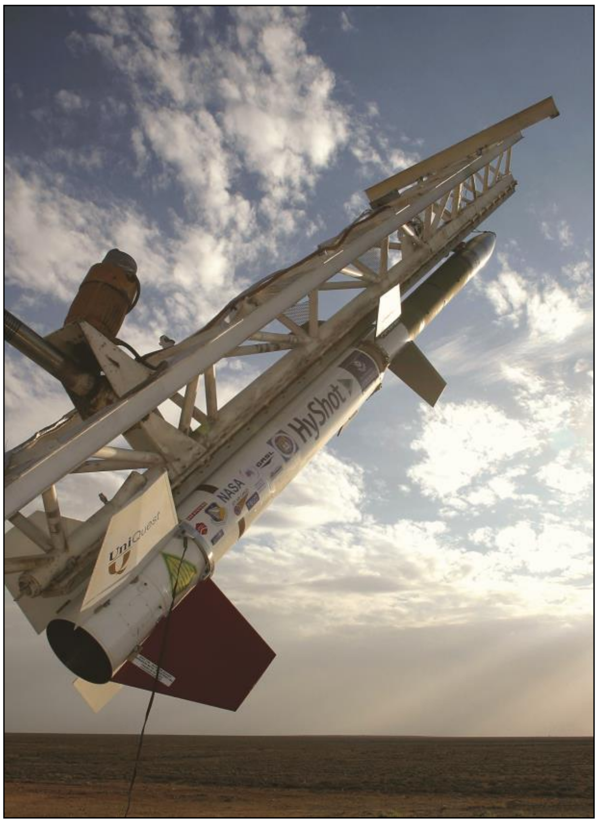
Queensland Hypersonic Testing Facility

2013 Annual Report

1 January 2013 to 31 December 2013



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Who we are

Hypersonic aerodynamics has been a major research activity at The University of Queensland over the last 34 years.

Our researchers have been active internationally during that period, and have been involved in collaborative research programs with approximately 20 universities and research organisations around the world.

Hypersonics research at UQ commenced in 1980 when Professor Ray Stalker AO, pioneer of the free piston shock tube driver technique which powers some of the most advanced facilities for hypersonic flow simulation in the world (now universally known as 'Stalker tubes'), started Australia's first research program on scramjet propulsion. Rapid progress in the 1980's and early 1990's led to the introduction of the Mechanical and Space Engineering degree program in 1993, which was expanded in 2005 into the Mechanical and Aerospace program with broader aeronautical content. Hypersonics continues to be the core discipline supporting the Mechanical and Aerospace program, and the primary field of research for the aerospace staff in the School.

Related to this activity is a strong program of research higher degree (namely MPhil and PhD) in Hypersonics. Our 100th research higher degree student (Dr David Gildfind) graduated in 2012. UQ has the largest alumni of hypersonics graduates from any university, and they have been extremely successful, finding employment in varied institutions such as National Aeronautics and Space Administration (NASA), Stanford, Oxford, Loughborough and Ecole Centrale (Paris) universities, Airbus, Defence Science and Technology Organisation (DSTO) and many Australian universities. Many opportunities for overseas study have arisen subsequent to or as part of the UQ hypersonics research program, including student placements at Oxford, Stanford, Ecole Centrale (Paris), EPFL (Lausanne), IRS (Stuttgart University) Universities, and the Indian Institute of Science.

Subsequent to the successful scramjet tests in the early 1980's (which were performed in the 'T3' Stalker tube at the Australian National University), the need for a more powerful facility was evident. Ray Stalker designed the T4 shock tube at UQ, which was commissioned in 1987, and has performed more scramjet tests than any other facility in the world.

Following on from this, in the mid 1980's Ray Stalker and Allan Paull applied the free piston driver concept to the so called 'expansion tube' facilities. These 'expansion tubes' operate by means of a cascade of shock tubes in series, and have the capability of flow at much higher speeds and pressures than conventional shock tubes. This was an extremely successful proof of concept study, and identified fundamental flaws and performance limits in the way previous expansion tubes had been operated. The next stage of development was to push the limits of the expansion concept in 1990, by means of a compound driver system upstream of the shock tube cascade. Thus the 'super-orbital' expansion tube was developed at UQ, capable of simulating the hyperbolic flight conditions of reentry from outside the Earth's gravitational field. The family of 'X tube' facilities X1,X2 and X3 was then developed by Richard Morgan and many colleagues and students. These X tube's have formed the backbone of our research in re-entry capsules and radiating and ablating flows ever since. They are also used to simulate flight in the atmospheres of the planets, including Mars, Venus, Jupiter and the moon Titan.

By 1993, understanding of scramjet operation had progressed to the stage that a viable propulsion unit could be produced, and a system designed by Ray Stalker, Allan Paull and David Mee demonstrated in T4 the operation of a scramjet powered flight vehicle developing more thrust than drag. This was the first ever published data of such an achievement.

In 1997 an opportunity to demonstrate scramjet operation in flight arose, and Allan Paull started the HyShot program. This was a non-thrust producing scramjet combustor, flown on a sounding rocket from Woomera, configured to demonstrate that supersonic air breathing propulsion was possible in flight, and to validate the results of ground based shock tube testing. Despite the first flight crashing due to a rocket fin failure, the second was a complete success. It demonstrated supersonic combustion in flight for the first time ever, some months before the first successful flight of NASA’s Hyper-X X43A scramjet in 2004.

The success of the HyShot program led to the HFiRE program, a ten flight $54 million collaborative scramjet research and development project involving UQ, Defence Science and Technology Organisation, National Aeronautics and Space Administration, Defense Advanced Research Projects Agency, Boeing and other aerospace participants. The experiences of the HyShot campaign led to the formation of the Defence Science and Technology Organisation Brisbane Hypersonics Branch, founded and led by Allan Paull, to handle the payload preparation and flight testing component of our collaborative scramjet program. Allan still maintains an advisory position as an Adjunct Professor at the UQ Centre for Hypersonics, which was formally established in November 1997 jointly between the departments of Mechanical Engineering (now the School of Mechanical and Mining Engineering) and Physics (now the School of Mathematics and Physics).

In 2010 the Scramspace project started based on funding from the Federal Government initiative to develop space capability in Australia. This was led by Professor Russell Boyce, and was configured around a program of laboratory research on scramjet fundamentals, and a demonstration flight of a scramjet using a flowpath developed by Allan Paull and the DSTO group. In October 2013 the Scramspace rocket failed on lift off from Andoya, Norway, and the payload was lost. The Scramspace program ended in November 2013, and the research outcomes and knowledge gained were very positive despite the loss of the demonstrator.

The ongoing HIFiRE program is led by Professor Michael Smart, and is building up to a peak of activity with a further three flights, demonstrating the use of advanced intakes in flight, and sustained and controllable flight. Advanced intakes using efficient compression processes and self-starting capabilities were developed and pioneered by Michael during his 10 years with NASA. These are a critical feature required for using scramjet propulsion for practical engineering applications, and for breaking the Mach 10 speed barrier required for scramjets to be viable as part of an access to space system.

In the re-entry field, the group participated in the 2010 return of the Japanese 'Hayabusa' re-entry vehicle, which recovered the first ever samples from an asteroid. Instrumentation developed on X2 was flown on the NASA observation flight monitoring the re-entry over Woomera. A Hayabusa 2 return is planned for 2020, and another observation campaign for 2014 of the Italian ATV 5 reentry vehicle is anticipated over the South Pacific in December 2014.

To summarise, Hypersonics is a growing area of research in the School, and covers a broad multidisciplinary range of topics, including fundamental studies of radiation, combustion and heat transfer, the design of hypersonic flight vehicles, numerical modelling, facility development and flight testing.

The Centre at a glance

Our objectives:

- to provide visible international leadership in the centre's areas of expertise in hypersonics,
- to maintain a high level of activity in both fundamental and applied research,
- to provide graduate and undergraduate training opportunities of the highest international standards and
- to play a pivotal role as collaborators in major international projects.

Our expertise:

- Development of hypervelocity test facilities
- SCRAMjet propulsion (experiment, analysis and design)
- Rocket flight testing
- Aerothermodynamic experimentation and analysis
- Advanced instrumentation for aerodynamic measurements
- Computational fluid dynamic analysis of hypervelocity flows
- Optical diagnostics for hypervelocity superorbital flows

Executive summary

2013 was a very active year in the Centre for Hypersonics with extensive research conducted in the laboratory, and the completion and flight of the Scramspace payload.

Many new collaboration ventures were initiated, three of which are the subject of Australian Research Council (ARC) applications currently under review.

We applied for an ARC Centres of Excellence through the Expression of Interest scheme. We had very strong support from a multitude of international partners, but it did not get invited to proceed further by the ARC.

The student body is very strong, and our students and staff presented through work extensively through international conferences and publication in the archival literature.

Commercialisation

KPI 1: *Fee for Service Activities*

The research program in the Centre for Hypersonics has been very successful, and has precluded us having the time to pursue commercial activities.

i. Establishment of operational procedures for the management of QHTF's fee for service activities within three (3) years of the Commencement Date.

   n/a

ii. Establishment of material promoting QHTF's fee for service activities internally and outside UQ within three (3) years of the Commencement Date.

   n/a

iii. Regular review of operating procedures and promotional opportunities for QHTF's fee for service activities

   n/a

iv. Sale of Rockets

   No commercial sales as yet. There is strong interest in the further development of larger rockets, and the establishment of a more extensive test facility off campus.

v. Testing Services

   As the inherent value of this research to the State exceeds by far the fees for commercial testing which could be raised instead, it was recommend in 2012 that this item be removed permanently, so that the best support can be given to developing the research capability of the State.

vi. Consulting Services

   n/a

Personnel

KPI 2: *Employment of Professional Staff*

Ten UQ Teaching and Research (T&R) Staff, nine Research Only (RO) staff, one administrative support staff, and four technical staff were employed in the area of hypersonics at the Centre for Hypersonics. There are also several staff members with adjunct or honorary appointments.

DSTO Brisbane employs six staff in hypersonics, and has between one and five resident visitors at all times. Teakle Composites employs four staff working in related technology.

Leadership Team

Director, Centre for Hypersonics
Richard Morgan

Prof Morgan is the Director of the Centre for Hypersonics, and he lectures in mechanical and aerospace engineering within the School of Mechanical and Mining Engineering. He has a strong research record in the development of hypervelocity impulsive facilities on which the UQ Centre for Hypersonics research program is based, including the 'X' series of super-orbital expansion tubes, and has extensive experience in hypersonic aero-thermo-dynamics and scramjet propulsion. Richard has been developing superorbital ground based facilities for many years, and has collaborative research program with NASA, ESA, Oxford University, Ecole Centrale (Paris) and AOARD in radiating flows, as well as continuing ARC support in this area since 1990, including two current ARC Discovery grants in partnership with European and American partners. He was involved as a flight team member in the 2010 airborne observation of the Japanese 'Hayabusa' asteroid sample return mission, for which he was a co-recipient of the NASA Ames 'honour' award for 2010. He regularly gives invited talks in international meetings, and gave a plenary presentation to the American Institute of Aeronautics and Astronautics (AIAA) Hypersonic Spaceplanes Conference in San Francisco in April 2011. Professor Richard Morgan was also one of three UQ advisors awarded a 2012 Excellence in Research Higher Degree Supervision award for encouraging student development through international student exchanges with overseas collaborators, whilst engendering internal cooperation within the study body.

Professor of Air-Breathing Propulsion
Michael Smart

Prof Michael Smart's research interests are in hypersonic aerodynamics, scramjets, compressible fluid flow. Professor Smart graduated with a Bachelor of Engineering (Hons) at UQ in 1985 and Master of Engineering Science at UQ in 1987, and was awarded a PhD at the Polytechnic University, Brooklyn, New York, in 1995. He was appointed an Associate

Professor in the Centre for Hypersonics in 2005 after spending 10 years as a research scientist at NASA's Langley Research Center in Virginia.
He is the chief investigator on the five-year National and International Research Alliances partnership collaboration between UQ, the Queensland Government, Boeing, USAF and DSTO to conduct scramjet-related flight tests as part of the HiFIRE program. As head of UQ's HyShot Group, Professor Smart leads scramjet related research within the Centre for Hypersonics, with particular emphasis on flight applications. He is heavily involved in the HIFIRE series of scramjet launches, which are using the T4 shock tunnel for validation of flight hardware. He recently received the 2012 International Congress for Aeronautics (ICAS) Von Karman Award for International Co-operation in Aeronautics.

Professor of Hypersonics
Russell Boyce

Prof Boyce managed the Scramspace project. Prof Boyce left UQ in December 2013 and is currently employed at the University of New South Wales, Australian Defence Force Academy (UNSW@ADFA).

Professor
David Mee

Prof David Mee's research interests are in Hypersonic and Supersonic Flow. David Mee is the Head of the School of Mechanical and Mining Engineering. After completing his PhD at UQ, he spent five years as a Research Fellow in the turbomachinery research group at Oxford University in the U.K. He returned to UQ as an ARC Queen Elizabeth II Research Fellow in 1991 and joined the academic staff of the Department of Mechanical Engineering in 1993. He became Head of the Division of Mechanical Engineering in 2007 and served as acting Head of the School of Engineering from January to July 2009 until he took on his current role. David has a strong research record in the field of hypersonics aerothermodynamics. He is recognised worldwide for his work on rapid response force balances, which are essential technology for categorising the performance of scramjet engines in transient facilities, such as our shock tubes. He was a member of the team that developed the first known scramjet. He has pioneered the use of stress wave force balances for measurement of multiple components of force on scramjet-powered vehicles and the techniques are in use around the world.

Staff

The following personnel participated in research, education and training activities (all staff listed are part of the School of Mechanical and Mining Engineering at UQ unless otherwise specified):

Name	Position
Emeritus Professor Ray Stalker	Research Consultant
Dr. Hans Alesi	Research Fellow (DSTO, HyShot)
Dr. Stefan Brieschenk	Research Fellow
Dr. Melrose Brown	Research Fellow
Professor David Buttsworth	Research Consultant (University of Southern Queensland)
Dr. Bianca Capra	Research Fellow
Dr. Michael Creagh	Research Fellow
Amy Deadman	Project Officer
Mr Igor Dimitrijevic	Electronics Engineer
Mr Myles Frost	Research Assistant (DSTO, HyShot)
Dr. David Gildfind	Research Fellow
Dr. Peter Jacobs	Reader
Dr. Ingo Jahn	Lecturer
Dr. Michael Macrossan	Research Consultant
Dr. Tim McIntyre	Senior Lecturer, UQ School of Mathematics and Physics
Dr. Judith Odam	Research Fellow (DSTO, HyShot)
Dr. Hideaki Ogawa	Research Fellow
Professor Allan Paull	Program Leader (DSTO, HyShot) and UQ Adjunct Professor
Dr. Ross Paull	Research Fellow (DSTO, HyShot)
Dr. Neil Mudford	Adjunct Researcher
Dr Sarah Razzaqi	Research Fellow
Professor Halina Rubinsztein-Dunlop	Head of School, UQ School of Mathematics and Physics
Dr. Todd Silvester	Research Fellow (DSTO, HyShot)
Dr. Phillip Teakle	Research Consultant, Teakle Composites, and Adjunct Associate Professor
Dr. Sandy Tirtey	Research Fellow
Dr. Vince Wheatley	Lecturer

Technical staff

Name	Speciality
Brian Loughrey	X3 expansion tunnel facility
Keith Hitchcock	T4 shock tunnel facility
Frans De Bur	X3 expansion tube upgraded driver installation
Barry Allsop	Electronics

Education

KPI 3: *Encourage involvement of Research Higher Degree students*

Statistics

The group had four research higher degree students commence in 2013, creating a cohort of 39. There were three PhD graduations in 2013, bringing the number of Research Higher Degree (RHD) graduations from the Centre for Hypersonics at UQ to a total of 40 for the period 2005 to 2013 (35 PhDs and five MPhils).

In addition, research students participated in several national and international conferences, and presented the results of their research in person.

See Appendix 1 for a list of current research higher degree students, and Appendix 2 for a list of publications from 2013.

RHD engagement

Many RHD students enriched their studies through periods overseas with our collaborators. Examples are: Umar Sheikh spent 12 months in 2012/2013 working with Ecole Centrale Paris (ECP) under the cotutelle program whereby a student undertakes a joint PhD between UQ and a French University, receiving a degree from both institutions. The work went well and the spectrometry system he had set up previously at UQ turned out to be very suitable and served as the model for two new systems in European laboratories.

Elise Fahy completed six months of her PhD study in École polytechnique fédérale de Lausanne in 2011/2012 working under an ESA grant on a collaborative project with multiple European groups into Ablation-radiation coupling.

At the same time, Professor Morgan was on SSP at ECP and our growing international ties led to a new ARC Discovery application for 2015, with partners from NASA Langley and NASA Ames Research Centre and Ecole Centrale Paris.

Undergraduate education

Many undergraduate students did their final year thesis projects with the group, and several students on Summer or Winter research scholarships were hosted in the Centre. The UQ Summer/Winter Research Program provides students with an opportunity to gain research experience working alongside some of the university's leading academics and researchers. By participating, they are able to extend their knowledge of an area of interest and develop their analytical, critical thinking, and communication skills.

Massively open on-line courses

edX is a not-for-profit online education venture founded by Harvard University and the Massachusetts Institute of Technology (MIT) that is committed to making high-quality educational experiences more widely available. By joining edX, The University of Queensland (UQ) has partnered with a consortium of "X-University" institutions including the University of California, Berkeley, the University of Texas System, Georgetown University, McGill University, École Polytechnique Fédérale de Lausanne, University of Toronto, and Australian National University.

The rapid developments in online learning are enabling millions of learners around the world to participate in these new forms of tertiary education. Joining this effort allows UQ to contribute to this activity to ensure the needs of our community are met.

The Centre has been invited to participate in the MOOC (massively open on-line courses) program pioneered by MIT, Harvard and Stanford Universities by offering a hypersonics course, the first to be offered in that field.

Some details of the MOOC courses available worldwide are contained in these links:

http://web.mit.edu/newsoffice/topic/massive-open-online-courses-moocs.html
http://edf.stanford.edu/tags/mooc
https://www.edx.org/

and the UQ Hypersonics course coordinated by Professor David Mee can be found online:

http://www.uqx.uq.edu.au/hypersonics

Engagement and collaboration

KPI 4: *Collaboration*

As previously noted, the Centre for Hypersonics and QHTF have served as the focus point for numerous funding grants and collaborative research projects. These research collaborations are outlined under *Research Summary* (KPI 5).

A large number of visitors were received in connection with the HIFiRE and ARC research programs. Visitors included:

Gustavo Mantana Aguiar was invited to complete his occupational trainee program with Dr Stefan Brieschenk (December 2013-February 2014). The objective of Mr Matana Aguiar's stay is to simulate the behaviour of various shock tunnel flows using the Navier-Stokes equations. This internship program was designed to assist Gustavo work towards the completion of his Bachelor of Mechanical Engineering degree, University of Sao Paulo – Brazil by completing his internship hours.

Benoit Carco was invited to complete his occupational trainee program with Dr Ingo Jahn (Sepember 2013 – February 2-14). The objective of this internship program was to design and manufacture a test arrangement for measuring unsteady aerodynamic forces in the Ludwieg tube facility at the University of Southern Queensland (USQ) and to measure unsteady forces for a simple test piece (e.g. cone or wedge). This internship program was designed to assist Benoit work towards the completion of his degree studies in the department of Ergonomics, Industrial Design and Mechanical Engineering by completing an Internship.

Sarah Frauholz was invited to complete her occupational trainee program with Professor Michael Smart (December 2013 – February 2014). The objective of Ms Frauholz's stay was to improve the computational accuracy of 3-D hypersonic inlet flows. This internship program is designed to assist Sarah work towards the completion of her Doctor of Philosophy, RWTH Aachen University – Germany by completing her research stay abroad.

Jens Kunze was invited to complete his occupational trainee program with Professor Michael Smart (October 2013 – March 2014). The objective of this internship program was to train Jens in the understanding of 3-D scramjet nozzle design. Jens was required to write a report describing the methods and results of his calculations. This internship program is designed to assist Jens work towards the completion of his Master of Science degree at Technische Universität München.

Research Summary

KPI 5: *Research and Development Excellence*

A large variety of small and large projects were undertaken in the Centre for Hypersonics in 2013. A summary of the larger projects follows.

Major projects

a. SCRAMSPACE

Designed and built in Brisbane, this is a $14 million, three-year research project to collect valuable data from an 8600km/h (Mach 8) high-speed test flight of a hypersonic scramjet.
SCRAMSPACE is the first and largest project funded by the Australian Space Research Program. It builds on Australia's world-class hypersonics heritage, and its core objective is to build capacity and capability, in particular a talent pool, for the Australian space and aerospace industry.

This is achieved partly by means of the Mach 8 flight experiment, for which a team of exceptional young scientists and engineers has been assembled, and partly through extensive ground-based research involving many PhD students at UQ and partner universities.

By addressing key scientific and technological questions, the consortium is conducting ground-tests at up to Mach 14 and a flight-test of a free-flying scramjet at Mach 8.

Unfortunately, the scramjet payload was not delivered to the correct altitude and speed during the flight test on 18 September 2013 due to a problem with the first-stage rocket motor.

While the final stage of the project, the flight test, did not deliver hypersonic flight data, the ground testing and modelling and analysis components of the project delivered many important research results that will be published in papers and theses in the coming years.

b. HiFiRE

The Hypersonic International Flight Research Experimentation (HIFiRE) program is investigating the fundamental science of hypersonics technology and its potential for next generation aeronautical systems and will involve up to ten flights. HIFiRE has been jointly established by DSTO and the US Air Force Research Laboratory (AFRL).

c. USQ Activities

ASRP-funded (Scramspace) dominated the activities of the TUSQ wind tunnel facility during 2013. A fast door opening scramjet inlet model was developed at USQ to provide benchmarking data for the PhD program of Alex Grainger, a UQ student. Door opening speeds of the order of 1 millisecond were achieved using a pneumatically actuated pull-ram and carbon fibre doors. Pressure measurements within the scramjet inlet were obtained and high speed schlieren imaging of the flow establishment process were taken. The results from time-resolved computational simulations of the door actuation process within the Mach 6 hypersonic flow are currently being analysed in conjunction with the TUSQ experimental results and submission of Alex Grainger's dissertation is expected to occur in 2014.

Internally-funded, free-flying experiments on a model of the Scramspace vehicle were performed by a USQ final year project student, Rod Ennis using the TUSQ facility. The model included the geometric detail of the inlet starting doors-open flow path and the external vehicle profile. The motion of the vehicle was tracked using high speed cameras, and internally-mounted accelerometers and gyroscopes with wireless serial port data acquisition to a computer external to the test section. The results are yet to be fully-analysed, but further free-flying work is anticipated in the near future.

Internally-funded ramjet testing by UQ Engineering students was also performed in the TUSQ facility using the Mach 2 nozzle as part of their design course under the supervision of Dr Vince Wheatley. Two days of testing on separate occasions occurred during the year and for the first time in the TUSQ student ramjet testing program, a visual signature of combustion was detected.

Grants

a. New grants and fellowships

***Comparison between hydrogen and methane fuels in a 3-D scramjet at Mach 8 (*Asian Office of Aerospace Research and Development)**
Total $116,185.09 (2013-2014)
Chief Investigators: Professor Michael Smart, Dr Vincent Wheatley

Project Summary

Gaseous hydrogen has typically been the fuel of choice for scramjets operating at speeds greater then Mach 7. This is because of its high scientific energy content, as well as its fast reaction characteristics in air. The disadvantage of hydrogen is its low density, which is a particular problem for small vehicles with significant internal volume constraints. The current study will investigate the use of gaseous methane as a fuel for a Mach 8 scramjet. This will involve experiments with a 3-D scramjet using a cavity based flame holder in the T4 shock tunnel at UQ as well as a companion fundamental CFD study. The performance of methane will be compared with hydrogen to establish the importance of its lower specific energy content and slower reaction characteristics. In addition, a scoping study will be performed to determine the capability for direct connect testing in the T4 shock tunnel.

Progress
We have assembled a strong UQ team for the research, including Dr Anand Veeraragavan (combustion), Dr Stefan Brieschenk (ignition systems) and Zachary Denman (PhD student), as well as Dr Vince Wheatley (computations) and myself (overall research lead). A circumferential cavity has been designed and added to the existing REST flowpath; design work on the wind tunnel model is progressing well. A spark plug based ignition system will also be added for the experiments that are scheduled for May 2014. We have also conducted a significant amount of fundamental computations to compare the reaction and ignition lengths of hydrogen, ethylene and methane. I have included a few snippets of the research for your interest.

I have been very pleased with the progress of the research, and look forward to some interesting results in 2014. Furthermore, the scoping study for direct connect testing in the T4 shock tunnel is almost complete.

Snippet 1: Cavity Design Methodology

The combustor of the Mach 8 REST scramjet engine will be modified to include a modular cavity. The entire engine with the modified combustor is shown in Figure 1. The initial dimensions of the cavity that have been selected for testing are L/D = 4.0, D = 10.9 mm and aft wall angle = 22.5 degrees. The cavity is designed such that the robust combustion of ethylene should occur without an external ignition source. The L/D ratio and aft wall angle selected have been tested by the Air Force Research Laboratory with success. The depth of the cavity was determined using the correlations developed by Davis and Bowersox (for cavity depth) and Colket and Spadaccini (for residence time). These expressions are shown in Equations 1 and 2 respectively. The cavity depth expression estimates the required depth of a cavity, given a freestream velocity, U_∞ and the required residence time, τ_r of the cavity.

$$D = \frac{\tau_r U_\infty}{100} \qquad (1)$$

$$\tau_{ign} = A \exp\left(\frac{E}{RT}\right) [O_2]^a \left[C_x H_y\right]^b \qquad (2)$$

The residence time required was approximated using the ignition delay correlations for ethylene. Axisymmetric simulations of the cavity flow were completed using Eilmer3 [4]. These simulations were completed to estimate the temperature in the cavity so that the ignition delay correlations could be utilised. Figure 2 shows both the cavity depth correlation and the ignition delay times for ethylene and hydrogen. A cavity depth of 10.9 mm is required for the autoignition of ethylene without an external ignition source.

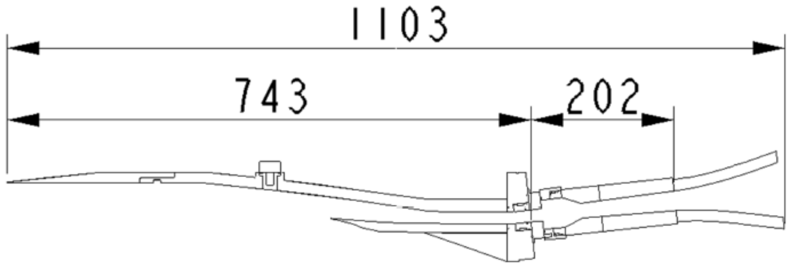

Figure 1: A cross-section of the flow path in the Mach 8 REST engine with modular cavity (dimensions in mm).

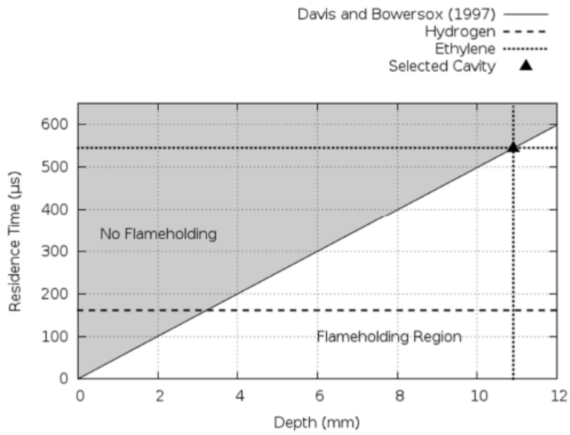

Figure 2: Depth of cavity based on Davis and Bowersox perfectly stirred reactor model, coupled with Colket and Spadaccini's ignition delay correlations for hydrogen and ethylene with $\phi = 0.8$ and $T = 1500K$.

Snippet 2: Premixed combustor Simulations

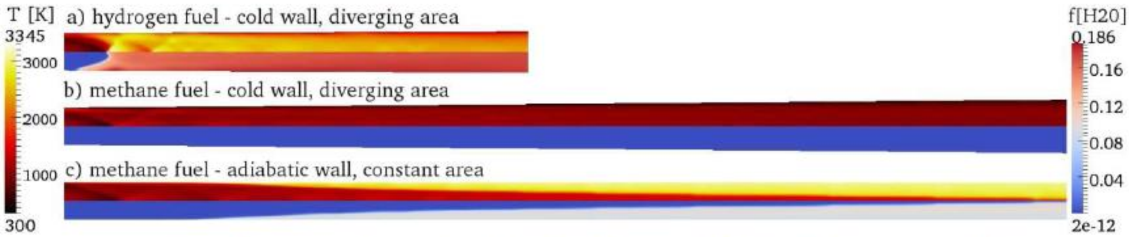

Figure 3: Temperature and water mass fraction distributions from turbulent URANS simulations of premixed combustion in axisymmetric scramjet combustors. a) Hydrogen fuelled, ϕ = 0.73, 300 K wall temperature, inflow from triple ramp inlet, diverging geometry. b) Methane fuelled, ϕ = 0.88, 300 K wall temperature, inflow from triple ramp inlet, diverging geometry. c) Methane fuelled, ϕ = 1, adiabatic wall, inflow from triple ramp inlet, constant area.

In order to establish the combustion characteristics of methane at the scale and conditions present in the combustor of the Mach 8 REST engine, a number of premixed axisymmetric URANS simulations have been carried out. These simulations were conducted with UQ's in-house hypersonic flow solver Eilmer3 using the k-w turbulence model. Finite rate methane chemistry is modelled using the 19 species, 84 reaction reduced version of GRI-Mech. For comparison, hydrogen combustion was also simulated using the Rogers and Schexnayder mechanism. In both cases, the fuel equivalence ratio (Ø) was set to have the equivalent potential heat release of a Ø = 0.8 ethylene-air mixture. The most informative simulations were run in diverging combustors with the cold walls characteristic of testing in impulse facilities. The inflow to the simulations was extracted from a separate simulation of a triple ramp axisymmetric inlet with approximately the same compression as the REST inlet. The high local temperatures produced through the interaction of the inlet shock train with the turbulent combustor boundary layer govern the ignition process. Figure 3(a) shows that hydrogen burns robustly at these conditions. The premixed hydrogen combustion process is unsteady and eventually results in the formation of a detonation, a process that does not occur in the experimental engine to the combustion being mixing limited. On the other hand, Figure 3(b) demonstrates that unforced ignition of the methane-air mixture does not occur at the conditions present in our scramjets, even for a combustor extended to over 1 m in length. This justifies the inclusion of a cavity flameholder and forced ignition system in the experimental model. The potential for methane combustion to occur out our conditions once the flow is ignited is demonstrated in figure 3(c). This shows the results of a stoiciometric simulation with adiabatic walls and a constant combustor area. The elevated temperatures in the boundary layer lead to ignition, after which the flame front propagates towards the centerline, reaching it at a combustor length of approximately 1.08 m and resulting in a combustion efficiency of 77%.

b. Progress reports on existing grants and fellowships

The science of scramjet propulsion (DP130102617)

Total $560,000 (2013-2015)

Chief Investigators: Professor Richard Morgan, Dr Tim McIntyre, Professor Michael Smart, Dr Anand Veeraragavan, Dr Ingo Jahn, Dr Sandy Tirty

Project Summary

We will produce laboratory test conditions that simulate the highest speeds at which scramjets might eventually fly, and develop the underlying scientific knowledge required to reach the ultimate limits of the viable flight envelope. The significance of the work lies in the family of advanced flight vehicles which will be enabled by the knowledge and experimental validation which will be gained, and the reinforcement of Australia's world leading position in hypersonics. The primary outcomes will be fundamental technical understanding of how the mixing, ignition and combustion processes occur and can be controlled at high Mach numbers, and an extensive data base of experimental data at conditions not previously obtainable.

Progress

2013 was an active year for the grant, with a postdoctoral fellow appointed, experiments being performed in both the T4 and X3 facilities, and good progress made by all four research students working on the project.

Ground testing of a 3-D REST scramjet was completed at Mach 12 flight conditions in the T4 shock tunnel, the first time that a full flowpath has been tested at such extreme conditions. A key aspect of the testing was the need to create a turbulent boundary layer on the intake of the engine, which was done using boundary layer trips. Engine testing using gaseous hydrogen as a fuel was very successful. Good combustion generated pressure rise was measured using both fuel injection in the intake and a combination of intake and combustor injection. This important data set is now under analysis, and forms the basis of a PhD nearing completion.

Another student is working on the numerical modelling of the vorticity induced mixing. The mixing of fuel and air is also being studied in a broad sense in the context of hydrocarbon fuelled scramjets using cavity assisted combustion for a Mach 8 REST engine which will be extended to Mach 12 conditions as the work matures.

A new paradigm using GPU computing is being investigated by making use of the GPU cores to accelerate the computation of the chemical reaction source terms, and good progress has been achieved in setting out the basic architecture for this work.

We are also engaged in the creation of a Massively Open Online Course (MOOC) which will be the world's first on Hypersonics, enhancing the reputation of Australia and identifying us as a nation leading and educating the future leaders in this area. It will play an important role in disseminating the results and significance of this and related research.

In 2013, work supported by this ARC project, provided the following new research findings:

- Wall-Modelled LES of planar and axisymmetric inlet-injected scramjets, demonstrated that inlet injection has benefits that go far beyond providing the fuel with additional time to mix. The interaction of turbulent fuel plumes with primary compression shocks at the combustor entrance, triggering the Richtmyer-Meshkov instability, has a transformational effect on the mixing process. The mixing rate is more than doubled, indicating that inlet injection is a crucial enabling concept for access-to-space scramjets, which require more rapid and complete mixing and combustion to be viable than their low Mach number counterparts.
- Simulation of oxygen enrichment provides a scramjet performance increase far in excess of that expected from simple analysis. Mixing and combustion rates increase dramatically due to increased turbulent kinetic energy production, enabling oxygen enrichment as a key candidate to enhance scramjet performance at high altitudes. The first ever fuelled, combusting, full-flow path simulations of scramjets operating beyond Mach 10 revealed that inlet injected fuel is well mixed as it enters the combustor, and burns rapidly in the combustor. The simulations also revealed the primary source of inefficiency in the engine, and a rich flow structure with many features that could potentially be exploited to overcome it. Extended an analytical model for hypersonic boundary layer combustion to reconstruct the complete boundary layer structure and to handle fuels other than hydrogen. This revealed the full set of mechanisms that underlie skin friction reduction due to boundary layer fuel injection and combustion. Crucially, we demonstrate that close to the maximum skin friction reduction can be achieved with a modest amount of fuel.
- A new high Mach number test flow condition for scramjets has been developed for the X3 expansion tube using a generic 2D hydrogen scramjet, and will act as a platform for testing at higher Mach numbers.

- A total of six journal articles, four conference papers, and a book chapter (under review) arose from the grant in 2013.

The general Richtmyer-Meshkov instability in magnetohydrodynamics (DE120102942)
Total $375,000 (2012-2014)
First named Chief Investigator: Dr Vincent Wheatley

Project Summary

Fluid dynamic instabilities limit the chance of inertial confinement fusion, a carbon-free process, achieving net energy production. In highly idealised circumstances it has been shown that one of these instabilities can be suppressed by a magnetic field, a phenomenon that this project will investigate in the general case.

Progress

This project is to examine and understand the effects of magnetic fields of arbitrary orientation and strength on the Richtmyer-Meshkov instability (RMI) in magnetohydrodynamics (MHD), along with non-ideal effects. This instability is detrimental to inertial confinement fusion, thus its suppression is desirable.

An analytical model was developed for the transverse field MHD RMI, where the initial magnetic field is parallel to the mean interface location. It's prediction of purely oscillatory interface behaviour was verified by comparing to the results of non-linear compressible simulations.[7] These simulations revealed the suppression mechanism for the instability to be the transport of vorticity on finite amplitude Alfvén wave that travel parallel and to the magnetic field, never leaving the vicinity of the interface. The transverse field model integrates across these waves and does not resolve their structure. The interface oscillates as these waves periodically reconstruct with alternating phase as they propagate, whereas an earlier paper attributed this solely to field line tension. The waves appeared to behave as solitons for the conditions first studied, but our study over a broader range of parameters revealed, amongst many other findings, that these waves split into transmitted and reflected waves when interacting with a high density ratio interface.

A for more complex analytical model for the MHD RMI was then developed for the case where the initial magnetic field can have arbitrary orientation. Again the interface behaviour is dominated by vorticity transport on MHD waves parallel and anti-parallel to the magnetic field. The interface-parallel transport of vorticity, due to the tangential field, continuously alters the phase of the induced velocities with respect to the interface, causing the growth rate to oscillate. Simultaneously, the induced velocities at the interface, and hence the growth rate, decay as vorticity is transported normally due to the normal component of the magnetic field.[9] In the limit of the magnetic field becoming transverse, the waves do not vanish, thus the oblique field model resolves the structure that was integrated across in the transverse field model. It also confirms that the model by other authors, that relies on field line tension only, is not a natural limit as the magnetic field becomes parallel to the interface.

With RA Pavaman Bilgi, we have automated and generalized my solver for the MHD shock refraction problem. This was used to map out solutions over a wide parameter space. The limit of regular refraction was identified and irregular refraction solutions were numerically generated. An article documenting these fundamental findings in preparation.

Implementation of MHD capability in our in-house compressible Navier-Stokes solver, eilmer3, is in progress. Ideal MHD capability has been validated while resistive terms and tensor thermal conductivity are currently being formulated appropriately.

The role of the RMI in another context, mixing and combustion enhancement in scramjets, was also investigated. Wall-Modelled Large Eddy Simulations of axisymmetric and planar inlet-injected scramjets, we demonstrated that inlet injection allows the interaction of turbulent fuel plumes with primary compression shocks at the combustor entrance, triggering the Richtmyer-Meshkov instability, which has a transformational effect on the mixing process. The mixing rate is more than doubled due to a radical alteration of the turbulent flow structure. We also demonstrated this effect in a complex 3D scramjet.

Design optimisation and physical behaviour of fuel injection and mixing for innovative scramjet concepts *(*DE120102277)
Total $375,000 (2012-2014)
First named Chief Investigator: Dr Hideaki Ogawa

Project Summary

Scramjets are a potential game changer for satellite launch and high speed flight. The phenomena that will make or break them are complex, and achieving optimal designs is hugely challenging. This project combines advanced optimisation techniques and flow simulations to find, and understand, optimal fuel injection for innovative scramjet designs.

Progress

Dr Ogawa left UQ for the Royal Melbourne Institute of Technology in 2013, and the project is continuing through that institution.

The converging shock driven Richtmyer-Meshkov instability in magnetohydrodynamics *(*DP120102378)
Total $120,000 (2012-2014)
First named Chief Investigator: Dr Vince Wheatley

Project Summary

Fluid dynamic instabilities limit the chance of inertial confinement fusion, a carbon-free process, achieving net energy production. The project will investigate the effectiveness and consequences of suppressing one of these instabilities with a magnetic field.

Progress

This project is to examine and understand the effect of various geometry magnetic fields on the cylindrical and spherical converging shock driven Richtmyer-Meshkov instability (RMI) in magnetohydrodynamics (MHD). This instability is detrimental to inertial confinement fusion, thus its suppression is desirable. Excellent progress has been made to date.

An outstanding PhD student, W. Mostert, was recruited to the project. During his first funded visit to UQ in 2012, PI Samtaney created a custom mapped grid version of his MHD code to study the problem at hand, and trained Mostert in its use. He also conducted simulations of the transverse field RMI for comparison to the analytical model developed by CI Wheatley as part of his DECRA project. It was found that the instability could be suppressed by an entirely different mechanism to that reported in the literature. The first stage of our investigations of the converging instability was to study the behaviour of the implosions that drive them. We initialize these implosions using Riemann problems, and the behaviour of the resulting flows in the presence of a magnetic field was unknown. We first studied a cylindrical implosion in the presence of a uniform magnetic field. The field was found to have major effect on the implosion, with the multiple shocks generated rapidly developing kinks and hence reflected shocks. The wave system then interacted non-linearly resulting in a rich and interesting flow structure.

During PI Pullin's funded visit to UQ in 2013, he extended an analytical technique known as shock dynamics to MHD for converging cylindrical shocks the presence of a singular magnetic field generated by a current along the axis of the cylinder. Remarkably, the shock Mach number weakens to zero as it converges, making this field a very poor candidate for fusion experiments, despite having been proposed in the literature. PI Pullin also greatly assisted with the analysis and interpretation of other results during his visit. PI Samtaney created a version of his code that can simulate this singular case, facilitating numerical comparisons to the theory. A paper reporting these findings is in preparation. During PI Samtaney's visit to UQ in 2013, he installed an adaptive version of his MHD solver and trained Mostert in its use, enabling more efficient simulations of 3D implosions. Cylindrical implosions were studied for azimuthal and saddle geometry fields, with the latter having a more complex flow structure than for the uniform field case, but a much more symmetric implosion. These results were published and presented at the International Symposium on Shock Waves, for which Mostert won the prize for best student presentation. Together with RA Gehre, PI Samtaney also conducted simulations of the planar RMI at arbitrary field angles for comparison to PI Wheatley's new analytical model developed as part of his DECRA project. It was found that the analytical model reasonably predicted the flow behaviour for any field angle. We also studied the transverse field RMI over a wider range of parameters, discovering a wealth of new flow physics.

We completed our simulations of 3D implosions over a wide range of field strengths, allowing us to plot the effect of field strength on implosion symmetry. From this we have determined that the saddle geometry field is most promising for suppressing the RMI while maintaining implosion symmetry. An article detailing these findings is in final draft. PI Samtaney has examined the converging shock driven RMI for a radial magnetic field over a broad range of parameters using a 1D linearized solver. Both the RMI and subsequent Rayleigh-Taylor instability are found to be suppressed for all wave-numbers for sufficiently strong fields. PI Wheatley has conducted a multi-dimensional simulation for comparison and presented these results at the 2013 APS Division of Fluid Dynamics Meeting (Pittsburgh). Mostert has also completed simulations of the cylindrical converging RMI for uniform and saddle fields and we are currently analysing the results.

Flow physics of porous wall fuel injection for scramjet combustion and drag reduction *(*DP120101009)
Total $320,000 (2012-2014)
First named Chief Investigator: Professor Russell Boyce

Project Summary

This project combines world-class Australian scramjet science with German advanced high temperature materials, exploring potentially transformational technology for satellite launch. Australia's credentials in the international space arena will strengthen, contributing to assured access to the space-based applications upon which we heavily depend.

Progress
Good progress was achieved in numerical investigation.

Ablative thermal protection systems *(*DP120102663)
Total $540,000 (2012-2014)
First named Chief Investigator: Professor Richard Morgan

Project Summary

The project will study ablative reentry heat shields by experiments simulating hypervelocity atmospheric flight. The results will enable the design of the advanced spacecraft which are needed to extend mans exploration of the universe. Data will be validated by comparison with flights such as the Japanese Hayabusa asteroid sample return mission.

Progress
2013 has been a very productive year for the grant, with three students submitting PhD theses, one of which has graduated, and two new PhD's commencing. In total, five PhD students are currently working under the grant, at various stages of completion. Collaboration between the partner institutions has been strong, with Prof Morgan spending 6 months Special Studies Program (SSP) at Ecole Centrale Paris (ECP) with Prof Laux, and also visiting partner organisation IRS in Stuttgart. A UQ PhD student finished his year co-tutuelle exchange at ECP in August, and another one has been accepted there for 2014.

A post doc, Fabian Zander, was appointed to work on the grant in 2013, and he has now moved to IRS to continue the collaboration under European funding. A new post doc has been appointed at UQ to replace Zander. The strong links established between the post doc and researchers at IRS during the exchange has now led to the preparation of another collaborative ARC Discovery proposal for 2015 with Prof Smart from UQ relating to the development and testing of insulation materials for spacecraft.

McIntyre and Buttsworth both visited IRS in connection with the grant, as did our post-doc. A masters students came from IRS to work with Buttsworth at USQ on instrumentation, two journal papers from which have been accepted (pending revision), and another student from IRS is continuing the work at UQ in 2014. Greendyke from AFIT visited UQ in September with a PhD student and did a series of experiments on X2 which are in the process of being written up. A follow on visit from AFIT is scheduled for September 2014. A follow on project with AFIT under AOARD funding is currently being negotiated.

Morgan and Loehle got reciprocal funding from the Go8-DAAD scheme to support further personnel exchange on the project, with special emphasis on students and early career researchers. During the SSP trip in Paris, the group was also involved in experiments on the ESA funded 'Rastas-Spears' re-entry project using the ECP plasma torch facility, and the ESA Ablation-radiation coupling project led by EPFL, Lausanne. Astrium (now a subsidiary of Airbus Space and Defence) supplied the materials for the program, and were pleased with our contribution, and are joining us as partners in a 2015 ARC Discovery application in a related topic on rapidly expanding radiative flows.

A former graduate and co-tutuelle student from this group (PhD 2012) is now a faculty member at ECP and she worked on our collaboration during the SSP secondment, strengthening our links and enhancing the outputs from the grant. Our co-tutuelle student at ECP in 2013 designed and set up a vacuum ultra violet (VUV) system for their plasma torch for ablation studies. The ESA ablation radiation coupling project involves re-entry testing in three different facilities (UQ, IRS and CIRA, Italy) and the VUV spectrometry system developed under this grant was chosen as the model for the program.

ECP are joining in again as PI's in our 2015 Discovery application which is a natural follow on from this project, as are NASA's AMES and Langley who have expressed great interest in the outcomes.

A very full experimental program was undertaken, with 12 test campaigns performed on the UQ X2 expansion tube, and the TUSQ facility at USQ, the plasma torch at ECP and the ARC driven facilities at IRS have also been very active.

The outcomes of the project have been widely published, with 12 journal papers submitted and 45 conference and workshop presentations and three invited/plenary talks in the first two years. Morgan presented a paper on behalf of the group at the 2013 VKI lecture series relating to the facilities for this sort of study, and McIntyre has been invited to present another in 2014 on the optical diagnostics used.

Hypervelocity Reentry (DP1094560)
Total $249,000 (2010-2012)
First named Chief Investigator: Professor Richard Morgan

Project Summary

During planetary entry from space, severe heating loads are created on the exposed surfaces of flight vehicles from the layer of plasma trapped behind the bow shock, many times hotter than the Sun. Design of the thermal protection systems is a major engineering challenge, and a limiting technology for space travel. Our aim is to do an experimental and analytical study of the associated radiating gases to gain the theoretical and practical knowledge needed to design a new generation of advanced spacecraft. Experimental data will be obtained from the unique Australian hypersonic ground facilities, and selected flight records, and the theoretical analysis will be performed in collaboration with NASA scientists.

Progress

The grant started well in 2010 as we were invited to participate in the airborne observation of the re-entry of the 'Hayabusa' asteroid sample return capsule, and also had two teams of students doing simultaneous ground based spectrometric measurements of the shock layer during re-entry and mothercraft break up. The shock tube instrumentation was adapted for use in flight in the form of a hand tracked UV spectrometer, and two ground based spectrometers were set up and operated by our students. One of the student packages used an automated tracking system, built as part of a parallel MPhil project in controls.

The UQ participants in the air borne observation team on the NASA DC8 flying laboratory were also co-recipients of the 2010 NASA Ames 'honour award' with the rest of the flight team, and the 2011 NASA Group Achievement Award. The follow on workshop for the Hayabusa re-entry was held at UQ in March 2011, giving good exposure of the results of our ARC research to the world leaders in this field. Eight PhD students have worked on the grant, and three of them have graduated during it. Many final year undergraduate projects have also worked on the project.

We have had good interaction with our partner investigators, and CI1 Morgan spent a six month Special Studies Program (SSP) on the project in 2010, working with collaborators in Ecole Centrale Paris, NASA Langley and NASA Ames Research Centers, and installing the UQ flight package with Buttsworth on the DC8 at Dryden AFB. During this SSP, 14 invited talks were given to various Institutions on the research which is being well received by our peers. The work during the visit to NASA Langley focused on methods for getting more accurate measurements in equilibrium flows, and the results of this were presented by Dr Gnoffo (PI) at the 2011 Aerospace Sciences Conference. Dr McGilvray (PI on the grant from Oxford University) visited UQ to work with the other investigators and students.

The group received the inaugural UQ award for 'Internationalisation' in 2010, and the UQ 2012 award for Research Higher Degree supervision. Two PhD students enrolled for their degrees under the co-tutelle scheme with Ecole Centrale, and also received Eiffel scholarships to support their study. From an educational point of view, it was a great success.

Experiments were performed in the X2 facility examining radiation in flows relevant to Mars, Earth, Jupiter and Titan entry. Diagnostic measurements have focused on measuring the intensity of UV and visible radiation emitted by the flow. New measurements have been performed at higher simulated altitudes. We conducted preliminary tests on measuring the radiation incident on the surface of the test model using a periscope arrangement to transport the light through a window on the surface to an external camera, which is now forming the basis for an ESA grant we are working on. We have further developed a total radiation gauge capable of measuring the radiative heat transfer to the surface of the vehicle.

In 2012 radiation measurements were extended into the vacuum ultraviolet. A spectrometer/camera system capable of operating at wavelengths down to 130 nm was obtained under extra UQ funding in support of the grant. A vacuum system for coupling the system to the expansion tube has been developed, and will also be used on the ESA program. A recent breakthrough made under the grant that positively influences the project is the development of an electrical preheating technique by our students to transiently raise the surface temperature of graphite containing samples to the order of 3000K. This matches flight values, and removes wall temperature as one of the parameters which we have previously been unable to match. Preliminary experiments using this technique have confirmed an enhanced rate of surface chemistry, characteristic of the high temperatures found in flight, and this system will be transported to Europe in May for further testing on facilities operated by our international partners. The work has been well published and presented at international meetings, including four keynote and plenary talks. It has created worldwide interest in the work, and the impact has exceeded our original expectations.

Staff Development and Publications

KPI 6: *Professional Development*

The professional development needs of staff are normally identified as part of the annual performance appraisal, undertaken by supervisors and signed off by the Head of School. Examples of the number of staff development opportunities are set out below. These examples are opportunities for teaching staff; however, through the Tertiary Educational Development Institute (TEDI), UQ offers a comprehensive staff development program for all staff.

Graduate Certificate in Higher Education

New academic staff are encouraged to complete the University's Graduate Certificate in Higher Education (GCHEd). This program is designed for university teachers and PhD students who seek to improve their educational practice. It introduces major conceptual issues, research directions, and innovative practices associated with higher education. It challenges and extends notions of learning, curriculum, pedagogy, assessment of student performance, and evaluation of teaching and courses within the higher education context. The University pays the tuition fees for eligible staff. One member completed this program in 2013, and another is enrolled in 2014.

Tertiary Educational Development Institute (TEDI)

TEDI has a long history of working with teaching staff, faculties and schools to improve the quality of teaching and learning at UQ. UQ's professional learning framework maps some of the many ways that academics learn about teaching in higher education. This learning happens in diverse ways and is most effective when driven by academics themselves. A number of workshops are offered on a regular basis and include: assessing learning, demonstrator/tutor training, teaching with technology and internationalising teaching.

Supervisory skills development

Research staff are encouraged to be active in research higher supervision (e.g. final year undergraduate thesis, masters thesis). They are required to complete a program of professional development run by the Graduate School in order to supervise PhD and MPhil students. However, as most research staff are on fixed term contracts that are shorter than the duration of a PhD candidature, the University does not permit them to serve as principle supervisors. Consequently, academic staff carry the principal supervisory load and a large proportion of the associate supervisory load.

Teaching development

ResTeach is a UQ scheme funded centrally to pay up to 20% of the salary of research staff to allow them to engage in teaching programs in the schools. A 20% ResTeach appointment 0 with a line through it would be awarded to a staff member to coordinate and deliver one 2 unit course to a moderately sized class. A lower fraction would be for a correspondingly lower teaching involvement. The School of Mechanical and Mining Engineering has also established its own “Teaching Support Program (TSP)”. This provides School funds to support teaching involvement from research staff in the School.

These programs have been very beneficial to the Centre in facilitating participation in teaching by research staff. In 2013 Dr David Gildfind taught into AERO3110 Aero Design and Manufacturing.

Special Studies Program (SSP)

The UQ Special Studies Program provides a period of sustained scholarly activity or professional experience contributing to research or teaching or both. In 2013, Professor Morgan undertook SSP, spending time at Ecole Centrale Paris working on ablation re-entry issues and the European Space Agency rastas spear project.

Research Higher Degree Student Development

The majority of hypersonics students enrol through the School of Mechanical and Mining Engineering, with a small number enrolling through the School of Mathematics and Physics. They all have access to a free University wide Skills Training program run by the Graduate School.

Students are also encouraged to participate in the Engineering Postgraduate Conference. This conference provides an opportunity for engineering postgraduate students to present their research to academia and industry, improve presentation skills, and network with potential employers and research partners. The conference also provides a chance for attendees to interact and gain an overview of research across the different engineering schools. Each year, the Centre for Hypersonics sponsors The Professor Raymond Stalker Prize for best presentation related to Mechanical and Aerospace engineering.

The Centre also trains research higher degree students (PhD and MPhil) to act as operators for the X3 Expansion Tube and the T4 Free-piston driven shock tunnel.

Conferences and Publications

Conference attendance has been strong, with many staff and students given the chance for professional development by presenting their work to international audiences and visiting other research organisations overseas.

Refer to Appendix 2 for a list of conferences attended and publications.

Appendix 1. Research Higher Degree Students

Name	Primary Supervisor	Program	Project Title
Sanchito Banerjee	Professor Russell Boyce	PhD	Nonlinear adaptive flight control for hypersonic vehicles.
James Barth	Dr Vincent Wheatley	PhD	Simulation of scramjet performance at access-to-space mach numbers
Kevin Basore	Dr Vincent Wheatley	PhD	Flow physics of scramjet fuel injection through porous walls
Mark Bateup	Professor Allan Paull	PhD	Hydro-carbon supersonic combustion
Daryl Bond	Dr Vincent Wheatley	PhD	Modelling and simulation of heat and mass transfer enhancement of micro-scales
Mathew Bricalli	Professor Russell Boyce	PhD	Ignition processes in scramjet accelerators
Guerric De Crombrugghe de Looringhe	Professor Richard Morgan	PhD	Aerothermodynamics of super orbital radiating flows
Zachary Denman	Dr Ananthanarayanan Veeraragavan	PhD	Optimisation of fuel-air mixing and burning in shape transitioning scramjet engines
Luke Doherty	Professor Michael Smart	PhD	Investigation of thrust generation in 3D scamjets for access-to-space applications
Mary D'Souza	Dr Timothy McIntyre and Professor Richard Morgan	PhD	Simulation of ablation layers in impulse facilities
Elise Fahy	Professor Richard Morgan	PhD	Superorbital Re-entry Shock Layers, Flight and Laboratory Comparison
Rolf Gehre	Dr Vincent Wheatley	PhD	Numerical investigation of the axisymmetric inlet-fuelled radical-farming scramjet with RANS and LES simulations of the injection, mixing and flow structure/combustion coupling
Alexander Grainger	Professor Russell Boyce	PhD	Mechanism for hypersonic scramjet inlet starting
Dillon Hunt	Professor Russell Boyce	PhD	Radical farming in an Axisymmetric Scramjet
Christopher James	Professor Richard Morgan	MPhil	Radiation from Simulated Atmospheric Entry into the Gas Giants

Steven Lewis	Professor Richard Morgan	PhD	Melting Models of CO2, in re-entry flow conditions
Juan Llobet Gomez	Dr Ingo Jahn	PhD	Vortex-fuel jet interactions to enhance mixing in scramjets
Philippe Lorrain	Professor Russell Boyce	PhD	Inlet-fuelled radical-farming scramjets at high flight mach number
Wouter Mostert	Dr Vincent Wheatley	PhD	The Converging Shock-Driven Richtmyer-Meshkov Instability in Magnetophydrodynamics
Daniel Oberg	Professor Russell Boyce	PhD	Combustion scaling of an axisymmetric inlet-fuelled, radical farming scramjet engine
David Petty	Dr Vincent Wheatley	PhD	Flow physics of hypervelocity scramjet combustion with oxygen enrichment
Hadas Porat	Dr Timothy McIntyre and Professor Richard Morgan	PhD	Hypervelocity re-entry
David Preller	Professor Michael Smart	PhD	Heat transfer measurements of a hypersonic wing body junction
Adrian Pudsey	Professor Russell Boyce	PhD	Hypersonic viscous drag reduction through multi-port injector arrays
Andrew Ridings	Professor Michael Smart	PhD	Scramjet experiments using divergent elliptical combustors
Jorge Sancho Ponce	Dr Timothy McIntyre and Professor Richard Morgan	PhD	Simulation of hypersonic radiation flow field coupling in expansion tubes.
Fabrice Schloegel	Professor Russell Boyce	PhD	The combustion scaling laws for radical farming scramjets
Arman Schwarz	Professor Michael Smart	MPhil	Optimisation of aerodynamic wing and fin root heating for hypersonic flight vehicles
Umar Sheikh	Dr Timothy McIntyre and Professor Richard Morgan	PhD	Effects of radiation heating on hypersonic re-entry
Ben Shoesmith	Professor Michael Smart	PhD	Computational and experimental assessment of the starting behaviour of hypersonic intakes
Rajinesh Singh	Dr Peter Jacobs	PhD	Exploring the dynamics and control issues of the supercritical carbon dioxide power loop

Tamara Sopek	Professor Russell Boyce	PhD	Fuel injection/mixing studies in hypersonic flows using advanced optical diagnostic techniques
Paul van Staden	Professor Russell Boyce	PhD	Scramjet drag reduction from porous combustion chamber wall fuel injection
Tristan Vanyai	Dr Timothy McIntyre and Professor Richard Morgan	PhD	Scramjet accelerators investigated using advanced optical diagnostic techniques
Han Wei	Dr Timothy McIntyre and Professor Richard Morgan	PhD	Interaction between shock layer and ablative products from heat shields during atmospheric entry
Brad Wheatley	Tim McIntyre	PhD	Physics boundary layer transition
Dylan Wise	Professor Michael Smart	PhD	Experimental investigation of a 3D scramjet engine at hypervelocity conditions
Fabian Zander	Professor Richard Morgan	PhD	Applications of advanced composites for hypersonic propulsion

Appendix 2. Publications

Conference Papers

Bateup, M., Paull, A. & Mee, D. (2013). *Ethylene augmentation of JP-8+100 in a supersonic combustor*. In JPC 2013: 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference. JPC 2013: 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, San Jose, CA, United States, (1164-1173). 14-17 July, 2013.

Brieschenk, S., Gehre, R.Wheatley, V. & Boyce, R. (2013). *Fluorescence studies of jet mixing in a hypersonic flow*. In ISSW29: 29th International Symposium on Shock Waves. ISSW29: 29th International Symposium on Shock Waves, Madison, WI, U.S.A., (1-7). 14-19 July, 2013.

Gildfind, D, Sancho Ponce, J. & Morgan, R. (2013). *High Mach Number Scramjet Test Flows in the X3 Expansion Tube*. In 29th International Symposium on Shock Waves. 29th International Symposium on Shock Waves, Madison, Wisconsin, United States. 14-19 July 2013.

Gehre, R., Peterson, D.Wheatley, V. & Boyce, R. (2013). *Numerical investigation of the mixing process in inlet-fuelled scramjets*. In ISSW29: 29th International Symposium on Shock Waves. ISSW29: 29th International Symposium on Shock Waves, Madison, WI, U.S.A., (1-6). 14-19 July, 2013.

Gildfind, D., Morgan, R. & Sancho, J. (2013). *Design and commissioning of a new lightweight piston for the X3 Expansion Tube*. In 29th International Symposium on Shock Waves. 29th International Symposium on Shock Waves, Madison, Wisconsin, United States. 14-19 July 2013.

Jacobs, C., MacDonald, M., Zander, F., Morgan, R. and Laux, C.O. (2013) *Ablation/radiation studies in the Ecole Centrale plasma torch facility*. In Aerospace Thematic Workshop, Aussois, France, April 7-12, 2013.

Jacobs, C.M., MacDonald, M.E., Zander, F., Morgan, R.G., and Laux, C.O. (2013) *Ablation-radiation studies in the Ecole Centrale Plasma Torch facility*. In 4th International ARA Days (Atmospheric Reentry Association), Arcachon, France, May 27-29, 2013.

Jacobs, C., Sheikh, U., MacDonald, M. Laux, C. & Morgan, R. (2013). *Vacuum ultraviolet radiation studies in a plasma torch facility from 170-200 nm*. In 44th AIAA Thermophysics Conference. 44th AIAA Thermophysics Conference, San Diego, CA, USA, (1032-1041). 24-27 June, 2013.

Jacobs, C.M., Sheikh, U.A., MacDonald, M.E., Morgan R.G., and Laux, C.O. (2013) *Vacuum ultraviolet radiation studies in a plasma torch facility*. In Proceedings of the 5th European Conference for Aeronautics and Space Sciences (EUCASS), Munich, Germany, July 1-4, 2013.

Jacobs P, Morgan R, Brandis A, Buttsworth D, Dann A, Dâ€™Souza M, Eichmann T, Gildfind D, Gollan R, Jacobs C, McGilvray M, McIntyre T, Mudford N, Porat H, Potter D, Zander F. (2013) *Design, Operation and Testing in Expansion Tube Facilities for Super-Orbital Re-entry*. STO-AVT-VKI Lecture Series 2013-AVT-218 Radiation and Gas-Surface Interaction Phenomena in High Speed Re-Entry. The von Karman Institute for Fluid Dynamics, Rhode St., Genèse, Belgium, 6 – 8 May 2013

Jahn, I. (2013). *Maximizing contacting filament seal performance retention*. In ASME Turbo Expo 2013: Turbine Technical Conference and Exposition. ASME Turbo Expo 2013: Turbine Technical Conference and Exposition, San Antonio, TX, USA, (1-12). 3-7 June, 2013.

Jahn, I., GIlespie, D. & Cooper, P. (2013). *Hydrodynamic air-riding in leaf seals*. In ASME Turbo Expo 2013: Turbine Technical Conference and Exposition. ASME Turbo Expo 2013: Turbine Technical Conference and Exposition, San Antonio, TX, USA, (1-10). 3-7 June, 2013.

James, C., Gildfind, D.Morgan, R. Jacobs, P. & Zander, F. (2013). *Designing and simulating high enthalpy expansion tube conditions*. In APISAT 2013: 2013 Asia-Pacific International Symposium on Aerospace Technology. APISAT 2013: 2013 Asia-Pacific International Symposium on Aerospace Technology, Takamatsu, Japan, (1-10). 20-22 November 2013.

James, C., Gildfind, D.Morgan, R. & McIntyre, T. (2013). *Theoretical validation of a test gas substitution for expansion tube simulation of gas giant entry*. In 44th AIAA Thermophysics Conference. 44th AIAA Thermophysics Conference, San Diego, CA, USA, (109-127). 24-27 June, 2013.

James, C., Gildfind, D.Morgan, R. & McIntyre, T. (2013). *Working towards simulating gas giant entry radiation in an expansion tube*. In 29th International Symposium on Shock Waves. 29th International Symposium on Shock Waves, Madison, Wisconsin, United States. 14-19 July 2013.

MacDonald, M., Jacobs, C.Laux, C. & Morgan, R. (2013). *Measurements of air plasma/ablator interactions in a 50 kW inductively coupled plasma torch*. In 44th AIAA Thermophysics Conference. 44th AIAA Thermophysics Conference, San Diego, CA, USA, (460-476). 24-27 June, 2013.

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