Corp. (ARC).

The ATP program objectives were to develop the propulsion (JHU/APL), fuels (ARC), and missile configuration (MMD) for an anti-air alternative to the then-existing SM (Terrier, SM-I) and Talos missile systems. The emerging technology of using a common chamber for both the boost propellant and ramjet combustion (IRR) was also to be investigated. The propulsion and solid-fuel technology programs were successfully carried out in a collaborative effort between JHU/APL and ARC. 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, Fig. 9). 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 (TARSAM-MR, Fig. 9(a)) was an IRR configuration which employed four half-axisymmetric conical (or flush-mounted during boost, pop-out, two-dimensional) inlets mounted 90° circumferentially aft of the forebody section. These inlets, in turn, fed a single IRR dump combustion chamber and attendant exit nozzle. The ramjet combustor was fueled by a 60% boron-loaded solid-fuel, low-to-medium-pressure gas generator. The vehicle was 200 in. long, weighed 1750 lbm at launch and 1195 lbm after boost to Mach 2.7, and had a predicted powered range on the order of 80 nmi, a range superior to the performance of SM-I.

The extended-range configuration (TARSAM-ER, Fig. 9(b)), on the other hand, used four fully axisymmetric conical inlets to feed four separate ramjet combustors, each with its own exit nozzle. Each combustor was, again, fueled from a single 60% boron-loaded, solid-fuel gas generator capable of a 5:1 turndown ratio. It was smaller than the medium-range version at 186 in. long and weighed 2064 lbm after boost to Mach 3 using the Talos booster. As a consequence of the latter, it was 348-in. long and weighed 6420 lbm at launch. However, it had a powered range of around 160 nmi, compared with the 120-nmi range of Talos (and its 7720-lbm launch weight). This

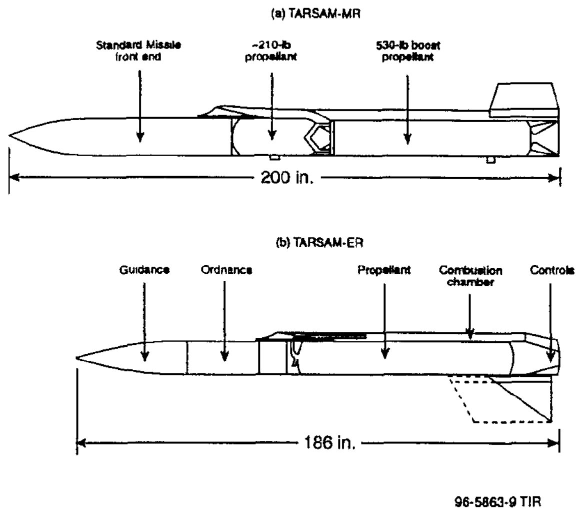

Fig. 9 Thrust Augmented Rocket Surface-to-Air Missiles. (a) Medium range, (b) extended range.

program was concluded as planned in 1971, but the proposed follow-on flight tests were not funded.

Concurrent with these ADR concept development efforts, the surface Navy focused attention on liquid-fueled ramjet-powered missile concepts since they had the potential for maximum range within a given launcher's volume/weight constraints, could engage and intercept hostile targets with power on, and were capable of substantive retargetting during flight. 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 which weighed 2200 lbm at launch and was 14.75 in. in diameter and 220 in. long. It cruised at Mach 3.3 at an 80K-ft altitude after boost to Mach 2.5. However, only component (inlet and combustor) tests were conducted on this engine/missile concept, primarily because the SM family of intermediate-range air defense missiles was already operational, and improvements in propulsive performance from the ramjet were not sufficient to warrant continued development of a new missile.

There was, however, a potential need for an anti-ship/strike weapon follow-on to Harpoon within the surface fleet. Consequently, 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 of the engine/missile configuration at the Arnold Engineering Development Center. The IRR-SSM (Fig. 10) was the same physical size as the IRR-SAM but weighed 2000 lbm at launch and carried a 300-lbm warhead. It weighed 1420 lbm at the end of boost (Mach 2.2), was capable of cruising at Mach 2.5 at 50K ft on up-and-over trajectories, or could

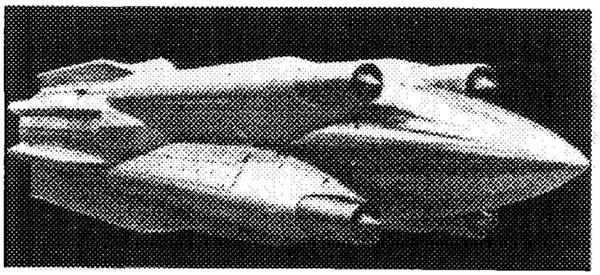

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Fig. 10 The IRR-SSM free-jet battleship model (ca. 1973).

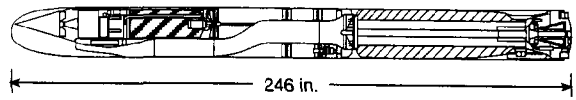

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Fig. 11 Schematic of IRR-TTM concept (ca. 1978).

cruise at sea level at Mach 2.2. Although successful in meeting its performance objectives (as most ramjet-powered vehicle concepts are), the Harpoon anti-ship missile was deemed adequate at that time and no further development was pursued.

However, interest existed in developing the technology for a submarine-launched long-range supersonic tactical missile. Consequently, 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). This concept is shown schematically in Fig. 11 and configured for torpedo tube launch. It had a 21-in. diameter, was 246 in. long, and weighed 3930 lbm at launch with a 900-lbm warhead and 2410 lbm at the end of boost. 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 60K ft.

This concept made extensive use of the U.S. Air Force's ASALM (Advanced Strategic Air-Launched Missile) "chin" inlet design. However, the ASALM was configured for a different flight envelope, requiring a new engine component database. Development of that database was initiated in 1975 and continued at a low level through completion of the exploratory development database in 1985.

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. One part of this effort was to address ways to increase the range of combat air patrol (F-14) aircraft weapons (missiles) to effect intercept at these ranges (see next section). The other part was to devise new, longer-range, ship-launched missiles that could counter these threats. In addition, during this same period, the Navy had developed the then-new Vertical Launch System (VLS, a self-contained box) to be used on all of its new ships for missile stowage and launch.

Out of these requirements came a number of surface-launched configurations that would meet the long-range high-speed-intercept requirements; all were ramjet (or DCR) powered. Of the ramjets addressed, most were IRRs (all coming after the introduction of the VLS requirement); an early example upon which the Navy chose to conduct exploratory development was called the Advanced Surface-to-Air Ramjet[8] (ASAR). Although this configuration was smaller in size than that which could fill the VLS (since it was initially designed for the MK 26 rail launcher), its engine components and integral booster were scaleable to a VLS-sized missile. Consequently, component exploratory development continued on this engine from 1972 through 1978 and advanced development from 1977 through 1981. These efforts culminated in an integral boost/ramjet transition/semi-free-jet ramjet engine trajectory test series in 1980–1981 run at the Hercules Allegheny Ballistics Laboratory test facilities. Figure 12 is a photograph of the test hardware.

Fig. 13 shows a schematic of the ASAR missile concept. It was 220 in. long with a body diameter of 16 inches. It weighed 2650 lbm at launch, carried a 200-lbm warhead, and cruised at Mach 3.8 at an 80K-ft altitude after boost to Mach 2.7. Later versions of this configuration, such as the Stand-Off Jammer Suppresser, were somewhat larger in that they filled the VLS, i.e., they had 19-in.-dia. bodies and were 256 in. long, but the technology employed was developed using the ASAR configuration.

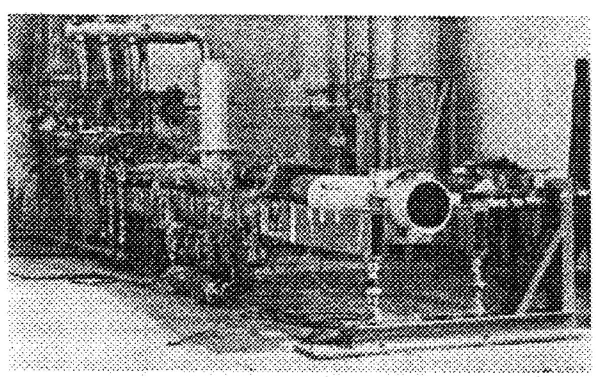

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Fig. 12 Advanced Surface-to-Air Ramjet booster transition hardware at Hercules Allegheny Ballistics Laboratory (ca. 1980).

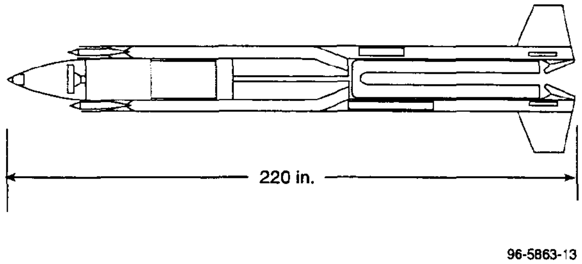

Fig. 13 Schematic of an Advanced Surface-to-Air Ramjet missile concept (ca. 1976).

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,[9,10] 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. It had the potential of tripling the range of the rocket-powered Sidewinder.

The RARE was one of the first SFIRRs ever developed. It employed a conical nose inlet and a rocket-ramjet system; the ramjet combustor used the chamber that housed the booster grain but had a separate upstream chamber through which the air and solid fuel mixed and ignited (Fig. 14). The fuel was principally magnesium (82%) with a little binder and oxidizer. The RARE used a sliding valve to prevent air from being introduced into the combustion chamber until booster burnout. It was boosted to about Mach 1 to simulate aircraft launch and had a cruise velocity of Mach 2.3.

One potential problem with RARE was that not all of the booster fuel was combusted/burned before the residual portion of the grain was ejected from the motor. To solve this potential boost-to-sustain transition problem, a dual, in-line combustion chamber approach, which had been used by NACA, was incorporated. This not only solved the booster fuel grain ejection problem but permitted ramjet combustion efficiencies as high as 85% to be achieved. The potential of alternative fuel formulations was also studied, boron-loaded fuel being the most attractive.

This concept was subsequently flight tested in a vehicle called the Low Mach Number Cruising Ramjet, which used a normal shock, rather than conical, nose inlet (Fig. 15). Three flight tests of the RARE vehicle were successfully conducted at Mach 2.3 between 1959 and 1960.

One SFIRR subsequent to RARE, called 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. The CROW was an axisymmetric IRR which was characterized by a solid-fueled ramjet sustainer with an integral solid booster packaged within the ramjet combustor (Fig. 16). It was 8 in. in diameter, 127 in. long, and weighed 370 lbm. The useful payload volume within the airframe was contained in a centerbody mounted behind an axisymmetric dual-cone compression spike and in parallel with the diffuser section. The ramjet fuel grain was an extended cruciform cylinder mounted behind the centerbody. The ramjet combustor was a right-circular cylinder downstream of the ramjet fuel grain, which also served as the rocket motor case for the solid-propellant booster. The rocket grain was separated from the ramjet grain by a bulkhead, which was connected to the centerbody of the rocket plug nozzle by means of a resonance damping rod. The bulkhead and nozzle centerbody were then jointly expelled through the nozzle by ram air pressure following booster burnout.

The CROW was designed for air launch at 50K 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.[11] Ground tests demonstrated that the CROW system

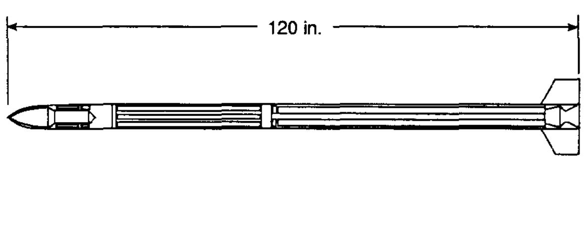

Fig. 14 Ram Air Rocket Engine propulsion test vehicle (ca. 1958).

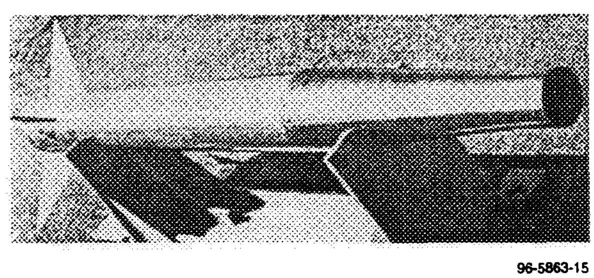

Fig. 15 Completed Low Mach Number Cruising Ramjet (ca. 1960).

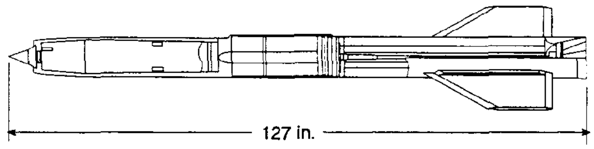

Fig. 16 Creative Research on Weapons vehicle (ca. 1963).

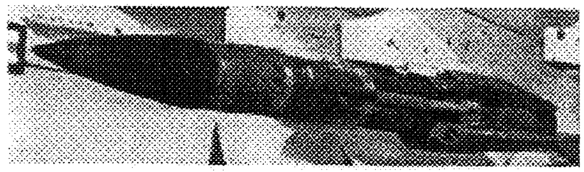

Fig. 17 Advanced Low-Volume Ramjet (ALVRJ) flight test vehicle (ca. 1975).

could operate from Mach 2.5 at a 45K-ft altitude to Mach 3.3 at 65K ft. These included both connected pipe and free-jet tests at NMC/PtMugu and The Marquardt Corp. (TMC). Numerous mixed-metal sustainer fuels, usually aluminum and magnesium in a viton polymer matrix, were studied, some using ingredients such as decaborane and hydrazine diborane. Thirty-six fuel formulations were tested over the course of the program.

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. An interesting and unique feature of the CROW development program was that it was supported with NMC/PtMugu institutional funds and conducted by a cadre of junior professional (entry-level) engineers and junior engineers.

The Navy's entry into aft-mounted side inlets on an LFIRR occurred in the mid-1960s with the initiation of the Advanced Low-Volume Ramjet (ALVRJ) program (Fig. 17). The ALVRJ[12,13] 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 JHU/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 NWC/CL developing and producing the integral booster, insulation system, and ejectable nozzle. The exploratory development phase of the program, which was conducted by Texaco Experiment, Inc. (TEI), of Richmond, VA, successfully demonstrated rocket booster, transition, and ramjet sustainer operation in connected pipe tests at a company-owned test facility and simulated flight operation of the ramjet sustainer in free-jet tests at the Ordnance Aerophysics Laboratory, Daingerfield, TX.

The ALVRJ was approved for advanced development in 1967, and a contract was concluded with Vought Aerospace, Inc., for its development and flight testing in 1968. United Aircraft Research Laboratory participated as a subcontractor to Vought for development of the ramjet combustor. The contract called for the flight demonstration of an air-launched, standoff, strike missile airframe/propulsion system based on the technology developed by TEI. The major program goals were to demonstrate, in controlled free flight, Mach 2.5 at sea level and Mach 3.0 at 30K ft to ranges in excess of 25 nmi and 100 nmi from the launch point, respectively, with sufficient margin in the flight vehicle to provide for terminally effective tactical payloads in subsequent operational derivatives.

The ALVRJ flight system was 15 in. in diameter, 179 in. long, and weighed 1480 lbm. Its propulsion system consisted of a liquid-fueled (JP-5) ramjet with an integral solid-rocket booster, four cruciform, outward-turning, two-dimensional inlets mounted approximately at the midbody, and an ejectable rocket nozzle. Initially, the inlets were inconel investment castings. The vehicle was tail controlled by four cruciform fins mounted to the inlet fairings at the aft end. The ramjet combustor, initially a deep-drawn inconel structure, was protected from heat and erosion by a flame-sprayed zirconium oxide coating and an insulating layer of Dow Corning DC93-104 silicon rubber. The combustor dome was fuel cooled. The booster propellant grain was a case-bonded star-perforated design composed of CTPB and ammonium perchlorate.

The advanced development program, which was extended from the originally contracted 4 to 11 years, resulted in a number of significant improvements to the TEI design and a successful, nearly flawless flight test program. Early in the program, the subsonic portion of the inlet ducts, upstream of the dump port section, was lengthened. Midway through the flight sequence, the combustor chamber material was changed from deep-drawn inconel to a more conventional rolled and welded steel, and the inlet structures were converted to sheet steel with welded seams, which reduced both complexity and cost. All three of these improvements were fully tested and validated on the ground and in flight.

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; each vehicle was launched by a Navy A-7 into 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 30K 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 FY80. 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, an LFRJ-powered missile concept, denoted the Generic Ordnance Ramjet Engine (GORJE) system (Fig. 18), was developed through engine testing at the NAWC/CL. As envisioned, it would provide an airbreathing propulsion system for the High-Speed Anti-Radiation Missile (HARM). Since a ramjet can provide higher average velocity with a lower peak velocity than a rocket, the use of a ramjet propulsion system in the HARM would relieve the then-current seeker dome aeroheating problem. The GORJE was designed to use the HARM forebody back to the propulsion system interface.

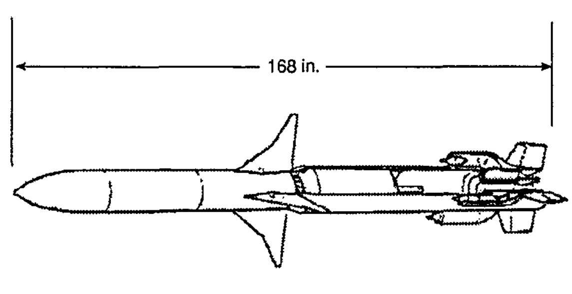

Fig. 18 Schematic of the Generic Ordnance Ramjet Engine (ca. 1974).

The configuration chosen was a parallel rocket ramjet. The rocket was located aft of the ramjet's liquid fuel tank but ahead of the combustor and, although packaged forward of the ramjet combustor, it exhausted the rocket combustion products through the ramjet combustor via a blast tube. Thus, the ramjet combustor was an annulus as shown in Fig. 18. The booster motor employed a reduced-smoke solid propellant.

A short length-to-diameter combustor ($L/D = \sim 1$) was used, and one of the challenges was to achieve high performance from such a short combustor. The combustor employed DC 93-104 silicone rubber for insulation; it allowed operation at higher combustion temperatures without combustor wall cooling. The combustor was expected to operate at ERs near 1, and, as expected, some evidence of combustor oscillations was observed during the direct-connect combustion testing.

The GORJE employed four side-mounted axisymmetric inlets with the entrance just aft of the trailing edge of the midbody control wings. Although it would have been desirable to locate the inlet entrance closer to the front of the missile, the aircraft interface prevented such a design since the HARM already had four wings. Consequently, the flow at the entrance to the inlets was distorted by the wings, but satisfactory inlet performance was confirmed through installed inlet wind tunnel tests. Since this concept did not employ an integral rocket, combustor port covers were unnecessary. Likewise, inlet covers were not used.

The ramjet used RJ-4I fuel contained in a fuel tank which was integrated within the hardback, and the tank contained a bladder for positive expulsion of the fuel. The fuel controller was a simple system designed to maintain a constant cruise speed, using a simple bellows for altitude control.

The ramjet engine was eventually integrated with the booster, and semi-free-jet propulsion tests were conducted during which the criticality of the combustor oscillation/instability problem was highlighted. Even though most of the expected 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 at TMC. These tests characterized all the combustor-inlet pressure oscillations, and methods were developed and incorporated to mitigate and contain them. This program also provided some of the impetus to initiate an extensive research and exploratory development activity to understand the causes and investigate control methods of combustion instabilities in short L/D liquid-fueled ramjet engines. The planned flight tests of this system were never conducted owing to 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 natural choice for this purpose was to have an airbreathing ramjet engine principally remain within the aircraft launcher constraints. The resulting vehicle was powered by an LFIRR and designated the Modern Ramjet Engine (MRE, Fig. 19). It had a 15-in. diameter and was limited to a 168-in. length, as was the GORJE. The complete system was to weigh less than 1500 lbm. The MRE employed an IRR engine and, since it would require maneuvering for the anti-air mission, it incorporated two cheek-mounted two-dimensional inlets and had bank-to-turn controls, the same as an airplane. The MRE concept utilized 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 by a consortium of the United Technologies Research Center (UTRC) (combustor and inlet development), the United Technologies Chemical Systems Division (CSD, formerly UTC) (engine integration), and the Boeing Aerospace Co. (advanced inlet development). The engine used liquid SHELLDYNE H (RJ-5) fuel and had a fuel control system that employed speed control and altitude sensing with inlet margin control, a much more complex algorithm than that used on previous ramjet-powered missiles and missile concepts such as the GORJE. The engine subsystems development was conducted at UTRC and CSD. The engine was successfully free-jet tested at TMC in 1976–1977.

In the mid-1970s, a number of propulsion systems and vehicle concepts were being investigated for a long-range anti-air missile. Consequently, both solid-fueled ramjet (SOFRAM) and liquid-fueled ramjet (LIFRAM) engine development and demonstration programs were initiated at NAWC/CL. The performance goals for both were to fly 150 nmi at a Mach 3+ cruise condition.

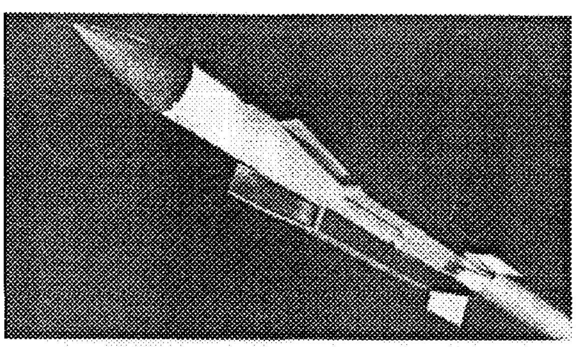

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Fig. 19 Modern Ramjet Engine test configuration (ca. 1976).

Although the SFRJ was (and is) perhaps the simplest of the ramjet engine cycles, it had the lowest development maturity level of any of the ramjet systems in the mid-1970s. Recall that the SFRJ (or SFIRR) has some inherent throttle capability, but it generally is not envisioned to have an active throttle. Since it is an all–solid fuel system, it is potentially less costly and simpler than other candidates because it lacks a fuel supply and management and control systems. It also offers the potential of a high volumetric loading efficiency and performance, but in a more limited operational envelop than its ADR and LFRJ counterparts.

The SOFRAM was investigated jointly by the U.S. Navy (NAWC/CL) and the U.S. Air Force (Wright Laboratory). Like the LIFRAM, it had an 8-in. dia. and was 144 in. long (Fig. 20). The overall propulsion system length was about 90 in. It was developed by CSD under joint services sponsorship. The engine was an SFIRR, with the integral booster employing a reduced-smoke solid propellant. Fuel for the booster and ramjet was an all-hydrocarbon formulation (UTX 18,818) packaged in a common chamber. All engine components were demonstrated in subsystem tests and subsequently in engine semi-free-jet tests. The engine (forebody, inlet, combustor, exit nozzle) was tested successfully at Mach 3 at a simulated altitude of 70K ft in the NASA Lewis Research Center's 10 ft × 10 ft supersonic propulsion wind tunnel in 1980.

The liquid-fueled ramjet counterpart to SOFRAM, the LIFRAM, was subjected to the same performance objectives and vehicle constraints. It underwent an engine demonstration program to develop and demonstrate LFRJ technology for a long-range air-to-air system. It was also an 8-in-dia. vehicle that was 144 in. long (Fig. 21). However, its propulsion system was only 80 in. long. It used two side-mounted axisymmetric inlets 180° apart (eventually dropped to about the 45° position and located 90° apart). It was configured to be an IRR system and designed to propel a next-generation long-range anti-air missile to replace the Phoenix system in a Sparrow-sized missile. The desired speed and range were M > 3 and R ~ 150 nmi, respectively. The engine/missile was limited to a maximum of 650 lbm. The engine was developed and demonstrated by NAWC/CL and TMC. It was successfully

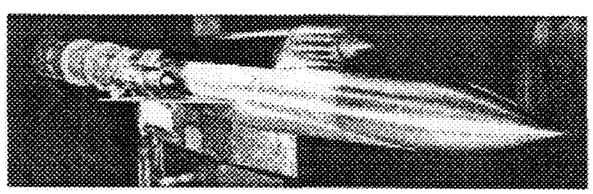

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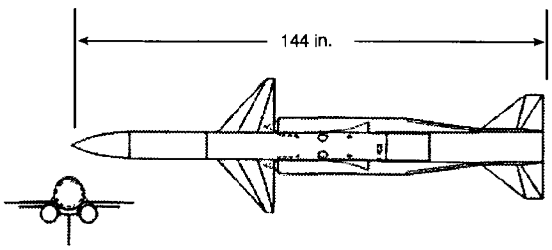
Fig. 20 Solid-Fueled Ramjet free-jet engine (ca. 1980).

(a)



(b)

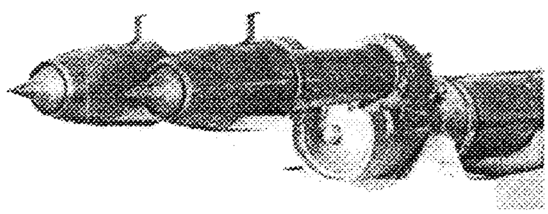


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Fig. 21 Semi-free-jet Liquid-Fueled Ramjet (ca. 1980). (a) Baseline configuration, (b) semi-free-jet engine.

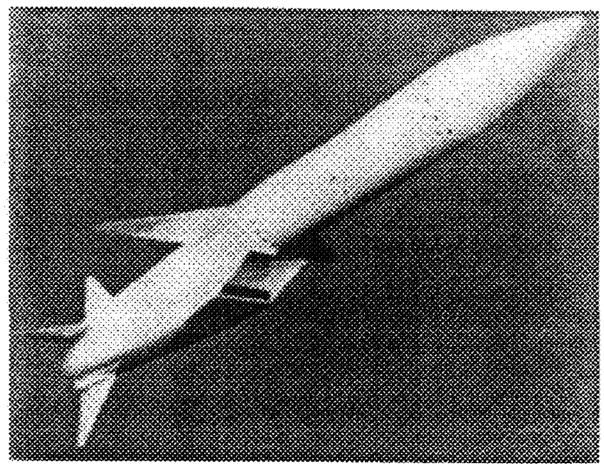

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Fig. 22 Advanced Common Interceptor Missile Demonstrator (ca. 1983).

demonstrated in semi-free-jet engine tests at TMC at Mach 3 in 1979 and 1980.

Following these endeavors, a second-generation LFRJ addressing the long-range air-to-air mission was developed during the early 1980s. The intent of this program was to demonstrate the advantages of a liquid-fueled ramjet propulsion system for the Advanced Air-to-Air Missile (AAAM) system (contractual team: Hughes, Raytheon and McDonnell Douglas, and Hercules and CSD). The resulting Advanced Common Interceptor Missile Demonstrator (ACIMD) engine was an LFIRR that used a single underslung two-dimensional inlet integrated with a 9-in.-dia., 144-in.-long vehicle (Fig. 22).

The ACIMD was developed primarily by the NAWC/CL with support from TMC. It employed a high-performance aluminized solid-rocket booster and liquid-hydrocarbon fuel, JP-10, for the ramjet, a fuel used extensively by both Navy and Air Force cruise missiles. The ACIMD 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 (AirResearch, Inc.), fuel control valve, and fuel tank bladder design and demonstration. A flight demonstration vehicle was designed and fabricated. However, the program was canceled before flight testing when the AAAM program was canceled in 1984.

Another SFIRR propulsion system was designed and developed for the Navy (NAWC/CL) by CSD from 1984 through 1989. It was intended to be a high-speed propulsion system that could fly at M = 2.5 at sea level for a range of about 50 nmi and carry a penetration or other warhead of similar size. The system was envisioned to be 168 in. long and 18 in. in diameter.

This SFIRR employed a chin inlet similar to the U.S. Air Force's ASALM configuration and the Navy's Supersonic Low-Altitude Target (SLAT, see below) missile systems. Air was introduced into the engine at two locations, in a bypass concept, at the front of the combustor and just aft of the fuel grain (Fig. 23). The combustor was developed through connected-pipe testing in full scale at nominal as well as extreme operating conditions ranging from −45 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 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. The booster employed segmented port covers aft of the fuel grain and a frangible glass cover at the head end of the combustor. 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 the development of a modern replacement, SLAT (Fig. 24), in 1986 using an LFIRR engine. SLAT was intended to fly at Mach 2.5 at sea level

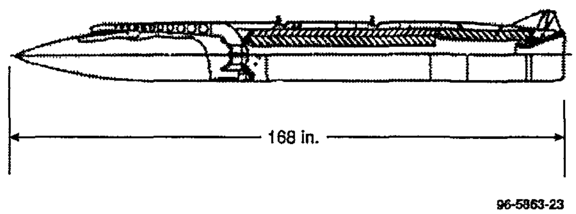

Fig. 23 Solid-Fueled Integral Rocket Ramjet vehicle design (ca. 1988).

for 50 nmi. It was developed by the Martin Marietta Corp. with support from TMC and CSD under contract to the Naval Air Systems Command. NAWC/CL was to provide 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.[3] SLAT was 21 in. in diameter and 216 in. long, and was designed to be recoverable and reusable. It employed JP-10 fuel but could use RJ-4I fuel as well. The fuel control system utilized a turbopump and cavitating venturi fuel control valve, as well as a pressurized fuel bladder for positive expulsion.

Since modifications to the original ASALM engine configuration had been made, a series of component and free-jet engine performance demonstration tests was conducted before the planned flight tests. SLAT's propulsive performance was as predicted in both the component development and demonstration and free-jet engine tests. During the combustor demonstration testing, combustor pressure oscillations (combustion instabilities) were encountered, but the cause was determined to be the test configuration rather than fundamental combustor phenomena. These oscillations were not observed during any of the free-jet tests.

Five flight tests were also 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,

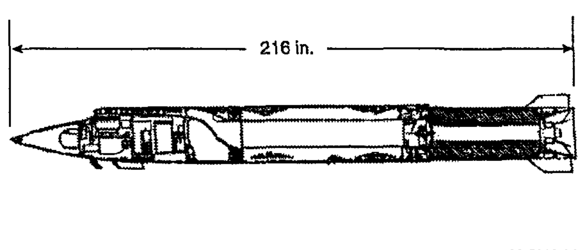

Fig. 24 Supersonic Low-Altitude Target propulsion system (ca. 1991).

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 (LDRJ), 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 thrust vector control system. There are no wings or other surfaces for control; thrust vectoring is accomplished by vectoring the aft portion of the airframe (the ramjet combustor and exit nozzle). The ramjet will utilize JP-10 as the sustainer fuel and a high-performance solid propellant to boost the missile up to the ramjet operating speed. The booster may be of the integral type or tandem ejectable. In either case, a portion of the booster would be housed in the ramjet combustor volume.

Scramjet and Derivative Engine Development

As noted in the introduction, the development of scramjet engines and their derivatives did not start until the 1950s in the NASA centers. The Navy's support of hypersonic propulsion began shortly thereafter (in the mid-1950s) at JHU/APL in the form of the External RamJet (ERJ) program.[1,5] 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-ever demonstration of 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. 25. This project continued through 1961 when it was successfully concluded.

Following these early successes, it was understood that much higher thrust and/or fuel-specific impulse could be achieved by putting a cowl opposite the aft part of the wedge or by ducting the flow through internal channels, much like other lower-speed airbreathing engine cycles. However, compared with the ramjet, the ducted scramjet also had to address and overcome higher materials temperatures and heating rates, surface skin friction, fuel ignition and kinetics, and other issues associated with hypersonic-speed flight. Early studies also showed that an internally ducted scramjet-powered missile could achieve powered ranges of several hundred miles when flying at Mach 8 at high altitude. Consequently, in 1961, 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

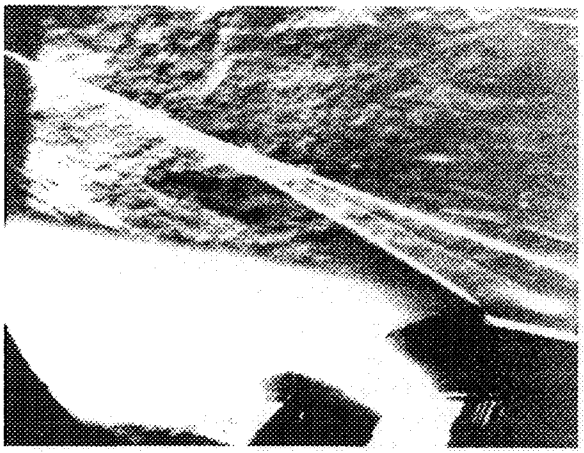

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Fig. 25 Supersonic combustion at rear of an externally burning ramjet (ca. 1958).

become known as the Supersonic Combustion Ramjet Missile, or SCRAM.

Figure 26 is a schematic of the SCRAM as it was envisioned in the mid-1970s.[14] It weighed 5470 lbm at launch and was tandem boosted to Mach 4. After boost, the SCRAM sustainer weighed 2020 lbm, was 158 in. long, and tapered from front to back to a maximum diameter of 26.2 in. The SCRAM was predicted to have a powered range of 350 nmi when flying at Mach 7.5 at a 100K-ft altitude or 47 nmi flying at Mach 4 at sea level using liquid HiCal 3-D (ethyldecaborane) fuel.

The SCRAM engine and its components underwent considerable development work from the early 1960s through its termination in 1977. Although this might seem like a long period for a given program, consider that conventional ramjet development started in the 1930s and continues even today. In any event, 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. dia. × 60 in. long, three-module SCRAM free-jet engine was tested in the 1968–1974 time frame from Mach 5.2 to 7.1[16] using liquid borane or mixtures of liquid hydrocarbon/borane fuels. This engine, shown installed in the JHU/APL test facility in Fig. 27, was the first ever 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: (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 during that same year by J. L. Keirsey of JHU/APL. His engine concept, the DCR discussed previously, overcame all three of the above objections.[1,17] 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.[1,16] It was incorporated into a missile concept which was predicted to be capable of meeting the long-range wide-area defense mission requirements of the late 1970s through the mid-1980s. Unlike the SCRAM, however, this missile was limited to Mach 6 flight speeds, principally because of passive cooling materials requirements. (The SCRAM was also intended to be passively cooled, but the envisioned materials never could be developed.) It was also quite capable of increasing that range by about 50% by cruising at Mach 4 rather than 6.

One version of the DCR-powered missile, called the Wide-Area Defense Missile (WADM) or Hypersonic WADM (HyWADM), is shown in an artist's rendition in Fig. 28. This vehicle was configured as a 21-in.-dia. cylinder to fit within the VLS. It weighed 3750 lbm, was

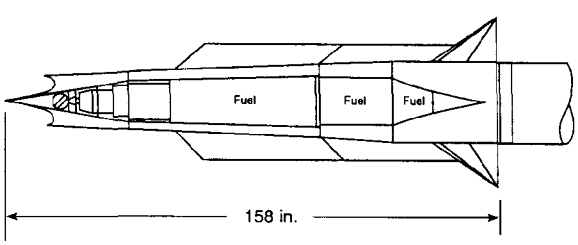

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Fig. 26 Supersonic Combustion Ramjet Missile system concept (ca. 1975).

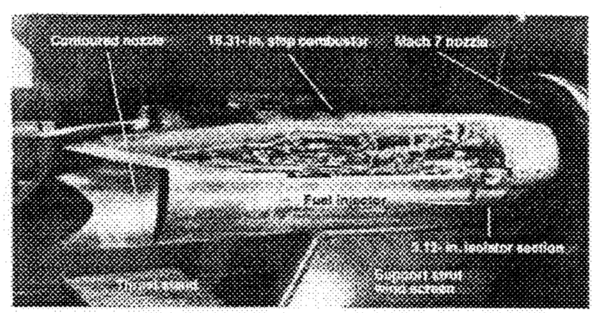

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Fig. 27 SCRAM engine configuration in Mach 7 free-jet tunnel.

256 in. long at launch, and was tandem boosted to around Mach 3.2. It could cruise at Mach 3.5 at sea level and to very long ranges when flying between Mach 4 and 6 at altitudes between 80K to 100K ft and deliver a 200-lbm warhead. Considerable exploratory development was conducted on this engine/missile concept through the Surface-Launched Missile Technology program. Not only were engine components such as inlets, isolator ducts, fuel injectors, fuel supply/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 considered for a counterforce/strike weapon, and development through flight test may be reinstated as early as 1998.

The National AeroSpace Plane Program

The objective of another scramjet initiative, the National AeroSpace Plane (NASP, Fig. 29) program, was the development of two X-30 aircraft capable of single-stage-to-orbit (SSTO) flight as well as horizontal takeoff and landing from conventional runways. The aircraft was to be hydrogen fueled and powered by airbreathing engines from takeoff to orbital velocities of approximately Mach 25. A sophisticated "low-speed accelerator system" was to power the vehicle up to a flight speed of approximately Mach 3, at which point the primary ramjet/scramjet engines took over to power the vehicle up to high hypersonic flight speeds. A rocket was to be available to provide the final thrust increment required for orbital insertion and for the reentry burn. Upon completion of a mission, the airplane-like qualities of the X-30 were to enable the vehicle to be powered on approach and, upon landing, be capable of rapid turnaround.

To make this a reality, the concurrent development of revolutionary technologies was required in almost every major aerospace discipline. One can look back and say that the national investment in NASP resulted in a significant advancement of the state of the art in aerospace technology, including computational fluid dynamics, for high-speed flight. To that end, NASP was an experimental airplane program, in the spirit of the X-1 and X-15 programs, geared to establishing the technological foundation for the future development of NASP-derived vehicles, which would have a wide variety of applications and missions.

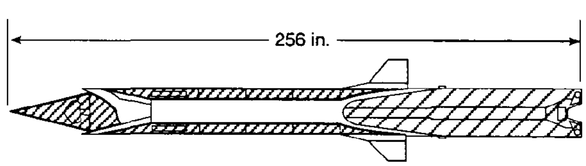

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Fig. 28 Schematic of the DCR-powered Wide-Area Defense Missile concept (ca. 1983).

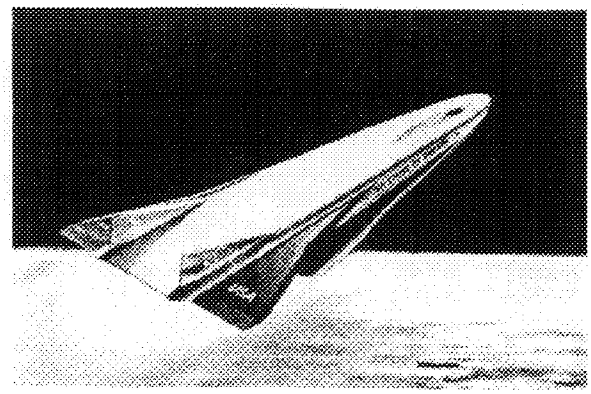
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Fig. 29 The National AeroSpace Plane (ca. 1993).

The NASP program evolved from a classified Defense Advance Research Projects Agency (DARPA) activity, code-named Copper Canyon, in which the feasibility of building an SSTO airbreathing vehicle was investigated. A select group of national experts was assembled to define the technical concept, evaluate the key requisite technologies, identify technical risks, and define approaches to reduce those risks. The Copper Canyon Team concluded that the development of such a vehicle, along with the associated technologies, was feasible with proper technical, managerial, and fiscal focus. Based on these conclusions, the secretary of defense established the NASP program in 1985, involving Air Force, Army, DARPA, Navy, and NASA participation.

A DoD/NASA Joint Program Office was formed at Wright Patterson Air Force Base in Dayton, OH, and eight industry participants, three engine companies, and five airframe companies were selected for the Phase 1 program effort to develop competitive concepts for the two proposed X-30 vehicles. At the same time, it was recognized that a large portion of the national expertise in hypersonic aerodynamics and propulsion-related disciplines resided in U.S. government and government-affiliated laboratories; therefore, in conjunction with the industrial activity, the government established a generic technology research effort called the Technology Maturation Program. The groundwork for what became known as the Phase 2 portion of the program was instituted to develop and demonstrate the key aerospace technologies required to establish sufficient confidence to justify a national commitment to actually build the X-30 vehicles in Phase 3. This technology demonstration phase was then slated to conclude with a "Phase 3 go-ahead decision" in October 1990. A positive Phase 3 decision was to have resulted in an experimental vehicle development program, with a goal of first flight in 1994.

In 1987, Phase 2A culminated in the evaluation of the eight industrial participants, and five companies were chosen to continue: the McDonnell Douglas Corporation (MDC), the General Dynamics Corporation/Fort Worth Division (GD/FW), Rockwell International's North American Aircraft (NAA) and Rocketdyne (RD) Divisions, and United Technologies Pratt & Whitney (P&W). Phases 2B and 2C entailed the continued development of six of the competitive vehicle concepts. Along with the evolution of the government technology maturation activities, each airframer (MDC, GD/FW, and NAA) developed independent vehicle concepts for each of the two engine company concepts (P&W and RD).

It had become evident in the early phases of the program that the NASP goals created a unique national challenge which required a unique program structure. Technical expertise residing at places such as NASA (Langley, Lewis, and Ames Research Centers), JHU/APL, and the Air Force Wright Laboratory was vital to the success of the program since, at the outset of the NASP program, the national industrial base in hypersonics had been the victim of severe atrophy.

In 1989, the Bush administration, after initially canceling the program, decided to initiate a program review by the newly formed National Space Council. Led by the vice president, the Space Council review identified the NASP Program as a "high priority national effort . . .," and recommended that the technology phase (Phase 2) be extended to 1993 to reduce technical risk and cost. The president approved the council's recommendations, giving the program new life and increased visibility. At about the same time, it was becoming evident that the national experience base in hypersonics built by this program was a valuable resource; therefore, the previously planned industry reduction to two or three contractors was eliminated in favor of a unique National Team program structure. Formally started in 1991, the National Team program approach combined the resources of the five prime industry contractors in a joint-venture partnership to focus technical and programmatic capabilities on the development of a single X-30 concept. Taking advantage of the best ideas from the individual competing teams, a single X-30 vehicle configuration, shown in Fig. (29), was developed by the National Team.

Although the establishment of a National Team in favor of competition was a departure from the traditional program approach, the groundwork for such a decision had been laid in 1989 when the Joint Program Office established an industrial materials consortium to accelerate the advancement of new materials technology. In addition to maintaining a strong industrial technology base, another benefit of the National Team approach was the elimination of industrial competition, which facilitated the incorporation of the technical expertise residing in the "government" directly into the development of the focused X-30 concept.[18,19]

Upon completion of the Phase 2D technology development portion of the program in 1993, the technology maturity was deemed not to be at the level required to justify a $15 billion investment to develop two X-30 aircraft, and a series of studies was conducted to design scaled-back alternative flight vehicles. These alternatives included the X-30X, Hyflite, and HySTP flight test vehicles, where the principal objective was to verify in flight the viability of the ramjet/scramjet propulsion system. At the end of FY94 the secretary of the Air Force decided to terminate the program and not pursue any of the proposed flight test options. The Air Force then turned its focus to the Mach 4 to 8 flight regime and hydrocarbon-fueled scramjets, thereby repeating the same program execution and decision cycle encountered in the days of the first Aerospace Plane Program in the 1960s.[1]

Closing Remarks

This presentation of ramjet history over the past 50 years has hopefully 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/scramjet development experience accrued since WW 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.

If any systems have been omitted, the authors apologize. Any omissions were not intentional, and the authors would be pleased with any additional information that is permitted to be provided in an open forum.

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