HIFIRE: AN INTERNATIONAL COLLABORATION TO ADVANCE THE SCIENCE AND TECHNOLOGY OF HYPERSONIC FLIGHT

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Abstract

The Hypersonic International Flight Research and Experimentation (HIFiRE) program was created to perform hypersonic flight tests intended to quickly and affordably gather fundamental scientific data that are difficult or impossible to obtain via ground testing alone. The program is being executed jointly by the United States Air Force Research Laboratory (AFRL) and the Australian Defence Science and Technology Organisation (DSTO), with significant support from partners Boeing in the U.S. and the University of Queensland in Australia. Intellectual, financial, and physical resources from the four partners have been combined to achieve these essential objectives with the overarching goal of advancing the art and science of hypersonic flight.

1 Introduction

Efficient hypersonic flight would dramatically reduce the time required for global travel and could make the deployment of orbital payloads significantly more routine and affordable. The successful development of hypersonic vehicles, however, first requires the generation of an extensive high-fidelity design database. Creating this database will require the collection of both fundamental and system-level performance data that cannot be gathered completely in existing ground test facilities due to the high flow energy and extreme thermal environment encountered in hypersonic flight. Flight testing is therefore crucial to the development of this database. Its development will also require extensive computational analysis and physical simulations to supplement the experimental data, particularly at flow conditions and/or physical scales that are difficult to access experimentally.

The emphasis of most hypersonic flight test activity over the past decade (e.g., X-43, X-51, and HyFly) has been on technology demonstrations rather than on capturing scientific data to advance the understanding of fundamental hypersonic flight phenomena.[1,2] To supplement the data collected in system-level flight tests, a new flight test program, Hypersonic International Flight Research and Experimentation (HIFiRE), was launched in 2006 to focus on gathering fundamental scientific data in the hypersonic flight regime that are difficult or impossible to obtain through ground testing alone.[3]

The HIFiRE program is investigating fundamental hypersonic air vehicle and propulsion phenomena and technologies deemed critical to practical and efficient hypersonic flight. And it is a program goal to do so in less time and at lower cost than has traditionally been possible. As a tradeoff for speed and affordability, however, the program has accepted more technical risk than is typically judged prudent for a flight test program.

Candidate technologies for investigation in the HIFiRE program include, but are not limited to, propulsion, aerodynamics, propulsion-airframe integration, aerothermodynamics, advanced flight control, high-temperature materials and structures, thermal management, instrumentation, sensors, and system components. The program scope encompasses a core flight research program and numerous coordinated research tasks, including ground experiments and the development and verification of computational analysis and numerical simulations. The program is comprised of a set of nine focused research elements, each intended to significantly increase understanding of specific hypersonic phenomena through computational analysis, ground testing, flight testing, and the correlation of data from all three methods of data generation. Each research effort will culminate with a flight experiment boosted to representative flight conditions in terms of Mach number and Reynolds number using low-cost sounding rockets.

The HIFiRE program is being executed by a multi-national, multi-agency, multidisciplinary team representing several components of government, industry, and academia under authority of Project Arrangement AF-06-0046, dated 31 October 2006. Design development and flight test efforts are being performed concurrently by multiple flight project teams, each representing the diverse interests of the Air Force Research Laboratory (AFRL) and NASA in the US, and the Defence Science Technology Organisation (DSTO) in Australia. Funding provided by the Queensland State Government through their Smart State Initiative helped enable the program.

Several organizations also have contributed to HIFiRE program execution and success. For example, a significant third-party relationship was established by primary program partners AFRL and DSTO with the Boeing Research and Technology group (BR&T) of The Boeing Company. Boeing is contributing financially and technically to the program. Additional industry contributors include ATK-GASL, BAE Systems Australia, and GoHypersonic Inc. (GHI). Significant research support has been secured from academia, predominantly the University of Queensland in Australia, which also has contributed financially to the program. Rocket launch services have been secured from both the US Navy (NAVSEA) at the US Army White Sands Missile Range (WSMR) and the German Aerospace Research Institute (DLR) at MORABA. Flight tests are executed by a 40+ person multinational team including members from AFRL, DSTO, NAVSEA, Kratos Defense & Security Solutions, the Royal Australian Navy (RANRAU), the Royal Australian Air Force (RAAF/AOSG), and DLR.

Key to HIFiRE program success has been and will continue to be the excellent cooperation and collaboration of all international and organizational team members, and the intellectual, financial, and physical resources provided to the program by all team members.

2.0 Science Objectives and Accomplishments of HIFiRE Flight Research Vehicles

Originally there were three flights planned for what is now the HIFiRE program (currently designated as flights 4, 7 and 8). The objectives of the three flights were to characterize scramjet propulsion system performance (HIFiRE-7), develop flight control algorithms (HIFIRE-4), and combine the two to undertake sustained flight of a scramjet powered vehicle (HIFiRE-8). These flights were originally funded by The University of Queensland, Boeing, DSTO, and the Queensland State Government through their Smart State Initiative.

It soon became clear, however, that additional flights were required to address the broader scientific and engineering challenges associated with hypersonic flight. The Air Force Research Laboratory (AFRL), with assistance from the Air Force Office of Scientific Research (AFOSR), therefore joined the program as a major partner and DSTO made a major investment in the program by providing a program office, increased staff, and substantial additional funding. The number of flight research vehicles planned for what was now called the HIFiRE program increased from three to nine. Following the increase in program scope resulting from the Program Agreement between the USAF and DSTO, ATK-GASL, BAE Systems, and DLR joined the program as collaborators. Additionally, although not formal partners, NAVSEA at WSMR and Kratos have worked collaboratively with the program to support launch services.

The nine flight experiments and associated flight research vehicles can be grouped into five categories of scientific and/or engineering objectives. One objectives category, addressed by the first vehicle, designated HIFiRE-0, is validating flight control systems, flight-critical electrical systems, and software for subsequent HIFiRE flight tests. A second objectives category, the focus of flight vehicles designated HIFiRE-1 and HIFiRE-5, is boundary layer transition and other fluid dynamic phenomena. The flight research vehicles designated HIFiRE-2, HIFiRE-3, and HIFiRE-7 address a third objectives category, namely advanced scramjet propulsion, while flight vehicles HIFiRE-4 and HIFiRE-6 focus on flight controls as a fourth objectives category. Finally, the HIFiRE-8 vehicle addresses the fifth objectives category, hypersonic vehicle integrated system performance. It should be noted that flight vehicle numbering does not correspond to the order in which experiments are flown. These nine flight research vehicles encompass a comprehensive set of science and technology investigations in the hypersonic flight regime, as summarized in Table 1.

HIFiRE Flight no.	Description
HIFiRE-0	Simple flight vehicle reorientation experiment (SL & TL DSTO)
HIFiRE-1	A blunted cone boundary layer transition experiment (SL AFRL, TL DSTO)
HIFiRE-2	A dual-mode scramjet experiment (SL & TL AFRL)
HIFiRE-3	Radical farming scramjet experiment (SL DSTO, TL DSTO)
HIFiRE-4	Reentry glider control experiment (SL Boeing, UQ, DSTO; TL DSTO)
HIFiRE-5	Elliptic cone boundary layer transition (SL AFRL, TL DSTO)
HIFiRE-6	Aero-propulsion glider adaptive control experiment (SL & TL AFRL)
HIFiRE-7	REST inlet scramjet thrust measurement (SL UQ, Boeing, DSTO; TL DSTO)
HIFiRE-8	30 second flight of airframe powered by REST scramjet (SL UQ, Boeing, DSTO; TL DSTO)

Table 1 Descriptions of the nine HIFiRE research vehicles. Note that SL denotes science lead and TL denotes technical lead.

Rocket-boosted trajectories employed to fly the HIFiRE research vehicles are either steep ballistic parabolic trajectories where the majority of the experiment is completed during a nearly vertical reentry or suppressed trajectories where the experiment is performed during ascent. Both trajectory types are illustrated in Fig. 1. Sounding rocket stages used in various combinations include Terrier, Talos, Orion, Oriole, and the Brazilian S-30, S-31, S40, and S44 motors.

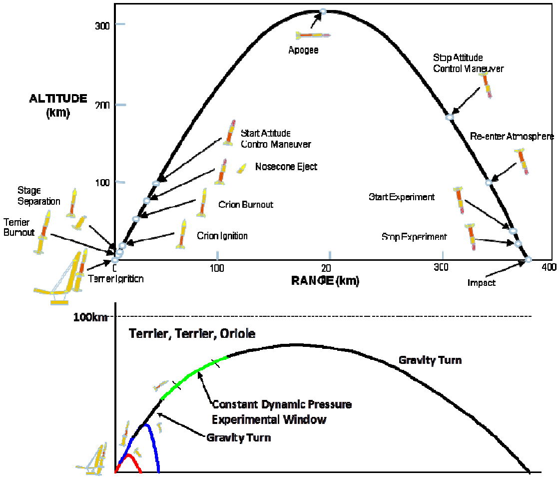

Figure 1 Depictions of ballistic and suppressed trajectories employed in HIFiRE flight experiments.

Grouped by the five defined categories, the nine HIFiRE flight experiments will next be described in more detail, either in terms of their intended flight experiment objectives and approach, or achieved objectives and approach in the case of experiments that have already flown.

HIFiRE-0 was launched at Woomera on 7 May 2009 using a two-stage Terrier-Orion sounding rocket stack. The main objectives of the experiment were to:

a) Demonstrate the proper function of DSTO-developed flight computers and operating system in terms of data collection and transmission, and control of payload mechanical devices.

b) Demonstrate that exo-atmospheric vehicle re-orientation could be achieved using cold gas thrusters and a combination of magnetometer and horizon sensor for attitude determination.

c) Develop the Woomera infrastructure to support the remainder of the HIFiRE program.

The flight achieved all planned objectives with some minor issues discovered relative to telemetry frame packing and the operating system controlling multiple flight computers. The vehicle was turned over successfully with a final angle of attack less than 2 degrees and effectively zero coning. Fig. 2 is a plot of measured vehicle elevation angle as a function of time during the reorientation maneuver. Recovery of the payload was achieved, which is important, as it provided additional information about the flight.

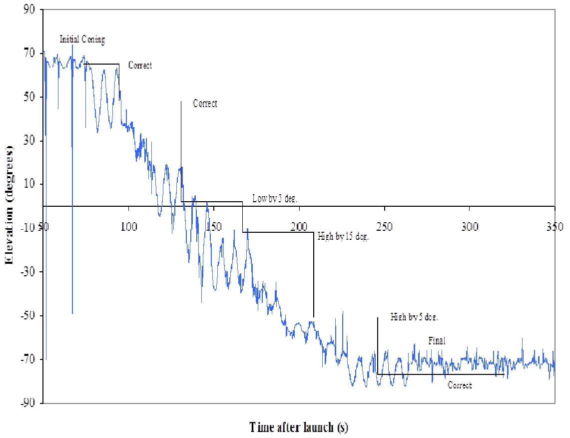

Figure 2 Time history of HIFiRE-0 elevation angle turned over using cold jet thrusters.

The first science flight of the HIFiRE series, **HIFiRE-1** was launched on 22 March 2010 at Woomera using a two-stage Terrier-Orion sounding rocket stack. The primary objective of HIFiRE-1 was to measure aerothermal phenomena in hypersonic flight. The primary experiment consisted of boundary-layer transition measurements on a 7-deg half angle cone with a blunted nose radius of 2.5 mm.[4,5] A secondary aerothermal experiment was a shock-boundary-layer interaction created by a 33-deg flare/cylinder configuration. A tertiary experiment employed two tunable diode laser absorption spectroscopy (TDLAS) systems to non-intrusively measure oxygen concentration and flow velocity, permitting the calculation of air mass flux from measured quantities. The experiment ready for flight is shown in Fig. 3.

Figure 3 The HIFiRE-1 cone boundary layer transition experiment payload ready for flight.

HIFiRE-1 ground test and computation generated an extensive database for boundary layer transition on axisymmetric bodies. This research has been summarized in numerous prior publications.[6,7]

Unlike previous flights, this payload did not have a nose cone covering the payload during ascent so that data could be gathered on both ascent and descent. Although the scientific objectives of the flight experiment were met, a number of problems occurred in flight and full payload re-orientation was not achieved. Most issues resulted from aerodynamic heating generated by the steep flair behind the cone and the lack of a nose cone, which destroyed the horizon sensors. Fortunately, heat conduction was delayed long enough that half the vehicle reorientation maneuver was completed. As a result, data collected during reentry were still valuable.[8]

HIFiRE-5 was flown from the Andøya Rocket Range (ARR) in Norway on 23 April 2012 using a two-stage booster stack comprised of a Brazilian S-30 first stage and an Improved Orion second stage. The launch was completed 12 weeks after DSTO first visited the ARR and was achieved because of the close collaboration between HIFiRE team members and DLR personnel. The primary objective of the HIFiRE-5 flight experiment was measuring boundary-layer transition on an elliptic cone, shown in Fig. 4, as a means of investigating the effects of 3-D flow on transition in flight.[9,10,11] A secondary experiment developed by DLR – a set of small sharp-edged C/SiC fins – was also flown on the experimental payload.

Figure 4 The HIFiRE-5 elliptic cone boundary layer transition experiment payload ready for flight.

New for HIFiRE-5 was use of an inertial measurement unit (IMU) and GPS as primary attitude determination and navigation systems, whereas the horizon sensor and magnetometer used on prior flights were employed as backup systems.

HIFiRE-5 was also the first non-cylindrical configuration flown. It was surprising the variation in drag and lift coefficients predicted by various aerodynamic analysis methods used to build the aero database and cross-check predictions. This begs an important question: Which aero dataset, if any, is correct? The answer is important because it impacts vehicle stability, scientific outcomes, and most importantly, range safety. One of the secondary objectives of this flight was therefore establishing tools that would accurately predict aero-coefficients for relatively complex configurations.

Unfortunately, when flown the HIFiRE-5 second stage failed to ignite. Despite this disappointing outcome that prevented scientific data from being gathered, technical milestones were still met for verifying the flight software, operating system, second generation flight computers, IMU, GPS, and predicted aerodynamic database. As some consolation, 200 sec of high-fidelity supersonic data was gathered and boundary layer transition was observed.

The first scramjet propulsion flight experiment of the HIFiRE series, **HIFiRE-2** was launched on 1 May 2012 at the Pacific Missile Range Facility (PMRF) in Kauai, Hawaii using a three-stage Terrier-Terrier-Oriole booster stack. The primary objectives of HIFiRE-2 were to measure, in flight, combustor operability and performance during the transition from transonic dual-mode combustion to pure supersonic combustion in a hydrocarbon-fueled scramjet. This was accomplished by accelerating a scramjet from Mach 6 to 8 with the Oriole third-stage of the booster stack. The HIFiRE-2 scramjet research payload is shown in Fig. 5. Secondary objectives included the use of diode laser-based instrumentation to measure combustor exit water concentration and temperature, the delineation of combustor lean blowout limits, and the validation of scramjet design and analysis tools.

Figure 5 The HIFiRE-2 scramjet mode transition experiment being prepared for flight.

Based on preliminary data analysis, indications are that all HIFiRE-2 flight test objectives were met, including flying through the specified Mach number and dynamic pressure (i.e., altitude) test window, and achieving engine mode transition from subsonic to supersonic combustion.

The primary objective of **HIFiRE-3** is to flight test an axisymmetric, hydrogen-fueled, “radical-farm” supersonic combustion experiment and compare data collected in flight to those collected on the ground in the UQ T4 shock tunnel. Fig. 6 illustrates the shock structure in an engine employing a radical farm reaction mechanism as predicted by CFD. It should be noted that there are no recirculation regions in the combustor and the mean flow conditions are not high enough in terms of temperature or pressure to promote fuel combustion. However, as a matter of design the engine generates a series of longitudinal shock diamonds wherein the pressure and temperature are high enough to create chemical radicals in the fuel-air mixture. Although the radicals are frozen in the low pressure and temperature flow region downstream of each shock diamond, they continue to be processed in subsequent shock diamonds via chemical reactions until combustion is eventually complete. An experimental result from the T4 shock tunnel displaying the pressure distribution produced by a radical farm combustion process is shown in Fig 7.

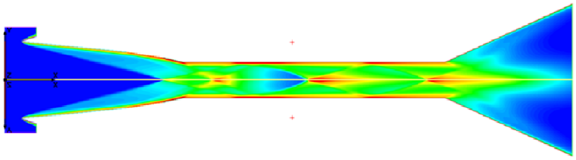

Figure 6 Shock structure in a radical farm scramjet combustor with conical inlet as predicted by CFD.

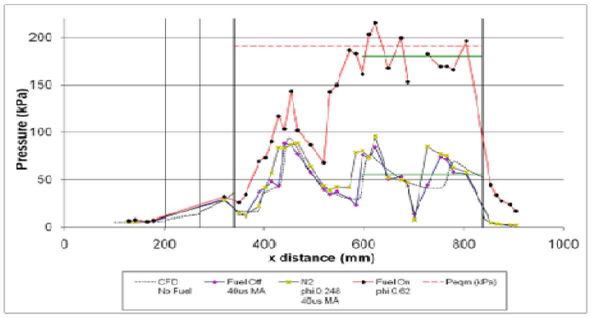

Figure 7 Pressure distributions in the HIFiRE-3 “radical farm” scramjet combustor measured in the T4 shock tunnel.

An interesting feature of this scramjet design is a 3-stage inward-turning conical inlet that has an internal (and total) contraction ratio of 4.6. As a result of its high contraction ratio the inlet will not self-start and a means had to be devised to start the inlet using mechanical variable-geometry air spillage devices. Start doors were therefore designed based on the work of Molder.[12] The resulting starting mechanism was successfully tested at the University of Southern Queensland in a Ludwig tube. Note that if an inlet unstart occurs in flight, it will be detected as an increase in inlet pressure and the start doors can be opened and closed again in 200 ms to re-start the inlet.

The HIFiRE-3 experiment was scheduled to fly during the same campaign as HIFiRE-5, but because of the ignition failure of the HIFiRE-5 second stage rocket motor the flight has been postponed until September 2012.

The primary objective of **HIFiRE-7** is to measure in flight the thrust generated by a scramjet employing a Rectangular to Elliptical Stream Traced (REST) inlet, developed by Smart[13], in preparation for flying the same engine integrated on an airframe for HIFiRE-8. The HIFiRE-7 scramjet with REST inlet is shown in Fig. 8. The engine is designed with inlet and isolator fuel injection. A typical engine pressure distribution as measured in the T4 shock tunnel is presented in Fig. 9. Because thrust cannot be measured in the T4 tunnel where this engine has been tested, it instead is derived from CFD analysis and by curve-fitting measured tunnel pressure data. A flight experiment was therefore required to establish the accuracy of this thrust prediction approach.

Figure 8 A scramjet engine employing a REST inlet as tested in the T4 shock tunnel.

Although the contraction ratio of the HIFiRE-7 inlet at nine is about twice that of the HIFiRE-3 inlet, it is self-starting due to design features such as swept inlet sidewalls and a fixed cowl notch that naturally facilitate air spillage during the starting process. The engine can operate on hydrogen, ethylene, or a mixture of the two fuels. In flight it will operate on pure ethylene, which required the development of a heater to maintain it in its gaseous phase.

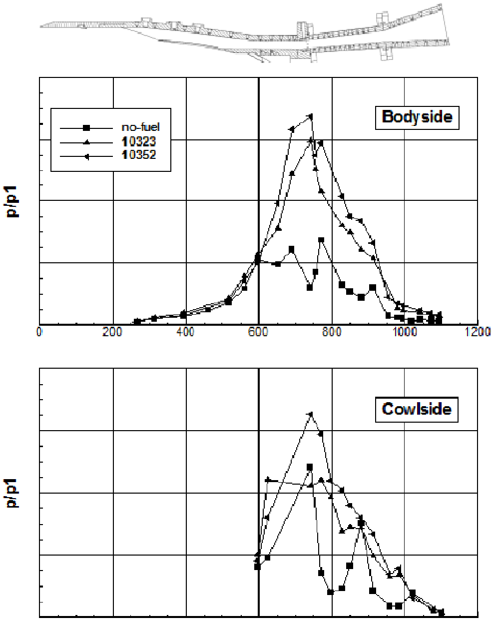

Figure 9 Comparison of pressure distributions in REST scramjet for equivalence ratios of 0, 0.5, and 0.84.

This flight will be the first that does not remain attached to the expended second stage motor during descent. While outside the atmosphere the payload will be de-spun, then released from the second stage and oriented for atmospheric entry. On entry it will be stabilized by a conical flare located aft on the payload. Fuel will be pulsed on and off at intervals of approximately 100 ms so that thrust increments can be measured over a range of equivalence ratios and altitudes, hence dynamic pressure. The HIFiRE-7 payload, depicted in Fig. 10, is scheduled to fly in June 2013.

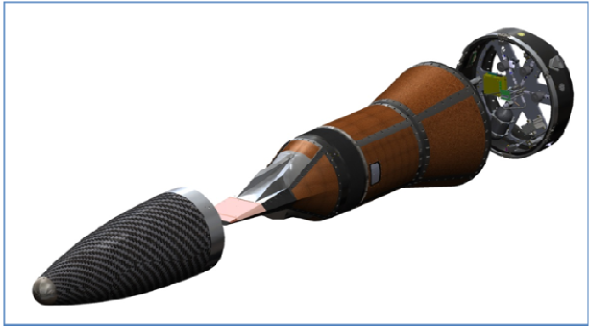

Figure 10 The HIFiRE-7 payload configuration designed to flight test the REST scramjet.

The **HIFiRE-4** flight experiment was included in the test matrix to develop and validate a flight control system for the HIFiRE-8 aero-propulsion flight research vehicle. This will be done using a high lift-to-drag ratio hypersonic glider. To provide for inertial symmetry during ascent, two HIFiRE-4 gliders will be secured under a nose cone and boosted to approximately 250 km altitude, where together they will be de-spun, separated from the booster and each other, and then oriented for atmospheric entry. Different control strategies developed by Boeing and DSTO are being implemented on each of the two otherwise identical vehicles.

Because HIFiRE-4 will be boosted along a steep parabolic trajectory to keep it within the test range, a portion of its flight will be exo-atmospheric, requiring the use of cold-gas thrusters to control the vehicle outside the atmosphere, transitioning to standard aerodynamic controls after dynamic pressure builds up sufficiently after atmospheric entry at about 50 km altitude. After entry the DSTO flyer will be controlled through a 25 degree change in flight path angle and then terminated. A secondary experiment will be performed with the Boeing flyer, controlling it further to horizontal flight and a relatively gentle water impact at the Andøya Rocket Range.

The HIFiRE-4 glider shape, illustrated in Fig. 11, was developed after many iterations and inputs from all collaborators. In the end the vehicle outer mold line was designed using Boeing's proprietary waverider optimization software. The aero-database was generated by Boeing using the Cart3D Euler CFD analysis code, which was later confirmed by DSTO analysis. Due to budget limitations, a bold philosophical approach has been adopted to forgo wind tunnel testing and rely totally upon aerodynamic force and moment predictions from CFD analysis to develop the flight control system.[14]

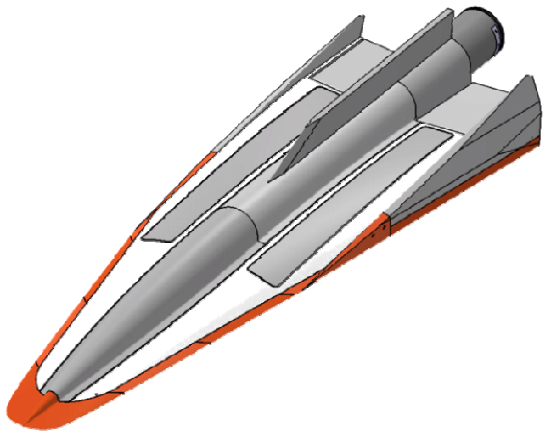

Figure 11 A Waverider hypersonic glider for the HIFiRE-4 flight control experiment.

Each flyer will have two telemetry up-links so they can be controlled and terminated, if required. This will be the first HIFiRE flight requiring a flight termination system; required because, at least in principle, the vehicles could glide outside the test range. In reality, however, they are unstable and would depart controlled flight, tumbling along a ballistic trajectory, if a control system failure was encountered.

Hardware-in-the-loop (HIL) testing of this vehicle required special development, done by BAE Systems Australia. This HIL Approach was successfully verified on HIFiRE-5 and HIFiRE-3, and will be used exclusively for HIFiRE-7 and HIFiRE-8 system testing. HIFiRE-4 is scheduled to fly in October 2013.

The objective of **HIFiRE-6** is to develop and flight test an adaptive vehicle control system that can accommodate aero-propulsive uncertainties that might be encountered in the extreme, difficult to test or analyze hypersonic flight environment.[15] The flight research vehicle – an un-powered inward-turning scramjet flowpath integrated on a waverider lifting body – will be boosted along a direct-ascent (i.e., suppressed) trajectory to a speed of about Mach 7 and a dynamic pressure of about 50 kPa using a 3-stage booster stack. Initially shrouded, near the test window entry point the shroud will be deployed, the vehicle separated from the booster motor, and the vehicle aerodynamically maneuvered to test window entry conditions.

The flyer will then glide unpowered, performing turning maneuvers to exercise its adaptive control system, decelerating to a speed where the inlet naturally unstarts. The flight experiment will officially terminate after this point.

The HIFiRE-6 propulsion-integrated aerodynamic design, illustrated in Fig. 12, was developed by Boeing using its proprietary waverider optimization software and method for integrating a waveriding inward-turning inlet and engine nacelle onto a waverider wing. An extensive trade study of vertical tail arrangements and sizes was performed on this vehicle to satisfy stability and control requirements at minimum drag impact, resulting in a vehicle with a high trimmed lift-to-drag ratio. The vehicle aero-database was generated by Boeing using the Cart3D Euler and Overflow RANS CFD analysis codes. Wind tunnel testing is planned to validate and supplement the aero database generated from CFD predictions. HIFiRE-6 is scheduled to fly in October 2014.

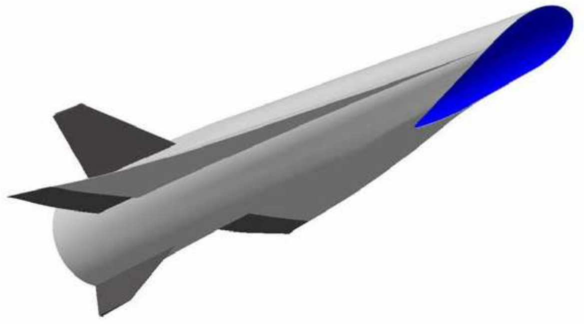

Figure 12 A waverider with an integrated inward-turning scramjet flowpath for the HIFiRE-6 adaptive flight control experiment.

HIFiRE-8 is intended to combine the REST scramjet engine from HIFiRE-7 and the control strategies and algorithms developed on HIFiRE-4 into a hypersonic cruise vehicle that will operate for 30 seconds at Mach 7 under scramjet power. The vehicle aerodynamic design, illustrated in Fig. 13, was developed by Boeing using the HIFiRE-6 concept as a starting point, then integrating the HIFiRE-7 scramjet flowpath onto the airframe while retaining as much design commonality between the two vehicles as possible.

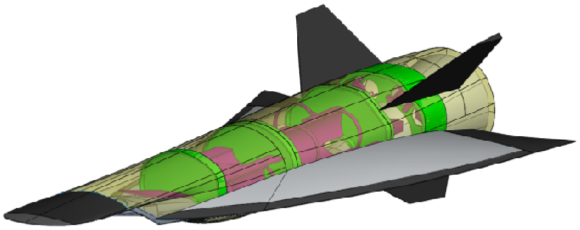

Figure 13 A waverider with a REST scramjet flowpath for the HIFiRE-8 integrated aero-propulsion flight test.

The most imposing challenge for HIFiRE-8 is aerodynamic heating and the relatively small budget available to deal with it. For this reason, extensive use will be made of ablative materials where appropriate. For the scramjet combustor, the Australian Defence Material and Technology Centre (DMTC) has been tasked with developing a suitable combustor design solution. There are a number of ceramic matrix composite contenders, with candidate solutions coming from the Australian Nuclear Science and Technology Organisation (ANSTO) as well. At DSTO carbon-carbon leading edge design solutions have been developed and extensive work has been undertaken to quantify the cooling properties of ethylene. At UQ studies of engine film cooling have been conducted and a new understanding gained regarding the superior film-cooling effectiveness of a burned hydrogen fuel layer compared to an unburned layer.[16] This work has been extended to ethylene with the same beneficial effects observed.

The HIFiRE-8 flight research vehicle is currently in the early design phase but maturing quickly. The vehicle is scheduled to fly in October 2014.

3.0 Government Roles and Program Contributions

Two government agencies have primary responsibility for executing the HIFiRE program, namely AFRL in the US and DSTO in Australia. There are, however, a few additional government agencies also participating in and contributing to HIFiRE, among them NASA, the US Navy, and DLR (the German Aerospace Center).

Program responsibilities for AFRL include:

- Develop hypersonic vehicle designs, scramjet propulsion component technologies, and experimental approaches.
- Perform computational analyses and numerical simulations of vehicles and scramjets.
- Conduct airframe and propulsion ground testing.
- Design and manufacture experimental flight components and payload hardware.
- Develop flight test instrumentation.
- Assess the merits of experimental approaches and payload concepts.
- Provide task-level reporting and documentation.

Program responsibilities for DSTO are identical to those of AFRL but include the following additional responsibilities:

- Provide launch vehicle systems and subsystems; integrate flight experiment hardware and launch vehicle systems.
- Conduct certification testing of launch vehicle systems and ground operations hardware.
- Lead flight readiness reviews.
- Provide launch site services and range operations; lead execution of launches.
- Provide for flight data telemetry, collection, and storage.
- Lead payload recovery operations.
- Lead accident and experiment failure investigations.
- Reduce and analyze boost trajectory and flight research vehicle performance data.

Responsibilities shared by AFRL and DSTO include project planning and management, conducting technical interchange meetings and design reviews, analysis of experimental data, and project-level reporting and documentation.

Government agencies supporting the HIFiRE program include NASA for advanced analysis and ground testing, and in the case of HIFiRE-2, payload systems integration, check-out, and flight test support. Also supporting the program with launch services is NAVSEA at WSMR in the US and DLR in Germany. It should also be mentioned that the Queensland State Government, through their Smart State initiative, supported the program by funding one-quarter of the initial three-flight program that launched HIFiRE.

4.0 Industry Roles and Program Contributions

The primary industrial contributor to the HIFiRE program is Boeing Research and Technology, the technology development arm of The Boeing Company. Boeing initially supported the program by funding one-quarter of the three-flight program that launched HIFiRE. Boeing shares responsibility with DSTO and AFRL for defining the science objectives of program flight experiments. Technically, Boeing developed conceptual designs of the HIFiRE-4 and HIFiRE-6 flight research vehicles; analyzed their aerodynamics, mass properties, stability & control, aero-thermal response, and flight trajectory/performance; and contributed to the development of their flight control systems. Supporting AFRL, Boeing also provided CFD-based aerodynamic analysis of HIFiRE flight research vehicles 1, 2, and 5. Following their flights, Boeing will help analyze flight data gathered from vehicles 4 and 8.

Other companies supporting AFRL's efforts on HIFiRE include ATK-GASL and GHI in the US. The former performed detail design and fabrication of the HIFiRE-2 experimental payload, and the latter is performing preliminary and detail design, analysis, and fabrication support for the HIFiRE-6 flight research vehicle.

DSTO also is receiving industrial support on the HIFiRE program. For flight experiments being led technically by DSTO and requiring payload flight control, BAE Systems Australia is supporting the development of advanced guidance, navigation, and control (GNC) systems. As part of this work, BAE Systems is using a hardware-in-the-loop approach to help verify and validate GNC systems that will be used on the HIFiRE-4, HIFiRE-7, and HIFiRE-8 flight research vehicles.

5.0 Academe Roles and Program Contributions

The primary academic contributor to the HIFiRE program is The University of Queensland (UQ) in Australia, which initially supported the program by funding one-quarter of the three-flight program that launched HIFiRE. The most significant contribution by UQ to the program is development of a REST-based scramjet engine that will be flight tested as HIFiRE-7 and used to power the HIFiRE-8 flight research vehicle. The engine has been designed and developed by UQ using high-fidelity analysis and testing in the T4 high-enthalpy shock tunnel. Significant portions of the HIFiRE-7 experimental payload design and analysis have also been performed by UQ.

Other academic organizations contributing to the HIFiRE program include Purdue University and the University of Minnesota in the US. The former has performed boundary layer transition experiments in their quiet wind tunnel, and latter has performed hypersonic flow and boundary layer transition analysis using their advanced CFD and boundary layer stability analysis codes.

6.0 Summary

The potential rewards of routine and efficient hypersonic flight are many. But several challenges remain before the full value of hypersonic flight can be realized. In fact, addressing technical challenges is itself challenging because of the high flow energy and extreme thermal environment encountered in hypersonic flight, which are difficult to exactly replicate in ground test facilities.

To address some of the challenges facing hypersonics, the HIFiRE program was created to increase the knowledge base for critical hypersonic phenomena and mature technologies enabling to hypersonic flight. The program plan consists of nine focused research projects that each culminate in a flight experiment. Each project addresses one or more technical challenges in propulsion, aerodynamics, propulsion-airframe integration, aerothermodynamics, flight control, high-temperature materials and structures, thermal management, and/or instrumentation and sensors.

A primary objective of the HIFiRE program is conducting flight experiments faster and at lower cost than has traditionally been achieved. This is possible in part because of the overall philosophy and approach employed in program execution, such as using low-cost sounding rockets to boost experimental payloads to hypersonic test conditions and accepting greater technical risk in performing the flight experiments.

Nine flight experiments are a key element of the program plan, four of which have already been flown. The completed flights have verified critical flight systems and instruments, gathered unique boundary layer transition data that shows behavior different from what has been previously observed, and demonstrated in flight for the first time scramjet engine mode transition from dual-mode transonic combustion to pure supersonic combustion.

To achieve the above and all that remains in the HIFiRE program plan, the resources of a very diverse and capable international team were assembled from government, industry, and academic institutions in the United States, Australia, and Germany. In no small part the capabilities, dedication, and hard work of this expert team have lead to a high level of mission success and will likely lead to many more significant accomplishments and findings in the remainder of the HIFiRE program and beyond.

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