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A Century of Ramjet Propulsion Technology Evolution

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A general review is presented of the worldwide evolution of ramjet propulsion since the Wright brothers first turned man's imagination to fly into a practical reality. A perspective of the technological developments from subsonic to hypersonic flight speeds is provided to allow an appreciation for the advances made internationally from the early 1900s to current times. Ramjet, scramjet, and mixed-cycle engine types, and their operation and rationale for use are considered. The development history and principal contributing development programs are reviewed. Major airbreathing technologies that had significant impact on the maturation of ramjet propulsion and enabled engine designs to mature to their current state are identified. The general state of flight-demonstrated technology is summarized and compared with the technology base of 1980. The current status of ramjet/scramjet technology is identified. Ramjet and scramjet propulsion technology has matured dramatically over the years in support of both military and space access applications, yet many opportunities remain to challenge future generations of explorers.

Introduction

HISTORY and technology reviews are written and read for many practical reasons,[1] including their usefulness to managers and engineers engaged in the advanced technology developments. Although history does not repeat itself, similar situations often have similar results, and thoughtful study of past technology developments can help us to recognize and avoid pitfalls to make desired outcomes more likely. In any event, study of history lets us see current problems more clearly. Because of the cyclic nature of research and developments, it is remarkable how many times something had to be rediscovered. This is a real and costly problem, and without a concerted effort to avoid it, it is apt to get worse in the future. Solutions have been suggested, which include staying current in our respective fields, capitalizing on making the knowledge explosion more tractable, and making new technology available to industry. Einstein ably characterized advances in technology as "If I have seen farther than others, it is because I stand on the shoulders of giants." Thus, this historical paper draws on the many outstanding chronicles of selected elements of airbreathing propulsion development, assembled and presented for your appreciation of how far the history of ramjet technology has come in the last 100 years. Ramjet technology has evolved from the early simple subsonic "flying stovepipe" to its role in the complex combined or mixed cycle concepts embedded within military and space access vehicle designs of today. This evolution spans far more than just years; it is also a vast revolution in development technologies. A brief review of this evolution, is provided; a rigorous presentation is beyond the scope of this manuscript.

The history of man's desire to fly has evolved from the imagination of Greek mythologists through the thoughts, designs, data, and experiences of many notable individuals, all whom contributed in various ways to the Wright brothers' first demonstration of level flight under power in 1903. It would seem this was the catalyst that initiated the evolution of ramjet technology because the first known reference to ramjet propulsion dates from 1913.

Review of the worldwide evolution of ramjet technology begins with ramjet engine types, operation, and motivation. Ramjet development history is reviewed. Principal international development programs are reviewed. Discussions are concluded with a review of the maturation of ramjet design technology, and the general state of ramjet/scramjet/mixed cycle technology.

Key enabling technologies, components, or events that had significant impact on the maturation of ramjet and scramjet propulsion and engine designs are summarized in Table 1. These significant elements are discussed in further detail throughout the paper and include the air induction system, vehicle aerodynamics, combustor design and materials, fuels, injection and mixing, solid propellant boosters, ejectable and nonejectable components, thermochemical and engine performance modeling, and ground-test facilities and methods.

Ronald S. Fry has made contributions to combustion and propulsion technology for the development of advanced airbreathing military applications for over 30 years. He has made contributions to the development of conventional standoff missiles, cluster weapon systems involving self-forging fragment technology, and military weapon systems involving fuel–air explosive and insensitive high-explosive technologies while in the U.S. Air Force from 1974 to 1979. He led and contributed to dramatic advances in the U.S. state of the art in metallized solid fuel ramjet technology while with Atlantic Research Corporation from 1979 to 1993. More recently, he has contributed to the development of a U.S. national plan for the advancement of hypersonics science and technology. R. S. Fry is currently a Senior Research Engineer at Johns Hopkins University, Chemical Propulsion Information Agency, a Department of Defense Information Analysis Center. He has received awards for outstanding sustained achievement from the JANNAF Airbreathing Propulsion Subcommittee, the National Defense Service Medal for Active Duty Service during the Vietnam War, and multiple U.S. Air Force commendation medals for outstanding performance. He has a B.S. in aerospace engineering and two M.S. in engineering in aerospace engineering and naval architecture and marine engineering from the University of Michigan. R. S. Fry performed his graduate work under the mentorship of A. Nicholls, whose early demonstration of stabilized detonation waves in a supersonic hydrogen–air stream contributed to the feasibility of supersonic combustion ramjet technology. He is a Senior Member of AIAA.

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Table 1 Top 10 enabling technologies for ramjet propulsion

1) High speed aerodynamics analysis
    - CFD code analysis and validation methodologies (external and internal flow)
    - Improved design tools and techniques
2) Air induction system technology
    - Fixed and variable geometry
    - Subsonic, internally/externally ducted supersonic and dual-flowpath designs
    - Mixed cycle flowpath development
    - Improved design tools/integration with the airframe
    - Improved materials, especially in the cowl region
3) Combustor technology
    - Improved design tools and techniques, such as mapping fuel and heat-transfer distributions
    - Improved insulators (ablative, nonablative)
    - Advanced structural materials
    - Combustion ignition, piloting and flameholding, and mixing
4) Ramjet/scramjet fuels
    - Higher-energy liquid and solid fuels
    - Low-temperature liquid fuels
    - Endothermic fuels
5) Fuel management systems
    - Liquid fuel injection and mixing
    - Improved injectors; wider range of operation, tailoring of atomization, and spray distribution
    - Solid ramjet and ducted rocket fuel grain design
    - Solid ducted rocket fuel value design
    - Variable-geometry injection systems, especially for DR
    - Improved feed systems, including turbopumps
    - Improved feedback control systems
6) Propulsion/airframe integration, materials, and thermal management
    - CFD code analysis and validation methodologies
    - High-temperature metals and alloys
    - High-temperature structures
    - Passive and active cooling
    - Carbon–carbon and ceramic metal matrix composites
7) Solid propellant booster technology
    - Tandem boosters
    - Integral rocket–ramjet boosters
    - Self-boosted ramjet (mixed cycle RBCC, TBCC, etc.)
8) Ejectable and nonejectable component technology
    - Inlet and port covers
    - Fixed- and variable-geometry nozzle technology
9) Thermochemical modeling and simulation development
    - Thermochemical tables
    - Ramjet cycle analysis and performance modeling
10) Ground-test methodologies
    - Direct-connect
    - Semifreejet and freejet
    - Airflow quality improvements
    - Instrumentation advances
    - Computational tools and flight-test correlation

Ramjet Design and Concept of Operation

Description of Ramjet Propulsion Systems

Simple in concept, the ramjet uses fixed components to compress and accelerate intake air by ram effect. The ramjet has been called a flying stovepipe, due to the absence of rotating parts that characterize the turbine engine. The ramjet gets its name from the method of air compression because it cannot operate from a standing start but must first be accelerated to a high speed by another means of propulsion. The air enters the inlet and diffuser, which serve the same purpose as a compressor. Compression depends on velocity and increases dramatically with vehicle speed. The air delivered to a combustion chamber is mixed with injected fuel. This mixture is ignited and burns in the presence and aid of a flameholder that stabilizes the flame. The burning fuel imparts thermal energy to the gas, which expands to high velocity through the nozzle at speeds greater than the entering air, which produces forward thrust. Because thrust strongly depends on compression, the ramjet needs forward velocity to start the cycle. Typically a booster rocket provides this, either externally or internally. All modern ramjet missiles use the integral rocket–ramjet concept, which involves solid propellant in the aft combustion or mixing chamber to boost the system to ramjet-operating conditions. On decay of rocket pressure, the nozzle and associated components are jettisoned and ramjet power begins. Low ejecta booster design trades involve using the less efficient ramjet nozzle in a tradeoff for volume, performance, and operational considerations. Elements of the ramjet power cycle and flowpath from Avery[2] and Thomas[3] are shown in Fig. 1. Note that variation in station nomenclature began early.

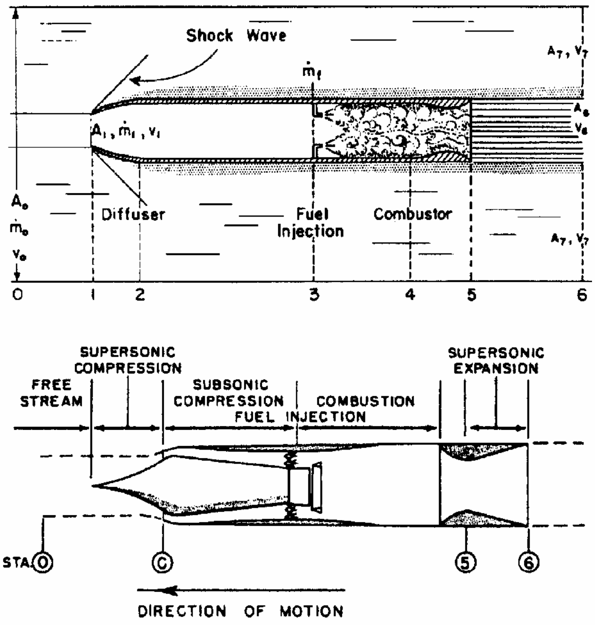


Fig. 1 Elements of ramjet power cycle and flowpath.

A typical Mach number–altitude airbreathing flight corridor is shown[4] in Fig. 2. Design challenges are compounded by flight conditions that become increasingly severe due to the combination of internal duct pressure, skin temperature, and dynamic pressure loading. These constraints combine to create a narrow corridor of possible conditions suitable for flight based on ram air compression. Relatively high dynamic pressure q is required, compared to a rocket, to provide adequate static pressure in the combustor (generally more than $\frac{1}{2}$ atm) for good combustion and to provide sufficient thrust. As speed increases, there is less need for mechanical compression. The upper boundary is characterized as a region of low combustion efficiency and narrow fuel/air ratio ranges thereby establishing a combustion limit. The lower boundary is a region of high skin temperature and pressure loading thereby establishing design and material limits. The far right, high Mach number edge of the envelope is a region of extreme dissociation, where nonequilibrium flow can influence compression ramp flow, induce large leading-edge heating rates, and create distortions in the inlet flow, while influencing fuel injection and mixing, combustion chemistry, nozzle flow, and, ultimately, performance. A region of low compression ratio is experienced at the very low Mach number region. The current state of the ramjet operational envelope, examined in further detail in the final section, has seen dramatic expansions from its early history, through the 1980s, to today.

The basic ramjet engine consists of an inlet, diffuser, combustor and exhaust nozzle (Fig. 1). The inlet collects and compresses air and conducts it via the diffuser to the combustor at reduced velocity thereby developing ram pressure and an elevated temperature. The combustor adds heat and mass to the compressed air by the injection and burning of fuel. Finally, the nozzle converts some of the energy of the hot combustion products to kinetic energy to produce thrust. Because the ramjet depends only on its forward motion to compress the air, the engine itself has no moving parts and offers higher Mach number capability than turbojet engines. However, unlike a turbojet or rocket engine, the ramjet requires an auxiliary boost system to accelerate it to its supersonic operating regime.

There are numerous reasons for using airbreathing engines instead of rockets: All of the oxidizer necessary for combustion of the

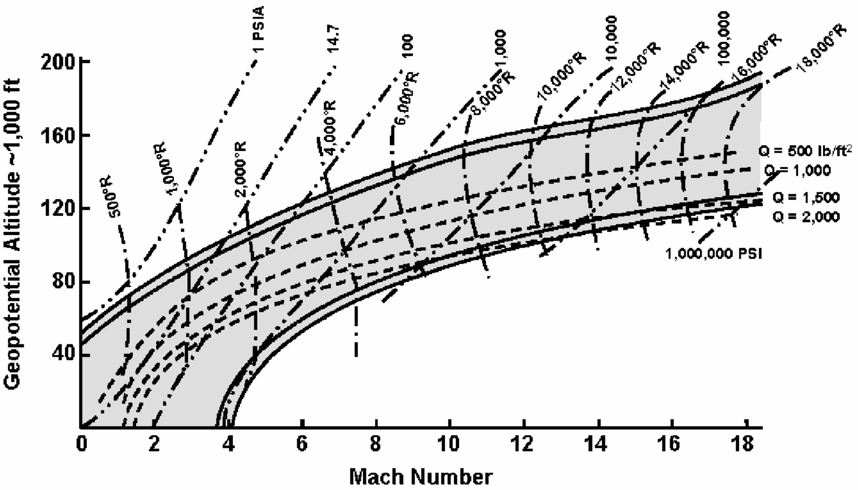


Fig. 2 Typical airbreathing flight corridor.

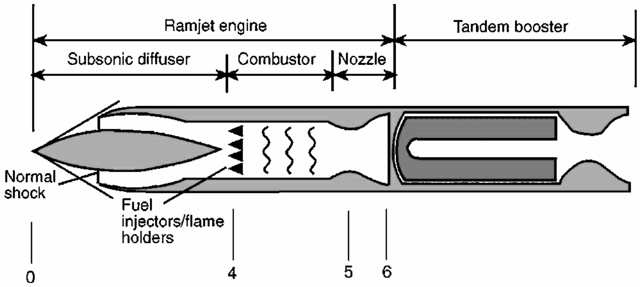
fuels comes from the atmosphere, the engines produce much higher engine efficiency over a large portion of the flight and a longer powered range than rockets, there is thrust modulation for efficient cruise and acceleration, they have the ability to change efficiently powered fight path and maneuverability, and they are reusable not just refurbishable. An additional feature for space access is a short turnaround time, with a potential cost reduction of 10–100 times per pound of payload.

Possible applications for scramjets include hypersonic cruise vehicles, hypervelocity missiles, and airbreathing boosters for space applications. Hydrogen fuel is desirable for high Mach number applications due to its high-energy content, fast reactions, and excellent cooling capabilities. For hypersonic missile applications and airbreathing systems operating below Mach 6, hydrocarbon fuels are preferred because of volumetric and operational constraints. Making use of the enhanced cooling capabilities of endothermic hydrocarbon fuels can increase the maximum speed for hydrocarbon-fueled missiles and vehicles to Mach 8. Attractive mission identified for scramjet-powered vehicles include a Mach 8 cruise missile as a standoff fast-reaction weapon or long-range cruise missile or boost propulsion for standoff fast-reaction weapon or airbreathing booster for space access.

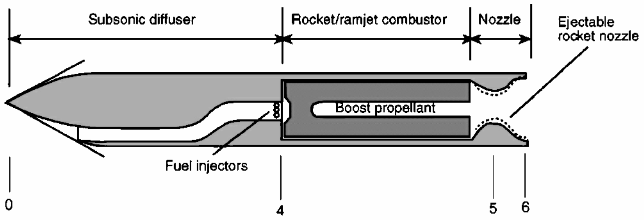
Subsonic Combustion (Ramjet) Cycle Behavior

Conceptual schematics of subsonic combustion ramjets and hybrid or combined cycle derivatives are shown in Figs. 3 and 4 following Waltrup,[5] whose past contributions have been most noteworthy. Figure 3a shows the traditional can-type ramjet (CRJ), liquid-fueled ramjet (LFRJ), and gaseous-fueled ramjet (GFRJ) 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 (typically Mach 0.3–0.4) through a normal shock system before reaching station 4. Fuel is then injected and burned with the air at low subsonic speeds before reaccelerating 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, inlet boundary layer and flow distortion, and exit nozzle throat size.

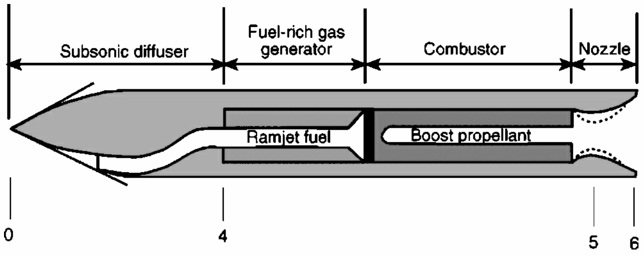
A more recent alternative to this concept is to use a common combustion chamber, commonly referred to as an integral rocket ramjet (IRR), for both the boost and sustain phases of flight. This generally requires a dump-type rather than a can-type combustor, but the cycle of operation of the ramjet remains the same. Figure 3b is a schematic of this concept for a liquid-fueled IRR (LFIRR) and Fig. 3c shows a solid-fueled IRR (SFIRR). In some applications, SFIRRs are preferred over LFIRRs, GFRJs, or CRJs because of the simplicity of the fuel supply, but only when the fuel throttling requirements are minimal, that is, when flight altitude and Mach



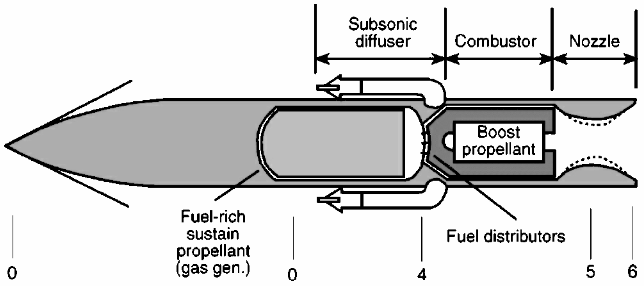
a) Conventional can combustor ramjet (CRJ)



b) Integral rocket/dump combustor ramjet (LFIRR)

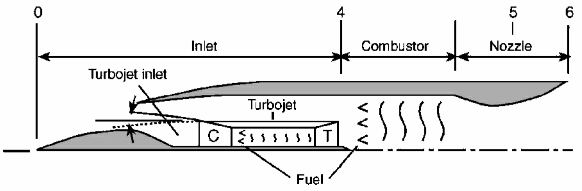


c) SFIRR

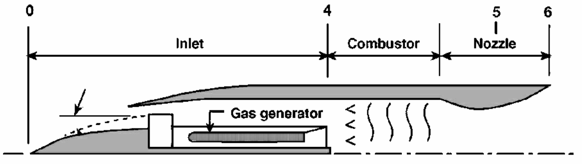


d) ADR

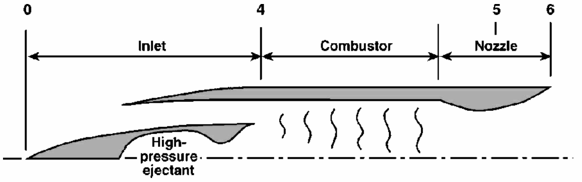
Fig. 3 Schematics of generic ramjet engines.



a) ATRJ



b) ATR



c) ERJ

Fig. 4 Schematics of generic hybrid (mixed cycle) ramjets that produce static thrust.

number variations are limited. The air-ducted rocket (ADR), shown in its IRR form in Fig. 3d, operates under the same engine cycle principles. 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 a compromise between the fuel supply simplicity of an SFIRR and the unlimited throttleability of the LFIRR, GFRJ, or CRJ. An ADR is generally used when the total fuel impulse does not adversely impact the powered range. The performance of the LFIRR or GFRJ is typically superior to the other four variants shown.

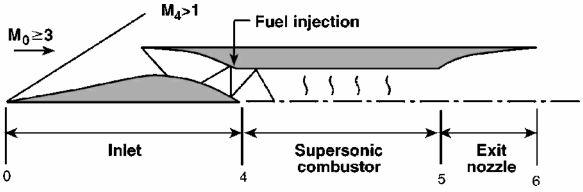
Although the ramjets shown conceptually in Figure 3 are viable vehicle propulsion systems, none can produce static thrust. Figure 4 shows three types of hybrid or combined cycle ramjet engine cycles that can. The first embeds a turbojet engine within the main ramjet engine and is usually liquid fueled and called an air-turboramjet (ATRJ) (Fig. 4a). Here, 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 flow at supersonic speeds. An alternative to the ATRJ is the air-turborocket (ATR) in which a low-to-moderate pressure rocket motor is used to drive a turbine and to provide a gaseous fuel for the ramjet (Fig. 4b). The turbine, in turn, drives a compressor, the combination of which produces static thrust. At supersonic speeds, the compressor, again, may be isolated from the main ramjet flow and the turbine idled so that the vehicle can operate as an ADR. The final hybrid ramjet cycle capable of producing thrust is ejector ramjet (ERJ) shown in Fig. 4c. Here, a rocket motor or gas generator produces a high-pressure, generally fuel-rich, supersonic primary or ejector flow that induces secondary air to flow through the engine even at static conditions. The ejector effluent and air then mix and burn (at globally subsonic speeds) and finally expand in the convergent–divergent exit nozzle.

There are three basic types of integral/rocket ramjet engines, namely, the LFRJ, the solid-fueled ramjet (SFRJ), and the ducted rocket (DR) as shown in Fig. 3. In the LFRJ, hydrocarbon fuel is injected in the inlet duct ahead of the flameholder or just before entering the dump combustor. In the SFRJ, solid ramjet fuel is cast along the outer wall of the combustor with solid rocket propellant cast on a barrier that separates it from the solid ramjet fuel. In this case, fuel injection by ablation is coupled to the combustion process. An aft mixer or other aid is generally used to obtain good combustion efficiency. The DR is really a solid fuel gas generator ramjet in which high-temperature, fuel-rich gasses are supplied to the combustor section. This provides for flame piloting and utilizes the momentum of the primary fuel for mixing and increasing total pressure recovery. Performance of the DR may be improved by adding a throttle valve to the primary fuel jet, thereby allowing larger turndown ratios. This is known as a variable flow DR (VFDR). The reader is directed to Zucrow,[6] Dugger,[7] and others[8] for additional ramjet fundamentals.

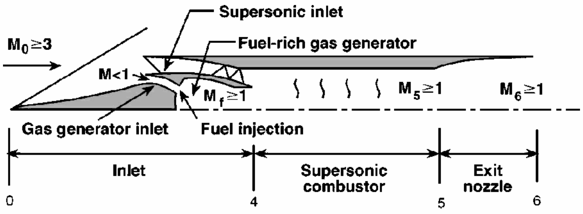
Supersonic Combustion (Scramjet) Cycle Behavior

Turning now to supersonic combustion engines, Fig. 5 shows a generic scramjet engine and two hybrid variants. Figure 5a shows a traditional scramjet engine wherein air at supersonic or hypersonic speeds is diffused to a lower, albeit still supersonic, speed at station 4. Fuel (either liquid or gas) is then injected from the walls (holes, slots, pylons, etc.) and/or in-stream protuberances (struts, tubes, pylons, etc.), where it mixes and burns with 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 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 ratio ER_0, and supersonic combustor area ratio (A_5/A_4).

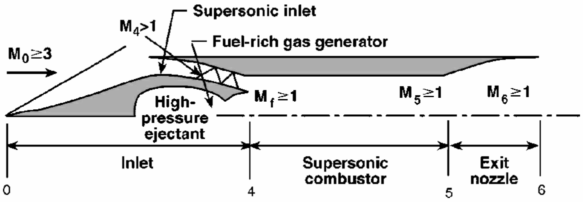
The unique combination of heat addition in a supersonic airstream with a variable strength shock system plus the absence of a geometric throat permits the scramjet to operate efficiently over a wide range of flight conditions, that is, as a nozzleless subsonic combustion ramjet at low flight Mach numbers, $M_0 = 3$–6, and as a supersonic combustion ramjet at higher flight Mach numbers, $M_0 > 5$. At low M_0 and high ER, the combustion process generates the equivalent of a normal shock system and is initially subsonic, similar to that of a conventional subsonic combustion ramjet, but accelerates to a sonic or supersonic speed before exiting the diverging area combustor, which eliminates the requirement for a geometric throat. As ER decreases at this same M_0, the strength of the precombustion shock system will also decrease to the equivalent of a weak oblique shock, and the combustion process is entirely supersonic. At high M_0, the strength of the shock system is always equivalent to either a weak oblique shock or no shock, regardless of ER. This is referred to as dual-mode combustion and permits efficient operation of the engine from $M_0 = 3$ to $M_0 = 8$–10 for liquid hydrocarbon fuels and up to



a) Supersonic combustion ramjet



b) DCR



c) ESJ

Fig. 5 Schematics of generic supersonic combustion engines.

orbital speeds for gaseous (hydrogen) fuels. The upper limit for the liquid-fueled cycle is, of course, due to energy consumption by dissociating and ionizing species at elevated temperatures that cannot be compensated for by additional fuel as in the case of, for example, a diatomic gas such as hydrogen.

The supersonic combustion ramjet (scramjet) engine (Fig. 5) is a hypersonic airbreathing engine in which heat addition, due to the combustion of fuel and air, occurs in a flow that is supersonic relative to the engine. The potential performance of scramjet engines using hydrogen fuel and variable geometry covers a wide Mach number range, from $M_0 = 4$ to 15+. Scramjet missiles using hydrocarbon fuels are usually of fixed geometry, except for inlet starting provisions, to minimize weight and complexity. Variable geometry scramjets can improve performance somewhat and are more suitable for vehicle applications where a broad Mach number range is needed. Both axisymmetric and two-dimensional scramjets have been developed. Axisymmetric engines are usually lighter weight but are more representative of high drag pod-mounted engines, whereas two-dimensional engines can be more easily integrated into a vehicle body.

Unlike a conventional ramjet engine, where the incoming airflow is decelerated to a subsonic speed by means of a multishock intake system, the flow in a scramjet is allowed to remain supersonic. In this case, the amount of compression performed by the inlet can be significantly reduced and normal shock losses eliminated with a corresponding increase in total pressure recovery. This can more than compensate for the high heat addition losses (Rayleigh losses) encountered. In addition, the reduced level of compression results in lower static temperatures and pressures at the entry to the combustor, which reduces the severity of the structural loads. The reduced temperature allows more complete chemical reaction in the combustor and can reduce the losses due to finite-rate chemical reactions in the nozzle.[9] In reality, flow in the scramjet combustor can be mixed flow at this Mach number with regions of subsonic flow near surfaces and supersonic flow in the core.

Two attractive approaches for providing (a broader Mach number operational range) scramjets with a lower Mach number capability are the dual-mode scramjet (DMSJ) engine in which both subsonic and supersonic modes of combustion are possible within one combustor and the hypersonic dual-combustor ramjet (DCR) engine. The dual-mode supersonic combustion ramjet engine was proposed in the early 1960s, U.S. Patent 3,667,233 by Curran and Stull, and was subsequently developed by the Marquardt Corporation (Marquardt) in their early DMSJ Engine. James Keirsey of Johns Hopkins University/Applied Physics Laboratory (JHU/APL) invented the DCR cycle in the early 1970s.

Characterization of the complex flow-field in DMSJs (first introduced by Curran and Stull in 1963) has been the subject of a number of previous investigations. Billig and Dugger,[10] Billig et al.,[11] and Waltrup and Billig[12,13] first provided analysis of experimental data and analytic tools, which allow a prediction of the flowfield such as upstream interaction and required isolator length for mid-speed scramjet combustor configurations. A well-known correlation for upstream interaction distance was formulated with dependence specified in terms of heat release (downstream pressure rise) and the entering momentum characteristics of the boundary layer before isolator separation. Heiser and Pratt[14] provide a thorough and extended treatment of dual-mode flowfields.

Although the scramjet offers these unique capabilities, it also requires special fuels or fuel preparation to operate efficiently above $M_0 = 6$ because of low static temperatures and short combustor residence times (<1 ms). For liquid fuels, this generally means using highly reactive (generally pyrophoric) fuels, fuel blends, or fuel/oxidizer pilots, which are logistically unsuitable. For gaseous fuels, it requires that the fuel be reheated or combined with a pyrophoric additive. To overcome this deficiency, an alternative to the pure scramjet is the DCR (Fig. 5b). The DCR has all of the features of the scramjet, except a portion of the captured air is diverted to a small, embedded subsonic dump combustor into which all of the fuel is injected. When a proper distribution of the fuel is maintained, a near stoichiometric flame can be maintained, the heat from which is used to prepare and preheat the remaining fuel so that efficient heat release can be realized in the supersonic combustor. Thus, the dump combustor acts as a hot, fuel-rich gas generator for the main supersonic combustor, similar in principle to the air-ducted rocket earlier described in the ramjet cycle section. This cycle, therefore, permits the use of conventional liquid hydrocarbon fuels or gaseous fuels such as hydrogen without resorting to logistically unsuitable additives. However, this cycle is limited in Mach due to the significant amount of air that is taken subsonically and dumped into the precombustor. Edwards[15] provides an excellent recent review of the history and current state of liquid fuel technology.

The final supersonic combustion cycle, which is a natural extension of the scramjet and DCR cycles, is the ejector scramjet (ESJ) shown schematically in Fig. 5c. Unlike the pure scramjet or the DCR, it is capable of producing static thrust using axial fuel injectors fed by a high-pressure fuel/fuel/oxidizer supply, yet retains the high-speed operating characteristics of the scramjet and/or DCR. These same injectors, perhaps complemented by staged injectors farther downstream, can be used for DMSJ operation, thus making it a viable candidate for a single-stage, but multiple-cycle, airbreathing engine concept for zero to hypersonic speed flight. The reader is directed to additional references for scramjet fundamentals.[14,16]

Combined and Combination Cycle Engines

Combined cycle engines are single flowpath, integrated engines capable of operation in two or more modes. Combination cycles have a bifurcated flowpath for the two modes of operation. Ramjet and scramjet engines cannot operate at Mach numbers below 2–3 because they depend on the high forward speed of the vehicle to compress the intake air. Therefore, another propulsion system is required for low-speed, single-stage applications. Either combined cycle engines or combination cycles are used to enable operation over the entire Mach range.

The rocket-based combined cycle (RBCC) consists of small liquid rocket motors located in the ramjet/scramjet flowpath. At low speeds, the rocket exhaust acts as an ejector, which induces entrained air to mix/burn with fuel added to the total mix. At ramjet/scramjet takeover speeds (typically Mach 2–3), the rockets are shut down and the ramjet/scramjet takeover. For access-to-space operations, rocket engines would be utilized again to propel the vehicle into low Earth orbit.

A turbine-based combined cycle (TBCC) system employs a turbojet engine for providing thrust from takeoff up to a Mach of 3–4 and then transition to ramjet/scramjet operation. The TBCC concept dates back to the 1950s, when a turbo ramjet, combining a turbojet with a ramjet engine, was used to power the French built Griffon II airplane that reached a speed of Mach 2. The TBCC is an integration challenge because the flowpath must be optimized for operation over the entire speed range. Variable geometry inlets and nozzles are required. Weight and volume selections are major considerations in the design process.

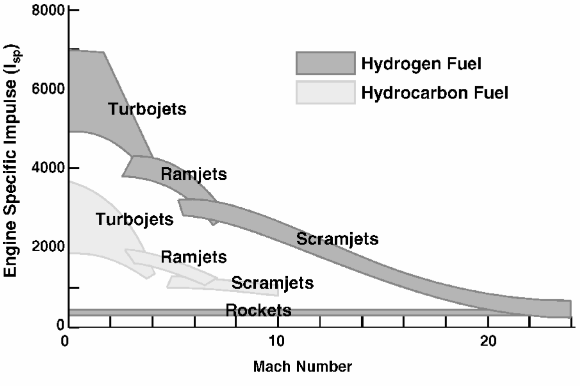
Let us now review the motivation for selecting airbreathing engines in general and given engine cycles for specific uses.

Performance of Airbreathing Propulsion Systems

The performance of an airbreathing engine, as measured by specific impulse I_{sp}, is considerably higher than that of a rocket,[17] and by the use of a scramjet, this advantage extends into the higher Mach regime, as shown in Fig. 6.[18] Both hydrogen and hydrocarbon fuels may be used in a scramjet; however, the higher cooling capacity of hydrogen and its faster reactions are required for the higher Mach numbers.

Combined cycle engines can play an important role as an accelerator or booster for space access applications. Early studies by Marquardt have shown payload advantages for combined cycle powerplants,[19] which have intermediate values of I_{sp} and thrust to weight (T/W) when compared to a conventional airbreather or pure chemical rocket.

From the mid-1950s to the early 1960s, significant progress was made toward developing a scramjet engine. Curran[20] produced in 1997 an excellent review of the progress in scramjet development



Courtesy of the Air Force Propulsion Directorate (circa 1990's)

Fig. 6 Characteristic performance by engine type.

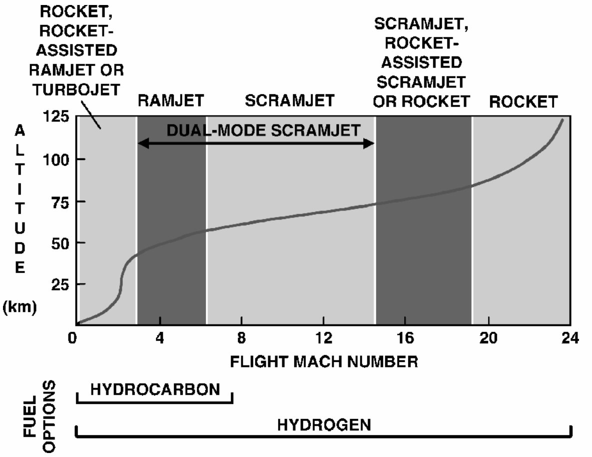


Fig. 7 Engine options as function of Mach number.

over the first forty years and supplemented his work in 1999.[21] There has been a considerable amount of laboratory testing and ground testing of scramjet engines in various countries, described in the cited references and briefly reviewed within this paper. A basic understanding of the supersonic combustion process has improved significantly over the years.

Selection of engines for high speed vehicles is dependent on the intended mission and the speed range of interest. Figure 7 shows a summary of various options as a function of Mach number. The choice of propulsion options and the operating range can be broadened by combining different propulsion options to create combined cycle or combination cycle engines, as discussed in the preceding sections.

Rationale favoring a Mach 6–8 missile includes providing substantially improved capabilities over a Mach 4 missile in terms of ranges attained within a given flight time or less flight time for a given range with the accompanying improved survivability. The higher kinetic energy and speed are additionally essential for increasing the probability of neutralizing various target types.

Having introduced the ramjet and scramjet cycles, let us now return to the evolution of ramjet engines for powered flight.

History of Ramjet and Scramjet Development

Subsonic Combustion History

Many excellent historical accounts chronicle the early years of ramjet development.[2,5,20,22,23,35,36] Highlights of this history are reviewed here. Avery[2] was among the first to review progress from the beginning years, while focusing on a 25-year period from the early 1930s, when testing of practical designs first began in 1955. Waltrup[5] provided a very thorough review of international airbreathing engine development from the beginning years to 1987, with an emphasis on the development of supersonic combustion ramjet (scramjet) engines. In 1996, Waltrup et al. provided a history of U.S. Navy ramjet, scramjet and mixed-cycle propulsion developments.[22] Kuentzmann and Falempin provide an account of French and international ramjet and scramjet development history.[24,34]

The history of ramjet concepts began in the early 1900s, with actual testing not beginning for another 30 years. While many international researchers were focusing on solving the thrust to weight challenges of internal combustion engines for flight, Lake (in the United States) and Lorin (in France) and their colleagues were examining jet propulsion devices that did not have in-stream obstructions, currently called ejector ramjets. The first patent of a subsonic ramjet cycle device, an ejector ramjet, was issued to Lake in 1909. Lorin published the first treatise on subsonic ramjets in 1913, but did not address high subsonic or supersonic flight. Morize (France, 1917) and Melot (France, 1920) engineered the ejector ramjet concept, with testing occurring in France during World War I (WWI) and in the United States in 1927. Although tests demonstrated an increase in static thrust, interest in this engine cycle waned until the late 1950s. Carter (in Great Britain) patented the first practical ramjetlike device for enhancing the range of artillery shells in 1926. Carter's designs showed considerable insight for the time and employed a normal shock inlet with either a conical nose/annular duct or central cylindrical duct. The first recognizable conical-nosed LFRJ patent was given to Fono (in Hungary) in 1928. These designs included convergent–divergent inlet diffuser, fuel injectors, flameholders, combustor, and convergent–divergent nozzle. Although these systems were designed for supersonic, high-altitude aircraft flight, they did not advance beyond the design stage.

Actual construction and testing of viable ramjet designs did not occur until the mid-1930s in France, Germany, and Russia. Leduc (France) ground tested a conical ramjet up to Mach 0.9. Work on a full-scale ramjet-powered aircraft had begun by 1938, with component ground tests conducted up to Mach 2.35 by 1939. World War II (WWII) temporarily halted further testing. In Germany, Trommsdorff led a successful effort in 1935 to develop artillery shells powered by multiple-shock, conical-inlet LFRJs. These shells actually accelerated from Mach 2.9 to 4.2 in tests conducted in 1940. Sänger and colleagues (in Germany) examined designs for an aircraft-launched ramjet-powered cruise missile but never constructed or tested one. The Germans did field the first operational ramjet-powered missile in the form of the V-1 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 1930s. Under Merkulov's direction, Russia successfully flight tested a tandem-boosted ADR using magnesium/aluminum solid fuel in 1939. These activities were subsequently replaced with designs to augment the thrust of existing aircraft using wing-mounted ramjet pods. Attempts were also thwarted by the events of WWII following initial flight testing in 1940. Reid (in the United States) and Marquardt (in Great Britain) began ramjet development efforts in the early 1940s in the form of aerial-guided projectiles and aircraft performance augmenters, respectively. These efforts continued after WWII and resulted in weapon systems such as the Bomarc (U.S. Air Force), Talos (U.S. Navy), and Bloodhound (Great Britain) antiaircraft missiles, as well as numerous basic and applied experiments at national research centers in both countries.

The ramjet engine began to receive attention during the second-half of the 1940s and reached a relative peak during the 1950s with a number of operational systems being deployed. France developed several operational ramjet missiles (VEGA, CT-41, and SE 4400) in the late 1950s and early 1960s. The ramjet, always needing an auxiliary propulsion system for starting, got squeezed between improved turbine engines and rockets during the 1950s and did not recover until reignited by the Russian SA-4, SA-6 and SS-N-19 design revolutions in the late 1960s and early 1970s. This period witnessed a surge in development activity by the United States and Russia in the development of low-volume IRR missile designs. The Russian activity led to the operational missiles SS-N-22 and AS-17/Kh-31.

The ramjet received expanded international development attention beginning in the 1980s, which continues today. During the 1980s France developed the operational Air-So Moyenne Portee-Ameliore (ASMP) and flight-tested Missile Probatoire Stato

Rustique (MPSR)/Rustique. The United States invested effort in supersonic low-altitude target (SLAT) and VFDR. During the 1990s, France continued its long history of development activity in ramjets with activity on MARS, MPSR/Rustique, Anti-Naivre Futur/Anti-Navire Nouvelle Generation ANF/ANNG, Vesta, and the next-generation ASMP-A. The People's Republic of China began development of a long-range antiship variant (C-301) of its C-101 and the more advanced Hsiung Feng. South Africa began development of a long-range air-to-air missile (LRAAM). Russia continued to demonstrate its understanding of this technology by beginning the development of AA-X-12 and SS-N-26. Israel entered the ramjet community by beginning development of a ramjet-powered version of Gabriel for extended range. Germany began development of an antiradiation missile ARMINGER. India began development of the PJ-10/Brahmos, a derivative of the Russian SS-N-26. The 2000s have seen this development activity continue and expand yet further in the United States supersonic sea skimming target (SSST), generic supersonic cruise missile (GSSCM), and high-speed antirachation demonstration (HSAD), The United Kingdom beyond visual range air-to-air missile (BVRAAM/Meteor), France (MICA/RJ), and elsewhere. These and other international development programs are reviewed in further detail later in this paper as a means of better understanding the evolution in ramjet technology.

Supersonic Combustion History

Many excellent historical accounts chronicle international scramjet development. Curran provided a review of the first 40 years of international scramjet engine development in 1997.[20] Waltrup reviewed international supersonic combustion development in 1987,[5] and Waltrup et al. reviewed U.S. Navy scramjet and mixed-cycle engine development in 1996.[22] Van Wie[25] chronicled the 59-year history of JHU/APL contributions to the development of high-speed vehicles, highlighting five great APL propulsion pioneers, Avery, Dugger, Keirsey, Billig, and Waltrup in 2003. Andrews[26] provided a very thorough historical review of scramjet development and testing in the United States in 2001. McClinton et al.[28] provided a worthy review of engine development in the United States for space access applications in 2001. Escher[27] provided an excellent review of U.S. developments in combined airbreathing/rocket propulsion for advanced aerospace applications in 1999.

Efficient airbreathing engines for operation into the hypersonic speed regime have been studied for over 40 years. The heart of these engine systems is the supersonic combustion ramjet (scramjet) cycle. Scramjet engine concept development, test facilities and instrumentation development, analysis method refinement, and component and engine testing have been pursued continually since the early 1960s. Efforts to integrate the scramjet with higher and lower speed propulsion devices for space access have been investigated sporadically since the 1960s and continuously since 1984. McClinton et al.[28] reviewed U.S. hypersonic airbreathing launch vehicle propulsion development efforts. The review addresses experiences and major accomplishments of historic programs; the goals, coordination between, and status of current programs in 2001; and a view of the future of hypersonic airbreathing propulsion development in the United States for future launch vehicles.

In 2001 McClinton et al.[28] discussed scramjet development in the United States in terms of generations, first generation 1960–1973, second generation 1969–1984, third generation 1984–1994, and fourth generation from 1995-today. Each generation was distinguished by its unique contributions of the level of understanding of supersonic combustion.

First Generation Scramjet Development (Beginning: 1960–1973)

The origins of employing combustion in supersonic flows in the United States can be traced back to interest in burning fuels in external streams to either reduce the base drag of supersonic projectiles or to produce lift and/or thrust on supersonic and hypersonic airfoils in the early 1950s.[5] In Europe, interest in supersonic combustion paralleled that in the United States throughout the 1960s and 1970s. The most extensive of the early (first generation) scramjet development programs in the United States was the NASA hypersonic research engine (HRE) program. The HRE program, started in 1964, was crafted to develop and demonstrate flight-weight, variable-geometry, hydrogen-fueled and- cooled scramjet engine scramjet technology. In France, both fundamental and applied research was being pursued, with initial connected pipe testing being conducted by ONERA at Mach 6 conditions in the early 1970s. In Germany, most of the reported work was on supersonic combustion was of a more fundamental nature. Russia had an extensive program in supersonic combustion and scramjet propulsion since the 1960s. Canadian interest in supersonic combustion began in 1960 at MacGill University in hypersonic inlet aerodynamics and gun-launched scramjet flight testing.

The first Generation witnessed the start of several major scramjet development programs in the U.S. during the mid-1960s, following the first scramjet demonstration by Ferri in 1960[29] and studies that verified the benefits of scramjet propulsion. The U.S. Air Force, NASA, and U.S. Navy sponsored programs tested six scramjet engines/flowpaths through major contracts at Marquardt, General Electric, United Technology Research Center (UTRC), Garrett, and General Applied Sciences Laboratory (GASL). Engine flowpaths from all of these contractors were tested at low hypersonic speeds (up to Mach 7). Most tests utilized hydrogen fuel, but the U.S. Air Force also funded hydrocarbon-fueled scramjet tests for missile applications, and the U.S. Navy (APL) performed several different hydrocarbon studies in the Supersonic Combustion Ramjet (SCRAM) project. However, the U.S. Air Force withdrew from scramjet research and development, not to return until the National Aerospace Plane (NASP) program in 1984. Following successful demonstration of scramjet performance, operability and structural/systems integration, NASA turned to development and validation of airframe-integrated engine flowpaths.

Second Generation Scramjet Development (Airframe Integration: 1973–1986)

The technology development focus in the United States shifted in the second generation to integration of hydrogen-fueled scramjet engines on a hypersonic vehicle following the first generation hypersonic propulsion demonstrators. A Mach 7 cruiser configuration was selected with turbojet low-speed and scramjet high-speed systems, in an over–under arrangement. NASA Langley Research Center (LaRC) led this effort, which focused on the sidewall compression scramjet engine. This engine included fuel injector struts and fixed geometry to minimize weight. Much of the research effort was placed on tool development. This included facilities, test methodologies, cycle analysis, data analysis, and computational fluid dynamics, (CFD). This time frame was also characterized by a downturn in research in the United States, and facility availability became an issue. Therefore, facilities were developed at NASA LaRC for efficient scramjet testing. Modest-sized facilities also remained available at GASL and were used to handle higher pressure validation tests. Component test facilities were also developed, including a combustion-heated direct-connect combustor facility and a Mach 4, high-pressure inlet test facility.

Component tests were performed to establish rules-of-thumb design models/tools. These models[30] were not incorporated into the U.S. scramjet toolbox until the late 1980s. Component tests were also used to develop databases for verification of analytical and computational methods. These second generation cycle analysis methods are simplistic by today's standards of CFD methods, nevertheless feature internal calculations such as shear and heat transfer to the combustor wall, fuel mixing, and estimated finite-rate chemistry effects on combustion. Scramjet tests for the three-strut engine were performed at NASA LaRC and GASL.

Aerodynamic and propulsion-airframe integration (PAI) assessment is required to set scramjet performance requirements. Aerodynamic and PAI tests were performed to quantify inlet capture, external nozzle performance, and scramjet-powered vehicle performance. Aerodynamic wind-tunnel tests were performed at flight conditions up to Mach 8. Structural designs for the sidewall compression engine were developed, including primary structure, cooling jackets, and thermal management. These designs used cooling channels rather than the offset fin approach used in the HRE, but maintained the high-temperature steel. France launched the ESOPE program, inspired at least in part by NASA's HRE activity.

During the mid-1970s, the sidewall compression flowpath tests demonstrated the required thrust, operability, and fuel cooling requirements to allow a credible vehicle design. About 1000 tests were performed on three engines. In addition, these studies validated the predicted scramjet performance and provided some justification for starting the NASP program.

Scramjet module and direct-connect research and testing using gaseous hydrocarbon fuels was started at NASA LaRC in late 1970s and was subsequently interrupted by the NASP program. After NASP, the U.S. Air Force took the lead in this area. Tests were performed using methane, ethane, and ethylene injected from the hydrogen fuel injectors.

Third Generation Scramjet Development (NASP: 1986–1994)

In the early 1980s the U.S. NASP program was formulated, with the objective of developing a single-stage-to-orbit "hypersonic combined-cycle airbreathing capable"[31] engine to propel a research vehicle, the X-30. The NASP program promise of flying a single-stage vehicle, powered by a combined cycle engine that utilized scramjet operation to Mach 25 was aggressive, when the state of technology in 1984 is considered. Subsequent development activity backed off such an aggressive approach. Neither scramjet engines nor flowpaths had been tested above Mach 7. In addition, no credible, detailed analysis of scramjet performance, operability, loads, or structural approaches had ever been performed for flight past Mach 7. Also, what was good enough for Mach 7 vehicle operation was not refined enough for the low-thrust margin (energy from combustion vis-à-vis air kinetic energy) at double-digit flight Mach numbers.[30] In other words, second generation scramjet technology was a good starting point, but considerable refinement and development was needed.

International activity in this period included many developments. Germany began development of Sänger II in the late 1980s as a proposed two-stage-to-orbit (TSTO) concept vehicle. Japan pursued development of combined cycle engine technology for flyback booster TSTO applications. Russia developed Kholod as a first generation hypersonic flying laboratory, derived from the SA-5 (S-200 family) surface-to-air missile. Russia initiated the comprehensive hypersonic research and development in the ORYOL program with the purpose of developing combined propulsion systems for advanced reusable space transportation. Finally, Russia employed another first generation flight-test vehicle GELA Phase I testbed for the development of Mach 3 ramjet missile propulsion systems. France initiated PREPHA aimed at developing a knowledge base on hydrogen-fueled dual-mode ramjet technology for single-stage-to-orbit applications.

Fourth Generation Scramjet Development (Resurgence: 1995–Today)

Following the NASP program, three new directions were taken in the United States. The U.S. Air Force went back to hydrocarbon-fueled scramjet missiles; NASA aeronautics went on to demonstrate the most advanced parts of the NASP propulsion technology, that is, scramjets; and the NASA rocket community embraced the engine technology afforded by rocket-airbreathing combined cycle engines. These three programs, HyTech/HySet, Hyper-X, and Spaceliner, are mentioned here, and their program contributions and status are reviewed later. The United States has since incorporated the development of high-speed airbreathing technology within an overarching approach called the National Aerospace Initiative (NAI). It is a partnership between the Department of Defense (DOD) and NASA designed to sustain the U.S. leadership through technology development and demonstration in three pillar areas of high speed/hypersonics, space access, and space technology. Ronald Sega, Director of the U.S. Defense Research and Engineering Agency (DARPA), points out that NAI will provide many benefits: never-before-available military capabilities to satisfy a broad range of needs; technologies required to provide reliable and affordable space transportation for the future, develop launch systems, and satisfy exploratory mission needs; and, finally, spur innovation in critical technology areas and excite and inspire the next-generation high-technology science and engineering workforce in the United States.

HyTech/HySET. The goal of the U.S. Air Force Hypersonic Technology/Hydrocarbon Scramjet Engineering Technology (HyTech/HySET) program is to advance technology for liquid hydrocarbon-fueled scramjets. Although this technology will be applicable to scramjet-powered strike, reconnaissance, and space access missions, the initial focus is on missile scale and applications.

The HyTech/HySET program has made significant advancements over the past 8 years in the following issues associated with liquid hydrocarbon-fueled scramjet engine development: ignition and flameholding methodologies, endothermic fuels technology, high-temperature materials, low-cost manufacturing technology for scramjet engines, and detection and cleaning procedure for coked heat exchangers. The engine development addressed issues associated with weight, cost, and complexity. An effective fixed-geometry scramjet engine was developed for operation over the Mach 4–8 speed range. HySET was unique in having developed scramjet performance and structural durability of complete engine configurations not just flowpaths.

Hyper-X. NASA initiated the joint LaRC and Dryden Flight Research Center hypersonic X-plane (Hyper-X) program in 1996 to advance hypersonic airbreathing propulsion (scramjet) and related technologies from the laboratory to the flight environment. This is to be accomplished using three small (12-ft long), hydrogen-fueled research vehicles (X-43) flying at Mach 7 and 10. The Hyper-X program technology focus is on four main objectives required for practical hypersonic flight: Hyper-X (X-43) vehicle design and flight-test risk reduction, flight validation of design methods, design methods enhancement, and Hyper-X phase 2 and beyond.

Hyper-X Phase 2 and beyond activities[32] include program planning, long-term, high-risk research, and refinement of vision vehicle designs. Propulsion related development activity in this arena includes the evaluation of the pulse detonation engine (PDE) for hypersonic systems, magnetohydrodynamics (MHD) scramjet studies, and design developments leading to highly variable-geometry scramjets. Powered takeoff and landing and low-speed operation of a hypersonic shaped vehicle using remotely piloted vehicles will address the low-speed PAI issue identified in NASP. Finally, this arena was active in planning/advocating future directions for space access vehicle and airbreathing propulsion development.[19]

Third Generation Space Access. During the late 1990's NASA established long term goals for access-to-space. NASA's third generation launch systems are to be fully reusable and operational (IOC) by 2025.[33] The goals for third generation launch systems are to reduce cost by a factor of 100 and improve safety by a factor of 10,000 over current conditions. NASA's Marshall Space Flight Center in Huntsville, AL has the agency lead to develop third generation space transportation technologies. Development of third generation launch vehicle technology falls under NASA's Space Transportation Program. The programs have had names like Spaceliner, Advanced Space Transportation Program (ASTP), and the Hypersonic Investment Area of Next Generation Launch Technology (NGLT). These programs focus development of technologies in two main areas: propulsion and airframes. The program's major investment is in hypersonic airbreathing propulsion since it offers the greatest potential for meeting the third generation launch vehicle goals. The program is maturing the technologies in three key propulsion areas, scramjets, rocket-based combined cycle and turbine-based combination cycle. Ground and flight propulsion tests are underway or planned for the propulsion technologies. Airframe technologies are matured primarily through ground testing. Selection and prioritization of technology is guided by system analysis for third generation "vision" vehicles. These vehicles are generally two-stage-to-orbit vehicles, which can be interrogated for safety, reliability and cost impacts of the proposed technologies.

Flight-tests supporting NASA's Third Generation Space Access focuses on incremental development and demonstration of key technology that can not be demonstrated to a Technology Readiness Level (TRL) of 6 in ground tests. These start with scramjet performance, operability and airframe integration (X-43A, X-43C and X-43D) for flight Mach numbers from 5 to 15. These first demonstrators are expendable to reduce test costs. The next step is integration of low-speed (Mach 0 to 3+) with the scramjet system in a reusable "combined cycle" flight demonstration (RCCFD). The first step for RCCFD is a Mach 0-7 reusable air-launched research vehicle, similar in size to the X-15. The final step would be a larger vehicle capable of operation to full airbreathing Mach number required for the 2025 IOC vehicle.

International activity in this period continued to include many developments. A joint French/Russian program Wide Range Ramjet (WRR) was initiated to develop technology for reusable space launcher applications. France also began the development of Joint Airbreathing Research for Hypersonic Application Research (JAPHAR) in cooperation with Germany as follow-on to the PREPHA (France) and Sänger (Germany) programs to pursue hypersonic airbreathing propulsion research for reusable space launcher applications. Furthermore France initiated Promethée aimed at developing fully variable-geometry endothermic hydrocarbon fuel dual-mode ramjet technology for military applications. The French efforts are leading toward LEA, a new flight-test demonstration of a high-speed dual-mode ramjet propelled vehicle at flight conditions of Mach 4–8 in the 2010–2012 time frame. In this era, Russia began openly discussing their development of AJAX, an innovative hypersonic vehicle concept envisioned to capture and recycle energy otherwise lost in flight at high Mach numbers. Russia also initiated second generation hypersonic flying laboratory work with Gela Phase II and the Mig-31 HFL. Australia conducted, with international support, the world's first verified demonstration of supersonic combustion in a flight environment under HyShot.

The development of vehicles for space access applications reflected maturation in propulsion technology and the technical interests of the times. Initial concepts, for example, the German Sänger–Bret Silbervögel of 1938, postulated single-stage-to-orbit (SSTO) vehicles based on pure rocket systems, or rocket-lofted boost-gliders, such as the U.S. Dyna-Soar. The U.S. Air Force supported Spaceplane development followed, which spawned imaginative upper atmospheric high-Mach air collection and oxygen extraction technologies. The understanding of scramjet technology had began. By the early 1960s, the maturation of advanced airbreathing technology encouraged a redirection toward complex fully reusable TSTO vehicles with airbreathing first stages (with combinations of turbojets, turboramjets, or ramjets/scramjets) and rocket-boosted second stages. The economic realities of the 1970s dictated using semi-expendable, pure-rocket approaches, typified by the space shuttle. The potentialities of the advanced airbreathing scramjet of the 1980s led to NASP and horizontal takeoff and landing concepts for airbreathing SSTO vehicles using complex propulsion systems dependent on new high-energy fuel concepts and the air collection and oxygen extraction technologies developed previously. The 1990s witnessed less ambitious goals of developing either pure advanced rocket systems (X-33 and X-34) or systems using straightforward scramjet technology (X-43A Hyper-X). The first flight demonstration of scramjet-propelled vehicle designs with true potential for enabling space access promises to become reality in 2003–2004.

These and other international development programs are reviewed in further detail later as a means of better understanding the evolution in scramjet technology.

Evolution in Ramjet and Scramjet Development Programs

The development of ramjet technology for multiple applications has proceeded in parallel throughout history. Applications have ranged from boost- to main-propulsion for aircraft, gun projectiles, missiles, and space launch vehicles. The intent here is to highlight international activity and selected programs as a means of identifying sources of technology advances, often resulting from parallel efforts in multiple applications.

The key enabling technologies, components, or events that had significant impact on the maturation of ramjet propulsion and engine designs, summarized in Table 1, are briefly discussed relevant to the worldwide development of vehicle concepts and systems. The history of the worldwide subsonic and supersonic combustion ramjet evolution is summarized by era in Tables 2–6 from the turn of the century to today. Presented in Tables 2–6 for each ramjet/scramjet system are known historical era, originating country, engine/vehicle name, engine cycle type, development dates, design cruise Mach number, altitude and range performance, system physical characteristics, and state of development. The ranges provided are a mix depending on the engine/vehicle development status: operational range for operational systems, predicted range for concept vehicles, or demonstrated range for flight-test vehicles. Additionally, those engines/vehicles that are discussed and illustrated in this paper are indicated. Many observations can be drawn from the data shown in Tables 2–6 and include the following.

1) Ramjet technology development has been consistently pursued internationally from very early days, accompanied by steady increases in airbreathing system capabilities.

2) Ramjet engines have received substantially more attention than scramjet engines, with scramjet development increasing steadily since the early 1990s, which reflects the accelerating pace in the solution of the challenges of high speed flight.

3) Although at the verge of success, flight testing of ramjet-powered engine concepts at hypersonic speeds has yet to be accomplished. At this writing the U.S. X-43A Hyper-X is planned for a second flight test in January 2004.

Ramjet Development 1918–Today

Ramjet Development: 1918–1960

This era saw the birth of ramjet-powered aircraft flight and its rapid maturing of technology into primarily missile applications and its transition from subsonic to supersonic ramjet flight. Table 2 summarizes ramjet evolution in the era from 1918 to 1960 and provides originating country, engine/vehicle name, development dates, performance, physical characteristics, and state of development. Countries actively engaged in development in this era were France, Germany, the United States, the United Kingdom and Russia.

The Germans flew the first operational ramjet-powered missile in 1940 in the form of the V-1 buzzbomb (Fig. 8) powered by a subsonic flight speed pulsejet engine launched by a solid propellant booster. The V-1 could be considered the first cruise missile. German engineer, Paul Schmidt, working from a design of the Lorin tube, developed and patented (June 1932) a ramjet engine (Argus pulse jet) that was later modified and used in the V-1 Flying Bomb. The German V-1 technology was transferred to other countries after WWII.

The first ramjet-powered airplane was conceived and variants tested by Leduc of France. The first powered flight of a ramjet-powered aircraft, Leduc-010 (Fig. 9), took place in April 1949

Fig. 8 German V-1 operational WW II missile (1933–1945).

Table 2 Worldwide ramjet evolution 1918–1960

Era	Country/service	Engine/vehicle	Engine type	Dates, year	Cruise Mach no.	Cruise altitude, ft	Powered range, n mile	Launcher	Total length, in.	Diameter, in.	Total weight, lbm	State of development
1918–1945	France	Melot research	ERJ	1918–1927	0.4	——	——	——	——	——	——	Component tests
1930–1955	France	Leduc aircraft[a]	Liquid-fueled ramjet (LFRJ)	1933–1951	0.4–2.1	10,000	——	Ground	——	——	——	Flight tests
	Russia	Stechkin research	LFRJ	1933–1936	0.4–2.0	——	——	——	——	——	——	Component tests
	Germany	V-1[a]	Pulse jet	1933–1945	0.3	20,000	220	Rail	312	30	4,800	Operational
	Germany	Sänger 1[a]	Ramjet (RJ)	1936–1945	4+	70,000	9,000	Rail	1,100	——	200,000	Concept vehicle
	Russia	Antipodal bomber[b]	RJ	1945–1955	4+	70,000	9,000	Rail	1,100	——	200,000	Concept vehicle
	Russia	Merkulov research	LFRJ	1936–1939	0.3	——	——	——	——	——	——	Flight tests
	United States	KDH-1 drone[b]	Pulse jet	1942–1946	0.3	20,000	145	Rail	134	8	——	Operational
1945–1960	United States	Cobra[b]	LFRJ	1945–1946	2.0	20,000	——	Rail	——	6	240	Flight tests
	United States	Gorgon IV	LFRJ	1945–1955	0.4	20,000	——	——	——	——	——	Flight tests
	United States	KDM-1 Drone[b]	LFRJ	1945–1949	2	35,000	60	Rail	264	30	1,600	Operational
	United States	P-51/F-80/B-26	LFRJ	1945–1955	0.4	20,000	——	Air	——	——	——	Flight tests
	United States	NAVAHO[a,g]	LFRJ	1946–1958	3.25	37,000–90,000	5,500	Ground	1,050	48	120,000	Flight tests
	United States	BTV[c]	LFRJ	1947–1948	2.4	30,000	10	Rail	——	18	——	Flight tests
	U.S. Navy	RTV[d]	LFRJ	1949–1950	2.4	30,000	25	Rail	——	24	——	Flight tests
	Russia	Burya[b]	LFRJ	1950–1958	3.15	35,000–70,000	4,320	Ground	1,000	67	130,000	Flight tests
	U.S. Air Force	BOMARC[a,f]	LFRJ	1950–1972	2.5–3.4	70,000–100,000	440	Ground	560	35	15,620	Operational
	United States	X-7[a]	LFRJ	1950–1959	4.3	84,000	——	Rail	——	28,36	——	Flight tests
	U.S. Navy	Talos[a]	LFRJ	1950–1980	2.7	70,000	120	Rail	386	28	7,720	Operational
	France	SIRIUS	LFRJ	1950–1970	2.7	——	——	——	——	——	——	Component tests
	France	Griffon II[b]	ATRJ	1951–1961	2.2	50,000	——	——	——	——	——	Flight tests
	U.S. Navy	Trition/SSGM[e]	LFRJ	1951–1958	3.0	70,000	2,000+	Rail/ submarine	——	——	——	Component tests
	U.S. Navy	RARE[b]	SFIRR	1955–1960	2.3	50,000	——	Air	120	5	153	Flight tests
	France	VEGA[b]	LFRJ	1955–1965	4.2	80,000	——	Rail	——	——	——	Operational
	U.S. Navy	CROW[b]	SFIRR	1956–1964	3.0	50,000	97	Air	127	8	370	Flight tests
	France	CT-41[b]	LFRJ	1957–1965	3	75,000	——	Rail	——	——	——	Operational
	France	SE 4400[b]	LFRJ	1957–	3.7	22,000	——	Rail	——	——	——	Operational
	U.S. Navy	Typhon[a]	LFRJ	1957–1965	4.1	100,000	200	Rail	333	16.75	6,160	Flight tests
	United Kingdom	Bloodhound[a]	LFRJ	1957–1991	2	23,000	108	Rail	306	21.5	2,300	Operational

[a] System discussed and shown. [b] System discussed. [c] Burner test vehicle (BTV). [d] Ramjet test vehicle (RTV). [e] Surface-to-surface quided vehicle (SSGM). [f] Boeing Company and University of Michigan Aeronautics Research Center (BOMARC). [g] North American Aviation designation (NAVAHO).

Table 3 Worldwide ramjet evolution 1960–1980

Era	Country/service	Engine/vehicle	Engine type	Dates, year	Cruise Mach no.	Cruise altitude, ft	Powered range, n mile	Launcher	Total length, in.	Diameter, in.	Total weight, lbm	State of development
1960–1970	France	Stataletex[b]	LFRJ	1960–1970	3.8–5	25,000	——	Rail	——	——	——	Flight tests
	U.S. Army	Redhead Roadrunner[b]	LFRJ	1960–1980	2.5	0–60,000	217	Rail	298	12	900	Flight tests
	United Kingdom	Sea Dart[a]	LFRJ	1960–1975	3.5	80,000	35	Rail	173	15.6	1,200	Operational
	United States	Hyperjet[b]	LFRJ	1960–1966	5+	30,000	——	Air	——	——	——	Flight tests
	United States	D-21[a]	LFRJ	1963–1980	4	1,00,000	2,600	Air	730	60	——	Operational
	Russia	SA-4/Ganef[a]	LFRJ	1964–	4	15,000	30	Rail	346	34	5,500	Operational
	U.S. Air Force	LASRM[b]	LFIRR	1964–1967	2.5	0–6,000	50	Air	168	15	1,566	Flight tests
	U.S. Navy	ATP/TARSAM-ER[c]	ADR	1965–1971	3.8	50,000–70,000	160	Rail	348	13.5	6,420	Component tests
	U.S. Navy	ATP/TARSAM-MR[c]	ADR-IRR	1965–1971	3.8	50,000–70,000	80	Rail	200	13.5	1,750	Component tests
	U.S. Air Force	ASALM[a]	LFIRR	1965–1980	2.5–4	10,000–80,000	56	Air	168	20	2,415	Flight tests
	Russia	SA-6/Gainful[a]	DRIRR	1965–	2.8	55,000	15	Rail	244	13.2	1,320	Operartional
	France	SE X 422[a]	LFRJ	1965–1967	2	30,000	——	Rail	394	20	4,190	Flight tests
	U.S. Navy	IRR-SAM	LFIRR	1966–1970	3.3	80,000	——	Rail	220	14.75	2,200	Component tests
	U.S. Navy	ALVRJ-STM[a]	LFIRR	1968–1979	3.0	0–40,000	28–100	Air	179	15	1,480	Flight tests
1970–1980	U.S. Navy	IRR-SSM	LFIRR	1971–1974	2.5	50,000	——	Rail	200	14.75	2,000	Free-jet tests
	Russia	SS-N-19/Shipwreck[a]	LFRJ	1972–	2	0	340	Rail/sub	394	33	15,430	Operational
	U.S. Navy	GORJE[b]	LFIRR	1972–1976	2.6	0	35	Air	168	12	750	Semi-free-jet tests
	U.S. Navy	ASAR[d]	LFIRR	1972–1981	3.8	80,000	——	VLS	220	16	2,650	Semi-free-jet tests
	France	Scorpion[a]	LFRJ	1973–1974	6	70,000	325	Rail	——	——	——	Component tests
	U.S. Navy	MRE[e]	LFIRR	1973–1977	3.0	30,000–70,000	150	Air	168	15	1,500	Free-jet tests
	Russia	GELA phase I[a]	LFRJ	1973–1978	3	0–55,000	——	TU-95	——	——	——	Flight tests
	U.S. Navy	IRR-TTV[f]/TTM[f]	LFIRR	1974–1985	3.0	60,000	——	Submarine	246	21	3,930	Component tests
	U.S. Air Force	ASALM–PTV[a]	LFIRR	1976–1984	2.5–4	10,000–80,000	56	Air	168	20	2,415	Flight tests
	U.S. Air Force	LFRED[h]	LFIRR	1976–1980	3	30,000	——	Air	——	——	——	Component tests
	U.S. Navy	LIFRAM[i]	LFIRR	1976–1980	3.0+	——	150	Air	144	8	650	Semi-free-jet tests
	U.S. Navy	SOFRAM[j]	SFIRR	1976–1981	3.0+	——	150	Air	144	8	650	Free-jet tests
	Germany	EFA	SFDR	1976–1980	——	——	——	——	——	——	——	Flight tests
	U.S. Navy	Firebrand[b]	LFRJ	1977–1982	3	0	44	Rail	200	14	1,200	Flight test vehicle
	U.S. Air Force	DRED[g]	DR	1977–1979	3	30,000	——	——	——	——	——	Component tests
	Russia	SS-N-22/Sunburn[a]	LFIRR	1977–	2.5	0	270	Rail	360	28	8,800	Operational
	Russia	AS-17/Kh-31[a]	LFIRR	1977–	3	0	44–90	Rail	204	14	1,322	Operational
	France	Rustique MPSR-1[b]	UFDR	1978–1985	3	40,000	35	Rail	144	8	360	Flight tests
	People's Republic of China	C-101[b]	LFRJ	1978–	1.8	0	30	Rail	295	21	4,070	Operational
	U.S. Army	SPARK	SFRJ/IRR	1978–1981	3	0	——	Rail	——	——	——	Flight tests
	U.S. Air Force	DR–PTV	FFDR	1979–1986	3.5	60,000	——	Air	——	——	——	Free-jet tests

[a] System discussed and shown. [b] System discussed. [c] Augmented thrust propulsion/thrust augmented surface-to-air missile-extended range, and -medium range (ATP/TARSAM-ER, -MR). [d] Advanced surface-to-air ramjet (ASAR). [e] Modern ramjet engine (MRE). [f] Torpedo tube vehicle/torpedo tube missile (TTV/TTM). [g] Ducted rocket engine development (DRED). [h] Liquid fuel ramjet engine development (LERED). [i] Liquid fuel ramjet missile (LIFRAM). [j] Solid fuel ramjet missile (SOFRAM).

Table 4 Worldwide ramjet evolution 1980–today

Era	Country/service	Engine/vehicle	Engine type	Dates, year	Cruise Mach no.	Cruise altitude, ft	Powered range, n mile	Launcher	Total length, in.	Diameter, in.	Total weight, lbm	State of development
1980–1990	France/Germany	ANS[c]	LFIRR	1980–1992	2.5	0	44	Rail	204	14	1,322	Flight tests
	France	ASMP[a]	LFIRR	1980–	3	0	185	Air	210	15	1,848	Operational
	U.S. Navy	ACIMD/AAAM[a]	LFIRR	1981–1989	3.2	80,000	150	Air	144	9.5	590	Component tests
	U.S. Air Force	BSFRJ[d] Tech	SFRJ	1982–1987	3	70,000	300	Air	——	——	——	Component tests
	U.S. Navy	Vandal (Talos)[a]	LFRJ	1983–	2.2	0	43.5	Rail	434	28	8,210	Operational
	U.S. Navy	SFIRR	SFIRR	1984–1989	2.5	0	50	Air	168	18	——	Component tests
	U.S. Navy	SLAT[a]	LFIRR	1986–1992	2.5	0	50	Rail	218	21	2,445	Flight tests
	U.S. Air Force	BECITE[e]	SFIRR	1987–1990	3	70,000	300	Air	——	——	——	Component tests
	U.S. Air Force	VFDR[a]	DR	1987–1997	3	50,000	50	Air	144	7	360	Component tests
	U.S./Germany	Cooperative technical program	SFDR	1989–1999	3	50,000	50	Air	144	7	360	Component tests
1990–2000	France	ASLP D2	LFIRR	1990–1996	2–3.5	——	——	Air	——	16	——	Component tests
	France	MARS[b]	LFIRR	1990–1996	4–5	90,000	——	Air	220	15	——	Component tests
	India	AKASH[b]	DRIRR	1990–	3.5	50,000	15	Rail	256	13	1,445	Flight tests
	United States/France	Cooperative technical program	UCDR	1991–1997	3	50,000	50	Air	144	7	360	Component tests
	People's Republic of China	C-301[b]	LFRJ	1991–	2	0–20,000	110	Rail	388	30	10,100	Operational
	United States/Japan	Cooperative technical program	VFDR	1992–1997	3	50,000	50	Air	144	7	360	Component tests
	France	Rustique MPSR-2[b]	UFDR	1993–1997	3.5	80,000	30	Rail	158	7.9	440	Flight tests
	Russia	MA-31/AS-17[b]	LFIRR	1994–	4.5	0	44–90	Rail	200	14	1,400	Flight tests
	South Africa	LRAAM[b]	LFIRR	1994–	4	80,000	45	Air	144	7	360	Flight tests
	U.S. Navy	LDRJ/LCMS[b]	LFIRR	1995–1999	4.0	7,000	700	Air	256	21	3,400	Flight tests
	France/Germany	ANF/ANNG[b]	LFIRR	1995–2000	3	45,000	18	Air	200	14	1,440	Component tests
	Russia	AA-X-12[a]	DR	1995–	3.5	70,000	65	Air	142	8	390	Flight tests
	Israil	Gabriel IV[b]	LFIRR	1995–	2.5	0	320	Rail	190	17.6	2,100	Component tests
	People's Republic of China	Hsiung Feng III[b]	LFIRR	1995–	2.5	0	320	Rail	190	17.6	2,100	Component tests
	United Kingdom	FMRAAM[b]	VFDR	1995–1999	3	70,000	100	Air	144	7	400	Development
	France	Vesta[b]	LFIRR	1996–2003	4	0	186	Air	200	14	1,848	Flight tests
	France	Rascal[b]	LFIRR	1996–	2–4	0–65,000	——	——	——	8–14	——	Component tests
	France	ASMP-A[b]	LFIRR	1998–	4	0	270	Air	200	14	1,848	To be Operational
	Germany	ARMIGER[b]	DRIRR	1996–	3	30,000	100	Air	156–173	8	500	Component tests
	Russia	SS-N-26/Yakhont[a]	LFIRR	1998–	2.5	0–50,000	60–260	Rail	350	27.5	5,500	Flight tests
	India/Russia	PJ-10/Brahmos[b]	LFIRR	1998–	2.8	0–50,000	162	Rail	354	28	8,000	To be Operational
	United Kingdom	BVRAAM/Meteor[a]	VFDR	1999–	4	50,000	54	Air	144	7	400	Component tests
	U.S. Navy	SFRJ Tech Pgm	SFRJ	1999–	5–6	0–80,000	1,000	Rail/VLS	168–256	9	2,200–3,700	Component tests
2000–2003	France	MICA/RJ[f]	LFIRR	2000–	3	50,000	50	Rail	144	7.1	370	Component tests
	United Kingdom/Sweden	S225XR	VFDR	2000–	3	50,000	60	Rail	144	7.5	400	Component tests
	People's Republic of China	Ying-Ji 12[b]	LFIRR	2000–	3	20,000	18	Air	200	13.8	1,440	Component tests
	U.S. Navy	SSST[a]	VFDR	2000–	2.5+	0	45–60	Rail	192–228	13.8	——	Flight tests
	U.S. Navy	GSSCM[b]	LFIRR	2002–	4.5	80,000	450	Rail/VLS	168	21	2,280	Component tests
	U.S. Navy	HSAD[b]	VFDR	2002–	4.5	80,000	100	Air	——	10	——	Component tests

[a] System discussed and shown. [b] System discussed. [c] Anti-navire supersonique (ANS). [d] Boron solid fuel ramjet (BSFRJ). [e] Boron engine component integration, test and evaluation (BECITE). [f] Missile intermediat de combat aerien/ramjet (MICA/RJ).

Table 5 Worldwide scramjet evolution 1955–1990

Era	Country/service	Engine/vehicle	Engine type	Dates, year	Cruise Mach no.	Cruise altitude, ft	Powered range, n mile	Launcher	Total length, in.	Diameter, in.	Total weight, lbm	State of development
1955–1975	U.S. Navy	External burn[b]	ERJ	1957–1962	5–7	—	—	—	—	—	—	Combustion tests
	Russia	Chetinkov research	ERJ	1957–1960	5–7	—	—	—	—	—	—	Component tests
	U.S. Air Force	Marquardt SJ	DMSJ	1960–1970	3–5	—	—	—	88	10 × 15	—	Cooled engine tests
	U.S. Air Force	GASL SJ[a]	SJ	1961–1968	3–12	—	—	—	40	31 in^2	—	Cooled engine tests
	U.S. Navy	SCRAM[b]	LFSJ	1962–1977	7.5	100,000	350	Rail	288	26.2	5,470	Free-jet test
	U.S. Air Force	IFTV[c]	H_2/SJ	1965–1967	5–6	56,000	—	—	—	—	—	Component tests
	U.S. Air Force–NASA	HRE[a]	H_2/SJ	1966–1974	4–7	—	—	—	87	18	—	Flowpath tests
	NASA	AIM[b]	H_2/SJ	1970–1984	4–7	—	—	—	87	18	—	Cooled engine tests
	France	ESOPE[b]	DMSJ	1973–1974	5–7	—	—	—	87	18	—	Component tests
1975–1990	U.S. Navy	WADM/HyWADM[b]	DCR	1977–1986	4–6	80,000–100,000	500–900	VLS	256	21	3,750	Component tests
	Russia	Various research	SJ/DCR	1980–1991	5–7	80,000–100,000	—	—	—	—	—	Combustion tests
	NASA	NASP[b]	MCSJ	1986–1994	0–26	0–orbit	Orbital	Runway	—	—	500,000	Free-jet test (M7)
	Germany	Sänger II[b]	ATRJ	1988–1994	4	0–orbit	Orbital	Runway	3976	550	800,000	Concept vehicle

[a] System discussed and shown. [b] System discussed. [c] IFTV incremental flight test vehicle.

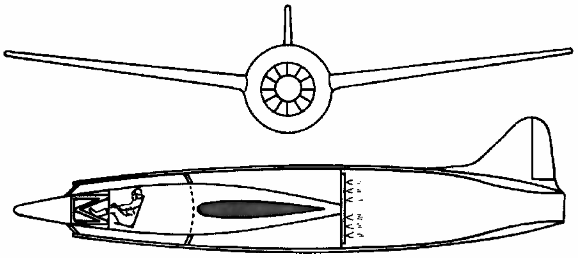


Fig. 9 France's first ramjet-propelled flight tested airplane (1933–1951).

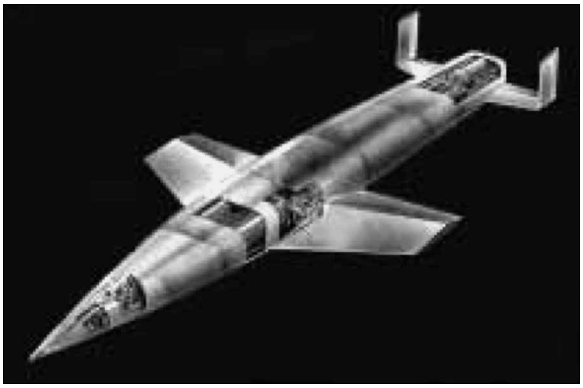


Fig. 10 German Sänger I Hypersonic Concept Vehicle (1936–1945).[34]

as an air-launched vehicle from another aircraft. Refined versions of this aircraft followed over the years with the subsequent development of the Griffin II. Throughout this chronology, the dates in the figure captions are intended to reflect a total time interval including development, testing, and operation if applicable.

In the late 1930s, Eugen Sänger, one of Germany's top theoreticians on hypersonic dynamics and ramjets, and his wife, mathematician Irene Bredt, had begun developing a suborbital rocket bomber, Sänger I (Fig. 10) or RaBo, (sometimes called the Antipodal Bomber) that would be capable of attacking targets at intercontinental ranges.[34] Highly advanced concepts, including swept, wedge-shaped supersonic airfoils, a flat, heat-dissipating fuselage undersurface that anticipated the space shuttle's design by 30 years, and rocket engines of extraordinary thrust were incorporated in the RaBo concept that would have taken many years to develop. In 1944, Sänger and Bredt were moved to an isolated laboratory complex in the mountains near Lofer, Austria, where a number of advanced research projects were underway. Most sources indicate that nothing much came of the Amerika Bomber project at Lofer, but this is clearly not the case. The Russians recovered copies of Sänger's RaBo reports and were so fascinated with the concept that they dedicated effort to designing an updated RaBo (Antipodal Bomber) equipped with huge ramjet engines for boost and cruise propulsion. The RaBo influenced Soviet manned and unmanned rocket work for years after the war. It influenced U.S. work, too, leading directly to the Walter Dornberger-sponsored Bell bomber missile (BoMi) project of the early 1950s, and ultimately the U.S. Air Force/Boeing X-20 Dyna Soar hypersonic glider program that laid the technical groundwork for the space shuttle. The Sänger work to achieve Earth orbit recognized the need for airbreathing propulsion and suggested a preference for a SSTO vehicle.

Both the Sänger–Bredt RaBo of 1945 and the postwar Soviet derivative used a long rocket sled to propel the vehicle to its takeoff speed of several hundred miles per hour. After launch, an onboard engine of some 200,000-lb thrust would propel the craft into a ballistic trajectory that peaked at altitudes of several hundred miles. The German version was intended to be able to reach friendly territory after making its strike, or possibly ditch near a U-boat. The Soviet version had ramjets to provide ascent boost and possibly return-to-base cruise capability after velocity decayed into the supersonic range. After the RaBo arced to altitudes of several hundred miles

Table 6 Worldwide scramjet evolution 1990–today

Era	Country/service	Engine/vehicle	Engine type	Dates, year	Cruise Mach no.	Cruise altitude, ft	Powered range, n mile	Launcher	Total length, in.	Diameter, in.	Total weight, lbm	State of development
1990–2003	United Kingdom	HOTOL[c]	SJ	1990–1994	2–8	—	—	—	—	—	—	Combustion tests
	Japan	PATRES/ATREX[b]	TRBCC	1990–	0–12	100,000	—	—	87	30	—	Component tests
	Japan	NAL-KPL research[b]	SJ	1991–	4–12	50,000-100,000	—	—	83	8 × 10	—	Component tests
	Russia	Kholod[a]	DCR	1991–1998	3.5–5.4	50,000–115,000	—	SA-5	36	24	—	Flight tests
	Russia/France	Kholod[a]	DCR	1991–1995	3.5–5.4	50,000–115,000	—	SA-5	36	24	—	Flight tests
	Russia/United States	Kholod[a]	DCR	1994–1998	3.5–7	50,000–115,000	—	SA-5	36	24	—	Flight tests
	France	CHAMIOS[b]	SJ	1992–2000	6.5	—	—	—	—	8 × 10	—	Component tests
	France	Monomat	DMSJ	1992–2000	4–7.5	—	—	—	—	4 × 4	—	Component tests
	France	PREPA[a]	DMSJ	1992–1999	2–12	0–130,000	Orbital	Ground	2560	Waverider	1×10^6	Component tests
	Russia	ORYOL/MIKAKS	SJ	1993–	0–12	0–130,000	Orbital	Ground	—	—	—	Component tests
	France/Russia	WRR[b]	DMSJ	1993–	3–12	0–130,000	—	Ground	—	Waverider	60,000	Component tests
	Russia	GELA Phase II[a]	RJ/SJ	1995–	3–5+	295,000	—	Tu-22M	—	—	—	Flight tests
	Russia	AJAX[b]	SJ	1995–	0–12	0–130,000	—	—	—	—	—	Concept
	U.S. Air Force	HyTech[a]	SJ	1995–	7–10	50,000–130,000	—	—	87	9 × 12	—	Component tests
	United States	GTX[d]	RBCC[e]	1995–	0–14	50,000–130,000	—	—	—	—	—	Component tests
	U.S. Navy	Counterforce	DCR	1995–	4–8	80,000–100,000	—	Air/VLS	256	21	3,750	Component tests
	NASA	X-43A/Hyper-X[a]	H2/SJ	1995–	7–10	100,000	200	Pegasus	148	60(span)	3,000	Flight tests
	France/Germany	JAPHAR[a]	DMSJ	1997–2002	5–7.6	80,000	—	—	90	4 × 4	—	Component tests
	United States	ARRMD[b]	DCR	1997–2001	3–8	80,000	450–800	Rail/Air	168–256	21	2,200–3,770	Component tests
	Russia	IGLA[a]	SJ	1999–	5–14	82,000–164,000	—	SS-25	197	—	—	Flight tests
	NASA	X-43C[b]	DMSJ	1999–	5–7	100,000	—	Pegasus	—	10.5 wide	—	Component tests
	Unites States	IHPTET[b]	ATR	1999–	0–5	0–90,000	—	—	—	15–40	—	Component tests
	United States	RTA[b]	TBCC	1999–	0–5	0–90,000	—	—	—	15–40	—	Component tests
	France	Promethee[b]	DMSJ	1999–2002	2–8	0–130,000	—	—	238	—	3,400	Component tests
	India	AVATAR-M[b]	SJ	1999–	0–14	0–orbit	Orbital	Ground	—	—	18–25 ton	Combustion tests
	United Kingdom	HOTOL Phase II	SJ	2000–	2–8	—	—	—	—	—	—	Component tests
	France	PIAF[b]	DMSJ	2000–	2–8	0–110,000	—	—	53	8 × 2	—	Component tests
	United States	MARIAH	MHD/SJ	2001–	15	—	—	—	—	—	—	Combustion tests
	Australia	HyShot[b]	SJ	2001–2002	7.6	75,000–120,000	200	Terrior Orion	55	14	—	Flight tests
	United States	Gun launch technology	SJ	2001–	—	—	—	Ground	—	—	—	Flight tests
	United States	ISTAR[b]	RBCC[e]	2002–2003	2.4–7	0-orbit	Orbital	Ground	400	Waverider	20,000	Component tests
	United States	X-43B[b]	RB/TBCC	2002–2003	0–10	100,000	200	Air	500	Waverider	24,000	Component tests
	Russia	Mig-31 HFL[b]	SJ/DCR	2002–	2–10	50,000–130,000	—	Mig–31	—	—	—	Planned flight tests
	United States	HyFly[a]	DCR	2002–	3–6.5	85,000–95000	600	F-4	225	19	2,360	Flight tests planned
	United States	SED[a]	SJ	2003–	4.5–7	80,000	—	—	—	9 wide	—	Planned flight tests
	France	LEA[a]	SJ/DCR	2003–2012	4–8	80,000	—	Air	—	—	—	Flight tests planned
	United States	RCCFD[b]	TBCC	2003–	0.7–7	0–orbit	Orbital	Ground	400	Waverider	20,000	Flight tests planned

[a] System discussed and shown. [b] System discussed. [c] Horizontal takoff and landing (HOTOL). [d] NASA Glenn Rc hydrogen fueled/cooled (GTX). [e] Reference vehicle designation (RBCC).

at speeds of over 10,000 mph, the spacecraft would descend and encounter the upper atmosphere. The pilot would execute a high-*g* pullout as the craft skipped off the atmosphere like a stone skipping on water. This cycle would be repeated several times as the vehicle slowed and descended on its global path. When it neared its target, the spacecraft would release a large conventional-explosive bomb that would enter the atmosphere at meteor speeds and strike with tremendous force. No reference source on the Sänger–Bredt project indicates that any RaBo hardware was built at Lofer. A 1947 U.S. technical intelligence manual on the Lofer base, however, contains an image of an incomplete nose and forward fuselage of a very unconventional aircraft that was never flown.

During and shortly after WWII, the United State developed a number of airbreathing-propelled drones. One example is the 1942 McDonald-developed Katydid KDH-1 pulsejet-powered target drone, whose design heritage appears to follow from the German V-1. Unknown quantities of drones were produced.

In the United States, the Marquardt Company, founded by R. Marquardt, began developing ramjet engines in 1944. Shortly after WWII, the U.S. military services developed and tested subsonic ramjet engines for a series of experimental applications. The propulsion goal in these early days of turbojet propulsion was to achieve low-cost airbreathing engines. Flight testing of these subsonic ramjets required only aircraft assist to reach ramjet flight speed.[35] Early interests in ramjet propulsion for high-speed subsonic aircraft applications led to two piloted experimental flight demonstrators. The first of these, conducted in 1946, employed a North American P-51 Mustang as the carrier aircraft with its dual-wingtip-mounted Marquardt subsonic ramjets. The second, flown in 1948, used the higher speed turbojet-powered Lockheed F-80 Shooting Star fighter. The ramjets were typically started fuel rich to achieve maximum thrust, accounting for the extended exhaust flames that diminished as flight speed increased. The F-80 briskly accelerated on ramjet power, with the turbojet set at idle. Larger 48-in.-diam experimental subsonic ramjets were subsequently developed and flown experimentally on the Douglas B-26 and demonstrated the potential for engine scale-up and added thrust. Subsonic ramjets were applied to production target drones and experimental missiles during this period. A leading example was the U.S. Navy Gorgon IV test vehicle first flown in 1947. Both this prototype missile and the derivative KDM-1 Plover target drone were powered by a single 20-in. ramjet burning gasoline and used parachute recovery permitting reuse of the vehicle.

The U.S. Navy Cobra was the first successful demonstration of a ramjet in supersonic flight, occurring in 1945. Cobra is a 6-in.-diam, normal shock inlet, tandem-boosted, liquid propylene oxide-fueled ramjet flight test vehicle that cruised at Mach 2 at 20,000-ft altitude. Its purpose was to demonstrate that a ramjet could produce the requisite thrust to cruise at supersonic speeds.

The U.S. Navy Bureau of Aeronautics developed an entire family of unmanned guided drone missiles under the name of Gordon between 1943 and 1953 for a variety of tasks, including ground attack and interception of bomber formations. In the mid-1940s, piston engines yielded insufficient performance and new ramjet and turbojet propulsion were beginning to show promise. Development of a ramjet-powered Gordon IV began in 1945 using the Marquardt XRJ30-MA ramjet engine, a derivative of which supported the Bomarc missile development a few years later. The swept-wing KDM-1 with an underslung ramjet first flew in 1947. There were 12 vehicles were produced and operational until 1949, when the hardware was used to develop a later version called Plover. The program was canceled in 1953 as advanced missile technology was developed.

Considerably less sophisticated normal shock inlets were used in the early history of ramjet engines. These were the real flying stovepipes with no moving parts and advertised as the simplest propulsion system known to man. The focus shifted from the ultrasimplicity of the normal shock ramjet in the mid-1950s to the supersonic inlet ramjet engine as employed in the Bomarc.

These subsonic ramjet flight test successes led to subsequent supersonic ramjet system developments. To do so, with only subsonic aircraft being available, required the use of rocket boosters. The operational Bomarc and Talos interceptor missiles were derived from this advancement in propulsion technology. Marquardt developed the engines for the Bomarc missile, producing over 1600 units in various versions. The ramjet-powered Navaho and Talos missiles were developed in this same era. Escher and Foreman[36] assembled a recent excellent review of these missile systems and recount useful technical and program information.

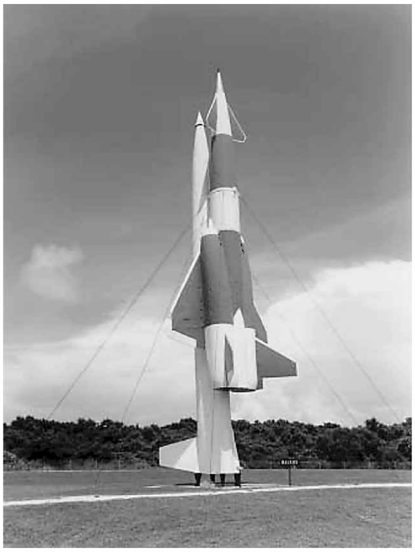


Fig. 11 U.S. NAVAHO operational missile (1946–1958).

The Navaho supersonic cruise missile (Fig. 11), developed in the 1950s for intercontinental ranges, was massive in size. At 48-in. diameter, 90 ft long and weighing in at 120,000 lbm, it is the largest ramjet engine developed in the United States. The missile used two engines mounted side-by-side, with each connected to an airflow duct leading from each of the two fuselage-side-mounted half-cone equipped inlets. The engines burned JP-4 or JP-5. The development program was canceled in 1957 due to its high cost together with improvements in surface-to-air missile (SAM) technology and the successful development of intercontinental ballistic missiles over supersonic cruise missiles.

Russia developed the Burya (storm) missile in parallel with the U.S. Navaho. Designed to be an intercontinental strategic missile, the Burya employed an LFRJ cycle and two tandem boosters that used kerosene/nitric acid fuel. Five successful flight tests of the Mach 3 missile reportedly occurred. The development was canceled in 1958, shortly after development of the Navaho was stopped.

The Bomarc and Talos antiaircraft interceptor systems were fully developed and operationally deployed by the U.S. Air Force and U.S. Navy, respectively. These rocket-boosted hydrocarbon-fueled ramjet-powered vehicles and derivatives routinely achieved speeds of Mach 2–3+ and altitudes from sea level to 40,000–70,000 ft and higher. In doing so, they recorded high degrees of mission reliability and operational effectiveness. The Bomarc supersonic interceptor missile (Fig. 12), deployed in the early 1960s by the U.S. Air Force and the Royal Canadian Air Force, employed two variations of a fixed-geometry ramjet engine. The A-series missile employed an axisymmetric cone-configured mixed compression inlet and annular air-cooled combustor that burned 80-octane gasoline. The B-series missile was fitted with an isentropic-configured fixed-inlet spike and burned JP-4 fuel. Launched vertically, the Bomarc interceptor rolled to its flyout azimuth, pitched over and accelerated to flight speeds of Mach 2.5–2.7 and altitudes of 65,000–70,000 ft under ramjet power. The ramjet engine was later certified for Mach 3.4 service.

In the early 1950s, after the need for a supersonic experimental research and flight demonstration vehicle was recognized, the United States initiated the X-7 program. This air-launched solid-rocket-boosted supersonic vehicle initially used several Bomarc hydrocarbon-fueled conventional ramjet engines ranging in size from 28 to 36 in. in diameter and achieved flight conditions of Mach 4.3 and 84,000 ft. Flown from 1952 to 1959, the X-7 was designed

Fig. 12 U.S. BOMARC operational missile (1950–1972).

Fig. 13 U.S. Talos/Vandal operational missile (1950–today).

for recovery and reuse and was later adapted as a ground-launched supersonic target for the U.S. Army.

The Talos supersonic interceptor missile (Fig. 13) evolved from the Bumblebee program under the direction of the JHU/APL initiated at the end of WWII. The Talos engine used a single, on-centerline ramjet engine with a double-cone configuration mixed compression inlet that fed to an air-cooled can combustor, which burned JP-5 fuel. Boosted to supersonic ramjet-takeover conditions by a separate solid propellant rocket, this ramjet-powered missile further accelerated and then cruised out supersonically to the aircraft-interceptpoint at high altitude. Its main limitations were in terminal intercept phase due to guidance inaccuracies and the axisymmetric inlet would unstart at high angles of attack followed by loss of control. The Talos was first fired in 1951 and introduced into the U.S. fleet in 1955. After the cancellation of the BQM-90 program in 1973, the U.S. Navy had to look for other target missiles to simulate attacking antiship missiles. In 1975, it was decided to convert some obsolete RIM-8 Talos missiles to MQM-8G Vandal targets as a short-term solution to simulate the terminal phase of a missile attack. Some 2400 Talos units were built, with the U.S. Navy presently using a Talos variant (Vandal) as a low-altitude supersonic target. This is the second and final operational ramjet-powered system fielded by the United States to date and the only ramjet-powered system in limited flight service today.

Refined versions of the Leduc-010, whose first flight was in 1949, followed over the years using air-turboramjetcycles to provide static thrust, with the most striking demonstration of ramjet supersonic flight speeds being achieved in the Griffon II from 1957 to 1961, which reached climb speeds of Mach 2.19 and Mach 2.1 at 50,000 ft (15.3 km) in 1959. Work on ramjets for aircraft applications generally stopped in the 1960s when the turbojet design was perfected and was shown to have lower fuel consumption than ramjets. Following the initial desires to employ ramjet technology in aircraft, subsequent development focused on advancing missile technology

In 1955 the U.S. imitiated one of the first SFIRRs ever developed, ram air rocket engine, RARE. It employed a conical nose inlet and rocket-ramjet flowpath; 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. This dual in-line combustion chamber approach was used to solve potential boost-to-sustaintransition problems. Magnesium and boron-loaded fuels were examined. Three flight tests of the RARE vehicle were successfully conducted at Mach 2.3 between 1959–1960.

In the 1955–1965 time frame, France developed, flight tested, and made operational three LFRJ missiles: the VEGA, the SE-4400, and the target vehicle, CT-41.

The U.S. Typhon development began in 1957. The engine employed an LFRJ design that used a Talos tandem solid propellant booster. The Typhon missile was much smaller than its Talos predecessor, yet still capable of flying almost twice the range. In addition to the reduced sustainer weight (1800 vs 3360 lbm for the Talos) the conical-inlet can combustor ramjet propulsion was more efficient and its subsystems and structure were more compact. It was successfully flight tested nine times from 1961 to 1963. Unfortunately, the Typhon was not introduced into the fleet because it outperformed the capabilities of the radar, guidance, control, and battle space coverage of the time. Despite its success, the program was canceled in 1965. However, the lessons learned and technology developed were to become the cornerstones of the Aegis weapon system 10 years later.

The U.S. Creative Research on Weapons (CROW) was developed with the goal of demonstrating SFIRR feasibility for delivering an air-launched payload to a desired location.[22] The axisymmetric IRR configuration used an SFRJ sustainer and an integral booster package contained within the ramjet combustor. The design employed ejectables including a bulkhead between the sustainer and booster grains and a rocket nozzle plug centerbody, which were expelled by ram air at transition. Six flight tests were successfully conducted demonstrating operational potential. The CROW concept, although briefly considered for use as an air-to-air missile and a high-speed target, never became operational.

The Bloodhound (Fig. 14) and the later Sea Dart (Fig. 15) were developed and used by the Royal Navy and employed in the role of long-range air defense. The Bloodhound is most easily recognized by its profusion of control surfaces and stabilizers; it has one fin on each of four boosters, two pivoting mainplanes, and two fixed horizontal stabilizers mounted in line with the wings. Two solid propellant boosters and an LFRJ sustainer propel the missile. The Bloodhound maneuvers with its mainplanes employing a twist-and-steer technique. Initially operational in 1964, almost 800 missiles were produced until 1991, when it was removed from service.

Ramjet Development: 1960–1980

A major milestone of this 20-year period was the conception and demonstration of IRR technology for missile applications. Table 3 summarizes ramjet evolution in the era from 1960 to 1980 and provides originating country, engine/vehicle names, development dates, performance, physical characteristics, and state of development. The

Fig. 14 U.K. Bloodhound operational missile (1957–1991).

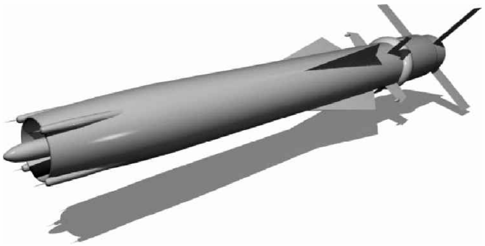


Fig. 15 U.K. Sea Dart operational SAM (1960–1975).

general pace of ramjet development accelerated during this era, with the People's Republic of China being added to the countries engaged in activities. As one witnesses the dramatic growth due to competition between maturing siblings, thus it is with the growth in international ramjet technology.

France developed the experimental LFRJ Stataletex missile from 1960 to 1970, which achieved Mach 5 at 82,000 ft in flight tests at the end of the 1960s.

To field a fully responsive target to validate the surface-to-air Hawk interceptor missile system, the U.S. Army sponsored development of the specially tailored MQM-42 Redhead Roadrunner tandem rocket-boosted ramjet-powered target vehicle in the mid-1960s. The old normal shock ramjet reappeared again in this system, which was designed to simulate Mach 0.9–1.5 hostile aircraft penetrating defenses at medium to low altitudes. Like the KDM-1 and X-7, this vehicle was designed for parachute recovery. The cost-savings payoff of reusability was demonstrated with over 90 flights accomplished with some 50 sets of flight hardware.

The United Kingdom began development of the Sea Dart (Fig. 15) as a lightweight area defense replacement for the Sea Slug in 1960. The missile employs a solid propellant booster and an LFRJ sustainer. Flight testing began in 1965, and if was operational as early as 1967. The Sea Dart accounted for seven kills in the Falkland conflict and is credited with downing an Iraqi missile headed for a U.S. cruiser in the Gulf War of 1991. The Argentineans reportedly ordered 100 missiles in 1986. Currently, the Sea Dart is being removed from Royal Navy service.

One of the earliest attempts in the United States to integrate the ramjet with a liquid propellant booster was the Hyperjet concept, flight tested at speeds over Mach 5 in the early 1960s using hydrogen peroxide and kerosene. Following rocket boost, the engine would transition to and accelerate in the ramjet mode. Although the Hyperjet's liquid propellant boost mode was repeatedly demonstrated in flight, logistics and field handling subsequently encouraged development of alternative designs.

In the late 1960s, the United States successfully developed and flight tested a small, high-altitude Mach 3+ reconnaissance vehicle designated the D-21 (Fig. 16). It was powered by a closely vehicle-integrated, high-speed version of the Bomarc RJ-43-MA JP-7-fueled LFRJ engine and was designed for carriage and launch from the SR-71 Blackbird at supersonic flight conditions. The engine design capitalized on the Bomarc production design. By 1972, it had flown operationally, achieving altitudes of 92,000 ft and ranges over 3000 miles. The D-21 was designed for supersonic launch from an SR-71 Blackbird aircraft and programmed to fly a racetrack-type reconnaissance course over large land masses at altitudes in excess of 80,000 feet and speed over Mach 3. On return to the launch zone, the reconnaissance package was to be jettisoned for midair parachute recovery. The operational design was eventually launched from the B-52.

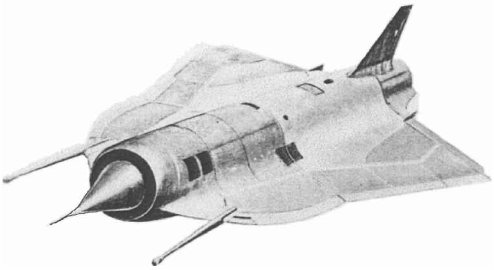


Fig. 16 U.S. D-21 operational reconnaissance vehicle (1963–1980).

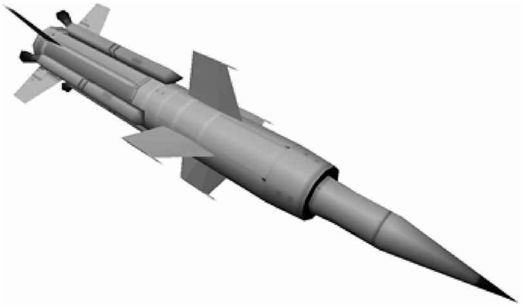
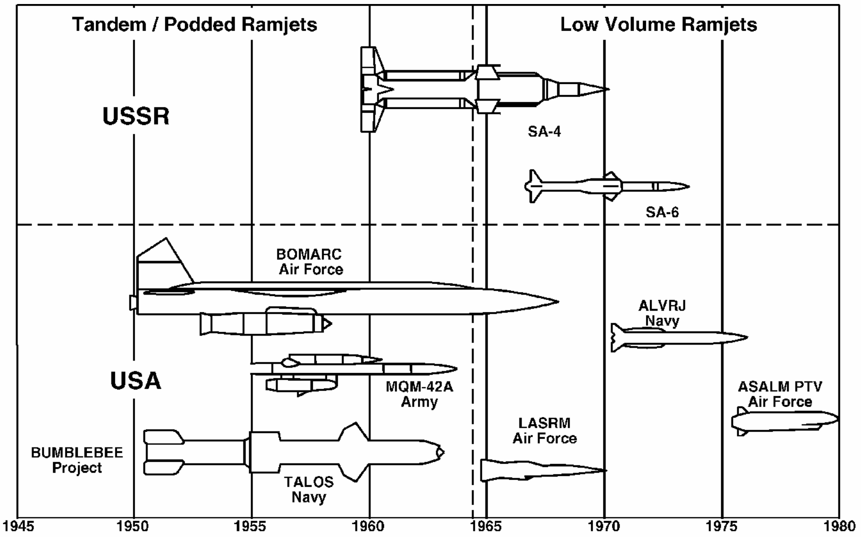


Fig. 17 Russian SA-4 operational SAM (1964–today).

Fig. 18 Russian SA-6 operational SAM (1965–today).

Ramjet-powered SAM development began in the early 1960s in Russia with the SA-4 Ganef, a solid propellant boosted LFRJ cycle that became operational by 1967 (Fig. 17). At least four variants of the medium to high altitude missile were produced between 1967 and 1973. The missile uses four solid propellant boosters mounted externally on the kerosene-fueled sustainer body.

Development of the Russian SA-6 Gainful second generation SAM began in the mid-1960s and was operational by 1970 (Fig. 18).



Courtesy of the Air Force Propulsion Directorate (circa 1970's)

Fig. 19 Early ramjet systems history (1945–1980).

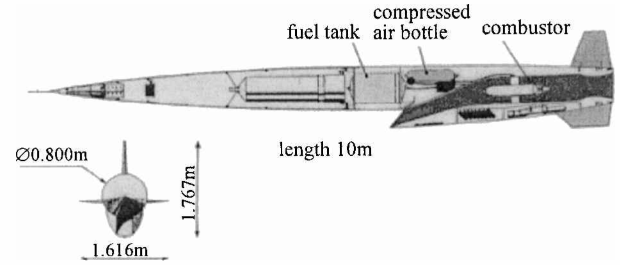


Fig. 20 French SE-X-422 flight-tested missile (1965–1967).

Fig. 21 U.S. ALVRJ flight-tested missile (1968–1975).

It uses a DR IRR cycle and is commonly attributed with starting the ramjet race. The October 1973 Yom Kippur War convincingly demonstrated the effectiveness of the IRR in tactical missiles. With employment of a DR cycle, the Russian SA-6 SAMs inflicted sharp losses on the Israeli fighters in 1973 and played prominently in the 1999 air campaign in Yugoslavia.

Before 1965, ramjet-powered missile systems, such as the U.S. Air Force Navaho and Bomarc, the U.S. Navy Talos, and the Russian SA-4 were externally boosted by a separable rocket system. This led to relatively large missiles, which were limited to launch from the ground or a ship. Launch from an aircraft or greater maneuvering capability, which require a smaller missile, became feasible with the development of the integral rocket–ramjet concept. In these more recent ramjets, the rocket booster was integrated within the ramjet combustor, thereby saving considerable volume (Fig. 19).[37]

As with the axisymmetric normal shock tandem-boosted ramjet, the flow-turning inlet integral rocket ramjet has undergone cyclical periods of interest, from the supersonic chemical propulsion low-altitude supersonic ramjet missile (SCP/LASRM) in the mid-1960s to advanced low-volume ramjet (ALVRJ) in the early 1970s to advanced strategic air-launched missile–propulsion test vehicle (ASALM–PTV) in the late 1970s to the SLAT in the early 1990s. Ramjet-powered air-to-surface missile exploratory development and flight testing began in the mid-1960s and extended through the 1980s. Solid and liquid IRR propulsion were selected for such applications. Beginning in 1964, the U.S. Air Force sponsored SCP/LASRM, an air-launched IRR supersonic missile development program. LASRM, the first low-volume IRR design, was flight demonstrated in the mid-1960s. The flight vehicle employed four aft-mounted, two-dimensional, inward turning inlets, was fueled with a heavy hydrocarbon, Shelldyne, and was designed to operate at Mach 2.5 sea level. The LASRM physical configuration is compared with contemporary systems in Fig. 19. Whereas flight tests were successful, a small operational envelope was experienced due to inlet unstart conditions.

France developed the SE-X-422 demonstrator (Fig. 20) from 1965 to 1967 for a long-range cruise missile application. The design employed an LRFJ with a single inlet located aft (Fig. 20). Three successful flight tests were conducted in 1967 and achieved Mach 2 at 30,000 ft.

The Navy ALVRJ vehicle (Fig. 21) was an LFIRR configuration of the late 1960s. The major program goal was to demonstrate controlled free flight at Mach 2.5–3 to ranges of 25–100 n mile with sufficient margin to provide for terminally effective tactical payloads.[22] It was similar in size and configuration to LASRM, except the four aft-mounted side inlets were outward turning, which provided better angle-of-attack operation, thereby permitting operation from sea level to intermediate altitudes. The JP-5-fueled ramjet employed a solid propellant carboxyl-terminated polybutadiene/ammonium perchlorate (CTPB/AP) integral booster, a DC93-104 insulation system, and an ejectable nozzle. Seven flight tests were flown, most between 1975 and 1979. Initial flight tests used flight weight heat-sink hardware, with later testing involving the DC93-104 insulation system. All goals, objectives, and specified data points were substantially achieved with the major contribution being the first successful demonstration of the in-flight ramjet takeover for an IRR design. A number of other advanced development efforts to support a 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. Whereas the Navy approved an STM concept directed toward tactical land targets, Congress canceled subsequent development based upon a review of tactical needs and requirements.

Russia began development of the SS-N-19 Shipwreck supersonic long-range antiship missile (Fig. 22) in the early 1970s. First thought to use turbojet propulsion, it was recently revealed[38] to be liquid fuel ramjet-powered. Made operational in 1981 as the first sublaunched

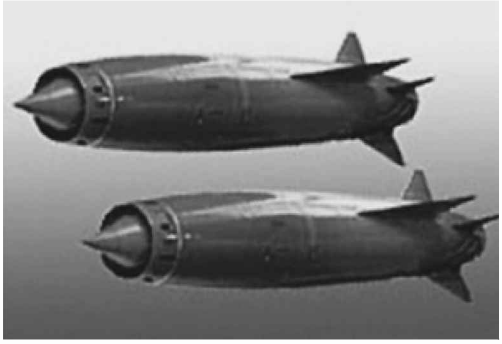


Fig. 22 Russian SS-N-19 operational missile (1972–today).

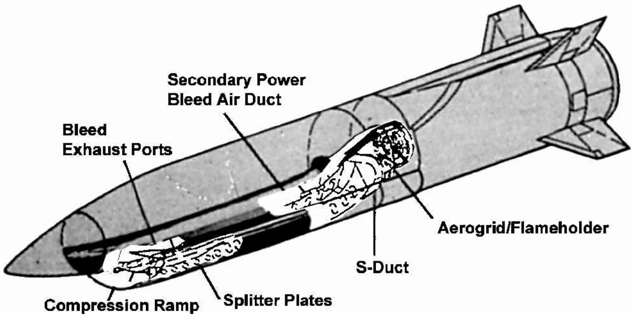


Fig. 23 U.S. ASALM flight-test vehicle (1965–1980).

antiship ramjet missile, the aptly named missile is in service today. It is deployed in both ships and submarines. The submarine Kursk, lost in the Barents Sea in August 2000, was reportedly conducting SS-N-19 live firings before it went down.

The generic ordnance ramjet engine (GORJE) missile was developed through engine testing from 1972 to 1976 as an airbreathing propulsion system for the high-speed antiradiation missile (HARM). Such a ramjet design could provide higher average velocity with a lower peak velocity than a solid propellant rocket. This was viewed as a solution to relieving the then-current seeker dome aeroheating problem. An interesting parallel rocket ramjet configuration was devised, which located the RJ-4 fuel tank forward of the solid booster followed by the ramjet combustor positioned aft. A short L/D ($\sim$1) annular ramjet combustor, which employed DC93-104 insulation, was used around a central blast tube for booster exhaust. The design employed four side-mounted axisymmetric inlets with the entrance just aft of the trailing edge of the midbody control wings. Aircraft interface requirements dictated this inlet configuration, which created inlet entrance flow distortion that was to plague the design performance. Because this design did not employ a traditional IRR configuration, neither combustor port covers nor inlet covers were necessary. Development of the LFIRR propulsion system was taken through semifreejet engine testing and was plagued with combustor oscillations and instability problems. Even though most of the expected pressure oscillations were accommodated by the inlet pressure recovery margin, some unanticipated higher frequency instabilities unstarted the inlets. The program provided impetus for development activities to understand causes and control methods of combustion instabilities in short L/D LFRJ engines. Planned flight tests were never conducted due to lack of funds and the development was concluded in 1976.

In the early 1970s, France pursued the exploratory development on *Scorpion* for a long range SAM mission.[39] This missile used a subsonic combustion LFRJ operating up to Mach 6 after a tandem boost to Mach 3 takeover. Successful ground testing was accomplished. Although this work did not proceed to flight demonstration, the analysis and experimental work demonstrated an important advance in high-speed ramjet technology.

The Russians employed a first generation flight test vehicle *GELA* phase 1 testbed.[64–66] This phase dealt with Mach 3 ramjet missile propulsion systems, which were developed from 1973 to 1978 and ultimately used on the SS-N-22 and SA-6 upgrades. Limited information is available on these early flight-test activities.

The potential of the IRR concept as a viable missile propulsion system attracted much attention, particularly with the advent of the Russian *SA-6*. The IRR concept enabled a compact air-launched missile configuration as shown in Fig. 19. Although most of these IRR systems operated at modest Mach number, the U.S. air-launched ASALM missile was tested to flight speeds approaching hypersonic Mach numbers. The U.S. Air Force sponsored the ASALM–PTV program and provided the most impressive flight demonstrations of the capability of the air-launched IRR.[5,40] Begun in 1968, the first ground test was in 1975. This propulsion system used the IRR approach first tested in the LASRM also under U.S. Air Force sponsorship, but with significant design differences. This vehicle employed a forward mounted “chin” inlet, which has the characteristics of improved packaging and improved performance at wider angles of attack (Fig. 23).[41] This permitted operation over a very wide flight envelope from Mach 2.5 sea level to Mach 4 at 80,000 ft. This inlet fed an ablatively cooled ramjet engine. ASALM tests demonstrated the capability of igniting ramjet fuel at -65°F and then achieving high combustion efficiency over a wide range of fuel/air ratios, as well as sustained operation at very low fuel/air ratios, which allowed for extended duration cruise. Whereas ramjet engine designs examined throughout these developments were challenged with operability concerns, combustion oscillations were relatively absent, unlike problems encountered in liquid and solid propellant rockets. ASALM was designed to fit the B-52 rotary launcher and provide significantly greater standoff range to the rocket-powered short-range attack missile (SRAM) plus air-to-air capability against aircraft. Seven successful flight tests were conducted between October 1979 and May 1980. Whereas MacDonald Douglas and Martin manufactured two different versions of the hardware for testing, the Martin/Marquardt version was flight tested. Unlike the similarly designed French ASMP, the ASALM did not see operational service, likely due to budget restrictions and the concurrent development of the AGM-86 air-launched cruise missile (ALCM). Nevertheless, the successful ASALM flight tests showed the potential of a high-speed air-launched IRR missile that could be carried in a bomber aircraft and could possess long standoff strike capability.[42] The marriage of the high-speed capability of the ramjet and the compact air-launched missile was successfully demonstrated.

The old flying stovepipe came back again in the late 1970s in the form of the U.S. Navy target vehicle Firebrand, used to simulate aircraft. Firebrand was designed as a parachute-recoverable ramjet-powered target suitable for ground and air launch. Propulsion included tandem solid propellant boosters and two Marquardt LFRJ sustainers located in aft pods. The original plan was to build nine Firebrand flight-test vehicles and begin flight testing in 1983. The program encountered funding difficulties and the vehicle came in heavy for planned air launch from a C-130 aircraft. Whereas the Firebrand was ultimately canceled in 1983, it provided technology and engine hardware used in subsequent programs. One such example was the conceptual ramjet engine (CORE) engine, which used inner portions of the Firebrand, and was the first in its day to employ a conventional flameholder to be successfully tested at the aerodynamically severe conditions of Mach 2.5 sea level. Although Vandal targets had been in use since 1975, the U.S. Navy decided in 1983 to continue use of the Vandal as a target and formulated a new requirement for a dedicated antiship missile target. The latter eventually resulted in development of the AQM-127 SLAT missile.

Russia began development of the SS-N-22 Sunburn (Fig. 24) in 1977. It was the first surface-to-surface missile (SSM) surface-launched (later air-launched) antiship missile with an initial operational capability (IOC) of 1982. This LFIRR engine design has had considerable influence on ramjet engine design and defenses against it capabilities. It is reported to be on the People’s Republic of China’s newly acquired Sovremenny-class guided-missile destroyers. The first Chinese test was reported[43] to be in 2001 and up to several hundred are potentially in their inventory today. This prompted Taiwan, Republic of China, to respond in 2001 with the development and

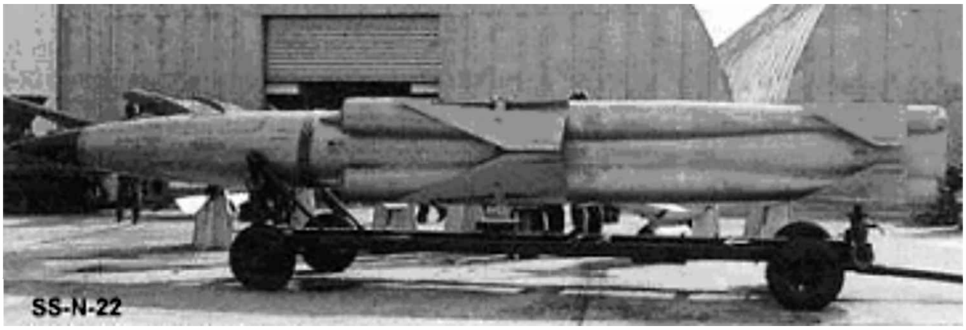


Fig. 24 Russian SS-N-22 operational missile (1977–today).

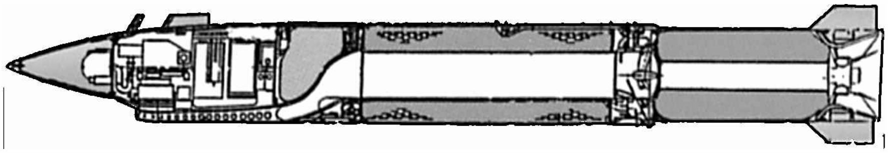


Fig. 25 U.S. SLAT flight-tested missile (1986–1992).

flight testing of an LFRJ antiship supersonic missile, the Hsiung Feng III.

In 1978, France began work on Rustique/MPSR-1,[44] which employs an unchoked flow ducted rocket (UFDR) engine and design concept oriented toward a mass-produced low-caliber missile with system advantages of storability, maintenance, and reliability characteristics comparable to those of solid propellant missiles. Rustique/MPSR-1 includes an air induction consisting of four two-dimensional inlets, single igniter for a nozzleless booster, and unchoked gas generator. No choked throat exists between the gas generator and the ramjet combustion chamber. The gas generator solid propellant burning rate depends on the combustion chamber pressure and self-modulation of the mixture ratio established by correct selection of the solid propellant pressure exponent for the expected range of speed and altitude conditions. This propulsion concept was flight tested (five ground launches) through the MPSR-1 and again in 1993–1997 in MPSR-2 (two ground launches).

In the late 1970s, in the People's Republic of China, development began of the C-101 or CSS-C-5 Saples, a shore-based, supersonic, antiship missile similar in configuration to the British Bloodhound SAM. It can also be launched from air and ship platforms. The requirements of high speed and long range resulted in a large missile with two tandem solid propellant boosters and two ramjet sustainer engines. The ramjets are mounted on stubs extending from the aft fuselage sides. The boosters are nestled under the stubs, between the ramjets and the fuselage. A tritail vertical stabilizer group consisting of a single, rectangular vertical stabilizer mounted ahead of a butterfly tail (two surfaces angled outward) provides control to the missile. A larger, longer ranged missile variant of the C-101, the C-301, was developed and fitted with four boosters.

Ramjet Development: 1980–2000

During this time frame, the intensity of international development activities increased in pace and number and moved convincingly into supersonic combustion. Table 4 summarizes ramjet evolution in the era from 1980 to 2000 and provides originating country, engine/vehicle names, development dates, performance, physical characteristics, and state of development. Whereas the countries engaged in ramjet developments did not expand during this era from those cited earlier, the international development activities did, which resulted in more operational systems. Wilson et al.,[45] Dunfee and Hewitt,[46] and Hewitt[47] provide recent reviews of worldwide developments in ramjet-powered missiles that have contributed to the following discussions of the developments during this era.

France initiated development of ASMP in 1980 to satisfy a requirement for an air-launched nuclear standoff missile. A competition between turbojet and ramjet propulsion preceded the start of this development. Flight-testing the French version of ASALM LFIRR technology occurred from 1980 to 1986. ASMP was subsequently deployed in 1986, was produced up to 1992, and is still in service today. Development of many variants has been pursued to varying degrees from 1991 to 2000 for air to air, air to surface (ASMP-C), and antiship anti-navire future/anti-navire nouvelle generation (ANF/ANNG) applications. Development of the air-to-air variant was shelved in the mid-1990s at the request of NATO partners. Development of the air-to-surface variant ended when development of the turbojet-propelled SCALP was selected for this role in 1994. France and Germany pursued development of the antiship variant jointly from 1995 until completion of design studies in 1998 when Germany withdrew. The development reverted to its old name of ANF and continued with plans for proof-of-concept testing of the propulsion system on the testbed VESTA and deployment in 2005. Development was stopped in 2000 due to budget shortfalls, but the potential for program restart still remains.[48] Development of a replacement (*ASMP-A*) began in 1996 and is currently in progress with an expected IOC of 2006.

The U.S. Navy began development of an advanced common intercept missile demonstrator (ACIMD) in 1981 as a long-range advanced antiair missile (AAM) replacement for the Phoenix. The LFIRR employed a two-dimensional midbody inlet and exhibited an ejectable solid booster nozzle. Development was canceled in 1989 before flight tests due to a shortage of funding.

The Firebrand flight conditions (Mach 2.5 sea level) were selected for the U.S. Navy AQM-127 SLAT development in the late 1980s, with the IRR configuration ultimately being selected over the simple normal shock configuration. The technology base developed under the ASALM program was used in the development of SLAT (Fig. 25) to provide aerial targets in support of test, evaluation, and training of shipboard defense systems. SLAT employed a supersonic single-duct chin inlet IRR configuration derived from the ASALM–PTV. Eight flight tests were conducted, but the program was canceled due to problems encountered in the flight tests, which were found to be unrelated to the propulsion. Development of this propulsion system is an example of successful transition of technology between programs. The successful ramjet engine and its development framework can be used for future systems. After the cancellation of the earlier BQM-90 and BQM-111 Firebrand programs, SLAT was the Navy's third attempt to develop a dedicated high-speed antiship missile threat simulator. A current effort in this area is the GQM-163 SSST.

The United States began developing VFDR technology in the 1980s. The VFDR missile (Fig. 26) concept was successfully developed from 1987 to 1997. The development, aimed at an advanced medium range air-to-air missile (AMRAAM) application, successfully took the design to the point of being ready for flight testing. The VFDR program included the following achievements: development

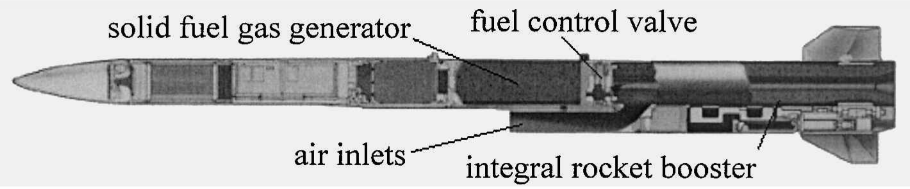


Fig. 26 U.S. VFDR component-tested missile (1987–1997).

of an integrated propulsion system, flight-weight hardware and thermal/structural design, nozzles booster that demonstrated 103% of design requirements in static firings for temperature cycling from −65 to 145°F, a flight-type gas generator and throttle valve assembly demonstrated in environmental tests, and sustainer combustion performance meeting or exceeding design requirements. More recently, an advanced design was tested in 2002 using a high-energy, reduced-smoke propellant in the two-inlet IRR configuration simulating conditions at Mach 3.25, 30,000 ft. The technology was not applied for various reasons until initiation of the U.S. Navy's SSST development in 2000.

In 1990, France initiated work on MARS, a ramjet-powered stealthy missile designed to be powered by an LFIRR and able to operate up to Mach 4. A model of MARS was displayed at the ILA 2000 Air Show, with component tests being conducted on the engine technology, air intakes, and general missile aerodynamic configuration by 2002.[49] The last report suggested additional funding was necessary for development to continue.

In the mid-1980s, India began indigenous development of a medium range SAM, the AKASH missile. Planned as a replacement for the SA-6 now in service, AKASH's design is based in large part on the SA-6 DRIRR configuration. Development was repeatedly delayed with flight tests finally being initiated in late 1990. Flight testing continues today with tests reported in 2000, 2001, and 2002.[50] Production to date appears to be on a very limited scale. India is currently assessing full production against the evaluation of other SAM systems available on the world market for comparable requirements.[51]

In the early 1990s, in the People's Republic of China, development began of the CSS-C-6 Sawhorse, a large, shore-based, antiship missile. It resembles a scaled-up C-101 CSS-C-5 Saples, but has a thicker fuselage. Although first seen in a Beijing display in November 1988, the IOC is unknown.[52] Export versions are designated the C-301. The missile employs four, tandem solid propellant boosters located above and below each LFRJ sustainer engine. The two ramjets are mounted on narrow pylons extending from the sides of the fuselage. A butterfly vertical tail stabilizes the missile, and each booster has its own single, angled stabilizer. Whereas it exhibits twice the range of the smaller C-101, the C-301 cruises at Mach 2 with adjustable cruising altitudes. Although the missile is available for export, it is not believed to be in full operational Chinese service.

Whereas the development of the Russian AS-17, Kh-31 Krypton (Fig. 27) began in the late 1970s, it was not until 1994 that it was deployed using LFIRR technology in an antiradiation missile configuration. It is in service today, with an upgraded air-launched version, the AS-17A/Kh-31P, and was revealed during a recent air show.[53] Although the upgraded AS-17 is not yet available for export, such opportunities are being actively pursued.

The Kh-31 made news in the mid-1990s, primarily due to its use as a missile target for the U.S. Navy. The Boeing Company imported airframes from Russia and modified them for use as MA-31 aerial targets. The first flight of an MA-31 occurred in mid-1996 with additional target vehicles under contract in 1999. However, Russian export restrictions imposed in 2001 made further deliveries uncertain.

The People's Republic of China and Russia are reportedly[54] jointly developing the KR-1 antiradiation missile, based on the Kh-31P. China and Russia are cooperating on the development, with initial missile deliveries having occurred in 1997.

In the early 1990s, South Africa began development of a DRIRR missile, LRAAM, with Israeli assistance.[46] Five preprototype flight tests had been conducted through 1995 on a four-inlet, nozzleless booster, magnesium-based, fixed-flow (no throttling) DR configuration. Today, the design seems to have evolved toward a two-inlet, throttleable hydrocarbon fuel design, which is viewed as a Darter air-to-air missile (AAM) variant. An estimated IOC is 2005.

Fig. 27 Russian AS-17 RJ operational missile (1994–today).

The U.S. Navy initiated development of a Mach 4 low-drag ramjet/low-cost missile system (LDRJ/LCMS) Fasthawk in 1995 with the expectation of flight testing in 1999. The system exhibited a forward concentric supersonic inlet and an LFRJ with a droppable solid propellant booster. Development demonstrated stable high efficiency in a short L/D combustor, a low-drag, roll control concept, and an efficient axisymmetric inlet design. Funding for the program was terminated in late 1998 despite showing good technical progress and demonstrating advances in structural design, control, and propulsion. Preparations for a flight-test demonstration were subsequently made in 1999, but the system has yet to be flown.

In the mid-1990s Russia began development to incorporate ramjet propulsion into the AA-X-12 RVV-AE-PD, an improved long-range version of the medium range beyond-visual-range AAM the AA-12 Adder (Fig. 28). There were 5 firings reported in 1995[55] and 10 ground tests reported in 1999,[56] with flight tests due to begin shortly thereafter. Reports[57] in 2001 suggested the baseline inlet configuration selected was a four-intake design; however, other options were still being considered, and projected fuel consumption was still higher than desired. A solid fuel DR engine is being used with automatic ram pressure controlled throttling. This seems to support the design advantages of an all-solids approach to this class of tactical missiles. This missile is the primary threat driving the U.K. BVRAAM missile requirement. An operational time frame of 2005 is projected.

Israel began development of solid propellant surface-to-surface guided missiles in 1960.[58] When the Gabriel entered service a decade later, they were the first Western designed-to-purpose antiship missiles to become operational. Development of a ramjet-propelled Gabriel IV, which began in the early 1990s, is a larger missile with greater range than earlier variants. Development is believed to be in component testing, but has stalled since the mid-1990s. The propulsion includes an integral solid propellant booster and an air-turboramjet sustainer engine. The Taiwanese SSM Hsiung Feng III, with an expected IOC of 2004, is a derivative of the Gabriel IV.

In the early-to-mid-1990s after a comprehensive study of the new medium-range AAM (MRAAM) threat capabilities, the United

Fig. 28 Russian AA-X-12 Adder RVV-AE-PD flight-tested missile (1995–today).

Kingdom, Sweden, and Germany, acting both individually and in cooperation, were evaluating all-solids ramjet propulsion for a new future MRAAM FRAAM.[46] The requirements established for these new missiles were very similar, prompting their consolidation for many reasons. Four missile configurations were in competition for satisfying these requirements to provide a capability for the new Eurofighter: the French MICA/RJ, the German A3M, the U.K./Sweden S225XR and the U.S. VFDR. This activity has evolved into the current development of the Meteor/BVRAAM. Germany is developing the propulsion system for the BVRAAM/Meteor, which employs a VFDR engine design likely derived from an earlier U.S./German cooperative development program conducted in 1989–1999.

France has been developing IRR technology since 1996 in support of the requirements for the ANF supersonic antiship missile and will now be used to power the ASMP-A. A missile design capable of operating at Mach 4–6 is expected to be available in 2006. Full-scale freejet tests at ramjet speeds of Mach 3 have been accomplished. France is using VESTA flight-test vehicles to demonstrate DR and LFIRR ramjet technology that could be applicable to a number of programs. Three VESTA flight tests of the propulsion system were conducted in 2002–2003. The first ground launches of ASMP-A are scheduled for 2004, with the first air launches in 2005–2006.[48] Flights of VESTA are also expected for trials of United Kingdom-led European ramjet technology development for the Meteor AAM.[49]

Germany began the development of ARMIGER missile in the mid-1990s to counter new antiaircraft defense systems currently in development. The missile is a Mach 3 IRR design using a boron-based solid-fueled DR (SFDR) sustainer and four midbody symmetrically positioned inlets. The missile has an asymmetric nose to accommodate the IRR seeker oriented at an angle relative to the flight direction to reduce friction heating that might confound the sensor. ARMIGER will use thrust controls, rather than control fins as a drag reduction measure. Whereas the missile is expected to enter service in 2008, technology advances are also expected to benefit the development of the Meteor missile.

While France has investigated both SFRJ and LFRJ technology, Matra BAe Dynamics Aerospatiale (MBDA) seems to emphasize development of the later technology, believing the liquid-fueled designs have greater inherent performance potential. Initiated in 1996, France is today pursuing development of a low-cost LFRJ Rascal concept. The design uses high-pressure nitrogen to force fuel directly into the combustion chamber and computer-controlled on/off injectors to control fuel flow. Component tests of this design were accomplished at Mach 2–2.5 at low altitude and Mach 3.2–3.7 at 64,000 ft.

Development of the Russian SS-N-26 Yakhont (Fig. 29), which began in 1998, was a significant step forward in terms of ramjet engine technology and threat to be countered. An engineering mockup was displayed at a recent air show of a land-attack derivative, Yakhont SS-NX-26 antiship cruise missile, with a reported extended range capability of 160 n mile for a total missile weight of 5,500 lbm. An IOC of 2003 is reported for the SS-N-26.

An Indian/Russian joint development of the PJ-10 Brahmos was initiated in 1998. The Mach 2.8 missile is a modified derivative of the Russian ramjet-powered SS-N-26 antiship missile. The propulsion system consists of an integral solid propellant booster and a liquid ramjet sustainer. Forward thrusters and aft jet vanes provide the initial control to turn the missile to the direction of the target, whereas an inertial navigation system controls the missile during the midcourse and the terminal phase through an active radar seeker, with special electronic counter measures. Brahmos first flight tested in mid-2001 and is in progress today. A full-scale mockup of the Brahmos supersonic cruise missile was on display at the Indian DefExpo 2002. A decision to begin commercial production of PJ-10 Brahmos was announced September 2002.[59] The missile was recently showcased at India's Republic Day celebrations in January 2003, and the first naval launch was conducted in February 2003. Flight testing is ongoing, with the last test focusing on evaluating the guidance and fire control conducted October 2003.

Fig. 29 Russian SS-N-26 operational missile (1998–today).

Fig. 30 U.K. BVRAAM Meteor component tested missile (1999–today).

The BVRAAM/Meteor (Fig. 30) is a new concept in air-to-air weapons that employs solid propellant booster, advanced VFDR sustainer motor technology, and the latest electronics to deliver the required combat performance. Meteor will have the capability to engage multiple targets simultaneously, at greater range than current medium range AAM and in all weathers, day or night. It will complement Eurofighter's advanced short-range AAM capability, and it also is being developed to operate from Rafale and (assuming Swedish participation) Gripen aircraft. Meteor will be developed under a collaborative program involving the United Kingdom (lead),

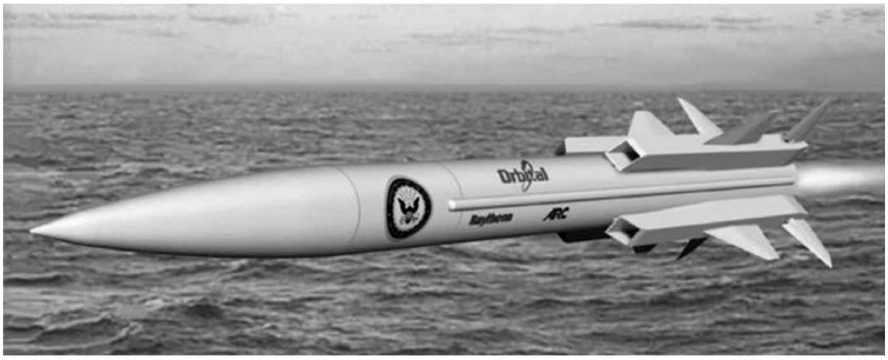


Fig. 31 U.S. SSST flight-tested missile (2002–today).

Germany, Italy, and Spain (the Eurofighter nations), France, and possibly Sweden. BVRAAM is designed to provide performance, particularly kinematic performance, several times that of existing MRAAMs.

There is no active radar guided AAM in service with the Royal Air Force. Sky Flash is a semi-active missile and requires the launch aircraft to illuminate the target throughout the time of flight of the missile, which makes it vulnerable to counterattack. BVRAAM will give Eurofighter the capability to engage multiple targets simultaneously, independent of parent aircraft maneuver, at greater range than AMRAAM and in all weathers, day or night. Following launch and in-flight target update, BVRAAM's active radar seeker takes control and autonomously searches for and locks onto the target.

Conventional rocket motor powered missiles rely on an initial boost phase to achieve the high speed required, followed by a coast phase to intercept the target. Latest generation, highly maneuverable aircraft are able to outrun conventional missiles at the extremes of their range. The VFDR airbreathing motor proposed for Meteor provides sustained power, following the initial boost, to chase and destroy the target. The missile's computer and the seeker, which provides the missile's ability to search, locate, and lock onto a target, will build on existing French technology, used in the Mica missile, to provide robust performance in the presence of electronic countermeasures.

The BVRAAM/Meteor missile design, offered by Matra BAE Dynamics and its consortium, was selected in May 2000 as most likely to meet U.K. needs over the life of the Eurofighter aircraft, beating out the Raytheon Systems, Ltd., led consortium.

PDE development activities in the United States have been pursued since the early 1990s. PDE missile system cost is predicted to be 30% of turbojet cost for a Mach 2.5 configuration with excellent fuel efficiency at high speed and to represent a potential 50% range increase at Mach 4. The PDE proof of concept was demonstrated in single-pulse tests in the early 1990s. Flight-scale multiple-cycle tests with multiple combustors and a rotary valve were tested in the late 1990s. Ongoing efforts are proceeding into subsequent development phases.

Ramjet Development: 2000–Today

This era witnesses the continuation of international efforts to push the edge of the high-speed performance envelope. Table 4 also summarizes ramjet evolution in the era from 2000 to today and provides originating country, engine/vehicle names, development dates, performance, physical characteristics, and state of development. Countries engaged in ramjet development expanded significantly to include Japan, India, Sweden, Israel, and South Africa during this era. Scramjet development activities in this era were generally focused in the United States, Russia, Germany, Japan, and Australia.

The U.S. Navy has supported SFRJ development activities for many years with the purpose of advancing the technology state of the art. Such activities gained continued support in 2000 for continued development for a long-range, reduced-cost Mach 5–6 air- and surface-launched missile design.

The People's Republic of China has displayed a model at several air shows of a ramjet-powered air-launched missile similar in configuration to the French ASMP missile. The designation Ying-Ji 12 suggests an antiship role similar to the French ANF missile.

Following the cancellation of the SLAT in 1991, the U.S. Navy had to continue the quest for a replacement for the aging Vandal targets in the role of antiship cruise missile threat simulator. In the late 1990s, the Navy evaluated the MA-31/AS-17 as an interim target. However, the MA-31 was not selected for large-scale production, and a new SSST missile (Fig. 31) was procured instead. Development began in 2000 on the GQM-163A Coyote nonrecoverable vehicle. The SSST is ground launched with a tandem Mk-70 solid propellant booster and uses an Aerojet (formerly Atlantic Research Corporation) MARC-R-282 VFDR ramjet sustainer that can reach speeds up to Mach 2.5 at sea level. Development testing was ongoing in 2003 with the vehicle successfully flighttested. Current plans call for production of six flight-test vehicles. If the tests are successful, up to 90 production targets may be ordered with an initial operational capability planned for mid-2004.[60]

The U.S. Navy initiated generic supersonic cruise missile (GSSCM) in 2002 as advanced cruise missile development for potential use in high-speed Tomahawk, high-speed strike or antiradiation applications. Low-drag LFIRR engine technology was proposed for the Mach 4–5 air- and surface-launched missile.

The U.S. Navy is presently developing a propulsion system that will enhance the capabilities of an evolving antiradiation missile (ARM) system. The U.S. Navy initiated a four-year HSAD Project in late 2002 to address time-critical target requirements. The HSAD Project is directed toward increasing the range and average velocity of an advanced version of the HARM system, the higher speed ARM system. Based on the results of industry and government conceptual propulsion studies and a DOD ARM roadmap, the United States selected an IRR, VFDR propulsion system with tail-controlled steering. Three modified HARMs are to be built for captive carry and two air-launches from an F/A-18C/D in a technology demonstration. A formal three-year development program could start in 2006.[47,61]

Scramjet Development 1955–Today

Scramjet Development: 1955–1990

This era witnessed the beginning of scramjet development, with early combustion testing of ejector ramjets being initiated in the late 1950s. Table 5 summarizes scramjet evolution in the era from 1955 to 1990 and provides originating country, engine/vehicle names, development dates, performance, physical characteristics, and state of development. Significant developments in rocket boost and airbreathing propulsion systems that have occurred from midcentury onward greatly influenced the debate over hypersonic vehicle options and missions. The turbojet first flew in 1939, the ramjet in 1940, the high-performance large liquid-fueled rocket engine in 1943, and the practical man-rated reusable throttleable rocket engine in 1960. These dates serve as general milestones for numerous other developments, including supersonic afterburning turbojets, turboramjets, rocket- and turbine-based combined cycle engines, and scramjets.

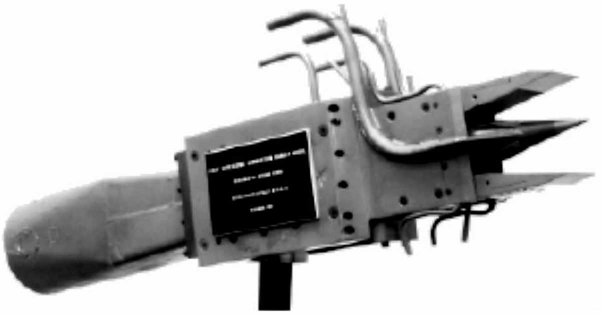


Fig. 32 First known freejet-tested scramjet in United States by Ferri (1963).

Fig. 33 U.S. hypersonic research engine AIM (1966–1974).

Other than the rocket, the ramjet has had the most direct effect on hypersonic design thinking. Ramjet technology matured rapidly following WWII. The emergence of scramjet propulsion cycle, successful ground-test demonstrations of liquid air collection under the U.S. Air Force Spaceplane program in the early 1960s, and the refinement of the airframe-integrated scramjet concept, all sparked great interest in scramjet propulsion for a wide range of hypersonic applications, interest which continues to the present day.

The first known scramjet, fabricated and free-jet-tested, was a fixed-geometry engine model designed by A. Ferri (Fig. 32) in 1960. Freejet tests of the complete engine were first performed in the GASL combustion-heated high-enthalpy blowdown tunnel in 1963. These tests, integrated with aerodynamic tests, demonstrated that scramjets could be a viable propulsion system for hypersonic vehicles.

The most extensive of the early (first generation) scramjet development programs in the United States was the NASA HRE program.[62] The HRE program, started in 1964, was crafted to develop and demonstrate scramjet technology. This program developed a flight-weight, variable-geometry, hydrogen-fueled and cooled scramjet engine designed to operate from Mach 4 to 7 and to be flight tested on the rocket-powered X-15A-2. The program progressed through component tests (inlet, combustor, and nozzle), flowpath tests, and flight-weight engine development and tests over a seven-year period. Following cancellation of the X-15 program in 1968, two axisymmetric engine models, the water-cooled structural assembly model (SAM) and the visually similar hydrogen-cooled aerothermodynamic integration model (AIM) (Fig. 33), were constructed and tested from 1971 to 1974. The two engines were tested to separately validate the flowpath operability and performance (AIM) and structural concepts (SAM). Flight-weight hardware was identified and developed to provide a complete scramjet engine system. During the HRE program, a total of 107 tests were performed on the two HRE dual-mode scramjet engines, establishing an impressive and comprehensive database on inlet and combustor performance at Mach 5–7.

France launched the ESOPE program in 1966, inspired at least in part by NASA's HRE activity. The ESOPE effort was to demonstrate a dual-mode scramjet in a flight-test program at Mach 7. However, activities were ultimately limited to ground testing in two test series held between 1970 and 1972. Both the U.S. HRE and French ESOPE scramjet activities were terminated in favor of the development of the IRR engine in support of missile applications.

During the 1960s, as the propulsion needs of a new generation of high-speed aircraft and reusable space transportation systems were addressed, integrating the rocket and the ramjet would now favor a specially designed integrated liquid-propellant rocket subsystem, an RBCC propulsion system. Improved performance benefits of rocket air-augmentation were attained by installing this rocket directly into the engine airflow path. Thrust and specific impulse for an ejector ramjet (ERJ) were approximately 15% higher than an equivalent rocket, rising to twice rocket levels at ramjet takeover conditions. The early Marquardt ERJ engine is a precursor of today's RBCC family of engines. Although this class of combined cycle propulsion has yet to achieve flight-test status, extensive component testing has been conducted simulating a wide range of Mach number and altitude conditions. ERJ combustion testing in the 1960s includes 16-in. gaseous hydrogen/air-fueled and 18-in. hydrogen/oxygen and JP4/hydrogen-peroxide-fueled configurations. Whereas hydrogen was preferred for space launch and hypersonic aircraft applications, conventional JP fuel with noncryogenic oxidizer was specified for conventional aircraft and missile applications. A fourth engine in this series, developed in 1968, used a fan-supercharged version of the EJR configuration called the supercharged ERJ (SERJ). This engine was designed to power a Mach 4.5 high-performance aircraft and provide low fuel consumption at subsonic flight conditions. The supercharging fan was simulated in the inlet by direct-connect airflow control. By mid-1968, SERJ was tested over a range of simulated ramjet flight conditions up to Mach 3. Full-scale SERJ flight testing was proposed with a reengine of the rocket-powered X-15. The X-15 program was concluded in 1975, and these tests were never conducted.

The U.S. Navy support of hypersonic propulsion began in the mid-1950s at JHU/APL in the form of the ERJ program. 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. The first-ever demonstration was subsequently conducted in 1958 of net positive thrust on a double wedge in a Mach 5 airstream. Following this early success, it was understood that much higher thrust and/or fuel specific impulse could be achieved. Two approaches were conceived by putting a cowl aft of the wedge or by ducting the flow through internal channels, much like other lower speed airbreathing cycles. However, unlike other cycles, the ducted scramjet also had to overcome many issues associated with hypersonic-speed flight, such as higher materials temperatures and heating rates, surface skin friction, and fuel ignition and kinetics. This work led to a follow on JHU/APL supersonic combustion ramjet missile (SCRAM) program.

The U.S. Navy initiated SCRAM in 1961 to develop and demonstrate the technology necessary to prepare for the flight of an internally ducted scramjet-powered missile. Early studies showed that an internally ducted scramjet-powered missile could achieve powered ranges of several hundred miles when flying at Mach 8 at high altitude. The SCRAM and its components underwent considerable development work from the early 1960s to its termination in 1977. A large number of inlets, isolators, fuel injectors, liquid and gaseous fuels, ignition aids, and combustors were tested between Mach 3 and 8. A 10-in. diam by 60-in. long three-module SCRAM freejet engine was tested in the 1968–1974 time frame from Mach 5.2 to 7.1 using liquid borane or mixtures of liquid hydrocarbon/borane fuels. Although the SCRAM program successfully demonstrated the technology necessary to proceed into flight testing, it had three unacceptable shortcomings: 1) logistically unsuitable pyrophoric and toxic liquid fuels and blends, 2) absence of sufficient room to house an active rf seeker, and 3) passive cooling requirements for the entire vehicle.

The U.S. JHU/APL devised the DCR as a successor to the SCRAM concept. Accordingly, the U.S. Navy initiated development of the Mach 4-6 hypersonic wide-area defense missile (HyWADM) or (WADM) in 1977 employing a DCR propulsion system with six forward fixed-geometry inlets, dual-feed subsonic gas generator combustion and four-feed subsonic/supersonic combustion. Engine component testing was conducted up to 1986, when funding for HyWADM was discontinued. DCR engine technology testing has continued intermittently since, with more activity resumed under the affordable rapid response missile demonstrator (ARRMD) and HyFly programs.

In the mid-1980s, the U.S. NASP Program was formulated, with the objective of developing a SSTO "hypersonic combined-cycle airbreathing capable"[31] engine to propel a research vehicle, the X-30. The NASP program promise of flying a single-stage vehicle, powered by a combined cycle engine, which utilized scramjet operation to Mach 25 was aggressive, considering the state of the technology in 1986. Neither scramjet engines nor flowpaths had been tested above Mach 7. In addition, no credible, detailed analysis of scramjet performance, operability, loads, or structural approaches had ever been performed for flight past Mach 7. Also, what was good enough for Mach 7 vehicle operation was not refined enough for the low-thrust margin (energy from combustion vis-à-vis air kinetic energy) at double-digit flight Mach numbers. In other words, second generation scramjet technology was a good starting point, but considerable refinement and development were needed.

Many significant contributions from the NASP program include hypervelocity scramjets, propulsion airframe integration methods/databases, capable structures, high-fidelity databases and design methods, and advancement of CFD methods. Extensive test programs were carried out for four basic scramjet engine concepts, providing comprehensive component and engine flowpath module databases for Mach numbers between 3 and 8. Large-scale flowpath testing up to Mach 12–14 was conducted but in pulse facilities with very short flow times. NASA LaRC performed over 1500 scramjet flowpath module tests to support the various contractor designs. Significant advancements were made in technology for hypervelocity scramjet design, design methods, test methodology (facilities and instrumentation), and database. However, scramjet technology for space access remained at least one generation behind scramjet technology for missiles, due primarily to the requirement for testing at such high Mach number. Additional discussion of NASP developments is beyond the scope of this paper.

The Germans began development of Sänger II in the late 1980s as a proposed TSTO concept vehicle. It employed an airbreathing hypersonic first stage and delta wing second stage. The German Hypersonics Program and its Sänger II reference vehicle received most of the domestic funding for spaceplane development in the late 1980s and early 1990s. Sänger II comprised a large hypersonic booster aircraft capable of Mach 4 cruise plus a small rocket-powered upper stage (HORUS) that could deliver people and cargo to low Earth orbit. The booster aircraft (to be powered by turboramjets) was designed for maximum commonality with a supersonic passenger transport (with a cruise range of 6000 n mile). Development would have been very costly and the program was canceled in 1994.

Scramjet Development: 1990–2000

Scramjet development came of age during this era, with the understanding of the technology that will soon enable scramjet-powered flight for the first time. Scramjet development in the 1990s initially focused on relatively near-term missile propulsion systems. Because of the basic difficulty of igniting and burning hydrocarbon fuels, missile designs employed methods to prepare the fuel or alternatively added highly energetic fuels or oxidizers for effective combustion. Several combustor designs have been investigated using various piloting techniques. The importance of active cooling for the hydrocarbon class of scramjet engines has been realized, as well as the value of using endothermic fuels. Scramjet development for space access continues to pickup momentum. Although axisymmetric engines were tested, the modular two-dimensional airframe-integrated supersonic combustion ramjet (SCRJ) engine emerged as the candidate of choice. This configuration permits development in reasonable-size ground facilities and requires a relatively modest flight-test vehicle for a single module testing. We have come to accept the airframe-integrated lifting body as the standard vehicle configuration. In 1997, Billig[63] observed it prudent to examine the possibility of radical changes in engine flowpath and in turn overall vehicle configuration to produce a more effective vehicle. Some developments are exploring flowpath variations. Whereas the SCRJ is the key to airbreathing hypersonic flight, it is unlikely to provide efficient propulsion all of the way to orbital speeds. This era has witnessed the beginning development of combinations with mixed cycle engine designs. The hydrogen-fueled SCRJ will offer acceptable performance to Mach 15. Hydrocarbon-fueled scramjet systems are being continued in exploration of propulsion technologies to speeds of Mach 8. Table 6 summarizes scramjet evolution in the era from 1990 to 2000 and provides originating country, engine/vehicle, development dates, performance, physical characteristics, and state of development. International scramjet development activities expanded dramatically during this era.

Japan has pursued development of combined cycle engine technology since the late 1980s and early 1990s for flyback booster TSTO applications. ATREX is one element of the combined cycle airbreathing propulsion system being developed that is designed to give effective thrust to a spaceplane from sea level to altitude of approximately 100,000 ft with a flight Mach number of 6 (Ref. 64). ATREX is a fan-boosted ramjet working on the expander cycle with three heat exchangers of hydrogen fuel, a precooler, an internal heat exchanger, and a regeneratively cooled combustor. The engine employs a tip turbine configuration that features compactness, light weight, and a variable-geometry inlet and plug nozzle, which allows operation under a wide range of flight conditions. Sea level static testing has been conducted since 1990 on ATREX-500, scaled down hardware with a fan inlet of 12-in. diameter and length of 87 in. Wind-tunnel testing has occurred since 1992 on an axisymmetric variable-geometry inlet, variable-geometry plug nozzles, and flying test bench hardware. Future flight testing of ATREX is planned.

Supersonic combustion ramjet research activities in Russia have been pursued since the late 1950s. These activities began to accelerate in the 1980s and 1990s. In 1991, a decision was made to use SAMs to flight test the hypersonic ramjets for the first time. Kholod (Fig. 34) was developed as a first generation dedicated hypersonic flying laboratory, derived from the SA-5 (S-200 family) SAM, due to its trajectory being congenial to the hypersonic flight-test requirements.[65] An HRE-type E-57 hydrogen-fueled engine was used, consisting of an axisymmetric three-shock inlet, a coaxial regeneratively cooled combustion chamber, and low-expansion annular nozzle. The E-57 engine, which had a 9-in. diam cowl, is designed to fly at Mach 3.5–6.5 between altitudes of 50,000 and 115,000 ft and remains attached to the booster rocket during the entire flight.[26,66,67] A total of seven testbed flights were performed, with four of these being cold-flow engine tests. These tests were not meant to demonstrate the viability of a specific engine applicable to a vehicle, but were intended to demonstrate in flight several technologies that were first developed in ground tests. These technologies included the following features: 1) dual-mode scramjet engine operation over a Mach number range of 3.5–6.5, including transition from subsonic combustion to supersonic combustion (mode transition); 2) fuel-cooled engine structures; and 3) active control of fuel distribution and flow rate as a function of flight condition, as well as measured engine structural temperatures to allow demonstration of the first two technologies. Russia conducted the first flight test (Mach 5.35) in late 1991 and two joint Russian–France launches in late 1992 and early 1995. The second test reportedly achieved supersonic combustion conditions at Mach 5.6. In the third test, the engine failed to operate.[68] In late 1994, the NASA initiated a cooperative project to explore the scramjet operating envelope from the ram–scram, dual-mode operation below Mach 6 to the full supersonic combustion mode at Mach 6.5. To accomplish this objective, the higher heating loads required redesign of the combustor, active cooling system, and modifications; meanwhile, the increase to Mach 6.5 required modifications to the SA-5 booster performance.

Fig. 34 Russian Kholod first generation HFL (1991–1998).

U.S. tests of the Russian proof-test engine were planned, but never conducted for facility/model safety reasons. NASA engineers analyzed the final 1998 flight-test results. Although reasonable agreement was noted between ground- and flight-test data,[32] reportedly some uncertainty existed whether in-flight supersonic combustion conditions were achieved. Although these flight tests did not fully accomplish their original goals, they were a good first step, which helped build confidence that more ambitious flight tests could be accomplished, and just as important, they provided the first comparison between ground test and flight of dual-mode scramjet combustor data. Although still available, it is unlikely that further flight tests will be conducted with Kholod because more capable second generation hypersonic flying laboratories have become available.

The Japanese National Aerospace Laboratory–KPL commenced design, fabrication, and testing of a side-wall compression-type scramjet engine in 1991 through 1994.[69] The flowpath design was based on the results of their research activities on the scramjet engine systems and components since the 1980s and had the objective of investigating component design and overall performance. A first generation hydrogen-fueled engine model E-1 was tested from 1994 to 1999 at Mach 4–6 conditions. The majority of testing was conducted on heat-sink hardware, with limited water-cooled and liquid hydrogen-cooled testing. Two new facilities were built to support these activities; a freejet-type hypersonic propulsion wind tunnel (RJTF1) and a free-piston high-enthalpy shock tunnel (HIEST2) from 1994 to 1999.

Design improvements were made, and a second generation E-2 engine was fabricated with testing beginning in early 2000 and continuing today. Design changes focused primarily on the attainment of positive net thrust and improvement in combustion performance at Mach 8 conditions. The majority of the testing was conducted on water-cooled hardware, with limited liquid hydrogen-cooled and heat-sink testing. The first successful firing tests at Mach 12 conditions were conducted in 2002–2003. A plan to conduct scramjet flight testing is now underway to confirm engine performance under real flight conditions. A future milestone is to design, fabricate, and test the combined cycle engine based on the scramjet test results.

French scramjet development activities reemerged in the late 1980s with PREPHA, a jointly funded government–industry–university program, and subsequently reinitiated in 1992. PREPHA was aimed at developing a knowledge base on hydrogen-fueled dual-mode ramjet technology for SSTO applications.[70] Generic wave-rider configurations were examined, which ultimately resulted in the design and test of CHAMIOS, a large-scale scramjet engine design that was ground tested at Mach 6.5. The hardware had a 77 in.^{2} (8 × 10 in.) entrance area and incorporated wall measurements and optical access.[71] Testing began in 1994 and continued through 1999, with further testing planned under other programs. Despite the potential of combined cycles for fully reusable space launchers, the PREPHA program ended in 1999. Follow-on developments were initiated to preserve the intellectual and material investment in the form of the WWR (1993–2003), JAPHAR (1997–2002) and Promethee (1999–2002) programs.[72]

Fig. 35 Russian GELA/Raduga operational flight test vehicle (1995–today).

The Russian Space Agency initiated comprehensive hypersonic research and development in the ORYOL (or OREL) program in 1993 to develop combined propulsion systems for advanced reusable space transportation, and includes SSTO and TSTO vehicle designs.[73] This program sought to focus over 40 years of experience in Russian research and development in supersonic combustion. Activities are continuing with the development of the Igla (shown subsequently) second generation hypersonic flying laboratory (HFL).

GELA or Raduga (Fig. 35) was conceived as a Russian prototype for a new generation of hypersonic cruise missiles. The GELA testbed represents a second-phase effort on development work conducted by Russia between 1980 and 1985 (Ref. 74). The first phase dealt with Mach 3 ramjet propulsion systems developed from 1973 to 1978, and ultimately used on the SS-N-22 and SA-6. A third phase of development seeks to build and test a Mach 6 missile, with a final phase seeking to achieve speeds up to Mach 8. The GELA missile was flight tested in 1994 from a Tu-22M (specially modified TU-95 Bear) bomber at supersonic speed and boosted by a liquid propellant rocket motor and reportedly reached Mach 4.5. This vehicle is designed to conduct hypersonic scramjet research at speeds up to Mach 6.3 and 295,000 ft. It has been successfully launched upwards of 500 times. The configuration shown in Fig. 35 is an expendable vehicle.

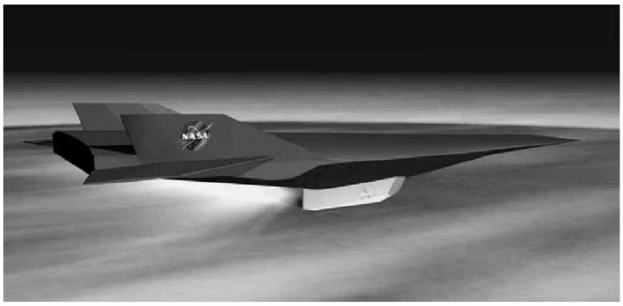
The U.S. Air Force has supported hypersonic engine technology activities since 1995 through the HyTech program. The fundamental objectives were to enable sustained hypersonic flight for missile or aircraft applications and to develop and demonstrate Mach 4–8 hydrocarbon-fueled, actively cooled scramjet engine technology through component direct-connect and freejet testing. The Hypersonic Technology Development HyTech/HySET program evaluated concepts proposed by four engine contractors. Each contractor developed hydrocarbon-fueled scramjet concepts and databases, of which two contractors were selected for the component demonstration in the first phase of the program. The Pratt and Whitney concept was selected to continue into the second phase under the HySET contract. This predominantly two-dimensional design heavily leveraged

20 years of hydrocarbon scramjet combustor development at UTRC. It also applied lessons learned from the hydrogen-fueled scramjet technology developed during NASP. The program is an applied research technology-based program to develop and demonstrate the structural durability and component performance of the inlet, isolator, combustor, and nozzle. Related technologies including inlets, composite leading edges, heat exchangers, and flameholding devices were all developed early in the program. These developments were followed by a full-scale performance demonstration of the engine design in a heavyweight uncooled copper engine. Integrated engine performance was demonstrated at Mach 4.5 and 6.5 conditions in freejet testing for this heavyweight copper engine, the performance test engine (PTE) under the HySET program.[75] The HyTech program has completed a major milestone in the successful testing of the world's first flight-weight, fuel-cooled hydrocarbon ground demonstration engine number #1 (GDE-1).[76] This testing took the components demonstrated in PTE and integrated them into an engine and then demonstrated the total engine performance and durability with uncooled inlet leading edges and fuel-cooled panels that form the engine walls. Testing was similarly conducted at Mach 4.5 and 6.5 conditions. A follow-on engine, GDE-2 is now being constructed for testing in 2004. An added feature of the GDE-2 is the variable-geometry inlet involving a pivoting inlet cowl flap. Technology from GDE-2 will flow into the NASA–U.S. Air Force X-43C and the DOD single engine demonstrator (SED).

The United States has supported hypersonic flight research through NASA's X-43A Hyper-X since 1995. The fundamental objectives have been to flight demonstrate the first integrated airframe-scramjet engine hypersonic vehicle and flight-validate key propulsion and related technologies. The program goal was to verify and demonstrate experimental, computational, and analytic design tools required for development of any hypersonic, airbreathing vehicle. Development focus was on an uncooled, hydrogen-fueled flowpath in support of hypersonic cruise aircraft and launch vehicles. Demonstration of critical technologies is planned in flight tests of the X-43A vehicle, two at Mach 7 and one at Mach 10. These vehicles are boosted to flight-test conditions using a modified Pegasus solid propellant booster, air-launched from a B-52 aircraft. Each vehicle is capable of about 10 s of powered flight. The program goal was to verify and demonstrate experimental techniques, computational methods, and analytical design tools required for the development of hypersonic, hydrogen-fueled, scramjet-powered aircraft. In addition, the program was to maximize the advancement of technology required for application of these engines to future aircraft and launch vehicles. The program included risk reduction and technology maturation tests of the Hyper-X scramjet in combustion, arc, and shock-heated facilities at Mach numbers of 7 and 10. Additional research tests conducted over the Mach 4–14 speed range characterized the Hyper-X engine concept over most of the scramjet operational range required for a launch vehicle. Over 800 tests (plus 700 post-NASP, non-Hyper-X tests) were conducted and data compared with both analysis and facility-to-facility. The final test/verification of the Mach 7 X-43A propulsion-airframe-integrated scramjet was accomplished using a full-scale powered model plus flight engine in the LaRC 8-ft high temperature tunnel (HTT).[77] This flowpath testing provided many firsts.[28] Vehicle design was accomplished using tools developed in the NASP program.

The first of the three X-43A flight-test vehicles was tested in June 2001 (Fig. 36). Unfortunately, the booster vehicle and the X-43A had to be destroyed before separation and scramjet takeover. A mishap investigation board found the flight failure was unrelated to the propulsion system, but occurred because the vehicle's control system was deficient in several analytical modeling areas, which overestimated the system's margins. The next flight is planned for early 2004, which would be 54 years since the first ramjet-powered aircraft flight of Leduc.

First conceived in 1993, the French government and industry are jointly funding a French–Russian program WRR, for reusable space launcher applications. The WRR prototype engine is a variable-geometry dual-mode ramjet that may involve either a rotating cowl (Promethée) or translating cowl (PIAF) inlet design. The vehicle is intended to fly at speeds from Mach 2 to 12, and uses kerosene fuel at the lower end of the speed range, then switches to hydrogen. Also of interest to this cooperative program is the study of integrating a detonation-based cycle and test methodology that allows examination of scale effects between small-scale flight testbed, 100-ft vehicle and full-scale space launcher.[71] The engine is a fuel-cooled design, which has involved testing of over 40 cooled-panel concepts to date. The cooperative program has faced some technological and budget problems, which produced delays, but strong interest exists for continuing the development. Subscale hardware (2 × 4 in. inlet entrance) testing at Mach 6 was conducted from 1995 to 1997.[78] Testing of small-scale hardware (2 × 8 in. variable-geometry entrance) designated PIAF was initiated in late 2002, with full-scale hardware testing to follow.[49] Concept demonstration ground testing of prototype hardware (CHAMIOS-sized 8 × 10 in. inlet entrance) at Mach 3–6.5 is planned in the near future. Subscale (2-ton vehicle with 2 × 16 in. inlet entrance) flight testing is expected to follow around 2010 to demonstrate operation at Mach 1.5–4 and 8–12. Prototype (30-ton vehicle with 80 × 10 in. inlet entrance) flight testing is envisioned in the 2020 at Mach 1.5–12. An operational full-scale ramjet 500-ton vehicle with 2 × 33 ft entrance is foreseen in 2030.



a) NASA hyper-X flight test.

b) B-52 with hyper-X release.

c) Ignition of Pegasus rocket booster.

Fig. 36 U.S. first flight of X-43-A, June 2001 (1995–today).

In the mid-1990s, Russia began openly discussing their development of AJAX, an innovative hypersonic vehicle concept. The concept fundamentally involves the capture of energy otherwise lost in flight at high Mach numbers and the recycling of this energy to increase the efficiency of the overall system.[79] The feasibility of the approach depends on developing the systems required to capture energy from the flow and efficiently recycle it. The design consists of three elements: an MHD generator, a plasma airflow management system, and an endothermic fuel heat regeneration process. The following list gives some of the AJAX technologies.

1) MHD generation of electrical power through deceleration of the inlet flow, with the power generated used to provide the inlet stream ionization necessary to enable the MHD interactions to occur and the excess power at high Mach numbers available for other uses including producing a nonequilibrium plasma around the vehicle.

2) Creation of a nonequilibrium cold plasma adjacent to the vehicle to reduce shock strength, drag, and heat transfer.

3) Steam reforming of the hydrocarbon fuel through chemical regeneration, utilizing the endothermic nature of the steam reforming process to cool the vehicle and its engines, while producing methane and ultimately hydrogen onboard the vehicle for use in the high-speed scramjet engine cycle.

The technologies associated with AJAX have been under investigation worldwide, and although there is much controversy regarding their effectiveness in modern hypersonic vehicles, it seems likely

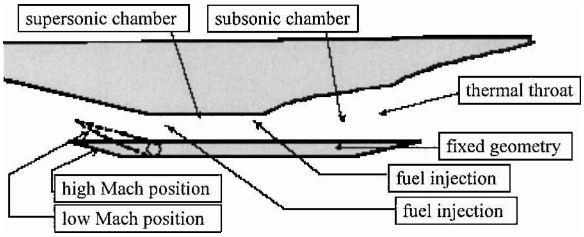


Fig. 37 France JAPHAR fixed dual-mode scramjet engine geometry (1997–2002).

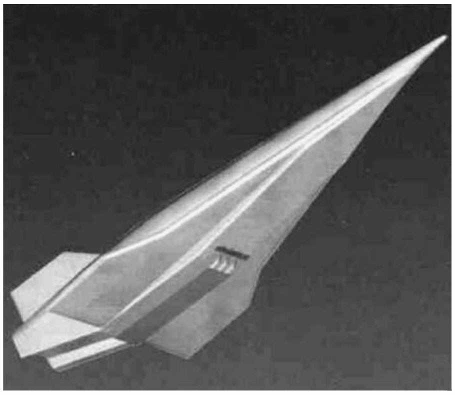


Fig. 38 Russian Igla second generation HFL (1999–today).

that one or more of the technologies may be incorporated in vehicles designed for Mach > 6 flight.

France began the development of JAPHAR in 1997 in cooperation with Germany as a follow-on to the PREPHA (French) and Sänger (German) programs to pursue hypersonic airbreathing propulsion research for reusable space launcher applications.[80] Studies were organized around a waverider concept vehicle with a flight Mach between 4 and 8. JAPHAR employs a fixed-geometry dual-mode scramjet engine design (Fig. 37) developed based on previous hydrogen-fueled PREPHA work. Basic objectives included improvement and validation of numerical codes for aerothermodynamics and defining a flight-test vehicle.[72] Component hardware (4 × 4 in. entrance) testing was conducted from 2000 to 2002 simulating flight Mach numbers of 4.9, 5.8, and 7.6. French–German cooperation formally ended in 2001.

In 1997, the DARPA initiated a program to develop ARRMD, as a low cost, air-launched Mach 4–8 missile. The program initially considered two hydrocarbon-fueled propulsion designs: the HyTech waverider two-dimensional engine and the axisymmetric DCR technology multiple-forward inlets. Both were potentially to make use of active cooling and a tandem solid propellant booster. The DCR engine was the design selected. Although the program was terminated in 2001 the DCR technology is being developed under the U.S. HyFly program, whereas the HyTech technology is being incorporated into the SED program.

One of the Russian second generation flying laboratories was developed under the Igla (Fig. 38) program.[65] The first flight test was conducted in mid-1999, and a dummy Igla airborne testbed was displayed at the Russian Moscow airshow (MAKS) 1999 air show. The waverider vehicle is designed to achieve Mach 5–14 at an altitude of 82,000–164,000 ft. The Igla is boosted to supersonic speeds by the Rokot system; on separation, the flying testbed is injected into an operational trajectory for the scramjet engine, and the test vehicle is recovered by parachute. The testbed employs regeneratively cooled scramjet engine modules previously tested in ground-based facilities. Funding will dictate the future of this activity.

The U.S. Navy has supported development of ATR technology under the Integrated High Performance Turbine Engine Technology (IHPTET) program for potential application to air-launched Mach 5 missiles since 1999. Engine development is focusing on the liquid air cycle engine turboramjet (ACETR) cycle with the purpose of reducing engine size and weight while maintaining theoretical performance. Although this engine cycle is immature and more complex when compared to alternative ramjet cycles, such an engine can provide increased loitering capability. Applications could include high-speed Tomahawk or other strike missile.

The United States is investigating turbine-based propulsion systems for access to space under the revolutionary turbine accelerator (RTA)/TBCC project as part of the Next Generation Launch Technologies (NGLT) activities.[81] Present turbine propulsion systems can propel vehicles to Mach 3. These current systems are costly, require high maintenance, and have low durability. Near-term development goals of RTA will concentrate on turbine accelerators that will reach at least Mach 4 and provide dramatic increases in maintainability and operability through the use of advanced technologies. Studies suggest that the use of turbine propulsion can provide the potential for aircraftlike, space flight operations that may significantly reduce launch costs and improve safety.[82] During the initial phase of RTA/TBCC, NASA GRC and general electric (GE) are designing a ground demonstrator engine for validation testing in fiscal year (FY) 2006. The demonstrator is a turbofan ramjet, designed to transition from an augmented turbofan to a ramjet that produces the thrust required to accelerate the NGLT vehicle to Mach 4+. The initial flight test vehicle RTA-1 will demonstrate the basic TBCC concept of using a conventional turbofan to accelerate an access-to-space vehicle to Mach 3 and then transition to a ramjet mode designed to boost the vehicle to Mach 4+. Included in the testing is demonstration of full-scale RTA enabling technologies along with reliability and durability of high-Mach turbine components, fuel, and control systems. In 2009, a second flight demonstrator RTA-2 will feature hardware at the scale of the vision propulsion system (VPS) product engine. RTA-2 combines the technology being developed in RTA-1 with advanced features from the DOD IHPTET and versatile affordable and advanced turbine engine (VAATE) programs and from NASA's ultra efficient engine technology (UEET) program to meet the VPS goals of thrust to weight ratio, specific fuel consumption, specific impulse, safety, and cost. Together, initial and potential final configurations for RTA-1 and RTA-2 are expected to provide a technology readiness level-6 confidence in the key technology features needed to achieve the goals of the VPS. The program is also designed to meet the aggressive safety, cost, maintainability, and performance goals for the third generation RLV concept established by NASA.[81]

The French Promethée project, initiated in 1999, was aimed at developing fully variable-geometry endothermic hydrocarbon fuel dual-mode ramjet technology for military applications. The design is a generic air-to-surface missile able to fly at speeds of Mach 2–8 and altitudes up to 130,000 ft. A full-scale combustion chamber was tested at simulated flight conditions of Mach 2–7.5. Under the original program, air-launched flight tests were planned at speeds of Mach 4, 6, and 8 between 2009–2012. The flight-test vehicle was to be nonrecoverable.[49] The Promethée project was started by France to acquire first-hand knowledge of hydrocarbon-fueled dual-mode ramjet technology for military applications.[72] The program includes system studies and definition of a generic vehicle, design and optimization of a combustion chamber, and ground demonstration leading to flight validation. The French technology development has now progressed from direct-connect testing under the Promethée program to semifreejet and freejet testing in support of a new flight-test program called LEA initiated in 2003 and expected to run to 2012.

India is conducting research and development activities for aerobic vehicle for advanced trans-atmospheric research (AVATAR), a reusable aerospace plane that is expected to be a 20-ton vehicle capable of 1000–2000 lbm payloads to low Earth orbit. A 3-ton subscale demonstrator vehicle AVATAR-M is under development.

Scramjet Development: 2000-Today

Scramjet technology developments are underway in many countries to capitalize on significant payoffs that hypersonic speed and long range can provide. Table 6 also summarizes ramjet evolution in the era from 2000 to today and provides originating country, engine/vehicle names, development dates, performance, physical characteristics, and state of development.

Australia[83] conducted, with international support, the world's first verified demonstration of supersonic combustion in a flight environment under the HyShot flight program. The demonstration results have received international endorsement for achieving supersonic combustion conditions. Two flight tests were conducted: one unsuccessful flight in late 2001 and a second successful flight in mid-2002, where supersonic combustion was observed. The model was a heat-sink copper scramjet configuration that retained the essential components of supersonic combustion, which consists of an intake and two combustion chambers. The thrust surfaces were removed for simplicity. Thus, strictly speaking, the model is not a scramjet and, hence, closely related to the gun-launched ram-accelerator work being pursued by many. The intake (4 in. width) is a simple wedge of 17-deg half angle followed by parallel combustion chambers (0.4×3 in.). Whereas the Kholod tests obtained dual-mode scramjet combustor data over a range of Mach number, the HyShot experiment obtained not only supersonic combustion data at a single Mach, but a wide range of dynamic pressures, which were compared to ground-test data obtained over the same range. The model was boosted into a highly parabolic trajectory by a two-stage Terrier-Orion Mk70 rocket. The spent motor and model payload fell back to Earth, gathering speed such that between 120,000 and 75,000 ft altitudes they were traveling at approximately Mach 7.6. The program demonstrated that 1) an understanding of supersonic combustion gained from shock-tunnel ground tests is sufficient to design a simple supersonic combustor that will operate in flight and 2) the test approach is a cost effective means to undertake hypersonic flight testing.

Among the second generation flying testbeds currently explored by Russia is the use of a MIG-31 interceptor as a launch aircraft for exploring conditions from Mach 2 to 10 (Ref. 65). Unlike the axisymmetric Kholod, the study of two-dimensional hypersonic engines are more easily integrated into the body of an aircraft. Use of this aircraft seeks to overcome the shortcomings common to existing ground-based experimental facilities, which cannot provide a full simulation of all of the conditions of complex engine exposure to aerodynamic and heat loadings at speeds of Mach 6–8. This variant of flying laboratory allows research at conditions of Mach 2–10, altitudes of 50,000–130,000 ft, dynamic pressures of 1.4–30 lbf/in.^{2}, and an operational time for the scramjet of 40 s. The recoverable scramjet test module is air launched using a modified SA-10 solid propellant booster up to Mach 10 conditions in a ballistic trajectory. Test history revealed at the 1999 Moscow Air Show indicated 100 min of direct-connect testing and 60 min of freejet testing.

The U.S. Navy and DARPA initiated the HyFly (Fig. 39) program in early 2002 to mature and demonstrate, in-flight, DCR scramjet propulsion technology to enable hypersonic long-range missiles.[84] This four-year demonstrator project evolved from existing Navy hypersonic efforts and from DARPA's ARRMD program. Direct-connect combustor testing begun in 2000 is continuing for Mach 3–6.5 and will continue for some time. Freejet tests at Mach 6–6.5 conditions were successfully completed in mid-2002 of the JP-10-fueled, uncooled DCR engine fully integrated into a flight-representative aeroshroud or missile body. Future development will include additional direct-connect and wind-tunnel ground tests of the full-scale flight-weight engine into 2004. Subscale ballistic flights of the engine mounted on a sounding rocket are in progress with Mach 4 and Mach 6 cruise flight tests anticipated in 2004 and 2005–2006, respectively. The Navy hypersonic propulsion developments are generally focused exclusively on missile applications, whereas the U.S. Air Force/NASA developments are aimed at both reusable platforms as well as one-time use vehicles.

NASA initiated the integrated system test of an airbreathing rocket (ISTAR) program in 2002 with the objective to flight test a self-powered vehicle to more than Mach 6 by the end of the decade, which would demonstrate all modes of RBCC engine operation. The engine employs a hydrocarbon-fueled liquid rocket system for initial acceleration, with a ramjet that ignites at about Mach 2.5, followed by conversion to scramjet operation around Mach 5. The engine will have the capability of accelerating to Mach 7. The strutjet RBCC engine design was selected for ground demonstration and subsequent flight testing. Ground testing of a flight-weight, fuel-cooled engine flowpath is scheduled to begin in 2006. The scramjet engine designs examined are expected to provide performance 15% above conventional rockets during the initial boost phases of the flight. Funding for the ISTAR flight test program was cancelled in late 2003, but ground testing is continuing.

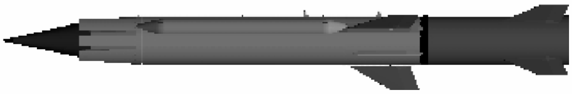


Fig. 39 U.S. HyFly flight demonstration vehicle (2002–today).

In 2002 the U.S. initiated X-43B as a follow-on development activity to X-43A Hyper-X. The program involves a flight demonstration of reusable RBCC or TBCC advanced vehicles in a notional 10-min flight in the Mach 0.7–7 range. The RBCC engine was expected to be a strutjet, hydrocarbon-fueled and cooled design. The TBCC engine is expected to trace it roots to the HyTech and RTA technology bases. In late 2003 NASA decided to focus upon the TBCC flowpath for the X-43B and has renamed the effort the reusable combined cycle flight demonstrator (RCCFD). Flight testing is planned for the 2010 time frame.

In 2003, France initiated LEA, a new flight-test demonstration of a high-speed dual-mode ramjet propelled vehicle (Fig. 40) at flight conditions of Mach 4–8. The program is planned to demonstrate the feasibility of a positive aeropropulsive balance.[85] It will allow definition and flight validation of ground development methodologies for predicting aeropropulsive balance and required design margins. The final propulsion system used may be a fixed geometry (JAPHAR) or variable geometry (Promethée or PIAF). It is not planned to alter the geometry in-flight if a variable geometry design is selected. The expected flight consists of an aircraft release, acceleration of the flight vehicle by a solid booster to the desired Mach number, booster separation, vehicle stabilization, and autonomous flight for 20–30 s. Six flights are planned between 2010 and 2012. Semifreejet and freejet inlet testing activities are currently ongoing in support of the planned flight-test program.[86,87]

The technology developed by the United States in the HyTech program will next flow into two newly funded flight-test programs, the NASA–U.S. Air Force X-43C flight demonstration begun in 1999 and the DOD SED begun in 2003. The SED (Fig. 41) program

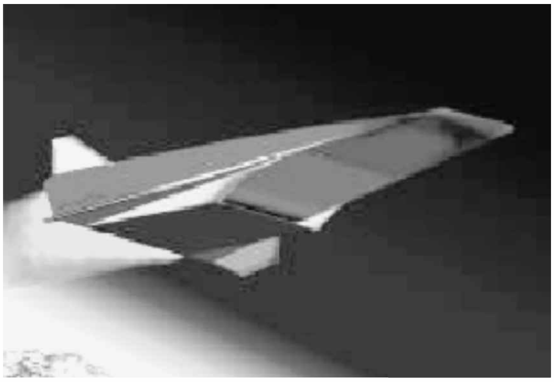


Fig. 40 France LEA concept flight test vehicle (2003–today).

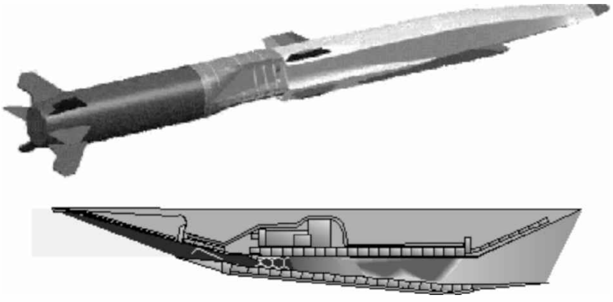


Fig. 41 U.S. endothermically fueled SED flight demonstrator (2003–2006).

will demonstrate the operation of the endothermically fueled scramjet engine in flight using a single flowpath and fixed-geometry, self-starting inlet. It is based on the use of the HyTech waverider two-dimensional engine configuration and features an army tactical missile system (ATACMS) solid propellant booster to accelerate the waverider test vehicle to a scramjet takeover Mach number of 4.5 with the scramjet engine further accelerating the vehicle to Mach 7. Five test flights are planned starting in 2005–2006 to precede the X-43C flight tests.

The most ambitious application of the U.S. HyTech technology is the joint NASA–U.S. Air Force X-43C program. This program seeks to develop waverider flight-test vehicles that will accelerate from Mach 5.5 to 7 using three flowpaths developed from the HyTech hydrocarbon-fueled scramjet engine. Each flight-weight fuel-cooled flowpath will feature the variable-geometry cowl flap of the GDE-2 engine. Like the X-43A, the X-43C will be air launched from a L-1011 and accelerated by a Pegasus solid propellant booster to Mach 7+. Ground testing will include single- and multi-module nose-to-tail propulsion airframe integration demonstrators and flight clearance engines. Three flight tests are scheduled, beginning in 2007.

General State of Ramjet, Scramjet, and Mixed Cycle Technology

Flight-Demonstrated Technology

The state of the flight-demonstrated ramjet technology base in 1980 was summarized by Thomas[87] and is shown here in Fig. 42. Fewer operational ramjet systems were known to have existed in the open literature. Those actually in existence included subsonic U.S. Navy drones, Bomarc, Talos, and D-21, the Bloodhound and Sea Dart in the United Kingdom, the SE 4400, VEGA, and CT-41 in France, the C-101 in the People's Republic of China, and the SA-4, SA-6, and SS-N-19 in Russia. Development activities were principally focused in the United States and Russia, with the French, Germans and Chinese beginning ramjet missile activities. Thomas noted that the major milestones of the period from 1960 to 1980 were the development of low-altitude short-range missile and the conception and demonstration of the IRR for missile applications.

The evolution of ramjet and scramjet technology from 1918 to today was reviewed in the preceding sections and summarized in Tables 2–6. An appreciation for the advances made may be obtained by reviewing Tables 2–6 and noting that the vast majority of the test database is seen to exist between Mach 3 and 8.

An interesting comparison may be made by superimposing the 1980 technology database shown in Fig. 43 and ramjet and scramjet system performance data provided in Tables 2–6 on the typical airbreathing flight envelope discussed earlier (Fig. 2). A direct comparison of the 1980 and 2003 ramjet technology bases is provided in Fig. 43. Worldwide development activities have advanced the demonstrated upper speed range considerably: Operational systems matured from Mach 3.5 to 4.5, prototype engines matured from Mach 4.5 to 7, advanced technology flight tests have matured from Mach 5.5 to 10, and ground-test feasibility testing has matured from Mach 8 to 10–18. The operational range of dynamic pressure has also correspondingly broadened. The state of the 2004 technology base, shown in Fig. 43, shows a dramatic expansion over the last 20 years.

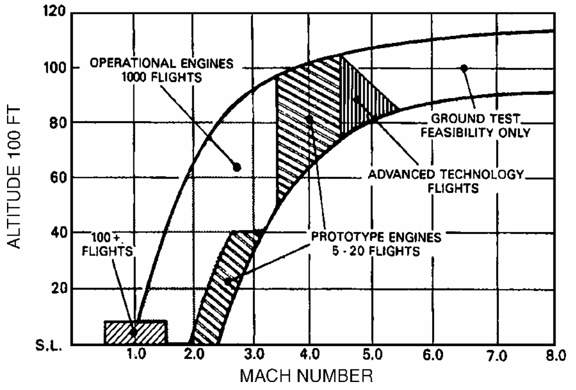


Fig. 42 State of flight-demonstrated ramjet technology base in 1980.

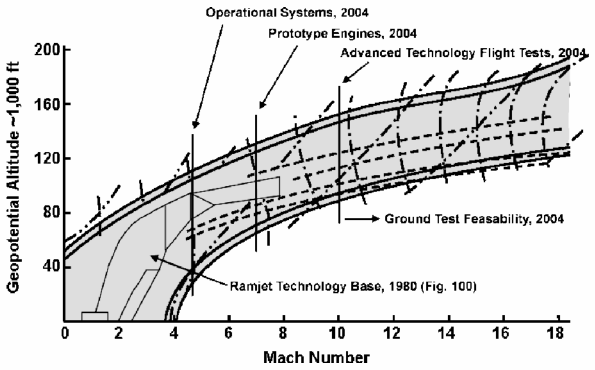


Fig. 43 Comparison of 1980 and 2004 flight-demonstrated ramjet technology bases.

Airbreathing engines and their supporting rocket technology for space access face the following potential issues, many of which also apply to military applications[89]: thrust limitations, especially around Mach = 1, demonstration of efficient engine operation over broad flight Mach number and altitude range, structural and propellant fractions for both airbreathing and rockets, logistics of fuel (H_2 vs kerosene), materials thermal environment, and engine design complexity.

Hypersonic airbreathing engines in combination with other engine cycles are the most promising for affordable access to space and high-speed cruise. High-temperature materials and efficient propulsion performance over a broad Mach number and altitude range are keys to successful development of these vehicles. A further examination of today's state of engine cycle maturity concludes this discussion.

Ramjet/Scramjet Engine Technology

As a result of research over the last 50 years, considerable advances have been made in airbreathing propulsion technology. Particularly significant is the state of flight testing at Mach > 7 that can be used to validate ground testing and the rapid advancements in liquid hydrocarbon scramjet engine technology. Although the X-43A is on the verge of demonstrating scramjet performance at Mach 7, currently only rocket propulsion has demonstrated flight performance at high Mach numbers beyond Mach > 6.

The maturity of ramjet/scramjet airbreathing propulsion technology resides at the actual system flight-test level at Mach 3, decreasing monotonically to system prototype at Mach 5, decreasing further to component test in a simulated flight environment at Mach 8–10 and continuing at this level out to approximately Mach 15. Newer airbreathing mixed engine cycles, such as RBCC and TBCC, are at the component test maturity at Mach < 7. Airframe development maturity follows slightly behind propulsion. Critical issues continue to be focused on airframe thermal performance, propulsion performance, overall flight efficiency, and development of flight-weight subsystems. It is now instructive to turn our attention to current research needs.

Summary

Advances in ramjet technology over the past century have been remarkable, involving dramatic advances in flight-demonstrated technologies. The road to discovery has not been without its distractions, which include world events as well as inconsistent support for the burgeoning technology by resident governments. Initial motivation began with the desire for propelling advanced aircraft, followed by missile technology, and now encouraged by the development of reusable Earth-to-orbit vehicles that employ airbreathing engines for at least a portion of, if not the entire, flight envelope. Since the turn of the century, the expansion of the operational envelope for ramjets has been dramatic and range from the beginning notions of flight to testing of engine designs that approach previously inconceivable speeds.

In 2004, we are approaching speed ranges entirely unheard of to the Wright brothers in 1903 or to Leduc, who in 1957 spoke of 600-mph limits for aircraft applications. Currently, sufficient knowledge exists to challenge the upper speed limits of pure ramjets ($M \sim 6$–8), dual-mode scramjets ($M \sim 14$), and pure or rocket-assisted scramjets ($M \sim 20$). Nevertheless, the greatest knowledge base exists in the Mach 3–7 flight range. Strides have been taken in recent years to expand this understanding to include the upper region to orbital speeds, as well as the lower region to static conditions. It cannot escape notice that since 1990 the international activity in ramjet and scramjet missile development has increased noticeably. Very strong international ramjet and scramjet capabilities are being created through many significant ongoing developments. Whereas propulsion approaches to future requirements continue to evolve, it appears that the combination of current programs has served to revive and reinvigorate a new generation of industrial and military capability.

Ramjet technology has matured to a high state of readiness for military applications. Greater standoff ranges and reduced time to target are consistently mentioned in conjunction with future missile requirements. Ramjet or scramjet solutions certainly provide the kinematic properties desired, but remaining factors such as affordability, payload integration, inlet packaging, and development risk all play important roles in a selection process. The attractive performance attributes of ramjet-powered missiles have been available for over 50 years; however, limited applications have come to being, at least within the United States Recent advances in integral booster design may help reduce many system-level concerns, and advances in targeting and information technology may create the need for the added range that ramjet propulsion can supply. Hybrid or mixed cycle ramjet technology is developing to support future supersonic and high-speed transport. Scramjet technology has matured considerably in the last 15 years and promises to open this new century of flight with the first flight of a scramjet-propelled vehicle with true potential for enabling space access. Still, substantial advances are required to support military and reusable launch vehicle applications. Advanced developments, such as PDE and MHD technologies, are progressing and show great promise for expanding the potential of high-speed airbreathing vehicles.

On a fundamental level, our understanding is maturing on turbulence and its effects at higher speeds, on wall shear and heat transfer, boundary-layer separation and reattachment, fuel injection and mixing, and chemical kinetics and combustion dynamics in an engine. CFD is becoming an increasingly important tool in understanding these fundamental processes, combined with an expanding database for validating physical and chemical models used. Strides have also been taken to expand the engineering design database on mixed cycle engine performance at low and high speeds to complement the extensive existing database in the Mach 3–7 range. Certainly, opportunities in research and development continue to exist and will do so well into this second century of ramjet history. To an aerospace engineer entering our field today, the outlook is bright and the future exciting. The authors are reminded of similar excitement surrounding the activity leading up to and culminating with the initial successful landing of NASA's Apollo 13 on the moon in 1969. The authors challenge the international community to maintain focus and resolve for a consistent effort to realize the promises for airbreathing flight into this new century as mankind continues to push back the frontiers of flight and seek a better understanding for our place in the universe.

It is apparent that airbreathing technology has matured to occupy an important place in the propulsion field. The authors have only touched the surface of the technology. Its future importance, although hopeful, cannot be foreseen based on past history. It is a truism that technology feeds on itself, that work in one area often is quickly applicable in an entirely different area. We can all contribute more effectively to using this process and explaining it to our communities and funding sources to justify its existence. We must be cautioned against the casual hindsight judgment of the idea whose time had come. More than once, participants were convinced wrongly that airbreathing's time had come, were tempted to assume that a favorite project or system's existence was inevitable, and found that this belief contributed to the failure of our own purposes. Ramjet and scramjet propulsion's time shall come only after solutions to challenging technical problems are resolved and the need is clear.

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