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Scramjet Engines: The First Forty Years

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A general review of the emergence and maturing of supersonic combustion ramjet (scramjet) engine technologies over the last 40 years is presented. The review is given in terms of the efforts completed or proceeding in the United States, Russia, France, Germany, Japan, Australia, and other countries. A brief account of the challenges of scramjet combustor development is given, and attention is directed toward other source references for more detailed accounts of technology evolution. Two emerging scramjet applications are identified, namely, hydrogen-fueled high-speed engines for access to space and hydrocarbon-fueled engines for hypersonic air-launched missiles.

Introduction

SOME 40 years ago, the hydrocarbon-fueled conventional ramjet engine (CRJ) was under continuing development for various high-speed missile applications. In the United States, the Lockheed X-7 reusable flight-test vehicle was validating ramjet engine performance in the Mach 3–4 regime. Internationally, the ramjet engine was well explored, and there was continuing interest in the performance of the CRJ at hypersonic flight speeds.

In the late 1950s, various papers[1,2] were published reviewing the history of CRJ development and projecting various design approaches to achieving increased flight speeds. Much of this early material was later to be captured in the proceedings of the Fourth AGARD Colloquium[3] held in Milan. There was, however, a considerable divergence of views on the practicability of extending the performance of conventional ramjet engines to speeds in excess of Mach 5.0 (for example, see the discussions of Mallinson[4] and Hawkins and Fox[5]).

Meanwhile, the feasibility of a supersonic-combustion ramjet engine was attracting attention. The possibility of adding heat directly to a supersonic stream, by means of a standing wave, had been proposed as early as 1946 by Roy.[6] Later, in 1959, Nicholls et al.[7] demonstrated stabilized detonation waves in supersonic hydrogen airstreams. Similar studies were also reported later by Gross and Chinitz.[8] Also, there were various investigations in this time period concerning heat addition to external flows around bodies to generate both lifting and propulsive forces. In September 1958, the First International Congress in the Aeronautical Sciences was held in Madrid. At that conference, Ferri briefly outlined some work in progress at the Brooklyn Polytechnic Institute and verified that steady combustion, without strong shocks, had been accomplished in a Mach 3.0 supersonic stream. This important news was reported in Ref. 9 and confirmed in Ref. 10; subsequently, Ferri was to emerge as the major leader in exploring scramjet technology in the United States.

Also in 1958, scramjet work was beginning at McGill University in Montreal. Swithenbank[11] reported some early work on inlets, fuel injection and combustion, and exhaust nozzles for supersonic combustion ramjet engines, focused on the high-speed range Mach 10–25.

The publication in September 1958 of a foundational analysis of scramjet engines, by Weber and MacKay,[12] served as a focus for the emerging interest in such engines. This analysis examined the relative performances of scramjet and CRJ engines (using hydrogen fuel) over the speed range Mach 4–7 and pointed out the potential superiority of the scramjet engine at speeds in excess of Mach 7.0. This analysis also clearly anticipated some of the major technical hurdles facing scramjet development including fuel injection and mixing without severe shock losses, combustor gasdynamic phenomena, wall cooling and frictional losses, and nozzle performance. Also discussed was the need for a diverging combustor shape to avoid the limitations of heat addition in constant area ducts due to thermal choking and the introduction of an integral method to account for the wall pressure forces on such divergent ducts. Quite clearly, the generic problems that needed to be addressed in scramjet research were outlined some 40 years ago.

In 1957, Avery and Dugger at the Applied Physics Laboratory of Johns Hopkins University initiated an analytical and experimental study of scramjet engines and their potential. Subsequently, in 1960, a well-documented study of the relative performances of kerosene-fueled CRJ and scramjet engines was published by Dugger.[13] Only the constant area combustor was examined. The conclusions of this work were similar to those of Weber and MacKay,[12] namely, that the performance of the scramjet engine would exceed that of the CRJ somewhere in the speed range Mach 6–8 and would be superior at higher speeds. Also in this latter paper the deleterious effect on engine performance of nonequilibrium flow in the nozzle of the CRJ was underscored. (Interestingly, the possibility that a detonation wave supersonic combustor might yield superior performance to a scramjet engine was also raised.)

Interest in the relative performances of the CRJ and scramjet did continue but, unfortunately, the lack of demonstrated scramjet component performance, on the one hand, and the lack of test data on hypersonic CRJ engines, on the other hand, prevented substantive comparisons. Subsequently, the thrust of high-speed engine work was concentrated on the scramjet engine; CRJ work was to lay dormant until interest was rekindled due to the development of the integral rocket–ramjet engine.

Today, the relative performances of the kerosene-fueled CRJ and scramjet in the Mach 5–8 region are again of key interest, as attention shifts to air-launched missiles operating at these higher speeds.

In a brief paper such as this, it is not possible to review, in detail, the key technological achievements and emerging efforts in various countries. Only a brief treatment of the most mature scramjet engine hardware is given and, in particular, those efforts that may proceed to flight test. Furthermore, only scramjet combustion technology work is discussed; this area still remains the key development challenge for the scramjet engine. Also, space does not permit any discussion of the various scramjet engine elements being developed by Aerojet and Rocketdyne under the NASA-sponsored Rocket Based Combined Cycle program[14] Several reviews of scramjet technology are currently available in the literature,[15–17] and more detailed articles have been published volume in the AIAA Progress in Astronautics and Aeronautics series in 2001.[18]

Scramjet Technology in the United States

The promising high-speed performance of the hydrogen-fueled scramjet engine and specifically its apparent potential for achieving near-orbital speeds, led to increasing attention on hypersonic cruise

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missions and, in particular, on the elegant, but elusive, single-stage-to-orbit (SSTO) aerospace plane concept. Of course, in the early 1960s, the increasing availability of funds for space-related studies, coupled with the sharp decline of resources for aeronautical research, was a key factor in focusing hydrogen-fueled scramjet work on SSTO concepts. In particular, the U.S. Air Force sponsored scramjet work was in direct support of an aerospace plane concept.

The leading figure in the development of hydrogen fueled scramjet engines in the United States in these early years was unquestionably Ferri. His technical direction and leadership of the talented teams at the Aerodynamics Laboratory of the Polytechnic Institute of Brooklyn (PIBAL) and at General Applied Science Laboratories (GASL) established a firm technology base for scramjet development. His early work at PIBAL and GASL[19] was directed to the supersonic diffusive combustion system. He elucidated the chemistry of the hydrogen–air system, analyzed the key turbulent mixing problems, and identified the critical problems of matching heat release to combustor shape to avoid strong shock generation. With these fundamentals established, Ferri investigated the problem of maximizing the performance of fixed geometry scramjet engines and, in particular, the development of an engine with good performance over a wide speed range. Ferri considered that such high-performance requirements could be met, provided that three-dimensional engine designs were used and coupled with wave compression effects produced by combustion; this latter effect was termed thermal compression. These techniques are described by Ferri and Fox,[20] and much later were reviewed by Ferri.[21] The validity of the performance gains claimed for the thermal compression approach was vigorously debated. However, one independent analysis by Billig[22] concluded that considerable performance gains were theoretically achievable at the lower flight Mach numbers, but pointed out the practical difficulties of tailoring the fuel injection process to produce the required regions of thermal compression. It is interesting to recall two engine programs executed by GASL in the 1960s. The first of these was the flight test engine concept developed under the U.S. Air Force funded Scramjet Incremental Flight Test Vehicle (IFTV) program, which was initiated in April 1965. The IFTV concept is shown in Fig. 1. Note that four hydrogen-fueled scramjet modules were located around the central vehicle body. The flight-test plan was to boost the vehicle to 5400 ft/s at 56,000-ft altitude and to demonstrate vehicle acceleration to at least 6000 ft/s. In the ground-test program to develop the scramjet modules, considerable problems and delays were encountered due to inlet–combustor interactions. The overall flight-test program was a tightly planned success-oriented effort and, in view of continuing technical difficulties, the program was canceled in August 1967. A nonpowered flight-test vehicle was, however, launched in January 1967.

The practicability of the modular scramjet design based on the three-dimensional thermal compression approach was unfortunately not demonstrated in flight test. A very interesting review of the development of one module for this IFTV vehicle is given by Peschke.[23] The IFTV program was canceled before the associated ground-test program of the scramjet module was completed. One might speculate on how the development of the scramjet engine may have evolved had this 1967 flight-test program been successful.

Another interesting engine concept was developed at GASL under U.S. Air Force sponsorship in 1964–1968. This engine was called the low-speed fixed geometry supersonic combustion ramjet. This was an engine designed to operate from Mach 3 to 12 without

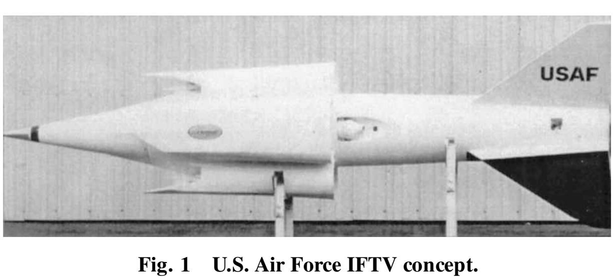

Fig. 1 U.S. Air Force IFTV concept.

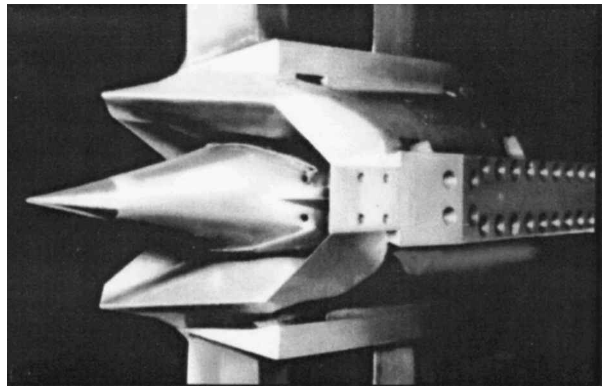

Fig. 2 Low-speed fixed geometry supersonic combustion ramjet.

variable geometry, but with an aerodynamic contraction ratio that varied with flight speed. This fixed geometry engine utilized the Ferri approach of a closely integrated inlet–combustor design, three-dimensional aerodynamics, tailored fuel injection, and thermal compression effects. Various inlet and engine models were tested under this program; the engine model shown in Fig. 2 was tested at a Mach number of 7.4. (Note that the current French/Russian program on a wide range scramjet is also aimed at operation over the speed range Mach 3–12. This engine concept, however, utilizes mechanically variable geometry).

In these various engine designs, the vision of Ferri in creating concepts that would tailor the aerothermodynamics of fuel injection, mixing, and combustion to the desired engineering features of the engine was apparent. The difficulties of engine design with the available computational tools of that time period, together with the twin challenges of assuring controlled heat release and avoiding internal flow separations, in a very demanding ground-test environment, made the timely achievement of such an ambitious undertaking very difficult indeed. Ferri inspired both United States and international research on scramjet engines. Tretjakov et al.[24] also noted that work in the former Soviet Union received impetus, following a meeting in 1966 between academician Struminsky and Ferri at New York University.

In addition to the engines devised at GASL, other scramjet engines were developed under U.S. Air Force sponsorship and successfully ground tested. These included a United Aircraft Research Laboratory variable geometry engine, a General Electric component integration model, and a Marquardt dual-mode engine. Short descriptions of the features of these engines are available in the literature.[25]

In addition to U.S. Air Force sponsored scramjet work, both NASA and the U.S. Navy funded significant engine programs. A major NASA effort was the Hypersonic Research Engine (HRE) program,[26] which began in 1964 and was aimed at flight testing a complete flightweight scramjet research engine on the X-15A-2 research airplane. Here again the opportunity to flight test an engine was lost when the X-15 program was terminated in 1968. Following this cancellation, emphasis shifted to ground test of two full-scale HRE models: a structural model known as the structures assembly model (SAM), which was tested in the NASA Langley Research Center 8-Foot High Temperature Tunnel, at Mach 7 conditions, and a model for demonstrating engine performance. This latter model, known as the Aerothermodynamic Integration Model (AIM), was ground tested at the NASA John H. Glenn Research Center at Lewis Field (Plum Brook) Hypersonic Test Facility at speeds corresponding to flight Mach numbers of 5, 6, and 7. These engine models were designed and fabricated by the AiResearch Manufacturing Company under the direction of Lopez. The HRE is shown in Fig. 3. The results of the HRE testing were impressive. A flightweight hydrogen-cooled structure was developed for the SAM engine, and this engine was tested from 1971 to 1972. Many lessons were learned on cooling circuit design and fabrication. The AIM, however, was a water-cooled, boilerplate engine design. At NASA John H. Glenn

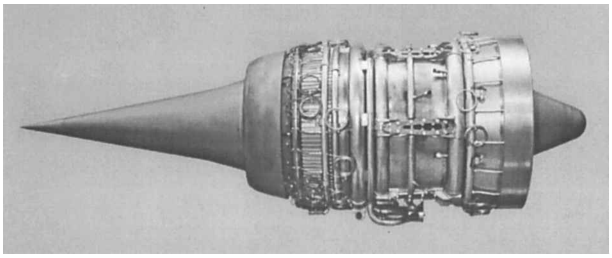

Fig. 3 NASA Hypersonic Research Engine.

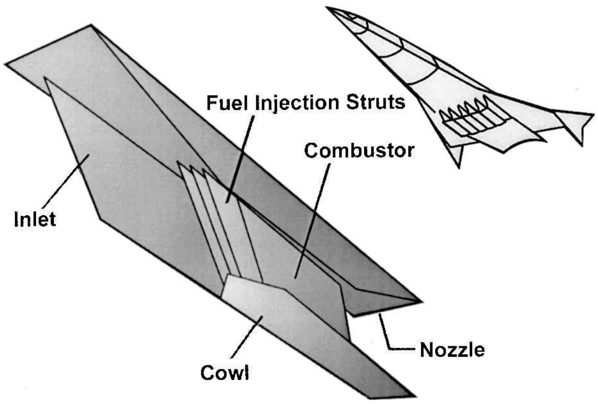

Fig. 4 NASA airframe-integrated engine configuration.

Research Center, the AIM engine checkout began in September 1972 with the first fuel-burning tests in October 1973. The program ended in April 1974 after a total of some 52 tests were completed (almost 2 h total running time). A comprehensive database on inlet and combustor performances was obtained in the Mach 5–7 range. It should also be noted that a two-dimensional combustor was built and tested (at North American, Rockwell) to aid in the development of the annular HRE combustor. This combustor rig gave early insight into the potential adverse effects of a diverging duct on combustor performance and stimulated much debate on the relative contributions of chemical kinetics and mixing to this loss in performance.

The AIM program was an impressive accomplishment in the mid-1970s demonstrating 1) high internal thrust performance, 2) smooth transition from a supersonic to subsonic mode of combustion, 3) strong interactions between fuel injector stages, and 4) combustor design approaches, fuel autoignition, and torch ignition. Overall, the AIM performance approached 70% of ideal performance and demonstrated the capability of the dual-mode engine over the Mach 5–7 speed range.

The axisymmetric configuration of the HRE has proven popular. The French ESOPE engine was a hydrogen-fueled, dual-mode axisymmetric engine also tested in the early 1970s, and several Russian engines have utilized this configuration.

In contrast to the axisymmetric HRE engine, NASA also focused on the rectangular airframe-integrated concept shown in Fig. 4. Note that in addition to the vertical forebody compression, the sidewalls of the inlet give additional horizontal compression. The in-stream struts are a key feature of this concept and provide a housing for distributed fuel injectors. Note also that provision is made for fuel to be injected, both normal and parallel to the stream in differing amounts; this approach permits some tailoring of the heat release in the diverging combustor. The early work on the integrated-airframe concept is well described by Henry and Anderson.[27] This engine configuration went through several generations of technology development aimed at improving the fixed geometry inlet and the swept strut injector, and verifying overall subscale engine performance.[28]

It was soon realized by the U.S. Air Force and NASA that a hypersonic research airplane was needed to flight demonstrate the hypersonic technologies emerging in the early 1970s. In December 1975, a Joint Steering Committee was established to plan an extended hypersonic technology base effort leading to a manned high-speed research vehicle capable of flight speeds of about Mach 8. This flying test bed was called the National Hypersonic Flight Research Facility and was intended to flight demonstrate many candidate hypersonic technologies and, in particular, engine–airframe integration. Had this project been pursued, it would have provided a significant hypersonic flight research facility. However, this effort did not come to fruition. An interesting and authoritative article on the need for a flying test bed was written in 1976 by Hearth and Preyss.[29] The later development of the airframe-integrated scramjet concept, and the corresponding technology base efforts at NASA Langley Research Center, are comprehensively described by Northam and Anderson.[30] Their work includes some 238 references. A further update on the work at NASA Langley Research Center is given in Ref. 31. The airframe-integrated engine configuration has also been studied extensively in Russia and Japan. In general, the related in-stream strut–fuel-injector technology has been the object of much research. Overall, this class of modular scramjet configuration has emerged as a preferred concept in recent years.

A distinctly different scramjet program, sponsored by the U.S. Navy, was carried out at the Johns Hopkins University Applied Physics Laboratory (JHU/APL) in 1962–1978. This program, known as the Supersonic Combustion Ramjet Missile (SCRAM) program, was oriented toward compact ship-launched missiles using storable reactive fuels such as the boranes and aluminum alkyls. The final configuration of the SCRAM weapon system is shown in Fig. 5; the use of a modular Busemann inlet design should be noted. The evolution of the program is well described by Billig.[32] Extensive tests were accomplished at JHU/APL on this engine configuration. Literally, several hundred tests were run using various injection techniques, combustor geometries, and reactive fuels such as HiCal-3-D and hydrocarbon–pentaborane blends. This test program was indeed a mother lode for scramjet technology and, in particular, for developing combustor–inlet isolators to prevent adverse flow interactions (for example, see the basic work by Billig et al.[33]). The SCRAM work also produced the classic modeling approach based on the Crocco power-law relationship, which was most successfully applied to modeling the scramjet combustion process including wall shear and heat transfer and for the overall optimization of scramjet engines, particularly dual-mode engines (for example, see Billig and Sullins[34]). Unfortunately, the use of reactive fuels was not ultimately acceptable to the operational customer, and work at JHU/APL was redirected to the dual-combustor ramjet (DCR) concept that can effectively utilize heavy hydrocarbon fuels.

Note that JHU/APL also performed work on supersonic combustors using hydrogen fuel, under NASA sponsorship. Two excellent sources describing the JHU/APL work are Refs. 35 and 36.

As already observed, the U.S. Air Force sponsored hydrogen-fueled scramjet work did not proceed into powered flight test, and such work was largely neglected until the initiation of the National Aerospace Plane program. Fortunately, some limited work on endothermic- and hydrocarbon-fueled scramjet engines did continue until the need emerged to concentrate resources solely on integral rocket ramjet systems.

The emergence of the National Aerospace Plane (NASP) program from Defense Advance Research Projects Agency (DARPA) sponsored SSTO studies in the 1984/1986 time period gave fresh impetus to U.S. scramjet development. The NASP program was a national multiagency, multidisciplinary effort aimed at developing the X-30 experimental SSTO vehicle. The most critical technology in the NASP program was the development of a hydrogen-fueled scramjet to operate over the wide speed range from about Mach 4 to Mach 15. The primary funded propulsion contractors, at first, were Pratt and Whitney and General Electric. Later, the two engine contractors became Pratt and Whitney and Rocketdyne.

A Joint Program Office (JPO) was established in 1986 to manage the NASP program and was located at Wright–Patterson Air Force Base. The subsequent history of the NASP program is well described by Chase and Tang.[37] In addition to directing the contracted efforts, the JPO managed a Technology Maturation Program (TMP) that was created to mature the essential technologies needed to develop

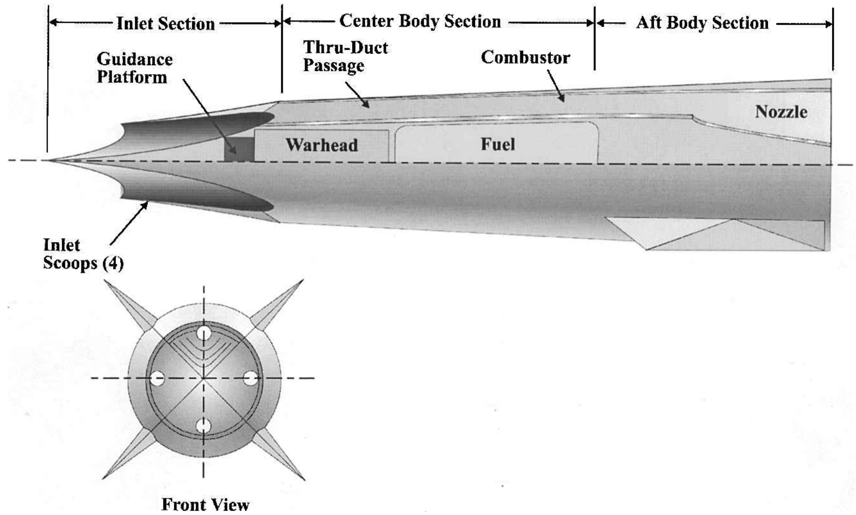

Fig. 5 SCRAM engine configuration.

a viable engine from the program baseline proposal. The development of this expanded technology base was principally performed at NASA Langley Research Center and other NASA centers, the JHU/APL, the U.S. Air Force Wright Laboratory, and the Naval Air Development Center.

In 1990, at the initiative of the NASP JPO, a consolidated NASP team was formed from the two engine contractors, the five airframe contractors, and the six federal laboratories participating in the program.

Also, a Government Work Package (GWP) program, which, together with the national contractor team, was aimed at completing the NASP technology development and preliminary design work replaced the TMP program. Details of these management structures are given by Waldman and Harsha.[38] It had been anticipated that a decision to build an X-30 experimental aircraft would be made in 1993; however, at that time, the program was examined with the object of reducing costs and technical risks. A series of hypersonic flight experiments was proposed under a program named HYFLITE. However, this program, in turn, was considered too expensive, and an alternate program, HySTP, was originated to provide scramjet data at high flight speeds. Unfortunately, funding for this program was not forthcoming, and the NASP program was terminated in January 1995. If the HySTP program had proceeded as planned, several flight tests might have occurred in fiscal years 1997/1999.

Both the NASP contracted and TMP/GWP programs generated an enormous amount of ramjet/scramjet engine research. Many of the details of this work remain classified, but a good indication of the overall scope and content of the engine test program is given by Voland and Rock.[39] The NASP configuration was a natural home for the class of rectangular airframe-integrated scramjets in development by NASA Langley Research Center. Fortunately, an extensive component technology base for this class of engine had been developed, and several modular engines had been tested, namely, a three-strut configuration, a parametric engine, which allowed for convenient variation of geometry and injector locations, and a step-strut design. Extensive testing had been performed in the Mach 4–7 regime. In addition, a novel two-dimensional reverse sweep inlet had been devised in which the leading edge of the central strut was swept in the opposite direction from the two sidewalls; this geometry offered an improved tradeoff between contraction ratio and mass capture.

During the NASP program, a large number of government and contractor experimental engines were tested at NASA Langley Research Center. These included a government baseline engine, a JHU/APL B-1 engine, several Rocketdyne engines, and a Pratt and Whitney engine (designated the C engine) as described in Table 2 of Ref. 39. Ultimately, two models of the definitive NASP-team engine, designated the E22A engine, were developed and tested during 1993/1994. The first model was a subscale parametric engine, SXPE, that was tested in three configurations at simulated Mach numbers from 5 to 8. Some 142 tests were run on the three configurations of this engine. The other engine model was a larger scale (30%) version of the E22A, named the Concept Demonstrator Engine (Fig. 6) which was tested at simulated Mach numbers of 6.3 and 7.0 (at 60% of flight dynamic pressure).

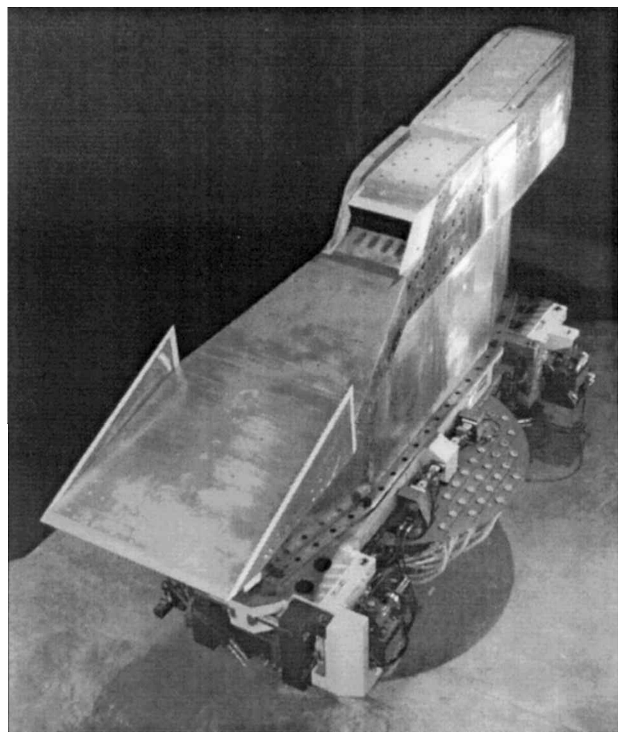

Fig. 6 NASP concept demonstration engine.

During and subsequent to the NASP program, NASA Langley Research Center maintained continuing emphasis on those hydrogen-fueled scramjet engines that have the potential and technological features for high performance at near-orbital speeds. The requirement for very high-enthalpy test facilities for such high-speed engines led NASA to sponsor the development of pulse facilities and their associated instrumentation. The work of Paull and Stalker and their colleagues at the University of Queensland, under NASA sponsorship, utilizing a reflected shock tunnel to produce flows simulating Mach 16 conditions is well known.[40] NASA also created a

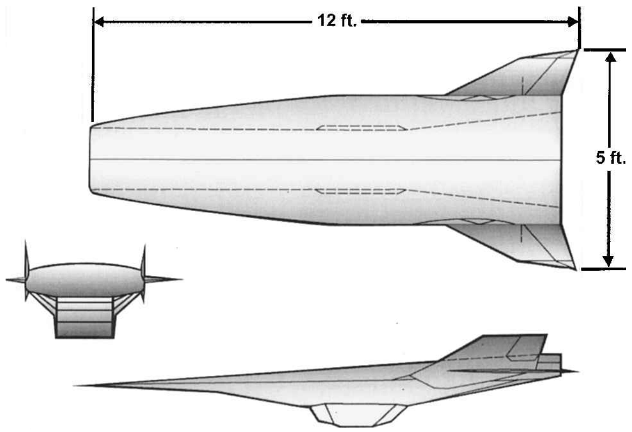

Fig. 7 NASA Hyper-X research vehicle.

new facility by installing a former NASA Langley expansion tube at GASL in 1989; in its upgraded version, this GASL facility is termed the HYPULSE facility. The ability to generate the test conditions required for hypersonic engine and combustor studies is demanding and, in the United States can only be approached by reflected shock tunnels such as the LENS, NASA Ames Research Center 16 in., California Institute of Technology T5 facilities, and the HYPULSE[41] facility. The development and utilization of scramjet test facilities is a vital part of a hypersonic propulsion enterprise; unfortunately, it is a vast topic that cannot be addressed in this paper.

A major new initiative[42] by NASA to explore the overall performance of airframe-integrated dual-mode scramjet-powered X vehicles is now underway. This initiative is termed Hyper-X. The first test vehicle, designated the X-43A, is a small hypersonic aircraft about 12 ft in length with a 5-ft wingspan, as shown in Fig. 7. The vehicle will be air launched, with a booster stage, from a B-52 aircraft and is similar in launch concept to the X-7 series of vehicles. Three X-43A flight tests are planned, according to Ref. 43. The first vehicle is targeted for a Mach 7 demonstration of the scramjet in mid-2001 with about 5+s of combustor burning time. The remaining two vehicles will be flown at Mach 7 and 10. Significantly, the vehicle for the Mach 7 flight test has been tested at simulated flight conditions in the NASA Langley Research Center 8-ft High Temperature Wind Tunnel. A very interesting comparison of ground- and flight-test data should be possible. In regard to the future of airbreathing hypersonic research, NASA has projected its vision[43] for about the next 15 years, which outlines a series of flight-test experiments, including a large-scale, reusable Mach 0–7 vehicle.

After the demise of the NASP program, the U.S. Air Force decided to focus its near-term hypersonic activities on hydrocarbon-fueled scramjet engines for missile propulsion in the Mach 4–8 regime. This new effort was termed HyTech, and the current key engine technology thrust is known as the Air Force Hydrocarbon Scramjet Engine Technology program.[44] The engine, under development by Pratt and Whitney, is a two-dimensional, dual-mode engine, using a mixed-compression inlet, and a fuel-cooled structure for the internal flow passage. The engine design has been integrated with a hypersonic missile configuration. Although this first effort is missile oriented, the HyTECH program should, in the future, address various applications, such as high speed and transatmospheric vehicle propulsion.

Scramjet Technology in Russia

In the former Soviet Union (FSU), a significant scramjet research and development program had been in progress for many decades. In the past, visibility of this program had been restricted by the limited availability of documentation in the English language. Fortunately, many more details of the truly foundational work of FSU scientists have become available during the 1990s due to their increased participation in international conferences. The scramjet research program has been carried out at many institutions including the Central Institute of Aviation Motors (CIAM), the Central Aerohydrodynamic Institute (TsAGI), the Institute of Theoretical and Applied Mechanics (ITAM), the Moscow Aviation Institute (MAI), and several design bureaus, such as Soyuz.

Several accounts of early Russian work on scramjets are now appearing. According to Tretyakov,[17] interest in supersonic combustion began in the 1950s, and in April 1957, Shchetinkov applied for a patent on a supersonic combustion ramjet engine. Tretyakov also notes that Struminsky initiated research on small test models in 1966 in Siberia.

It is apparent from the reports of early Russian researchers that they shared the same common concerns about scramjet engines in regard to the feasibility of efficient combustion in a reasonable length, thermal choking limitations, and inlet–combustor interactions as American workers. The publication in 1973 of a foundational paper by Shchetinkov[45] on supersonic combustion and pseudoshock phenomena illustrated the early achievements of such research. Later, additional publications showed that combustion-related phenomena similar to those experienced in U.S. testing were encountered by Russian researchers. For example, the decrease in combustion efficiency in divergent ducts[46] and the complex structure of pseudoshocks: For the latter a major Russian database was generated (for example, see Penzin[47]). Overall, Russian research addressed, in depth, the mixing and combustion processes occurring in two- and three-dimensional ducts, with various fuels, fuel ignition systems, and flame stabilization devices for both scramjet and dual-mode engines. Also, in common with U.S. researchers, much research was performed in notional engine configurations to study overall inlet–combustor performance. Two dual-mode scramjet classes are extensively referenced in the CIAM literature, namely, a two-dimensional class of models and an axisymmetric class, using either hydrogen or kerosene fuels. A fixed-geometry two-dimensional model utilizing a three-shock inlet with a design Mach number of 6 has been extensively tested at CIAM; the results have been documented by Vinogradov et al.[48–50] The axisymmetric class has also been tested extensively using both hydrogen and kerosene fuels (see Albegov et al.[51]). An interesting feature of these engine designs is the use of multiple cavity flame stabilizers. The axisymmetric model is reminiscent of the NASA HRE and French ESOPE approaches but differs radically in the details of the internal combustor flow path.

An axisymmetric hydrogen-fueled engine was successfully flight tested in November 1991 and demonstrated operation in both the subsonic and supersonic combustion modes.[52] The flight test concept utilized a Hypersonic Flying Laboratory (HFL) named Kholod. The engine and its support services were mounted on the nose of a modified SA-5 vehicle and remained attached to the HFL throughout the flight (see Fig. 8). A second, similar flight test was conducted in November 1992 with the support of ONERA; this engine operated in the range $M = 3.5$–5.35, again demonstrating both subsonic and supersonic combustion modes. These successful flight tests were a most significant achievement and a tribute to the dedicated and persistent efforts of Russian scientists who have apparently pursued the goal of scramjet-flight test since about 1970. A third flight test, also with French support, was carried out in March 1995, but the engine did not operate because of HFL system problems.

In another associated international venture with the Kholod vehicle, NASA contracted with CIAM to extend the flight-test envelope to demonstrate the full supersonic combustion mode to Mach 6.5. NASA and CIAM worked jointly to analyze the engine flow path performance and to assess the thermal loading on the Mach 6.5 engine, with particular concern for the cowl leading-edge environment.[53] Some modifications to the inlet and isolator/combustor of the engine were required. The flight test was successfully launched on 12 February 1998, and engine data were obtained in the speed range Mach 3.5–6.4. The subsequent analysis of the flight data led to the preliminary conclusion that the engine operated as a dual-mode scramjet, but in the subsonic burning mode.[54] Note that these flight-test engines were actively cooled with hydrogen. Currently, work is in progress to explore endothermic fuel cooling of model scramjet combustors.

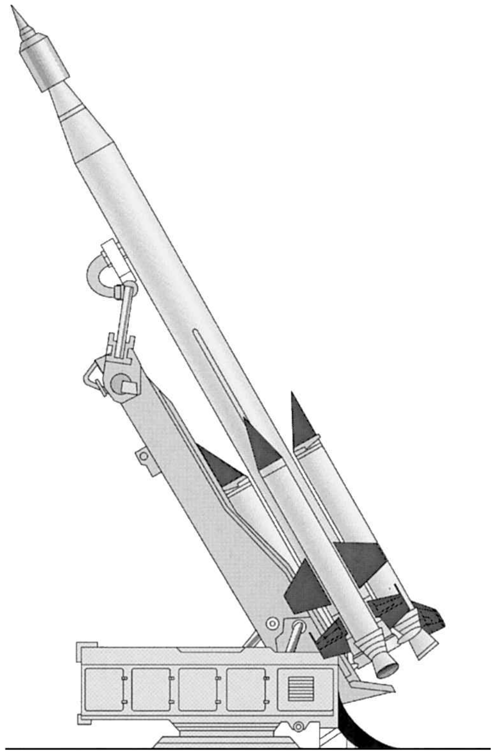

Fig. 8 Kholod HFL.

A second generation hypersonic flying test bed, IGLA, has also been frequently discussed in the Russia literature.[55] IGLA is a winged gliding vehicle, mounted on top of a large booster rocket (RS-18), and accelerated to speeds of the order of Mach 16. After separation, the vehicle glides down to lower speeds where the scramjet is started. The engine installation is shown as a three-module, rectangular, hydrogen-fueled scramjet engine with regenerative cooling. Two series of tests of a scaled module, consisting of an inlet and combustor, have recently been reported,[56] at Mach 2–6, and Mach 6–7.2 conditions, to determine inlet performance. The testing of this module will be extended to higher Mach numbers and will include combustor operation with hydrogen and/or hydrocarbon fuel. If this overall program is successfully accomplished, it will provide most valuable data on scramjet performance at the higher speeds.

Further details of scramjet technology efforts in Russia are emerging in various technical meetings. Three excellent source references are Refs. 16, 18, and 24.

Scramjet Technology in France

In France, work on supersonic combustion began in the early 1960s and a valuable series of experiments was reported by Mestre and Viaud[57] in 1964. In these investigations, kerosene combustion in a constant-area duct was studied at Mach 2.5 entry conditions and shown to be practicable. The limitations of constant area heat addition were encountered and, in addition to the usual wall pressure distributions, valuable measurements of stagnation pressure losses were made; useful data were also obtained on the ignition of kerosene/airstreams. Ultimately in the French program, both kerosene and hydrogen combustion were studied, and various injection schemes were tried, such as wall, strut, and slot configurations. Work was also extended to divergent duct geometries.

Following this early work, a significant program, ESOPE, was launched in 1966. In general, this program sought to demonstrate a dual-mode scramjet concept proposed by Marguet and Huet.[58] Initially a Mach 7.0 flight-test program was envisaged, but here again the ESOPE program was to become a ground-test program due to resource limitations.

The overall design of ESOPE is an axisymmetric engine with an annular combustor, similar to the NASA HRE. Also like the HRE, the ESOPE program was supported by a basic scramjet technology program (for example, see the works of Leuchter[59] and Hirsinger[60]).

Two ESOPE test series were reported.[61] The first series (1970) demonstrated the need for improved fuel injection and mixing. Modifications were made and in a second test series (1972), the engine performance was much improved.

Unfortunately, and in parallel with U.S. experience, further work on scramjet was largely terminated in favor of the development of the integral rocket ramjet engine. Also, as in the United States, work on the scramjet engine was to be revived in the late 1980s and a very significant program, PREPHA, emerged in 1992.

The PREPHA program, most recently discussed by Sancho et al.,[62] began as an hypersonic research and technologies program primarily focused on hydrogen-fueled scramjet technology, but including studies of computational fluid dynamics (CFD), materials, vehicle systems, and test facilities. In addition to forebody, inlet, and nozzle/afterbody studies, two rectangular combustion chambers have been tested. The first dual-mode chamber (100×100 mm^2) included a single-strut injector that was tested at ONERA at a simulated flight Mach number of 6. Two strut-injection concepts were tested: One strut incorporated normal, angled, and base injection sites. The other strut utilized a rear section composed of a series of expansion and compression ramp injectors. The relative performances are discussed by Scherrer et al.[63] The second combustor called CHAMOIS (cross-sectional area about 0.05 m^2) utilized three injection struts and has been successfully tested by Aerospatiale, at Bourges, at a nominal flight Mach number of 6: Further details are given by Bouchez et al.[64]

This latter effort has demonstrated a sound methodology to investigate scramjet combustion phenomena by use of CFD models of varying sophistication to obtain qualitative and quantitative models of the flow, for comparison with experimental measurements. In turn, such CFD models have provided a structured approach to addressing typical engine problems in the areas of ignition, flame stabilization, mixing and combustion efficiencies, total pressure losses, and unsteady flow phenomena. A particularly interesting aspect of this investigation was the determination of the point of origin of the precombustion shock in the combustor. Clearly, various levels of CFD modeling including differing turbulence and kinetic models are providing significant tools to approach design optimization of scramjet engines. In general, it would be very desirable to add simultaneous optical flow visualization to the existing tools of CFD modeling and physical measurements. One impressive product of the CHAMOIS testing described by Bouchez et al.[65] has been the development of a lightweight, carbon/carbon strut with a sharp hydrogen-cooled leading edge (radius less than 2 mm) potentially capable of surviving Mach 12 conditions.

One other interesting aspect of strut technology is the design and test of a hydrogen-cooled Inconel 718 strut.[66] This strut is designed to withstand both leading-edge and sidewall thermal loads corresponding to flight speeds up to Mach 7.5.

A related French–Russian program is the partnership formed between Aerospatiale and the MAI to develop a Mach 3–12 wide range ramjet (WRR) prototype. As noted earlier, in the United States, Ferri had pursued the goal of developing a Mach 3–12 engine in the early 1960s by utilizing aerothermodynamic flow effects in a fixed geometry duct. The WRR approach, described by Bouchez et al.,[67] favors the more structured approach of using a variable geometry combustor made up of movable panels, actuated under computer control, to maximize performance. At lower speeds, the WRR operates in a subsonic combustion mode using kerosene fuel, and at higher speeds, supersonic combustion with hydrogen fuel is used. It is postulated that still higher speeds may be attained by utilizing an oblique detonation wave mode. In the WRR configuration, it will be possible to use a physical variable throat and avoid the sensitivities associated with the dual-mode scramjet that uses a fixed geometry combustor operating with a thermal throat.

Thus, in the WRR, the engineering challenge of developing a mechanically variable geometry combustor/nozzle system, for dual-fuel operation, is squarely faced. The propulsion community will watch the evolution of the WRR engine with interest.

Although the PREPHA program ended in 1999, two scramjet programs continue. The first effort, an initial three-year program under the sponsorship of the French Ministry of Defense is called PROMETHEE[68]: Its main aim is to explore the feasibility of a dual-mode hydrocarbon-fueled scramjet for an air-launched missile. A generic missile has been defined, and three engine concepts have been explored; a unique rotating-cowl dual-mode engine has been selected for further work. The second effort is termed Joint Airbreathing Propulsion for Hypersonic Application Research (JAPHAR), which began in 1997. One focus of JAPHAR[69] is the evaluation of a hydrogen-fueled dual-mode scramjet to operate, potentially, over the speed range Mach 2–12. To evaluate the net propulsive effect of the engine it is essential to integrate it with a suitable vehicle. To determine the design of such a vehicle, DLR, the German Aerospace Research Center, carried out studies of a waverider configuration, and ONERA evaluated a winged-body configuration. From these studies a common vehicle design was evolved that incorporated the best features of the two approaches.

This program can now proceed to develop a second-generation scramjet engine, building on the lessons learned from previous programs, and optimizing overall engine performance within the constraints of integration in a realistic vehicle design. A definitive engine design should emerge from this effort.

Scramjet Technology in Germany

Germany has a long tradition of excellence in gasdynamics, and many foundational contributions, both theoretical and experimental, have been made to explain supersonic heat addition phenomena (for example, see the many references in the work by Zierep[70]). In 1987, a hypersonic technology readiness program addressing a reference concept of a two-stage reusable space transport system (Sanger) was initiated, which, in turn, stimulated a revival of basic hypersonic research at various German universities. This basic research effort was terminated in December 1995, but fortunately some aspects of this work have continued, as described by Koschel.[71]

Also, under the overall hypersonic program, a joint German–Russian scramjet technology research and development effort was initiated in 1993 with TsAGI and primarily MTU as the participants. There has been an informative series of progress reports on this program by Sabel'nikov et al.[72] Extensive use has been made of the TsAGI test facilities, and the experimental program has addressed connected-pipe testing of a versatile rectangular subscale combustor, as well as freejet testing of subscale scramjet engines. The combustor consisted of four sections including an isolator, a rectangular divergent section in which a step configuration can be introduced, a variable geometry divergent section, and a diffuser section. At least three different injector types have been investigated: tube injectors, wall-mounted ramp injectors, and wedge-shaped fin injectors, that is, a partial span swept strut. Both single-point and staged-injection locations have been tested. Various combustor tests have been made at Mach 6 conditions, adding valuable additional data to the current knowledge base, particularly on strut-class injectors.

The subscale rectangular scramjet engine was also tested at Mach 5 and 6 conditions. This engine consisted of a three-ramp inlet, an isolator, a divergent (or alternatively a step configuration) combustor, and a divergent exhaust nozzle. At Mach 6 conditions, this engine exhibited strong coupling effects between the combustor and inlet. At Mach 5, there were reduced interactions. Full details of the Mach 5 and 6 tests are given by Walther et al.[73] Additional testing of this engine at Mach 7.2 conditions is discussed in Ref. 74.

Also, the possibility of flight testing a subscale engine, installed on the Russian Raduga-D2, at Mach 6 conditions has been explored. The Raduga-D2 vehicle is typically air launched from a Tupolev TU-22M at supersonic speed and is powered by a rocket engine.

As already noted, Germany and France are jointly working on a dual-mode engine, under the JAPHAR program.

Scramjet Technology in Japan

Japan has a long history of working technologies relevant to scramjet engines, including some significant work on pseudoshock phenomena in the late 1960s. Supersonic combustion studies were reported some 20 years ago; more recently a very capable ramjet test facility was installed at the National Aerospace Laboratory, Kakuda Research Center (NAL-KRC). This facility, which became operational in 1994, is able to simulate flight conditions corresponding to Mach 4, 6, and 8 (with a facility exit nozzle size of 51 cm square). The facility has a stored clean-air capability utilizing a ceramic heater and also two separate vitiated air heaters for Mach 6 and 8 conditions. Significantly, it is possible to run Mach 6 test conditions using either clean or vitiated air.[75] An interesting comparison of Mach 6 testing with both clean and vitiated air is given by Mitani et al.[76]

Since 1994, an extensive series of tests has been performed on a two-dimensional subscale engine at simulated flight Mach numbers of 4, 6, and 8, using hydrogen fuel. The engine utilizes a sidewall compression inlet similar to the NASA airframe-integrated scramjet engine. The dimensions of the engine are 20 cm wide, 25 cm height, with a length of 2.1 m. The combustor fuel injection system utilizes pilot fuel injectors (top wall and/or side wall) and main fuel injectors, which provide both perpendicular and parallel fuel injection sites. The parallel injection takes place at the base of a step in the combustor sidewall with perpendicular injection just downstream of the step. The combustor has been run without struts, with a partial strut spanning one-fifth of the duct height, and a full-span strut; however, in none of these cases has the strut been used as a fuel injector. Rather, the strut has been used to give further compression of the flow. Additionally, shock-generating ramps have been inserted in the flow path to attenuate inlet–combustor interactions. A status report on the technological evolution of these engines is given by Yatsuyanagi and Chinzei,[77] with more recent developments reported by Sato et al.[78] and Tani et al.[79] Reference 79 gives a very informative discussion of the effects of varying the engine internal geometry (isolator, struts, and ramps) on internal aerodynamic performance. In addition to the existing heat sink and water-cooled versions of the test engine, it is planned to test a hydrogen-cooled engine in the near future. There have also been detailed studies of the relative performances of various fuel injection struts using both normal and parallel fuel injection in varying proportions.[80] Although a central full-span strut ensures initial fuel distribution across the height of the duct, its presence splits the flow into two smaller channels. It also generates a bow shock that can cause boundary-layer separation at the wall, adding further blockage to the already reduced flow area; furthermore, the reflected shock can interact with the fuel injection/ignition process. In addition to these broad studies of conventional fuel injection strut phenomenology, there has also been work on improving the strut injector performance by use of innovative geometries.

Despite this strong background on strut injection phenomena, many of the engine tests at Mach 4, 6, and 8 (Ref. 81) reported in the literature have been basically without utilizing strut injection in the combustor design. These engines have utilized ignition plasma torches, and this technology has been extensively researched in Japan[82] and elsewhere.

A new large-scale free-piston, high-enthalpy shock-tunnel, HEIST, was installed at NAL-KRC in 1997: It should be capable of testing scramjets in the speed range of Mach 8–15.

Scramjet Technology in Australia

As noted earlier, the work of Stalker and his colleagues at the University of Queensland is well known. This work started in 1981 with the T3 hypersonic impulse facility at the Australian National University, and in 1987 it transitioned to the T4 tunnel at the University of Queensland: The T4 tunnel is capable of simulating orbital flight conditions. Experimental work has evolved from the testing of simple combustors to the testing of complete scramjet models, and net positive thrust has been demonstrated. A broad range of technology efforts has been undertaken, primarily using hydrogen fuel, including fuel mixing and combustion studies, the effects of shocks on mixing and burning, skin-friction measurements, and numerous gasdynamic investigations. The continuing pursuit of improved scramjet efficiencies is well described by Paull and Stalker.[40] A significant flight-test program, HyShot, is planned for mid-2001.

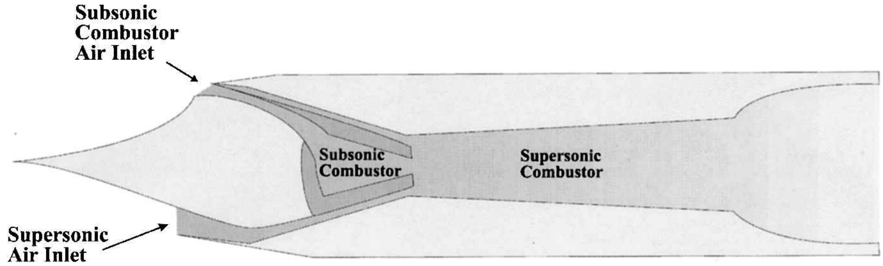

Fig. 9 Dual-Combustor Ramjet.

Two scramjet vehicles are to be launched with the object of obtaining the correlation between flight- and ground-test supersonic combustion data.

Other Scramjet Technology Efforts

Many other nations are embarking on supersonic combustion research. Experimental work on supersonic combustors in India has been published,[83] and both analytical and experimental[84] studies are reported by the Chinese Academy of Sciences, People's Republic of China.

Additional work related to hypersonic propulsion is being pursued elsewhere in Europe. Broadbent[85] has compiled a useful survey of some work in the United Kingdom. Also, at Sheffield University, Swithenbank et al.[86] pursued extensive scramjet engine mixing and combustion studies for many years. Another substantial university program was conducted by Cookson et al.[87] at the College of Aeronautics, Cranfield, using both hydrogen and hydrocarbon fuels. One early scramjet combustor configuration tested by Rolls Royce and reported by Harper[88] was a simple step combustor (with wall fuel injectors upstream of the step and also injection from the base of the step). This combustor was tested at temperatures corresponding to Mach 5–7 with both hydrogen and methane fuels. The step configuration gave stable operation and smooth transition between supersonic and subsonic combustion modes.

Emerging Trends

Up to this point, most of the discussion has focused on the development of hydrogen-fueled engine technologies. In general, this work has been aimed at providing engine technology for hypersonic air vehicle concepts that include both two-stage-to-orbit and SSTO vehicles. The modular two-dimensional airframe-integrated scramjet engine has emerged as the candidate of choice, as is evident in the IGLA and JAPHAR vehicles. This configuration permits engine development in reasonable size ground facilities and requires a relatively modest flight test vehicle for module testing. The relatively large height of the engine determines many of the relevant technological features, such as the use, primarily, of strut injectors. Also the associated inlet designs have driven extensive development of two-dimensional, sidewall compression systems and of two-dimensional isolators.

However, in recent years, due to budget limitations, scramjet engine development has focused on relatively near-term missile propulsion efforts. In particular, the U.S. Air Force, as already noted, is addressing hydrocarbon-fueled missile propulsion in the Mach 4–8 regime under the HyTech Program[89]; similar work is proceeding in France. In these missile engines, due to the basic difficulty of igniting and rapidly burning the heavy hydrocarbon fuels, it is essential to prepare the fuel for effective combustion or, alternatively, to add very energetic fuels or oxidizers. From an operational viewpoint, such energetic additions are usually unacceptable. Fortunately, over the long history of hydrocarbon-fueled scramjet development, many combustor design approaches have been proposed and investigated, such as the well-known DCR[90] shown in Fig. 9. In this design, two combustors are used, an initial subsonic combustor, operating fuel-rich, and a coaxial supersonic burner to complete the combustion process. Other hydrocarbon-fueled engine designs use various piloting techniques. Such techniques include the wall pilot, the split-inlet pilot, and the catalytic pilot; these schemes, and more general combustion concerns are extensively discussed by Waltrup.[91] More recently the use of cavity-based fuel injector/stabilizer configurations, combined with barbotage injection, have been successfully demonstrated with JP-7 fuel.[92]

Another technology area that has received only limited attention in the literature is active cooling of the hydrocarbon class of engine. Much analysis has been done, and practical combustors have advanced from early heat-sink approaches, through water-cooled, to actively cooled metal and composite structures. Active cooling is greatly enhanced by the use of endothermic fuels. Although the capabilities of these fuels are well known, there has been very little work published on the practical engineering of the overall endothermic fuel cooling system. These systems require catalytic conversion, multiphase operation, and fast cold-start capabilities; active cooling will probably be essential for speeds exceeding about Mach 6.5 to achieve thermal balance of the engine.

There has been some discussion on the ultimate speed capabilities of hydrocarbon-fueled scramjet engines. A recent analysis by Waltrup[93] yields estimates that, for the axisymmetric missile class of vehicle the upper speed bound lies between Mach 9 and 10.

Conclusions

The scramjet engine is the key to airbreathing hypersonic flight. Because of the energy limitations of currently available fuels, the scramjet is unlikely to provide efficient propulsion all of the way to orbital speeds. Furthermore, effective performance at the higher speeds will demand the highest component efficiencies. Some potential improvement in high-speed performance may be anticipated by liquid oxygen augmentation of the combustion system (for example, see Roudokov's discussion in Papers 4 and 9 of Ref. 16). However, it is anticipated that the hydrogen-fueled scramjet will offer acceptable performance to about Mach 15.

The early encouraging explorations of supersonic combustion phenomena in the late 1950s/early 1960s perhaps gave the impression that the scramjet engine could be developed using the same structured and largely controlled approach appropriate to subsonic combustors, that is, fuel injection, distribution, mixing, ignition, stabilization by pilot zones, flame propagation, etc. However, in the scramjet, the presence of supersonic/subsonic flows with corresponding shock fields, coupled heat release/shock generation, shock/boundary-layer interactions, and thermal occlusion effects very soon demonstrated that scramjet combustor development was no simple endeavor. Once again, the pioneering work of Ferri in addressing these problems, in complex three-dimensional engine configurations, is noteworthy. Since that time, more tractable engine flow path systems have been investigated. At present, two-dimensional engine designs, with or without strut fuel injectors, are beginning to emerge and should provide a common configuration on which the community could focus future research efforts and resolve current flow path anomalies.

The unexpected complexities of scramjet combustion and, in particular, combustor–inlet interactions, have frustrated progress in the past 40 years. Indeed, it has taken the propulsion community over 30 years, since the conception of the engine, to achieve a successful flight test. Of course, the overall scramjet international effort has also not been consistently funded, and so there have been many dormant periods in research. However, significant progress has been made, but more substantive progress in developing improved understanding of scramjet processes, leading to preferred scramjet engine designs, is needed, so that effort can be focused on eliminating anomalies and refining such designs. Furthermore, development will be hastened if effort is concentrated on configurations that lend themselves to structured, standard engineering approaches that control the flowpath phenomena. One such early proposal was a multistep burner[94] where a standard step burner element is used sequentially to spatially anchor heat release along the combustor, to control heat release as a function of length. An actively controlled system could optimize overall performance.

As an observer of the work in progress, this writer is reminded of Kuchemann's comment in the prolegomena to his well known book[95] that it was Prandtl who introduced the concept of healthy flows: We are well advised to search for such healthy flow solutions for scramjet combustors. Let us hope that international efforts can succeed in developing engine configurations in which healthy combustor flows can be baselined, so that robust airbreathing hypersonic propulsion can be confidently improved. Certainly, there are no grounds for complacency with current published combustor performance levels.

With regard to hydrocarbon fueled systems, it is hoped that budget support will continue to enable exploration of such propulsion technologies to speeds of about Mach 8. This class of engine will almost certainly play a role in developing future hypersonic air vehicles and offers considerable scope for innovation and invention.

We have come to the 40th anniversary of scramjet engine research; in the next few years it appears that major flight testing will take place in the IGLA and Hyper-X programs. The possibility of additional flight testing by other nations has been raised in the literature. Thus, the current scramjet engine configurations and their supporting technologies will be put to the test of flight validation, and further data regarding the future viability of scramjet powered hypersonic flight should soon be available. Indeed it is time for increasing international collaboration on key technological scramjet issues through dedicated workshops. Although this remark is in the context of scramjet combustor technology, it is obvious that dedicated workshops on other scramjet components (particularly inlets and nozzles), CFD methods, and basic research problems are required.

Regarding future hypersonic propulsion, the potential of the oblique-detonation wave engine is under continuing investigation.[96,97] There are also emerging efforts to capitalize on the manipulation of ionized flows to improve engine-vehicle performance. It should also be observed that over the last 40 years, we have come to accept the airframe-integrated lifting body configuration as a standard vehicle configuration. Billig[98] has recently pointed out that it would be prudent to examine the possibility of a radical change in the engine flow path and, in turn, the overall vehicle configuration to produce a more effective vehicle. Billig has presented configurations based on a flowpath derived from streamline tracing of inward turning flowfields that can potentially reduce drag and heating loads. The design of the SCRAM engine mentioned earlier was based on the use of similar techniques. Thus, despite the maturing of the early scramjet engine technology base,[99] fresh opportunities exist to improve the robustness of hypersonic propulsion and avoid the marginality associated with orbital and suborbital missions. It is anticipated that the truly mature scramjet engine will indeed rule over a wide flight domain.[100]

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