Airbreathing Hypersonic Propulsion at Pratt & Whitney – Overview

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Pratt & Whitney (P&W) is developing the technology for airbreathing 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. Two successful flight tests in 2004, one approaching Mach 7 and the other near Mach 10, of the P&W-designed, NASP-derived, Hyper-X hydrogen-fueled scramjet have provided flight data for code validation. The Air Force Research Laboratory (AFRL) Hypersonic Technology (HyTech) Office has put programs in place to continue the NASP vision, incrementally, by developing 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. Flight tests of a flight-weight, fuel-cooled hydrocarbon scramjet under the Scramjet Engine Demonstrator-WaveRider (SED-WR) program are planned for 2008–2010 under AFRL and Defense Advanced Research Program Agency (DARPA) sponsorship. The application of scramjet engine technology as part of combined cycle propulsion systems is also being pursued. 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 are being studied for application to hypersonic cruise vehicles and reusable launch systems. P&W's recent activities and future plans for hypersonic propulsion will be described.

I. Introduction

The development of ramjet and scramjet technology began at United Technologies Corporation (UTC) in the 1960s at the United Technologies Research Center (UTRC). Ramjet engine technology was validated in flight tests starting in the 1970s with the Advanced Low Volume Ramjet (Fig. 1) and Advanced Strategic Air-Launched Missile (Fig. 2), and commencing in the 1990s with the Advanced Air-to-Air Missile (Fig. 3). A resurgence of scramjet activity was experienced at P&W in the mid-1980s with the onset of the NASP program. NASP was aimed at developing and flying an integrated low-speed accelerator, ramjet, and scramjet propulsion system. A broad technology base in hydrogen scramjet components and engines for the X-30 flight demonstrator (Fig. 4) was established including validated design tools and methodology during the 10-year NASP program.[1]

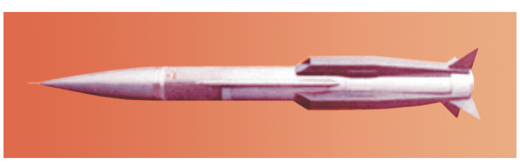

Figure 1. Advanced Low Volume Ramjet (ALVRJ) – Navy

Figure 2. Advanced Strategic Air-Launched Missile (ASALM) – USAF

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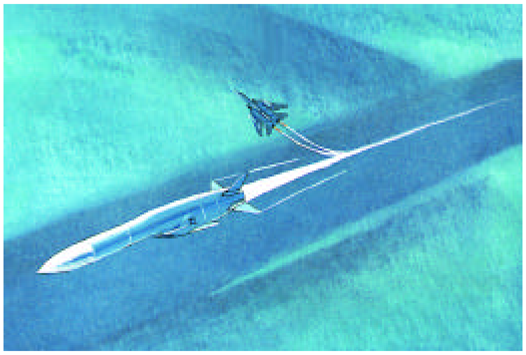

Figure 3. Advanced Air-To-Air Missile (AAAM)

Figure 4. X-30 National Aero-Space Plane (NASP)

The original NASP engine design was used as the foundation for the scramjet design of the Hyper-X vehicle. The flight test of the hydrogen-fueled Hyper-X vehicle was successfully executed in 2004 with flights nearing Mach 7 and Mach 10. In parallel to NASP, UTRC was developing technologies for hydrocarbon-fueled scramjets under the AFRL-sponsored Scramjet Component Technology (SCT) program. The hydrocarbon scramjet is less energetic than the hydrogen scramjet but more logistically supportable. Endothermic cooling technology development and direct connect tests of hydrocarbon fueled scramjet combustors were accomplished under the SCT program.[2]

The Secretary of the Air Force initiated the HyTech Program at AFRL in 1995 to maintain a core competency in hypersonic propulsion technology after NASP. P&W was awarded the 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. The HySET program has exploited breakthroughs in two major areas: first, the piloting scheme developed minimizes intrusions into the flowpath to increase the slim thrust-to-drag margins inherent in previous scramjet designs; second, it has demonstrated the execution of endothermic fuel cooling. The AFRL and P&W ground tested the first uncooled liquid hydrocarbon-fueled scramjet performance test engine (PTE) at simulated flight Mach numbers of 4.5 and 6.5 in 2000 and 2001. This was followed by the first successful ground test of a flight-weight, fuel-cooled scramjet engine (Ground Demonstrator Engine, Build 1 [GDE-1]) at the same flight conditions in 2003. A second build of the flight-weight, fuel-cooled engine (Ground Demonstrator Engine, Build 2 [GDE-2]) with a closed-loop fuel system, variable inlet flap, and full authority digital electronic control (FADEC) is ready to test in 2005. The Air Force and DARPA sponsored SED-WR program, led by a joint team from P&W and Boeing, is poised to flight test the flight-weight, fuel-cooled scramjet propulsion system starting in 2008 and accelerate the vehicle from Mach 4.5 to at least 6.5.

Reusable architectures may benefit from combined cycle propulsion systems that use either rocket propulsion or gas turbine propulsion to accelerate to scramjet takeover speeds. Both rocket-based combined cycle (RBCC) and turbine-based combined cycle (TBCC) propulsion systems have the potential to make future space propulsion safer, more reliable, and less costly than today's spacecraft. For a Reusable Launch Vehicle (RLV), this translates to two orders of magnitude increase in safety, two orders of magnitude decrease in operating cost, and transition to airline-type operation. Hypersonic cruise vehicles offer global range and reduced time of flight. Both two-dimensional (2-D) systems and three-dimensional (3-D) systems will be investigated.

II. Hyper-X (X-43A)

Following NASP, P&W worked with Boeing St. Louis (at the time, McDonnell Douglas) to design the engines for a Dual-Fuel Airbreathing Hypersonic Vehicle[3] and its X-Plane demonstrator, which became the Hyper-X (X-43A). NASA's subsequent competition to build and fly the X-43A was won by a team led by Microcraft (now part of ATK) and included North American Rockwell (now part of Boeing) and GASL (now part of ATK). NASA Langley Research Center (LaRC) modified P&W's flowpath design of the X-43A engine and GASL fabricated the engine. The X-43A (Fig. 5) established the record for the fastest speed ever achieved by an aircraft powered by an airbreathing propulsion system on March 27, 2004 (Mach 6.83). The X-43A then beat its own record on November 16, 2004 when it flew Mach 9.68. Using a combination of P&W's NASTAR code and NASA's VULCAN code, P&W conducted pretest predictions of the engine performance for the Mach 7 flight that compares well with X-43A flight data.

Figure 5. X-43A Captive Carry and Flight

III. Hydrocarbon Scramjet Engine Technology (HySET)

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.

The scramjet design 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 (GRC) in the 1 ft x 1 ft Supersonic Wind Tunnel (Fig. 6) 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 (Fig. 7) to investigate angle-of-attack (AOA) effects and aspect ratio effects on the inlet.[4]

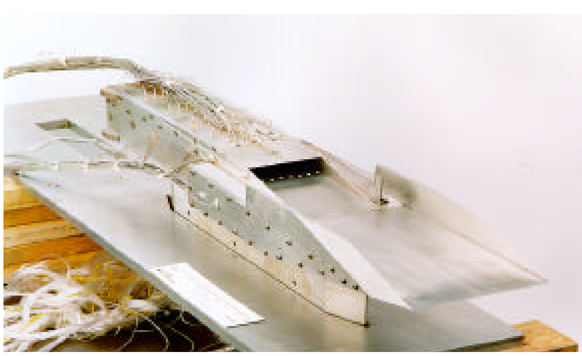

Figure 6. NASA GRC Inlet Rig

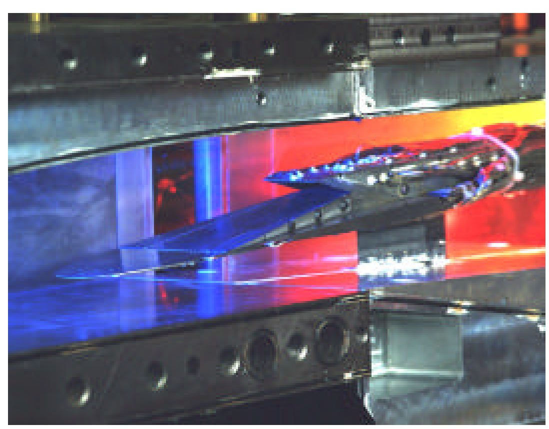

Figure 7. UTRC Inlet Rig

Extensive combustor direct connect rig tests have been performed in HySET. Over 500 test points were conducted using JP-7 fuel at UTRC to evaluate pilot concepts and validate heat flux predictive tools. Combustion efficiency met program goals at Mach 4 and 6 conditions.[5] Additional direct connect combustor rig tests were performed at Mach 4.5 and 6.5 (Fig. 8). Over 180 data points were used to determine fuel scheduling, validate engine ignition and start sequences, and validate operability and performance.[6]

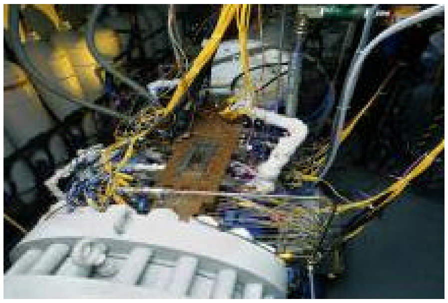

Figure 8. HySET Direct Connect Combustor Rig

Full-scale engine tests began in 1997 with a copper heat-sink rig run at Mach 8 conditions using gaseous ethylene fuel (Fig. 9). 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 PTE (Fig. 10) was run in a freejet facility using heated JP-7 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.[7]

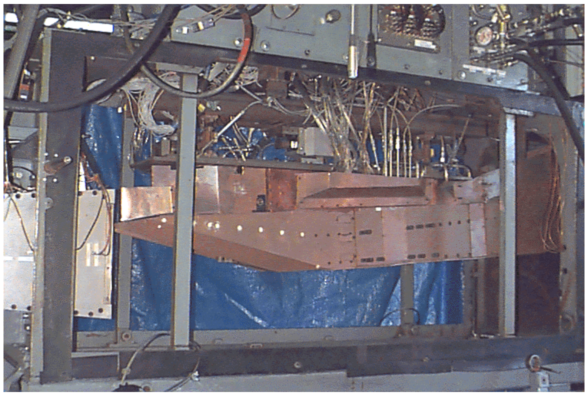

Figure 9. 1997 Freejet Engine Test

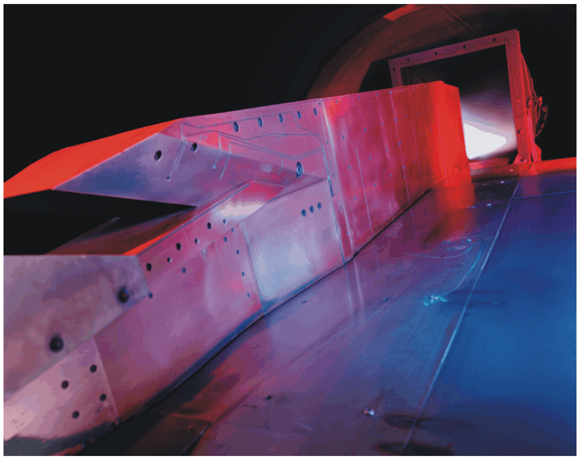

Figure 10. Performance Test Engine

Additional freejet tests were conducted in 2003 with the fuel-cooled, flight-weight flowpath GDE-1 (Fig. 11). The tests evaluated thermal, mechanical, and structural durability. Hardware condition at the conclusion of the test program was excellent. Engine performance exceeded the PTE performance due in part to better matching of the fuel temperature anticipated at the injection sites. A total of 60 test points were conducted at Mach 4.5 and 6.5 conditions.[8]

To reduce program risk prior to the next build of the freejet engine, a series of cowl flap tests were conducted at flight Mach 7 conditions. The variable inlet cowl flap will optimize the captured airflow and aerodynamic contraction ratio throughout the flight envelope to provide the maximum inlet efficiency. The variable geometry hardware including high temperature seals (Fig. 12) performed flawlessly.

The second build of the fuel-cooled, flight-weight GDE-2 has completed fabrication and is ready for test. This engine features a variable inlet flap, closed-loop fuel cooling and combustion system, hot fuel distribution valve, and FADEC

Figure 11. Ground Demonstrator Engine, Build 1

(Fig. 13). A bolted assembly is incorporated in place of the welded construction in GDE-1 to produce a more robust design that is maintainable for reusable missions. A ceramic composite cowl leading edge is also included.[9]

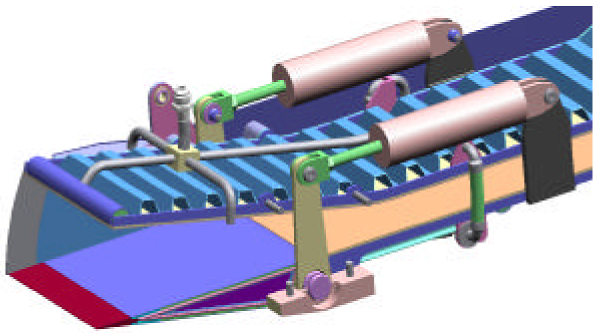

Figure 12. Moveable Cowl Flap Risk Reduction Tests

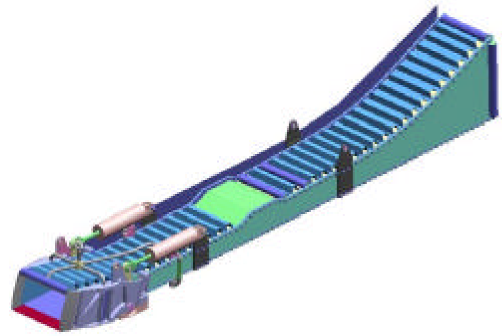

Figure 13. Ground Demonstrator Engine, Build 2

IV. SED-WR Flight Test Program

A team of P&W and Boeing — sponsored by and in conjunction with the AFRL and DARPA — will conduct flight tests of a hydrocarbon-fueled, flight-weight dual mode scramjet under the Scramjet Engine Demonstrator-WaveRider program. The program was initiated in 2003 and the System Level Preliminary Design Review (PDR) was completed in late 2004. SED-WR is scheduled to begin flight tests in 2008. Several minutes of engine operation will be demonstrated and the aircraft will fly autonomously (Fig. 14).

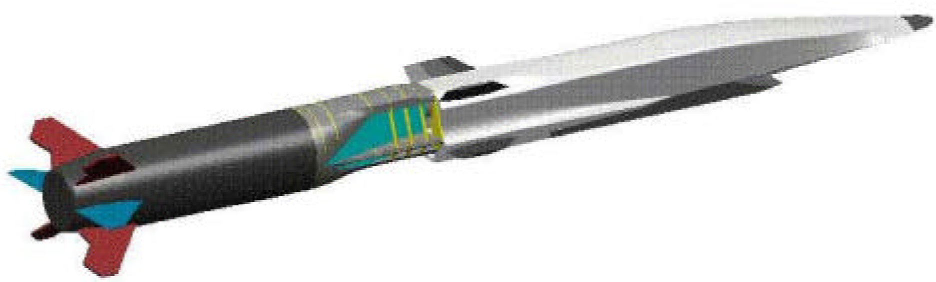

Figure 14. Scramjet Engine Demonstrator – WaveRider

V. Future Plans

Combined/combination cycle propulsion systems will be developed for reusable applications such as hypersonic cruise vehicles and reusable launch vehicles. Turbine-based combined cycle propulsion design challenges include mode transition from gas turbine power to ramjet and/or scramjet power and back to gas turbine power. Cocooning of the gas turbine while the ramjet/scramjet operates is also desired. Integration of the gas turbine with the ramjet/scramjet and the aircraft for both 2-D, high-speed flowpaths and 3-D flowpaths is challenging. Likewise, for rocket-based combined cycle, the designer must consider the location of the rocket and ramjet/scramjet flowpaths relative to each other, whether to imbed rockets into the high speed flowpath and where, and mode transition between rocket power and ramjet/scramjet power. Two-dimensional and three-dimensional RBCC concepts are also feasible. These challenges must be met before combined cycle flight demonstrations in a representative vehicle configuration are realized.

References

[1]Andreadis, D., “Scramjet Engines Enabling the Seamless Integration of Air & Space Operations,” *The Industrial Physicist*, Aug./Sept. 2004.

[2]“Hypersonic Technology Scramjet Engine Reaches Major Milestone,” *Technology Horizons*, Vol. 2, No. 4; Dec. 2001.

[3]Bogar, T.J., Alberico, J.F., Johnson, D.B., Espinosa, A.M., Lockwood, M.K., “Dual-Fuel Lifting Body Configuration Development,” AIAA 96-4592.

[4]Kandebo, S.W., “Landmark Tests Boost Scramjet’s Future,” “Testing Key to Scramjet Success,” *Aviation Week & Space Technology*, Mar. 26, 2001.

[5]Kazmar, R.R., “Hypersonic Missile Propulsion System,” AIAA Paper, Nov. 1999.

[6]Faulkner, R.F., Weber, J.W., “Hydrocarbon Scramjet Propulsion System Development, Demonstration, and Application,” AIAA-99-4922.

[7]Kazmar, R.R., “Hypersonic Propulsion at Pratt & Whitney – Overview,” AIAA Paper, Oct. 2002.

[8]Wishart, D.P., Fortin, T., Guinan, D, Norris, R.B., Modroukas, D., “Design, Fabrication and Testing of an Actively Cooled Scramjet Propulsion System,” AIAA 2003-0015, Jan. 2003.

[9]Faulkner, R.F., “The Evolution of the HySET Hydrocarbon Fueled Scramjet Engine, AIAA Paper, AIAA-2003-7005.