HYPERSONIC PROPULSION AT PRATT & WHITNEY — OVERVIEW

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Abstract

Pratt & Whitney (P&W) is developing the technology for hypersonic components and engines. A supersonic combustion ramjet (scramjet) database was developed during the National Aero Space Plane (NASP) program using hydrogen fueled propulsion systems for space access vehicles and serves as a point of departure for the current emphasis on hydrocarbon scramjets. The Air Force Hypersonic Technology (HyTech) Office has put programs in place to develop the technologies necessary to demonstrate the operability, performance and structural durability of a liquid hydrocarbon fueled scramjet system that operates from Mach 4 to 8. Fuel-cooled superalloys and lightweight structures are being developed to improve thermal protection and durability and to reduce propulsion system weight. The application of scramjet engine technology as part of combined cycle propulsion systems is also being pursued under NASA and U.S. Air Force sponsorship. The combination of scramjet power and solid rocket booster acceleration is applicable to hypersonic cruise missiles. Scramjets that use gas turbines for low speed acceleration and scramjets using rocket power for low speed acceleration are being studied for application to reusable launch systems and hypersonic cruise vehicles. P&W's recent activities and future plans for hypersonic propulsion will be described.

Introduction

The development of scramjet technology began at the United Technologies Corporation (UTC) in the 1960s at our United Technologies Research Center (UTRC). A resurgence of activity was experienced at P&W in the mid-1980s with the onset of the NASP program. NASP was aimed at developing a horizontal takeoff, horizontal landing single-stage-to-orbit (SSTO) vehicle. A broad technology base in hydrogen scramjet components and engines was established including validated design tools and methodology during the 10-year NASP program. In parallel to NASP, UTRC was developing technologies for hydrocarbon fueled scramjets under the Air Force Research Laboratory (AFRL)-sponsored Scramjet Component Technology (SCT) program. The hydrocarbon scramjet is less energetic than the hydrogen scramjet but more logistically supportable.[1]

Endothermic cooling technology development and direct connect tests of hydrocarbon fueled scramjet combustors were accomplished under the SCT program. Following the NASP and SCT programs, the Secretary of the Air Force initiated the Hypersonic Technology Program in 1995 to maintain a core competency in hypersonic propulsion technology. P&W was awarded the current Hydrocarbon Scramjet Engine Technology (HySET) program in 1996 under this initiative. The goal of the HySET program is to develop and demonstrate the operability, performance and durability of a Mach 4 to 8 hydrocarbon fueled scramjet to enable the development of expendable and reusable hypersonic vehicles.

Reusable architectures may benefit from combined cycle propulsion systems that use either rocket propulsion or gas turbine propulsion to accelerate to scramjet takeover speeds. NASA and the U.S. Air Force are developing both rocket-based-combined-cycle (RBCC) and turbine-based-combined-cycle (TBCC) propulsion systems. NASA desires to make future space propulsion safer, more reliable and less costly than today's spacecraft. For a 3rd Generation Reusable Launch Vehicle (3GRLV), this translates to two orders-of-magnitude increase in safety, two orders-of-magnitude decrease in operating cost, and transition to airline-type operation. NASA's Integrated System Test of an Airbreathing Rocket (ISTAR) program will ground test a hydrocarbon fueled RBCC propulsion system capable of accelerating a self-powered vehicle to about seven times the speed of sound, demonstrating all modes of engine operation. P&W, Aerojet and Rocketdyne have combined their resources into a contractor team, the Rocket Based Combined Cycle Consortium, to execute this program.

A large payoff for lightweight materials is resulting from trade studies for RLVs. Composite materials are being evaluated for application to scramjet propulsion systems. They offer the potential for increased thermal management margin as well as weight reduction when combined with active fuel cooling. Lower density (~0.1 lb/cu in.) versus typical superalloys (~0.3 lb/cu in.) while maintaining high strength at high temperatures make composites attractive for RLVs.

Hydrocarbon Scramjet Engine Technology

The AFRL-sponsored HySET program is developing the technologies necessary to demonstrate the operability, performance and structural durability of a liquid hydrocarbon fueled scramjet propulsion system that operates from Mach 4 to 8. Technology objectives were established during Phase I through the development of a Technology Program Plan that allocated requirements from the system level to the component level. An air vehicle and a propulsion system preliminary design were derived from these requirements. The air vehicle was selected as a near term spinoff of the technology for an expendable missile as shown in Figure 1. The vehicle uses side-mounted solid rocket boosters that accelerate the missile to Mach 4, where the airbreathing scramjet propulsion system is started. The solid rocket boosters are jettisoned and the scramjet accelerates the missile to the Mach 8 cruise condition. After a sustained cruise, a pushover maneuver is initiated and the missile is guided toward its target.

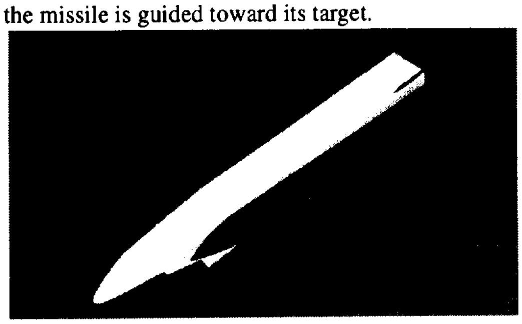

Figure 1. HySET Missile Design

The scramjet preliminary design is shown in Figure 2. It consists of a mixed compression inlet, isolator, pilot, fuel-cooled combustor, nozzle, and engine subsystems. During Phase I, 383 inlet rig test points were run at the NASA Glenn Research Center in the 1- by 1-ft Supersonic Wind Tunnel (Figure 3) over the Mach range from 4 to 8 to evaluate performance and operability. Aerodynamic contraction ratio kinetic energy efficiency and weight flow ratio met or exceeded objectives. Subsequently, 300 inlet tests were conducted in the UTRC Small Scale Inlet Test Facility (Figure 4) to investigate angle-of-attack effects and aspect ratio effects on the inlet.[2]

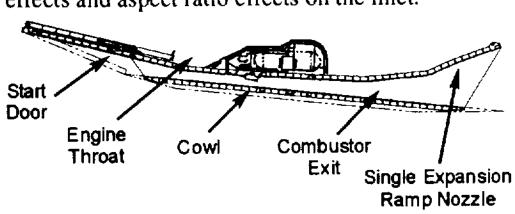

Figure 2. Scramjet Cross Section

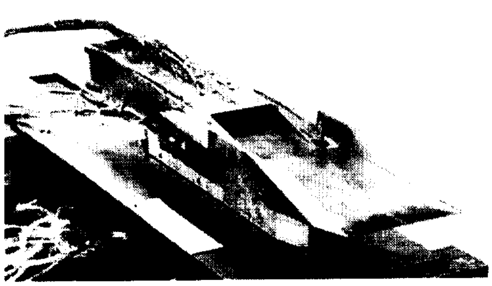

Figure 3. NASA GRC Inlet Rig

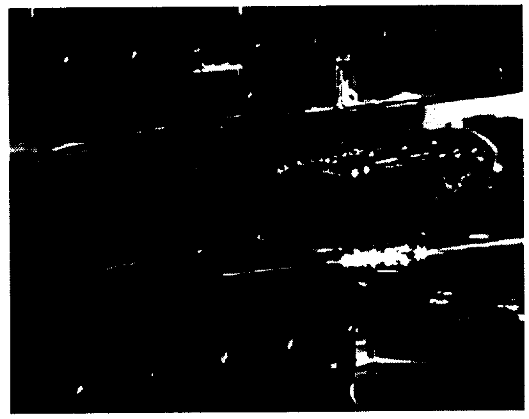

Figure 4. UTRC Inlet Rig

Extensive combustor direct connect rig tests have been performed in HySET. Over 500 test points were conducted using hydrocarbon fuel at UTRC to evaluate pilot concepts and validate heat flux predictive tools. Combustion efficiency met program goals at Mach 4 and 6 conditions.[3] Additional direct connect combustor rig tests were performed in the GASL facility (Figure 5) at Mach 4.5 and 6.5. Over 180 data points were used to determine fuel scheduling, validate engine ignition and start sequences and validate operability and performance.[4]

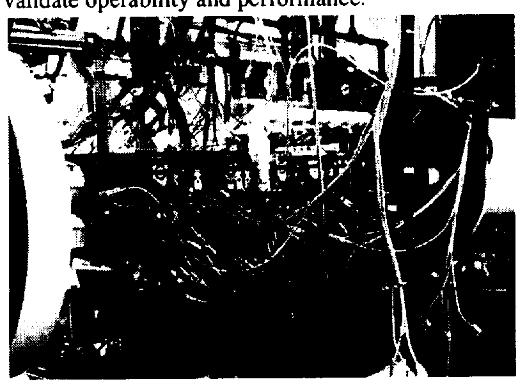

Figure 5. HySET Direct Connect Combustor Rig at GASL

Full-scale engine tests in the GASL freejet facility began in 1997 with a copper heat-sink rig run at Mach 8 conditions using gaseous ethylene fuel (Figure 6). Nineteen data points were recorded to prove the feasibility of hydrocarbon-fueled scramjet engines and validate analytical tools that had been developed during the NASP program using hydrogen fuel. Starting in April 2000 and culminating in January 2001, the copper heat-sink performance test engine (PTE) was run in the GASL freejet facility using heated hydrocarbon fuel and cracked endothermic products. Net positive thrust was measured during the test in agreement with predictions. This marked the first time that a hydrocarbon scramjet was successfully demonstrated without energetic fuel additives. During the 95 test points, the PTE met or exceeded performance objectives at Mach 4.5 and 6.5.

Figure 6. 1997 Freejet Engine Test in GASL Facility

The latest freejet tests are being conducted at GASL with the fuel-cooled, flightweight flowpath ground demonstrator engine (GDE) (Figure 7). The tests will evaluate thermal, mechanical and structural durability.

Figure 7. HySET Ground Demonstrator Engine

Integrated System Test of an Airbreathing Rocket

The ISTAR hydrocarbon RBCC propulsion system is envisioned to power a flight test vehicle from a B-52 or L-1011 aircraft flying at about Mach 0.7 to scramjet operation (about Mach 7). The propulsion system will get its initial power from rockets integrated into an air duct, which improves the rocket only performance by about 15 percent. At about Mach 3, the propulsion system transitions from air-augmented rocket mode to dual-mode scramjet as the rockets are gradually turned off. Acceleration continues until the Mach 6 to 7 range when the fuel has been transitioned forward and scramjet operation has been achieved. The RBCC modes of operation are depicted in Figure 8.[5]

During the Jumpstart Phase of the program, a flowpath selection process was executed. Three concepts were evaluated based on cost, technical risk, schedule risk, and technical merit. The flowpath selected, shown in Figure 9, was fully evaluated and documented in the Conceptual Design Review in June, 2001. The results were that the engine selected did not meet the Mach 0.7 to 7 mission requirements.[6]

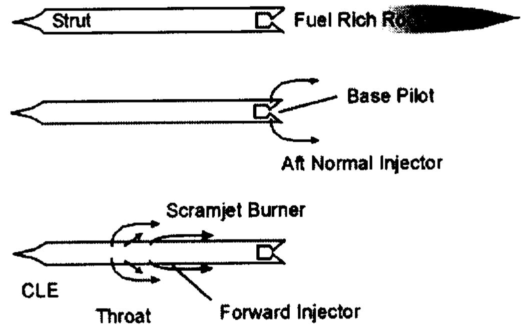

Figure 8. RBCC Modes of Operation

The Transition Phase of ISTAR employed a *Tiger Team* to improve the capabilities of the Jumpstart concept. Three more candidates were selected for evaluation: a fixed geometry concept (Configuration X), a partially variable geometry concept (Configuration Y) and a more variable geometry system (Configuration Z). As shown in Figure 10, Configuration Y was selected based on the least mission performance uncertainty, the highest fuel margin, and increased stability margin. [5]

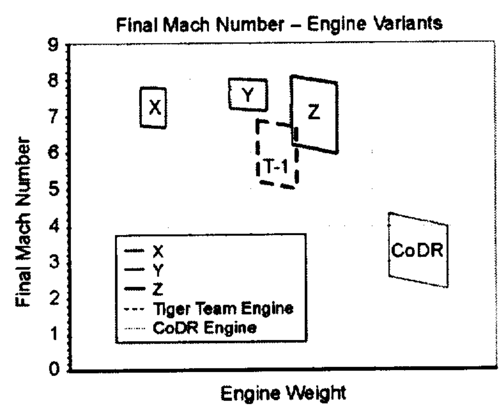

Figure 10. ISTAR Engine Selection Results

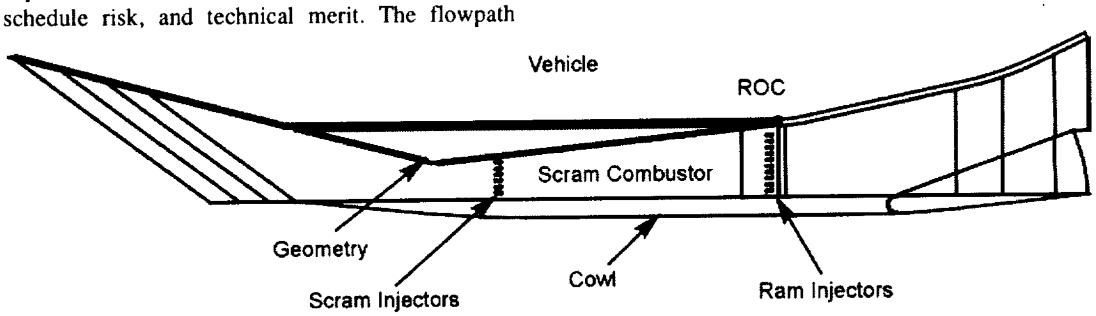

Figure 9. ISTAR Jumpstart Propulsion System

Structures and Materials

P&W has a vast database of high-temperature, high-strength materials that has been applied to hypersonic propulsion systems. For expendable systems, fuel-cooled superalloys have been incorporated to manage the thermal environment and keep manufacturing costs low. As reusable systems develop, a payoff for lightweight, high-temperature, high-strength material is evident.

Engine durability has been demonstrated through the development of fuel-cooled structures. A 6- by 15-in. metal heat exchanger panel was run for a total of 160 seconds at Mach 7 conditions in the UTRC combustor rig (Figure 11) with no deterioration.[4] Two 6- by 30-in. metal panels were tested in the UTRC combustor rig for a total of 1200 seconds. One of these panels was subsequently tested in the AFRL's radiant heat facility (Figure 12) for 19 thermal cycles and a total test time of 58 minutes. A full-scale, sidewall metal panel (Figure 13) was also successfully tested in the AFRL radiant heat facility. A 28-in. metal combustor section box (Figure 14) was evaluated in acoustic tests and overpressurization tests at AFRL successfully. Also, sharp leading edge test specimens of uncooled composite materials were tested by AFRL in the Arnold Engineering Development Center at Mach 8 conditions.

Composite materials are being investigated for reusable scramjet engine applications, but there are limitations that must be addressed. Carbon fiber/carbon matrix composites, known as carbon/carbon, require protection from oxidation. Anti-oxidation coatings are generally applied, when available, in the surface temperature region of interest. Composites are inherently porous, making them difficult to use in conjunction with fuel cooling. However, the lower density of composites coupled with the high temperature resistance and low thermal conductivity make this class of materials worth pursuing. P&W is working collaboratively with SNECMA on combining fuel cooling with composite materials. P&W and UTRC are working under the AFRL-sponsored Advanced Combustion Chamber Concepts program while SNECMA is funded through the French Directeur Generale d'Armements in conjunction with ONERA.[7] P&W also participated in the NASA GRC-sponsored Structures, Materials and Thermal Management program from September 1999 to May 2001. The results of this effort indicated that high-temperature, lightweight composites were needed to achieve an acceptable propulsion system weight for a single-stage-to-orbit (SSTO) RBCC powered vehicle. A subsequent program, currently underway, the NASA GRC-sponsored Maintainable Composite Panel program, is pursuing a composite heat exchanger which is repairable.

Figure 11. UTRC Combustor Rig with 6- by 15-in. Panel

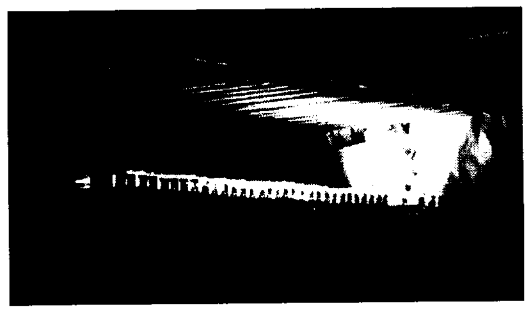

Figure 12. AFRL Radiant Heat Facility with 6- by 30-in. Panel

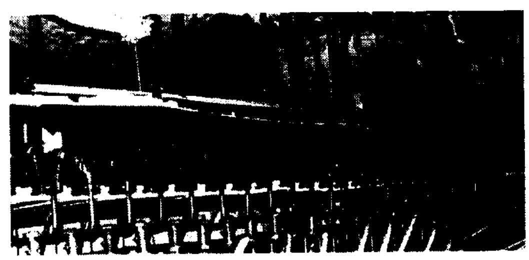

Figure 13. Full-Scale Sidewall Panel in AFRL Radiant Heat Facility

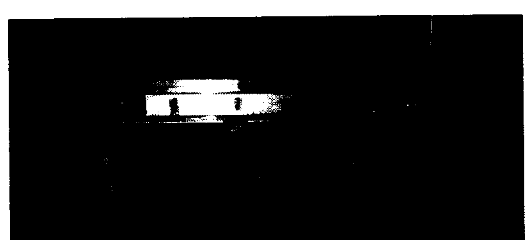

Figure 14. Combustor Box Section Acoustic and Pressure Test

Future Plans

The second build of the HySET Ground Demonstrator Engine (GDE-2) is planned to initiate ground test in late 2003. The flight demonstration of a GDE-2 type engine is planned for the joint NASA/U.S. Air Force X-43C program. Three adjacent engines will be flight tested in this stretch version of NASA's X-43A Hyper-X vehicle in 2007. The 14- to 16-ft vehicle will be rocket-boosted to Mach 5. The HySET derived scramjets will accelerate the vehicle from Mach 5 to about Mach 7 in approximately 5 minutes.[8]

Combined cycle engine ground test and flight demonstrations are also planned. Conceptual design of a dual mode scramjet for a TBCC propulsion system is underway under NASA GRC sponsorship. Ground tests of the TBCC and ISTAR RBCC propulsion systems are planned for the 2006–2008 time period. Flight tests of either or both propulsion systems are contemplated in the 40 ft class X-43B flight demonstrator by 2010. A subsequent large-scale reusable vehicle is envisioned in 2016 as a follow-on to X-43B and predecessor to an operational third generation RLV and/or second generation space operations vehicle in the 2025 timeframe.[8]

A 2.5- by 10-in. cooled composite heat exchanger panel will be evaluated in the NASA GRC Cell 22 Rocket Test Facility under the NASA GRC-sponsored Maintainable Composite Panel program. Subsequently, a 6- by 30-in. panel of the same configuration will b e tested in the UTRC combustor rig. A parallel program, the NASA GRC-sponsored Refractory Composites Inc. Small Business Innovative Research program, will provide an alternative material cooled composite 2.5- by 10-in. and 6- by 30-in. panel for evaluation in the same rigs as above.

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