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Corin Segal
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1 Introduction

1.1 The Ramjet and the Supersonic Combustion Ramjet (Scramjet) Engine Cycle

An invention attributed to René Lorin of France in 1913 (Hallion, 1995), the ramjet is a remarkable air-breathing engine in its conceptual simplicity. Lacking moving parts and achieving air compression only through internal geometry change, it is capable of extending the operation beyond flight speed when the gas-turbine engine becomes inefficient. The ramjet does not, however, operate from takeoff, and its performance is low at subsonic speeds because the air dynamic pressure is not sufficient to raise the cycle pressure to the efficient operational values.

Above a flight speed of around Mach 3, cycles using rotating machinery, i.e., compressors, are no longer needed to increase the pressure, which can now be achieved by changes in area within the inlet and the diffuser leading to the combustion chamber. Engines without core rotating machinery can operate with a higher maximum cycle temperature as the limit imposed by the turbine presence on the cycle maximum temperature can now be increased. The ramjet cycle with subsonic air speed at the combustion chamber entrance becomes more efficient. As the speed further increases, the terminal shock associated with subsonic combustion leads to both significant pressure losses and elevated temperatures that preclude, in great part, recombination-reaction completion, thereby resulting in considerable energy loss. It becomes more efficient to maintain the flow at supersonic speed throughout the engine and to add heat through combustion at supersonic speed. Figure 1.1 shows the estimated specific impulse for several cycles as the flight Mach number increases (McClinton, 2002). The rocket-cycle specific impulse is included for comparison. The ramjet or the scramjet must be combined with another propulsion system for takeoff.

Schematically, the differences between subsonic and supersonic combustion ramjet engines are shown in Fig. 1.2. The subsonic conditions in the

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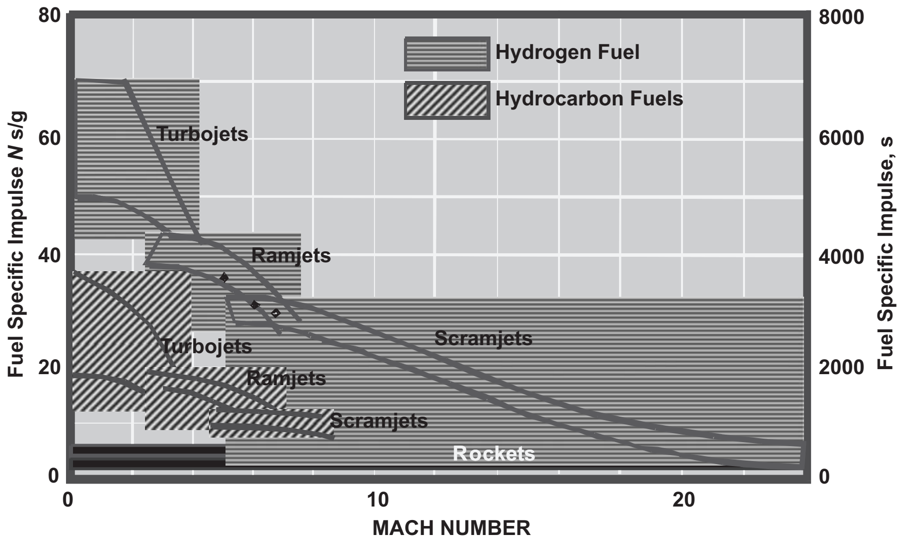

Figure 1.1. Specific impulses of several air-breathing cycles and rocket propulsion indicate the advantage of the scramjet engine over the other cycles for flight in excess of Mach 6. The diagram includes operation with hydrocarbon and hydrogen fuels.

combustion chamber in the former require the presence of a physical throat in the nozzle to maintain the desired inlet operational conditions, whereas the supersonic combustion chamber, in fact, requires an area increase as heat is released through combustion. For comparison, Table 1.1, offered by Ferri (1973), shows several critical parameters for the cases of supersonic vs. subsonic combustion at a selected flight condition: Mach 12 at an altitude of 40 km with hydrogen used as fuel, assumed to be in stoichiometric ratio with the engine airflow. The differences indicated in the table point to significant differences. The stagnation pressure recovery, which is a measure of the losses in the inlet and diffuser system, is about 30 times larger in the scramjet in comparison with the subsonic combustion ramjet because of the absence of the terminal normal shock. Because, in a first approximation, the engine thrust loses 1% for each 1% of loss in pressure recovery, the performance for the supersonic-combustion-based cycle is clearly evident. The temperature at the subsonic combustion chamber entrance is quite large. Severe dissociation is present at this temperature, and recombination reactions cannot take place within the combustion chamber. The net effect is, in fact, a reduction in

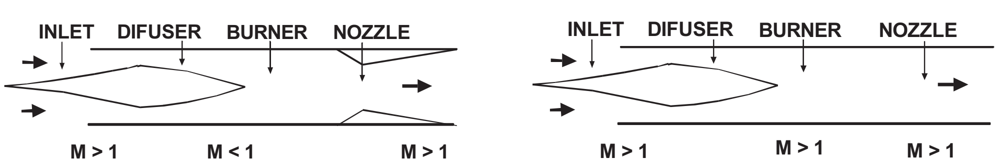

Figure 1.2. Schematic of subsonic and supersonic combustion ramjet engines.

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Table 1.1. *A comparison of several relevant parameters between subsonic and supersonic combustion-based ramjets during Mach 12 flight*

Combustor chamber entrance	Supersonic	Subsonic	Combustion chamber exit	Supersonic	Subsonic
Ratio of burner entrance to capture area	0.023	0.023	Ratio of exit area to capture area	0.061	0.024
Stagnation-pressure recovery	0.5	0.013	Ratio of nozzle throat to capture area	0.061	0.015
Pressure (atm)	2.7	75	Pressure (atm)	2.7	75
Temperature (K)	1250	4500	Temperature (K)	2650	4200
Mach number	4.9	0.33	Mach number	3.3	0.38

temperature. Heat released because of fuel–air chemical reactions would occur in this case only further downstream in the nozzle, where, because of expansion, the temperature will decrease. Achieving chemical equilibrium within the nozzle so that the recovered heat can be converted into kinetic energy would require prohibitively long and therefore heavy nozzles. Thrust is further increased based on the ratio of the nozzle throat to capture area, which limits the amount of airflow through the engine in the subsonic-combustion-based ramjet. The scramjet will, in fact, substitute the mechanical throat with a thermal throat that results when the flow is slowed through tailored heat release. Finally, the considerably lower static pressure in the scramjet engine reduces the structural load on the engine duct, resulting in a lighter construction and overall increased system efficiency.

Technologically, the scramjet engine presents considerable difficulties that derive both from its operational characteristics and from the point of view of integration with the vehicle. Some of them are subsequently listed.

With air residence time of the order of milliseconds between engine capture and exit through the nozzle, fuel mixing time at the molecular level becomes a limiting factor. Mechanisms that accelerate mixing result in increased momentum losses, and they have to be traded for overall efficiency. The problem is compounded when liquid fuels are used because additional processes, including liquid breakup and vaporization, are present.

Flame stability becomes a key issue at high speeds and some kind of flameholder must be present when the residence time is increased. The chemical composition in the flameholding region is not only vastly different from the rest of the engine but is also characterized by large gradients in composition and temperature. Fuel–air-ratio tailoring must be such that the flameholding regions are stable for the entire range of the flight regime and engine-throttling conditions.

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Prolonged operation as the vehicle accelerates through the atmosphere requires cooling of both the vehicle and engine components. The fuel on board will be the most appropriate candidate for this process to eliminate the need for a separate cooling agent and heat exchangers that would add to the vehicle's structural weight. In general, the engine fuel flow will not match exactly the cooling requirements, and some kind of fuel bypass will be required. Furthermore, for certain conditions, the fuel will not have the cooling capacity to satisfy the mission requirements: Heiser and Pratt (1994) indicate that, beyond Mach 10, hydrocarbon fuels can no longer satisfy the vehicle cooling requirements and cryogenic hydrogen would become, in this case, the fuel of choice.

Because neither subsonic nor supersonic combustion ramjets can operate from takeoff and produce competitive propulsive performances at low speeds, other thermodynamic cycles will be needed, either turbojets or rockets. If the mission includes operation beyond the Earth's atmosphere, rockets will have to be present on board. It is inefficient to incorporate several separate propulsive systems that operate in a certain sequence. Furthermore, various propulsive systems may be designed to operate in combined cycles, thereby achieving a synergetic enhancement of each individual cycle performance. Beyond the scramjet incorporation in combined-cycle architectures, the narrow shock-wave angles experienced during hypersonic flight make the entire vehicle forebody part of the engine intake system. The nozzle has a considerable length and will be part of the vehicle afterbody. There is thus a close interaction between the engine and the vehicle with the vehicle geometry and flight attitude that influences the engine airflow thermodynamic and flow-field conditions and the engine operation, in turn affecting the aerodynamic forces and moments experienced by the vehicle. The engine and the vehicle designs cannot therefore be uncoupled.

1.2 Historical Overview

The first design of an operational ramjet-engine-equipped airplane is René Leduc's demonstrator shown in Fig. 1.3, which was designed to separate from the airplane that brought it to altitude. Conceptually the design began in the 1920s, was patented in 1934 (Hallion, 1995), and immediately attracted the attention of the French government. World War II delayed its flight until 1946, and free-gliding tests began achieving powered climbs in 1949. At the time Leduc was developing his concept and actively pursuing the realization of his ramjet-equipped airplane, developmental work was taking place in the USSR, England, Germany, and the United States. Recognizing that the ramjet cycle becomes more efficient at higher speeds than the airplanes were capable of achieving at the time, experiments used projectile-launched

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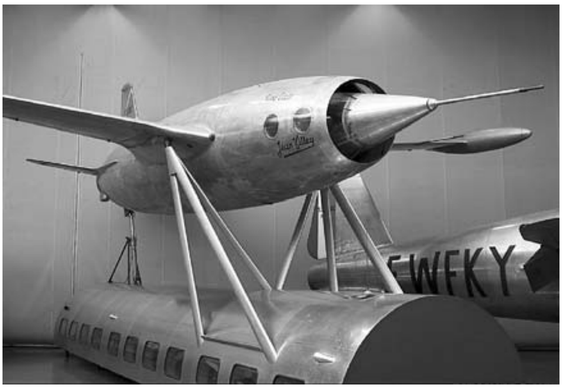

Figure 1.3. Leduc 0.10 at Musee de l'Air et de l'Espace at Le Bourget, France. The aircraft used a ramjet engine, and it was mounted on top of Languedoc aircraft for launch in flight.

ramjets or two-stage devices with a rocket-booster first stage separating from the ramjet-powered stage at high speeds. Liquid-fueled ramjet engines were used in the USSR in 1940 to boost the performance of a propeller-driven, Polikarpov I-152 biplane (Hallion, 1995; Sabel'nikov and Penzin, 2000), thus preceding Leduc's ramjet-powered flight to claim the first flight using ramjet-powered airplanes. Theoretical studies and experimentally projectile-launched ramjets were underway in Germany with Lippisch and Sänger's work in the 1940s and eventually reached Mach 4.2 at the end of the burnout (Avery, 1955). In the United States the early work of Roy Marquardt led to ramjet engines mounted on the wingtips of North American P-51 Mustangs as early as 1945, and later, larger versions of Marquardt ramjets were installed on the Lockheed P-80, allowing the airplane to fly under the ramjet power alone. Most of the ramjets developed in the following period focused on missile technology.

Along with the development of ramjet engines for airplane or missile applications, the concept of heat addition to a supersonic airstream took shape in the latter part of the 1940s. Captivating and presenting a valuable history of the scramjet development are Avery's article (1955), Hallion's report (1995), which covers the early scramjet research period through the Hypersonic Research Engine (HRE) program in the 1960s, and the articles by Waltrup et al. (1976) and Curran (2001), which describe scramjet-related activities in Australia, France, Germany, Japan, and the USSR. All these documents include ample references, including additional review publications.

In a 1958 study, which has become a point of reference, Weber and McKay noted that combustion can take place in supersonic airflows without creating considerable losses through shock-wave generation. Their study indicated that both the conventional ramjet and the scramjet efficiencies increase with speed in the range of Mach 4–7 and that the scramjet is more efficient than the ramjet above Mach 7; with an appropriately designed inlet, the scramjet advantage over the ramjet could be extended to Mach 5 flight. The results of this study identified many of the pertinent technical issues in the high-speed

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range, including the difficulties associated with flameholding in a supersonic flow, achieving an acceptable degree of mixing without causing severe shock losses, the significance of the inlet design on the cycle efficiency, the need to delay choking through heat release and thereby adopting a diverging combustion area, structural heat loads, and nozzle efficiency.

The work of Antonio Ferri at the beginning of the 1960s (Ferri, 1964) made a substantial contribution to the understanding of mixing and diffusive combustion processes in supersonic flows and was, to a large extent, the major driver for the technological developments that were about to arise. Ferri expanded on his earlier research in his review in a 1973 article indicating that, because the local temperature in the flame region is high, chemical reactions are fast compared with diffusion and heat conduction is due to mixing; therefore the process is dominated by transport properties. Although chemical kinetic rates are fast, the process nevertheless occurs at a finite rate and the reaction is distributed over an entire region in the flow; in regions of low pressure and temperature, the mixing and chemical time may become comparable and considerable mixing may take place before chemical reactions are completed, resulting in flame distribution over a large reaction zone. This heat release affects the pressure in the neighboring region and may even generate shocks in the unburned gas. Further, Ferri indicates that heat addition to a supersonic flow within a fixed geometry can be achieved efficiently for a broad range of flight Mach numbers, because the flow is less driven toward choking than it would be in the case of subsonic combustion; a three-dimensional design is thus capable of producing thrust efficiently if the geometry is chosen to correspond to the compression produced by combustion and, at the same time, satisfies the requirement for locally generating low Mach numbers for flame stability without substantial inlet contraction. The basis of the modeling of the physical processes is explained, emphasizing the three-dimensional nature of the flow field wherein finite-rate chemistry is coupled with the fluid dynamic processes that are dominated by the transport properties.

Large research projects were initiated in the early 1960s, most notably NASA's HRE Project (Andrews and Mackley, 1994). The goals were to build and test in flight a hypersonic research ramjet–scramjet engine using the X-15A-2 research airplane that was modified to carry hydrogen as the fuel for the scramjet engine. Two models were fabricated to test the structural engine integrity and to demonstrate the aerothermodynamic performance. The 8-ft., Mach 7 wind tunnel at NASA's Langley Research Center was used to test the structural assembly model (SAM), and the performance was evaluated on the aerothermodynamic integration model (AIM) at Mach 5–7 conditions at NASA's Glenn Research Center at the Plumbrook Hypersonic Test Facility. A pretest model is shown in Fig. 1.4. The SAM was evaluated with flightworthy hardware, and hydrogen was used as a coolant. Local heat and mechanical

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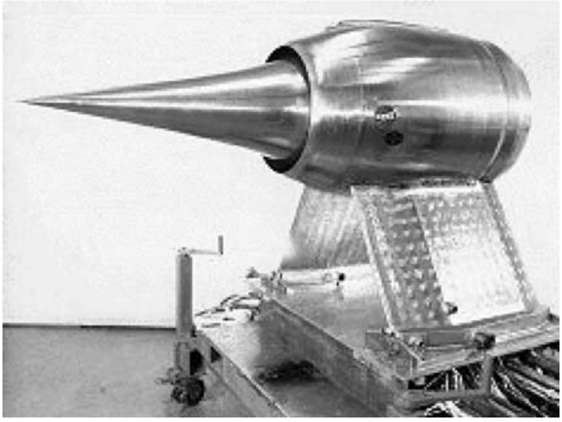

Figure 1.4. A pretest model of the HRE.

loads were estimated, and material fatigue damage was assessed in more than 50 cycle loads. Thermal stresses expected in flight were duplicated in the wind tunnel, and a considerable database of surface temperature, cooling loads, and thermal fatigue was generated during this program. The AIM was a water-cooled, ground-based model with full simulation of Mach 5 and 6 enthalpy and reduced Mach 7 temperature. Both ramjet and scramjet operational modes were investigated, and critical technological areas were evaluated, including inlet boundary-layer transition, transition from subsonic to supersonic combustion and fuel distribution, and interactions between inlet and combustor and combustor and nozzle during transient operation.

The history of scramjet research in the USSR is just as old as that in the United States. Beginning with the work of Shchetinkov in the late 1950s (Sabel'nikov and Penzin, 2000) and continuing in the following decade, the Soviet researchers focused on the major issues encountered in the scramjet engine: chemical conversion efficiency at high temperatures, heat transfer at low-pressure conditions, and design operation efficiency. Shchetinkov and his group of researchers proposed using porous walls for fuel injection as a means both to address wall cooling and to reduce friction.

During this early research in the USSR, Shchetinkov's work identified supersonic combustion as dominated by mixing as the limiting factor and formulated solutions for the mixing length and the requirement for a divergent section to maintain a high level of efficiency. Furthemore, the contributions emerging from this group extended to analyses of combined cycles that included scramjet operation, including ram-rockets and atmospheric air collection (later known as liquid–air collection engines – LACEs).

At the time when NASA was studying the HRE concept, a joint NASA/U.S. Air Force working group recognized the potential of the scramjet technology and set a common goal to pursue the technology that would result in a scramjet-operated vehicle within the 1960s (Hallion, 1995). This program

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was based both on the research evolving around the HRE program and on flight testing of hypersonic engine and airframe models by use of the X-15 airplane. These plans were severely impaired by the cancellation of the X-15 programs and came to an end toward the latter part of the decade. During the same period, however, the U.S. Air Force evaluated several scramjet engines in ground testing, including a variable-geometry Mach 5 engine developed by UTRC, a Mach 7 component integration engine developed by Ferri at GASL, and a Marquardt flight-weight dual-mode combustion scramjet (Waltrup et al., 1976). The Scramjet Incremental Flight Test Vehicle (IFTV) (Peschke, 1995), although tested in flight in only an unpowered configuration, produced valuable advances concerning fuel-injection tailoring for engine heat release and inlet compatibility during component ground testing. Hallion (1995) describes in detail the ground developmental testing and the aerodynamic nonpowered flights accomplished during this exciting program, which took the concept to flight hardware.

The axisymmetric configuration was also evaluated by Soviet (Vinogradov et al., 1990) and French researchers during the ESOPE program and was used in later international flight-testing programs (Voland et al., 1999; Falempin, 2000). Several flight tests of axisymmetric scramjet models boosted by SA-5 rockets took place in 1991 and 1992 in collaboration with ONERA researchers and were repeated in 1998 (Voland et al., 1999) as part of the Central Institute for Aviation Motors (CIAM) in Moscow and NASA interactions. All these engines were based on cavities for flameholding and used distributed hydrogen fuel injection to optimize the axial heat release. The original configuration used in CIAM studies is described in detail by Vinogradov et al. (1990). The ESOPE program in France, an axisymmetric hydrogen-fueled scramjet in the early 1970s focused, as in the United States and the USSR, on mixing-efficiency improvements and, similar to the U.S. HRE Program, ended following ground testing before flight-test hardware was built.

The airframe-integrated scramjet concept that emerged in subsequent years led to NASA's rectangular scramjet configuration. This configuration generated a complex inlet-flow structure and included in-stream struts with fuel injectors that could modulate the heat addition as required by the flight regime. This concept, which was evaluated extensively at NASA during the 1970s (Northam and Anderson, 1986), was later adopted in other programs [for example, National Aerospace Laboratories (NAL) studies in Japan; see Chinzei et al., 2000]. Figure 1.5 shows the rectangular engine configuration that is suitable for modular engine design and is particularly attractive for integration with the airframe when the application is in a transatmospheric vehicle. The swept inlet cowl provides flow stability over a large flight regime, and fuel-injection modulation from the struts allows operation over a broad Mach number range with a fixed geometry.

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Figure 1.5. The rectangular engine configuration used for the National Aerospace Plane Program's concept demonstration engine mounted atop its pedestal and the six-component force measurement system in preparation for testing in NASA Langley's 8-ft. high-temperature tunnel.

If the rectangular-shaped engine is appropriate for integration in a larger airframe, for a transatmospheric vehicle, the axisymmetric engine is well suited for a hypersonic missile. The Supersonic Combustion Ramjet Missile (SCRAM) Program developed in the latter part of the 1960s and early 1970s at JHU/APL (Silver Spring, MD) used a compact design with the scramjet engine surrounding the missile components. A contoured inlet was designed to provide starting and stability over the entire flight regime and the internal area distribution included an isolator to protect the inlet flow from the pressure rise in the combustion chamber (Billig, 1993). This program made a substantial contribution to the study of shock-train pressure rise and the interactions between shock waves and boundary layers in the isolator. Combustion modeling studies performed during this program played an important role in establishing design criteria for supersonic combustion chambers.

The emergence of the National Aerospace Plane (NASP) Program in the United States gave a new effervescence to hypersonic activities. The concept of a single-stage-to-orbit (SSTO) vehicle using air-breathing propulsion for the transatmospheric part of the trajectory, with rocket propulsion for the final insertion into orbit, was an extension of earlier concepts of rocket-based, entirely reusable SSTO concepts at Boeing and Rockwell (Hallion, 1995) with the addition of air-breathing propulsion. Figure 1.6 shows a concept of a proposed NASP configuration as anticipated toward the end of the 1980s. The NASP represented a significant step forward from the Space Shuttle: Using horizontal takeoff and landing, its operation resembled that of an airplane more than that of a rocket; fully reusable for more than 150 flights, it was designed to operate efficiently both during ascent and during maneuvering at

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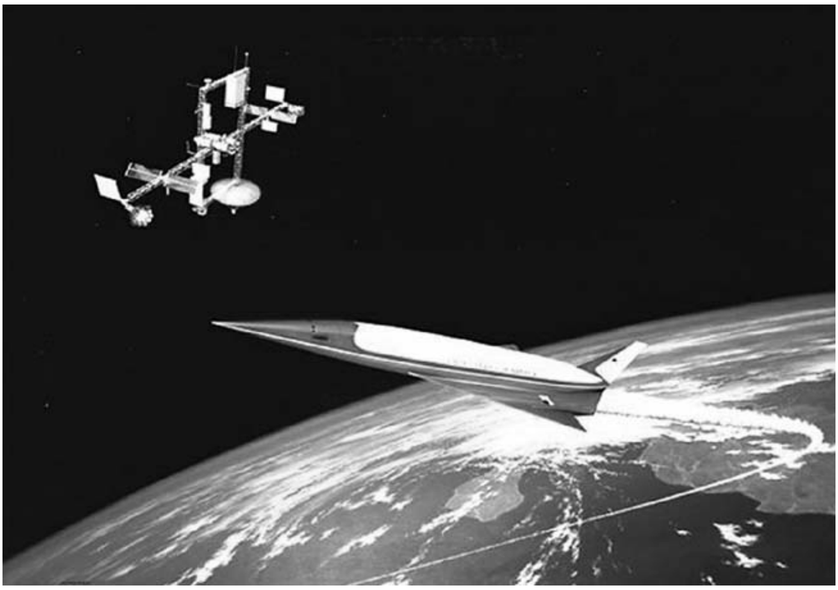

Figure 1.6. An artist's rendition of the NASP.

high altitudes, making maneuvers and orbital changes; finally, it would reenter and land under its own power.

The NASP posed technological challenges in materials, propulsion, aerodynamics, sustainability, and flight control, and, as a result, it became a catalyst for noticeable advances made in all these areas. New composite materials were developed to satisfy requirements for lightweight and structural resistance and to optimize their performance by minimizing weight as well as increasing load-carrying capacity. Metallic and carbon foams were conceived to produce materials with a wide range of thermal conductivities for use in thermal protection systems as well as in heat exchangers, which are necessary during extended hypersonic flights to maintain vehicle integrity. New concepts of combined-cycle propulsion systems evolved such that synergistic advantages can be extracted, and extensive testing was undertaken in the Mach 4–7 range. Air-breathing-propulsion-related high-Mach-number experiments were undertaken in shock and expansion tunnels. But perhaps the most significant achievement of the research undertaken during this project was the development of predictive tools in the area of computational fluid dynamics, with applications to both external aerodynamics and internal flows with chemical-reaction modeling for propulsion applications. Supported by an unprecedented development of computing power, predictive models for both fluid and solid mechanics have advanced, including both numerical schemes and the modeling of the physical processes. Today the degree of accuracy acquired by these models allows their integration into the early stages of the design process.

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