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Hypersonic aerodynamics has been a major research activity at The University of Queensland for nearly 40 years.

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Our researchers continue to be active nationally and internationally, and are involved in collaborative research programs with approximately 40 universities and research organisations around the world.

Objectives and Expertise

Objectives

- Provide visible international leadership in the Centre’s areas of expertise in hypersonics.
- Maintain a high level of activity in both fundamental and applied research.
- Provide graduate and undergraduate training opportunities of the highest international standards.
- Play a pivotal role as collaborators in major international projects.
- Contribute to providing the skilled workforce required to support Australia’s growing space industry.

Expertise

- Development of hypervelocity test facilities
- Scramjet propulsion (experiment in the laboratory and in flight – analysis and design)
- Rocket flight testing
- Aerothermodynamic experimentation and analysis
- Advanced instrumentation for aerodynamic measurements
- Computational fluid dynamic analysis of hypervelocity flows
- Optical diagnosis for hypervelocity superorbital flows
- Study of radiating and ablating flows
- Development of reusable air breathing access to space systems
The Centre for Hypersonics – at a Glance

The three years covered by this report have been a time of unprecedented progress, and a growing global awareness of the significance of hypersonic technology. This was well illustrated in the recent statement by Michael Griffin, the Pentagon’s new Undersecretary of Defense for Research and Engineering, who said that “development of hypersonic capabilities is (his) ‘highest technical priority’".

“I’m sorry for everybody out there who champion some other high priority, some technical thing; it’s not that I disagree with those. But there has to be a first, and hypersonics is my first…”1

This is reinforced by the comments of Newt Gingrich, former Speaker of the US House of Representatives:

“The U.S. is on the brink of a tremendous tipping point of commercial, military and political opportunities. This historic moment is enabled by a combination of reusable rockets and hypersonic-vehicle technologies”2.

In fact, the coming intersection of reusable launch and hypersonic flight offers the kind of opportunity not seen since the invention of the steam-powered locomotive. These technologies could soon allow humans to travel anywhere on the globe in a couple of hours — and provide consistent low-cost access to space. This will be a tremendous boon to U.S. commerce. Meanwhile, a fleet of hypersonic military vehicles could revolutionise the way we defend our country. If the railroad opened and secured our continent, the combination of reusable rockets and hypersonics will open and secure our solar system3.

The strategic work performed in the Centre for Hypersonics over many decades has set up the infrastructure and skill base required for Australia to participate in this new technology as a major provider of services and hardware.

A major development within the group includes an increased level of collaboration with DST (formerly DSTO and DST Group) culminating in a 5 year $10 million collaborative agreement signed in November 2018. The agreement involves the development of a new hypersonics ground test facility (X3R), which was designed and built at UQ, and the establishment of a new hypersonics laboratory at a new DST site to be opened at Eagle Farm, Brisbane in 2019.

It is envisaged that this laboratory will become an international hub for research in hypersonics, and will help cement Queensland’s place as a major player in space research for many decades to come. The agreement also supports a broad based research program in hypersonics, incorporating most of the staff at the UQ Centre for Hypersonics. This is a very positive development, and goes a long way towards meeting our objectives, in particular with regard to providing high quality graduate education and international exposure.

Our collaborative activities with DST date back to the 1980’s when UQ did a fundamental study of the Australian ‘hover roc’ project which developed into the ‘Nulka’ decoy missile, and escalated strongly in the late 90’s when the flight testing program pioneered by Professor Allan Paull from UQ led to the HyShot and HIFIRE international flight testing programs. The success of these projects led to the establishment of a Hypersonics branch of DST at Pinjarra Hills, Brisbane led by Professor Paull. This collaboration has continued, and the relocation of the DST Hypersonics groups to Eagle Farm will greatly strengthen the relationship. Professor Morgan’s position at UQ is now co-funded by DST with a focus on new hypersonic facility development.

1 https://www.defensenews.com/pentagon/2018/03/06/hypersonics-highest-technical-priority-for-pentagon-rd-head/
2 https://aviationweek.com/space/opinion-how-seize-revolution-hypersonics-and-space
3 http://aviationweek.com/space/opinion-how-seize-revolution-hypersonics-and-space
Professor Paull has now assumed the DST Chair of Future Space Technologies at UQ, which ensures an ongoing close collaboration between UQ and DST and our large group of international collaborators.

Several new research initiatives have commenced, including ARC Discovery Project grants, ARC DECRA awards, and a major research program with the National University of Singapore. In addition, new AFOSR/AOARD (US Air Force Office of Scientific Research) grants have been awarded and collaboration with our existing overseas collaborators continue.
Key Performance Indicators

KPI 1 – Commercialisation

Commercialisation – The research program in the Centre for Hypersonics has been very successful and all-encompassing of our time which continues to preclude us from pursuing commercialisation activities.

<table>
<thead>
<tr>
<th>Activities</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Establishment of operational procedures for the management of QHTF’s fee for service activities within three (3) years of the Commencement Date.</td>
<td>There were no fee for service activities in 2016-18</td>
</tr>
<tr>
<td>Establishment of material promoting QHTF’s fee for service activities internally and outside UQ within three (3) years of the Commencement Date.</td>
<td>There were no fee for service activities in 2016-18</td>
</tr>
<tr>
<td>Regular review of operating procedures and promotional opportunities for QHTF’s fee for service activities.</td>
<td>There were no fee for service activities in 2016-18</td>
</tr>
<tr>
<td>Sale of Rockets.</td>
<td>There were no commercial sales in 2016-2018. There has been strong recent interest in the further development of larger rockets, and the establishment of a more extensive test facility off campus, to be led by USQ is being proposed. The propellant manufacturing and rocket testing facilities that have been established at UQ are a timely resource, and will be very useful for the future development of a local rocket industry. In 2016, a small rocket gas generator was developed for Ariane Group, with the intention of doing scaled wind tunnel tests to investigate possible plume interaction and base heating effects in the new Ariane 6 rocket, due for first flight in 2020. The scaled rocket worked successfully in the test program, but was subsequently cancelled as no wind tunnel operators were prepared to have rocket exhaust products released in their facilities. R. Morgan worked with Ariane Group during his SSP in 2018 on the base heating issues.</td>
</tr>
<tr>
<td>Testing Services.</td>
<td>As the inherent value of this research to the State exceeds 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.</td>
</tr>
<tr>
<td>Consulting Services.</td>
<td>There were no consulting services activities in 2016-18.</td>
</tr>
</tbody>
</table>
Defence Connect Announcement of 5 year Collaboration Agreement with DST and UQ, 20 November 2018

By: Louis Dillon

Defence Science and Technology (DST) and the University of Queensland (UQ) have announced a collaboration agreement to undertake advanced research in flight science and enabling technologies.

The $10 million agreement will see the consolidation of both parties’ test facilities to help muster the expertise of academic and industry researchers and international partners.

Professor Richard Morgan, UQ's director of the Centre for Hypersonics, has been appointed to provide expertise in the development and operation of advanced large-scale test facilities and facilitate close collaboration under the agreement.

Professor Morgan is the only non-US scientist to have received a hypersonic systems and technologies award from the American Institute of Aeronautics and Astronautics.

High-speed flight science is one of the priority areas to be developed under the Next Generation Technologies Fund, a program focusing on research and development in emerging future technologies.

UQ has undertaken major research projects on hypersonic aerodynamics over the past two decades, and the Centre lists its objectives as:

- 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.

The Centre's areas of expertise are:

- Development of test facilities based on shock wave generation (shock tunnels, expansion tunnels, light-gas guns, blast generators);
- Scramjet propulsion (experiment, analysis and design);
- Rocket-launched flight testing;
- Aerothermodynamic experimentation and analysis;
- Advanced instrumentation for aerodynamic measurements;
- Computational fluid dynamic analysis of high-speed transient and steady flows; and
- Optical diagnostics for hypervelocity superorbital flow.
## KPI 2 - Personnel

<table>
<thead>
<tr>
<th>Number</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>UQ Teaching and Research Staff</td>
</tr>
<tr>
<td>6</td>
<td>UQ Research Focused Staff</td>
</tr>
<tr>
<td>5</td>
<td>UQ Technical Staff</td>
</tr>
<tr>
<td>15</td>
<td>UQ Honorary / Adjunct Staff</td>
</tr>
<tr>
<td>9</td>
<td>DST staff</td>
</tr>
<tr>
<td>1</td>
<td>Teakle Composites staff</td>
</tr>
</tbody>
</table>

The figure overleaf will appear in the *Times Higher Education* in March 2019.
**Australian space research gathres speed**

As global demand for nano- and microsatellites intensifies, The University of Queensland is leveraging its world-leading scramjet technology to develop a system that could dramatically reduce the cost and improve the commercial viability of sending these small satellites into space.

The scramjet was launched into space in 1997. It marked the beginning of the age of spaceplane technology and led to innovations that have fundamentally altered the way we think about spaceflight.

While much has changed in the 20 years since the first University-launched scramjet, the technology used to send satellites into orbit remains surprisingly simple.

Every year, hundreds of satellites are launched from countries across the globe, and as this early days of space exploration, each is sent into orbit via rockets — rockets that are expensive and challenging.

But with the small satellites launch market now capable of taking up to 100 billion in the past decade, governments and private enterprises worldwide discover their potential for a range of applications from telecommunications to Earth observation — there's a growing need for less expensive satellites to be launched into space.

The scramjet is an extension of this technology, allowing for a more efficient and cost-effective means of launching small satellites. It has the potential to revolutionize the space industry, reducing the cost of launching small satellites, which is crucial for companies looking to establish a presence in space.

**Australia has the technology to create the world’s most sustainable space launch system: it’s an opportunity too good to pass up — Professor Smart**

Work with small class facilities, private companies, and government agencies to develop a hypersonic missile.Populate a hypersonic missile is gaining momentum, with many countries around the world working on developing hypersonic technology. This technology has the potential to change the way we think about space travel, as it could significantly reduce the time and cost of traveling to space.

By improving the design and development of hypersonic missiles, Australia can position itself as a leader in this emerging field. This not only has the potential to bring significant economic benefits but also offers the opportunity to contribute to global efforts in addressing climate change and space exploration.

**The University of Queensland**

**CREATE CHANGE**

**Annual Report (2016-2018)**

10
Leadership Team

Professor Richard Morgan, Director

Professor Richard Morgan is the founding Director of the Centre for Hypersonics and 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; this includes the ‘X’ series of superorbital expansion tubes. Richard 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 programs with NASA, ESA, Oxford University, Ecolé Centrale (Paris) and AOARD in radiating flows. He is leading the DST funded ‘X3R’ shock tunnel project, which will be the largest reflected shock tunnel in Australia, and will be housed in a new DST Laboratory at Eagle Farm, Brisbane.

Professor Morgan has had continuing ARC support in this area since 1990, including two ARC Discovery Projects grants in this reporting period in partnership with European, Japanese 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.

Richard 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. In 2014, Richard gave the ‘Cullpepper’ plenary lecture at the AIAA Aerospace planes conference in memorial to Professor Ray Stalker, the pioneering Australian Researcher from UQ who passed away in February 2014. In 2017, Professor Morgan received the AIAA Hypersonic Systems and Technologies Award. He is only the fourth recipient of the award and the first non-American based researcher to be so honoured.

Professor 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. With the signing of a 5 year collaborative agreement between UQ and DST in November 2018, Prof Morgan’s position is co-funded by DST, and he will focus his work primarily on facility development and strengthening the collaboration between the two groups and their international partners.

Dr Ingo Jahn, Deputy Director

Dr Ingo Jahn’s research interest are in hypersonic flows and vehicle design. Dr Jahn graduated with a Master in Engineering Science from The University of Oxford in 2003. He completed his PhD at the Oxford Thermofluids Laboratory (Osney Lab), which was awarded in 2011. From 2007 to 2012 he worked for Rolls-Royce plc in Derby, United Kingdom, where he led research on Advanced Seals and Oil Systems for large gas turbine aero-engines. He has been part of the academic staff at UQ since 2012 and took up the role of Deputy Director in the Centre for Hypersonics in 2018.
Ingo has a wide research record covering hypersonic aerodynamics & control, hypersonic combustion fundamental, aerospace gas turbines, and turbomachinery and power cycles operating with complex fluids. His current research foci are fluid structure interactions in hypersonics and efficient aerodynamic control of hypersonic vehicles. These activities are supported by ARC Discovery Project grants and AFOSR grants in partnership with collaborators from Europe and America.

Professor Michael Smart

Professor Michael Smart’s research interests are in hypersonic aerodynamics, scramjets and compressible fluid flow. Professor Smart graduated with a Bachelor of Engineering (Hons) from UQ in 1985. He completed a Master of Engineering Science at UQ in 1987, and completed a PhD at the Polytechnic University, Brooklyn, New York, in 1995. He was appointed as an Associate Professor in the Centre for Hypersonics in 2005 after spending ten years as a research scientist at NASA’s Langley Research Centre in Virginia.

Michael is the chief investigator on the five-year National and International Research Alliances partnership collaboration between UQ, the Queensland Government, Boeing, USAF and DST Group to conduct scramjet-related flight tests as part of the Hypersonic International Flight Research Experimentation (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 received the 2012 International Congress for Aeronautics (ICAS) Von Karman Award for International Co-operation in Aeronautics.

In 2018, Michael founded the company ‘Hypersonix’ to develop Scramjet assisted access to space launch systems with the objective of giving Australia a strong commercial foothold in the space industry (see page 7).

Professor David Mee

Professor David Mee’s research interest is in hypersonic and supersonic flow. After completing his PhD at UQ, he spent five years as a Research Fellow in the turbomachinery group at Oxford University in the UK. He returned to UQ as an ARC Queen Elizabeth II Research Fellow in 1993 and joined the academic staff in 1999. David became the Head of Division of Mechanical Engineering in 2007 and the Head of School of the School of Mechanical and Mining Engineering from 2009-2017.

David has a strong research record in the field of hypersonic aero thermodynamics. He is recognised worldwide for his work on rapid response force balances, which is 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 conducted the first known wind tunnel test in which a scramjet vehicle produced net thrust. He has pioneered
the use of stress wave force balances for measurement of multiple components of force on scramjet powered vehicles; these techniques are in use around the world.

### Academic and Research Staff

<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr Hans Alesi</td>
<td>Research Fellow (DST; DLR, Germany from 2018)</td>
</tr>
<tr>
<td>Dr Daryl Bond</td>
<td>Research Fellow</td>
</tr>
<tr>
<td>Dr Aaron Brandis</td>
<td>Adjunct Research Fellow (NASA, Ames)</td>
</tr>
<tr>
<td>Dr Stefan Brieschenk</td>
<td>Adjunct Research Fellow (Rocket Lab, New Zealand)</td>
</tr>
<tr>
<td>Professor David Butsworth</td>
<td>Honorary Professor (University of Southern Queensland)</td>
</tr>
<tr>
<td>Dr Bianca Capra</td>
<td>Honorary Research Fellow (UNSW Canberra/ADFA)</td>
</tr>
<tr>
<td>Dr Wilson Chan</td>
<td>Adjunct Fellow (DST)</td>
</tr>
<tr>
<td>Dr Troy Eichmann</td>
<td>Adjunct Fellow (DLR, German Aerospace Agency)</td>
</tr>
<tr>
<td>Mr Myles Frost</td>
<td>Research Assistant (DST Group, HyShot)</td>
</tr>
<tr>
<td>Mr Donald Fry</td>
<td>Adjunct Professor (NOEA)</td>
</tr>
<tr>
<td>Dr David Gildfind</td>
<td>Lecturer (currently on ARC DECRA award)</td>
</tr>
<tr>
<td>Dr Rowan Gollan</td>
<td>Lecturer</td>
</tr>
<tr>
<td>Dr Carolyn Jacobs</td>
<td>Honorary Lecturer, University of the Sunshine Coast</td>
</tr>
<tr>
<td>Dr Peter Jacobs</td>
<td>Associate Professor (Reader)</td>
</tr>
<tr>
<td>Dr Ingo Jahn</td>
<td>Senior Lecturer</td>
</tr>
<tr>
<td>Dr Chris James</td>
<td>Research Fellow</td>
</tr>
<tr>
<td>Dr Steven Lewis</td>
<td>Research fellow (DST)</td>
</tr>
<tr>
<td>Dr Michael Macrossan</td>
<td>Honorary Research Consultant</td>
</tr>
<tr>
<td>Dr Matthew McGilvray</td>
<td>Honorary Senior Fellow (Oxford University)</td>
</tr>
<tr>
<td>Associate Professor Tim McIntyre</td>
<td>Associate Professor, School of Mathematics and Physics (UQ)</td>
</tr>
<tr>
<td>Professor David Mee</td>
<td>Professor</td>
</tr>
<tr>
<td>Dr Neil Mudford</td>
<td>Honorary Senior Fellow</td>
</tr>
<tr>
<td>Dr Noel Morris</td>
<td>Postdoctoral Research Fellow. Deceased 2018.</td>
</tr>
<tr>
<td>Professor Richard Morgan</td>
<td>Professor</td>
</tr>
<tr>
<td>Dr Judith Odam</td>
<td>Research Fellow (DST Group, HyShot)</td>
</tr>
<tr>
<td>Professor Allan Paull</td>
<td>Program Leader (DST Group, HyShot) and UQ Adjunct Professor. Appointed as UQ staff member from 1/1/2019.</td>
</tr>
<tr>
<td>Dr Ross Paull</td>
<td>Research Fellow (DST Group, HyShot). Deceased 2017.</td>
</tr>
<tr>
<td>Dr Hadas Porat</td>
<td>Research Officer (DST Group)</td>
</tr>
<tr>
<td>Dr Sarah Razzaqi</td>
<td>Postdoctoral Research Fellow (DST Group)</td>
</tr>
<tr>
<td>Dr Todd Silvester</td>
<td>Adjunct Fellow (DST Group, HyShot)</td>
</tr>
<tr>
<td>Professor Michael Smart</td>
<td>Professor</td>
</tr>
<tr>
<td>Dr Phillip Teakle</td>
<td>Research Consultant, Teakle Composites, and Adjunct Associate Professor</td>
</tr>
<tr>
<td>Dr Sandy Tirtey</td>
<td>Adjunct Lecturer (Rocket Lab, New Zealand)</td>
</tr>
<tr>
<td>Mr Pierpaolo Toniatto</td>
<td>Research Officer</td>
</tr>
<tr>
<td>Dr Anand Veeraragavan</td>
<td>Senior Lecturer</td>
</tr>
<tr>
<td>Associate Professor Vince Wheatley</td>
<td>Associate Professor</td>
</tr>
<tr>
<td>Dr Fabien Zander</td>
<td>Adjunct Fellow (University of Southern Queensland)</td>
</tr>
</tbody>
</table>
## Technical Staff

<table>
<thead>
<tr>
<th>Name</th>
<th>Specialty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mr Barry Allsop</td>
<td>Electronics</td>
</tr>
<tr>
<td>Mr Frans De Beurs</td>
<td>X3 expansion tube upgraded driver installation</td>
</tr>
<tr>
<td>Mr Neil Duncan</td>
<td>X3 shock tunnel facility</td>
</tr>
<tr>
<td>Mr Samuel Grieve</td>
<td>T4 shock tunnel facility (now with Faculty Workshop Group)</td>
</tr>
<tr>
<td>Mr Keith Hitchcock</td>
<td>T4 shock tunnel facility</td>
</tr>
</tbody>
</table>
KPI 3 – Education and Engagement

Encourage involvement of Higher Degree by Research Students

See Appendix 2 for a list of current RHD students, and Appendix 3 for a list of 2016-18 publications.

HDR Education

We currently have 27 Higher Degree by Research (HDR) students enrolled in the Centre. A further 2 students submitted their thesis in 2018. There were also three PhD graduates in 2016, eight in 2017, and seven in 2018, bringing the number of HDR graduations from the Centre for Hypersonics at UQ to 18 for the period 2016 to 2018. The total number of HDR graduates from the Centre now stands at 138.

Steven Lewis received the Dean’s award for Outstanding Higher Degree by Research Thesis from the UQ Graduate School for his 2017 Thesis entitled “Hypervelocity Shock-Layer Emission Spectroscopy with High Temperature Ablating Models”.

In addition, research students participate in many national and international conferences, and present the results of their research in person, with further details of these engagements below.

PhD graduates again found employment in respected overseas institutions including the California Institute of Technology (Caltech), Princeton University, the University of Illinois, Oxford University, Tokai University, and Rocket Lab (NZ). Rocket Lab is pioneering the development of innovative space propulsion systems, indicating the value and relevance of the experience they gained at UQ to state of the art in this field.

Other graduates are employed locally with Gilmour Space. Domestically, graduates have become academic staff at RMIT, USQ, USC and UNSW Canberra. A core group of graduates have taken up positions at DST Brisbane and DST Adelaide, putting their hypersonics expertise to use to help assure national security. Other graduates took up positions in consulting engineering firms and in the financial industry.

HDR Engagement

Many HDR students enriched their studies through periods overseas with our collaborators.

- Christopher James spent 12 months in 2014/2015 working with École 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. He kept up the collaboration on return to UQ and was awarded his PhD in December 2018.
- Tamara Sopek spent time at Stanford University, working with the pioneering Professor Ron Hanson on optical diagnostics.
- Sangdi Gu spent one month in the United States of America. Here he presented at The American Institute of Aeronautics and Astronautics Science Meeting and conducted research at NASA Ames with our ARC Discovery Project partner investigator.
- Sreekanth Raghunath, was supported by a UQ Postgraduate Travel Grant to spend one month at Texas A&M University working
- Kyle Damm visited the computational fluid dynamics laboratory at Seoul National University, Korea. The visit duration was 18 months and significantly enhanced the development of the steady-state and adjoint flow solvers with the hypersonics researchers there looking at boundary layer transition in their hypersonic tunnel.
- Sholto Forbes-Spyratos, was supported by a UQ Postgraduate Travel Grant to spend 3 months in 2018 at the Institute for Space Systems at the German Aerospace Centre, DLR, to develop new trajectories for their Space Liner.
- PhD students Brad Wheatley, Andreas Andrianatos, Steven Lewis and Sangdi Gu visited collaborators at IRS, Stuttgart.
- Andreas Andrianatos visited the HIEST facility at JAXA in 2017 for meetings with ARC Discovery Grant partner investigator Dr Hide Tanno.
Undergraduate Education

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. The Centre typically hosts ten of these students per year.

Oliver Street's internship was particularly successful; his work on extracting quantitative data from flow visualisations was a major contribution to a paper presented at the AIAA International Space Planes and Hypersonic Systems and Technologies Conference in Orlando, Florida, USA and he is now undertaking a PhD within the Centre.

Undergraduate students continued to undertake final year thesis projects with the group. Jonathan Ho has continued onto a PhD at Stanford. Heather Muir won a John Monash scholarship for study at Cambridge University and Kieren Wood has also gone on to study at Cambridge University.

Staff Awards and Teaching Grants

- Vincent Wheatley was awarded an Australian Award for University Teachers (AAUT) Award for Teaching Excellence in 2017.
- Vincent Wheatley was also awarded a UQ Teaching Innovation Grant in 2017 and a UQ Teaching Fellowship in 2018 for the project “Authentic, active and inspired learning – transforming large courses”
- Ingo Jahn and Rowan Gollan were awarded a UQ Teaching Innovation Grant in 2018 for the project “Lab in the clouds: using the cloud to deliver customised computing environments – easily deployed for teaching at scale or remotely.
- Ingo Jahn, Rowan Golan, and Peter Jacobs also received a “Citation for Teaching and Learning Excellence” for the CFD course that included the use of the UQ compressible CFD codes in 2016 and 2017 saw the introduction of the latest Eilmer4 version of the flow solver.

Massively Open Online Course (MOOC)

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 the Australian National University.

In 2014, the Centre commenced participation in the MOOC program pioneered by MIT, Harvard and Stanford 2Universities by offering a hypersonics course “Hypersonics – from Shock Waves to Scramjets”. It was the first to be offered in that field. Over 26,000 students from over 120 countries have enrolled in the course (see Table 1).

The online resources developed for the course have also been adapted by Associate Professor Vincent Wheatley to deliver compressible flow theory to undergraduate engineers at UQ. This allows students to focus on solving challenging problems from research and industry when on campus. The inclusion of these resources into the curriculum was a major factor in him winning a 2017 Australian Award for University Teaching.
Table 1 MOOC Enrolments (2014 –2018)

<table>
<thead>
<tr>
<th>Year</th>
<th>Enrolments</th>
<th>Male %</th>
<th>Female %</th>
<th>Other %</th>
<th>High School %</th>
<th>University %</th>
<th>Advanced Degree %</th>
<th>USA %</th>
<th>India %</th>
<th>AUS %</th>
<th>UK %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>8,697</td>
<td>91.0</td>
<td>9.0</td>
<td>30.6</td>
<td>40.2</td>
<td>26.3</td>
<td>22.3</td>
<td>17.7</td>
<td>4.4</td>
<td>4.0</td>
<td></td>
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<tr>
<td>2015</td>
<td>6,661</td>
<td>88.0</td>
<td>12.0</td>
<td>34.6</td>
<td>41.4</td>
<td>21.7</td>
<td>20.6</td>
<td>21.3</td>
<td>3.3</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>3,168</td>
<td>87.6</td>
<td>11.4</td>
<td>36.4</td>
<td>40.5</td>
<td>20.5</td>
<td>21.1</td>
<td>17.7</td>
<td>4.8</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>3,873</td>
<td>88.0</td>
<td>11.3</td>
<td>0.7</td>
<td>35.5</td>
<td>35.5</td>
<td>22.6</td>
<td>17.9</td>
<td>21.4</td>
<td>3.4</td>
<td>3.6</td>
</tr>
<tr>
<td>2018</td>
<td>3,328</td>
<td>88.9</td>
<td>10.8</td>
<td>0.3</td>
<td>34.8</td>
<td>34.8</td>
<td>23.0</td>
<td>20.1</td>
<td>17.6</td>
<td>3.7</td>
<td>4.8</td>
</tr>
<tr>
<td>2019*</td>
<td>457</td>
<td>90.6</td>
<td>9.4</td>
<td>36.9</td>
<td>36.9</td>
<td>20.6</td>
<td>15.8</td>
<td>20.5</td>
<td>4.7</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>26,184</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*as at 20 February 2019

The UQ Hypersonics MOOC, coordinated by Professor David Mee, can be found online⁵.

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⁵ https://www.edx.org/course/hypersonics-from-shock-waves-to-scramjets
KPI 4: Collaboration

Engagement and Collaboration

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

The Centre hosted a number of visitors in connection with the HIFiRE, the ARC research programs, and the GO8-DAAD award which we hold with IRS (Institute of Space Systems) Stuttgart. Following on from the successful Asia Pacific International Symposium on Aerospace Technology (APISAT) in Cairns in November 2015, UQ hosted a series of lectures in Aerothermodynamics. The meeting was chaired by Richard Morgan and was attended with invited speakers from Japan, Germany, China, Korea and Australia.

Associate Professor Vincent Wheatley co-chaired the 2016 International Workshop on the Physics of Compressible Turbulent Mixing at the University of Sydney. This workshop brought together over 100 international research leaders in the field, primarily focused on shock induced mixing in applications as varied as inertial confinement fusion and scramjets.

UQ staff members organised the AIAA International Space Planes and Hypersonic Systems and Technologies Conference. Dr Vincent Wheatley was on the organizing committee of the 2017 conference in Xiamen, China. Dr Anand Veeraragavan was on the organising committee of the 2018 conference in Orlando, Florida, USA. He also gave the Australian country report in Hypersonics at this meeting.

In addition, the Centre sponsored a seminar on 30 November – 1 December 2015. The theme of the seminar was “aerothermodynamics” and “diagnostics”. The seminar was attended by Centre staff as well as visiting academics from KAIST (South Korea), JAXA (Japan), IRS (Stuttgart) and Tsinghua University (China). UQ presentations included seven HDR students presenting their work.

Dr Peter Jacobs spent his Special Studies Program (SSP) in Semester 2, 2016, at École Centrale, Paris and at the University of Oxford. Dr Anand Veeraragavan spent his 2017 SSP between Stanford and the University of Illinois Urbana-Champaign (UIUC) focusing on advanced laser based diagnostic techniques for high speed flows. This has also initiated collaboration with these two world-leading groups.

Associate Professor Wheatley was also on the organising committee of the 1st International Conference on High-Speed Vehicle Science and Technology, which was held in Moscow, Russia in 2018.

Staff also travelled overseas to present Australian Research progress in the area of hypersonic flows with visits to the Whittle Laboratory (University of Cambridge) and Osney Laboratory (University of Oxford) in 2016, 2017, and 2018. The focus of these visits was to strengthen out collaborative ties with the UK.

Two Hypersonics Symposia, supported by the French Embassy and Airbus, were held in 2016 jointly with Centrale Supelec, Paris, one in Brisbane and other in Paris, co-chaired by Professor Morgan and Professor Christophe Laux from Centrale. This coincided with the signing of a collaborative agreement between UQ and Centrale Supelec, arising primarily form the close collaboration between our groups in Hypersonics since 2005.

In March 2017 we hosted a small workshop for visitors from the Temasek Centre at the National University of Singapore (NUS), whose delegation included the following:

- Professor KHOO Boo Cheong
- Associate Professor TEO Chiang Juay
- Dr CUI Yongdong
- Dr LI Jiun-Ming
- Dr NGUYEN Van Bo
- Dr NADESAN Thirukumaran
- Ms NG Keng Bee
- Mr WEI Han
This was a very productive exchange, which subsequently led to a $600. He also collaborative research program with NUS, which is ongoing.

**Visiting Academics**

A number of visiting academics were invited to the Centre during the period 2016-2018. These included:

- Dr Corin Segal: University of Florida, USA (2015)
- Professor Dale Pullin: California Institute of Technology, USA (2015)
- Associate Professor Matt McGilvray, University of Oxford (2016, 2017, 2018)
- Dr Gaiji Yamada, University of Tokai, Japan (2017)
- Dr Matthew Smith: National Cheng Kung University of Technology, Taiwan (2017)
- Dr Thirukumaran Nadesan: National University of Singapore (2018)
- Dr Han Wei, NUS (2018)
- Dr Yongdong Cui: National University of Singapore (2018)
- Professor Klaus Hannemann: DLR, Germany (2018)

**Visiting Research Students**

Several Visiting Research Students (formerly called Occupational Trainees) were invited to work in the Centre during 2016-2018 (Table 2). These students are typically HDR or coursework masters students from other countries who are required to do an internship overseas as part of the degree requirements from their home institution. The students generally are enrolled in European countries and attend a university with which the Centre collaborates. Table 3 lists research topics undertaken by Visiting Research Students.

<table>
<thead>
<tr>
<th>Year</th>
<th>Country</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>United Kingdom</td>
<td>1</td>
</tr>
<tr>
<td>2016</td>
<td>France</td>
<td>2</td>
</tr>
<tr>
<td>2016</td>
<td>Netherlands</td>
<td>1</td>
</tr>
<tr>
<td>2016</td>
<td>Scotland</td>
<td>1</td>
</tr>
<tr>
<td>2017</td>
<td>United Kingdom</td>
<td>1</td>
</tr>
<tr>
<td>2017</td>
<td>Australia/NZ</td>
<td>1</td>
</tr>
<tr>
<td>2017</td>
<td>France</td>
<td>1</td>
</tr>
<tr>
<td>2017</td>
<td>Netherlands</td>
<td>1</td>
</tr>
<tr>
<td>2007</td>
<td>USA</td>
<td>1</td>
</tr>
<tr>
<td>2018</td>
<td>United Kingdom</td>
<td>1</td>
</tr>
<tr>
<td>2018</td>
<td>Singapore</td>
<td>2</td>
</tr>
<tr>
<td>2018</td>
<td>Netherlands</td>
<td>1</td>
</tr>
<tr>
<td>2018</td>
<td>USA</td>
<td>3</td>
</tr>
<tr>
<td>2018</td>
<td>France</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 3. Visiting Research Student Research Projects (2016-2018)

<table>
<thead>
<tr>
<th>Project Description</th>
<th>Research Focus</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-equilibrium recombination processes in high enthalpy flows</td>
<td>Calculation of rocket performance during hypersonic flight</td>
<td>Computational fluid mechanics of combustion</td>
</tr>
<tr>
<td>Assess advanced propulsion systems for surface to orbit aerospace vehicles</td>
<td>High response diamond based heat transfer gauge development</td>
<td>Computational fluid mechanics for compressible flows</td>
</tr>
<tr>
<td>Measuring transition in hypersonic flows in T4</td>
<td>Design of a hypersonic flight experiment test bed</td>
<td>Simulation of roughness-induced boundary layer transition</td>
</tr>
<tr>
<td>Expansion tube studies of high temperature gases</td>
<td>Development of non-intrusive approach to measure regression rate inside hybrid rocket engines.</td>
<td>Feasibility of non-integer system identification for heat transfer measurements in shock tubes</td>
</tr>
</tbody>
</table>
KPI 5 – Research and Development Excellence

Research Summary

The Research Summary includes work done at UQ and by our collaborators at the University of Southern Queensland (USQ).

University of Southern Queensland

Research at USQ (2016-2018) centred on combustion, hot surfaces, fluid-structure interaction, and hypersonic control. References are to publications in listed in Appendix 4.

Combustion

Axisymmetric cavity combustion at Mach 2 flight enthalpy conditions has been demonstrated using an annular cavity with slot injection of hydrogen [16, 18, 27]. Diagnostic tools for fuels and combustion measurements in the TUSQ facility have also been developed [1, 5], and further activity in this area is continuing. We are seeking to develop a new condition for the TUSQ facility where we can duplicate flight enthalpy at Mach 4 in order to test a rotating detonation wave engine combustor coupled to a realistic inlet and thrust nozzle [6]. Rotating detonation wave engines is the focus of an ARC-DECRA application being planned by a new member of USQ staff, Dr Fabian Zander (appointed to USQ in 2018) in 2019.

Hot surfaces

Methods for prescribing non-uniform temperature distributions on hot surfaces has been investigated [19], and a new method for heating axisymmetric disk-like heat shield models has been developed based on TIG welding principles. Publication of this technique is anticipated in 2019.

Free Flight Experiments

Free-flying experiments on models of the HEXAFLY-INT hypersonic glider and its separation from the service module have resulted in several publications [10, 11, 22, 28, 31]. Subsequent work was performed for DST on the HIFiRE-4 for aerodynamic coefficient database verification and on the HIFiRE-8 configuration, looking particularly at the question of booster separation and whether active mechanical separation devices would be required or whether passive separation associated with the aerodynamic drag differential would be sufficient.

Fluid-structure interaction

The pioneering work in the TUSQ facility has received substantial international recognition and activity in this area is now being supported through ARC-Discovery funding for “Fluid-Structural Interactions in High-Speed Flows”, and the AFOSR funding for “Characterisation and control of a flap undergoing hypersonic fluid-structure interaction”, both in collaboration with UNSW. Publications arising from this area are [13, 21, 30], with further manuscripts currently being prepared for journal publication.

Hypersonic control

The pivoted wing-with-elevator experiment which was initiated through fundamental fluid-structure interaction work [3] has seen publication at various forums [12, 15, 23], and has been used as the focus of further development of moving-mesh capabilities in Eilmer [9]. A pivoted wing with a hinged elevator was tested in TUSQ as a hypersonic control capability demonstration. The wing was pivoted at the ¼ chord location and the elevator occupied approximately 15 % of the chord length of the wing. The wind was 3D printed with an internal cavity that allowed a gyro plus level shifting electronics, and servos for the elevator to be installed. A simple feedback control arrangement was implemented and successfully demonstrated that it was possible to either damp out or amplify the wing oscillations, depending on the phasing of the actuation of the elevator relative to the gyro signal. We anticipate hypersonic aerodynamic control work forming an important part of the TUSQ portfolio in the near future.
Support for other research areas

The vacuum chambers of the TUSQ facility have been used in other research relating to ejectors, and several publications [2, 4, 7, 8, 17, 24, 26] have arisen by virtue of this equipment.

Energy Deposition

An axisymmetric model with forward and aft electrodes sandwiching a cylindrical graphite sample has been developed for experiments on heat shield ablation and chemistry in the hypersonic flow produced by TUSQ. Experiments using a slightly modified version of this model have also been performed to investigate the possibility of hydrogen combustion against hot carbon surfaces in hypersonic flows.

Free Flight Experiments

Internally-funded, free-flying experiments on a model of the HEXAFLY-INT hypersonic glider were performed at USQ in collaboration with colleagues from UNSW Canberra. USQ, The University of New South Wales (UNSW) and The University of Sydney formed the Australian arm of the EU-funded consortium working towards flight testing of the glider configuration in 2018. 3D printed models were assembled with an instrumentation package consisting of a 6-axis gyro board, microcontroller, battery and blue tooth for data download. Models were lead-ballasted to achieve the correct centre of mass. Measurements of moment coefficients were achieved and future work with additional instrumentation including pressure sensitive paints,

IR surface temperature detection, and two axis Schlieren visualisation are planned for 2016. Following the success of the free flight work with the HEXAFLY-INT configuration, a program of free flight experiments sponsored by the DST Group on the HIFiRE-4 glider configuration was completed in 2016, with further tests on HIFiRE8 completed in 2017.

Fluid-structure interaction

High quality experimental data on hypersonic fluid-structure interactions does not currently exist but is necessary for validation of both CFD models and reduced-order modelling of hypersonic fluid-structure interactions.

Recent work in the TUSQ facility is targeting the development of such data. Experiments on a cantilevered plate in the Mach 6 hypersonic flow were performed in collaboration with colleagues from UNSW. The cantilevered plated was instrumented with pressure transducers and pressure sensitive paint was also used. Schlieren flow visualisation was also used to identify flow structures and the dynamics of the plate deformation. Experiments were also performed on a wing structure in collaboration with colleagues from UQ. The wing was free to oscillate about its ¼ chord location, and was initially set at 15 degrees prior to flow onset. The step-like flow establishment process initiated periodic wing oscillations about the zero angle of attack and analysis of Schlieren images revealed hysteresis in flow structures that developed.

University of Queensland

CFD development

For the compressible-flow CFD project at The University of Queensland, the end of 2016 brought the release of the core of the Eilmer4 flow simulation code and its associated documentation. Eilmer4 can be used for the simulation of transient and steady two- and three-dimensional flows which have complex high-temperature thermochemistry. Presently, other capabilities include conjugate heat transfer with solid structures and shared-memory parallel execution on multi-core computers. Applications of the code include the design and analysis of hypersonic-flow pulse facilities for the testing of subscale aerothermodynamic models and scramjet compression inlet analysis. The source code for Eilmer4 is available from a public repository on BitBucket.6

Further developments in 2017 and 2018 have focussed on the creation of a steady-state solver and the adjoint solver for design optimisation studies. On more fundamental flow physics, we have further developed high-
temperature thermochemical models in the flow simulations codes, such as a two-temperature model for ionising argon. Recently, in collaboration with Paris-Saclay University, we have introduced advanced state-specific models to the flow solver.

In 2018, Lockheed Martin’s StellarLab sponsored the development of a boundary condition to model electron emission from thermionic material surfaces. This sponsorship supported Will Landsberg to work on the implementation and testing. The modelling work is now included in Eilmer4 and this work was a foundation towards submitting an ARC Linkage Project application in December 2018.

**Hypersonic International Flight Research Experimentation (HIFiRE)**

The Hypersonic International Flight Research Experimentation (HIFiRE) program continued its investigation of the fundamental science of hypersonics technology and its potential for next generation aeronautical systems and will involve up to ten flights.

HIFiRE is jointly established by DST Group and the US Air Force Research Laboratory (AFRL). The HIFiRE 7 scramjet was launched from Andoya, Norway on 31 March 2015. It was boosted successfully to a Mach 7 re-entry. The HIFiRE 7 payload entered the atmosphere at the correct orientation and the scramjet engine started. However, telemetry was lost on the vehicle at an altitude of 63 km, which was before fuel was turned on. The telemetry failure was traced to overheating of electronics in the telemetry power system.

**Trajectory Optimisation**

The research student, Sholto Forbes-Spyratos, supervised by Dr Ingo Jahn, Dr Michael Kearney and Prof Michael Smart has been applying advanced methods taken from the area of control to optimised vehicle trajectories for a rocket-scramjet-rocket system. By using pseudo-spectral methods, Sholto has been able to establish improved trajectories that better integrate the different vehicle stages yielding up to 10% increase in payload to orbit and reducing dynamic pressure seen by the third stage by more than 30%, without changing the vehicle design. These are significant improvements further increasing the viability of scramjet based access to space systems.

**Computational modelling**

Computational modelling of the performance enhancements of porous injection over porthole injection in a 2D radical farming scramjet was completed. This modelling assumed that the porous walls are a uniform substance with permeability described by a semi-empirical relation that includes experimental data (provided by partner DLR of their supplied Ceramic Matrix Composite porous ceramic injectors). Results from this and combustion efficiency are increased with porous injection. Further, they show that for the same engine and operating condition, the combustion chamber could be reduced by 25% and achieve the same combustion efficiency when porous injection is used. Preliminary 2D computational studies were performed on the interaction that separated ordered channel structures (i.e. idealized individual pores) would have on a hypersonic cross flow. Estimates of the porous percentage and associated mass flow were conducted with electron microscopy. Due to the irregular nature of the porous material an off-parameter sensitivity study was performed to examine the influence of the material’s composite composition on the resultant integrated mass flow through the material. Three-dimensional CFD modelling of the experimental configuration for the fundamental T4 experiments was completed. This was used to identify the quality of the flow on the test surface for the experiments and assisted in the design of the experimental model for the test campaign 2.

**Experimental campaign**

The first experimental campaign was conducted in the T4 Stalker Tube to determine the performance of a scramjet engine with oxygen enriched porous fuel injection. This was a first. A significant effort was focused on analysing these results, which show, through pressure measurements, that thrust and specific impulse increased with oxygen enrichment. Results from this study were presented in the Journal of Fluid Mechanics.
The T4 test section was modified to allow for optical diagnostics (PLIF) measurements and model mounting from the bottom of the test section. Appropriate tunnel test conditions were established to ensure information on the porous injectant gas temperature and pressure could be captured with the PLIF system. This was scheduled to be done at ambient conditions and in a hypersonic cross flow. Design of the test model, including integration with the porous sample from DLR, and appropriate implementation of boundary layer trips for turbulent flow studies, was completed. DLR supplied four porous samples for the test campaigns.

The first test campaign required the design and manufacture of a new wind tunnel model (a heavily instrumented flat plate with porous injection and interchangeable leading edges. The system of mounting the model from the floor of the test section worked well. The testing involved injecting hydrogen (the fuel) through one of the porous injectors supplied by the PI from DLR Stuttgart. The schlieren flow visualisation of the injection indicated that there may have been some discreet jets within the porous injection. It was decided not to push further with the testing program until that issue was resolved. This test campaign was useful in identifying the issues that would need to be solved before test campaign 2.

An analysis of the wind-tunnel results from test campaign 1 also indicated that the quality of the flow over the plate was poorer than required due to the blockage to the flow under the test plate. A major re-design of the test plate was undertaken and thermocouple heat transfer gauges were replaced with higher-sensitivity nickel thin-film heat transfer gauges. In order to ensure a successful outcome of the project, the mounting of the porous injector was altered. Also, two additional porous inserts were designed and manufactured in case the non-uniformities in the porous injector identified in the first tests precluded an appropriate injection being achieved. One porous injector consisted of a dense array of 0.5 mm diameter holes that would serve as a quantifiable porous injector. Test campaign 2 was completed and much improved flow quality and results were obtained. An extensive set of flow conditions and fuel injection rates was completed. Schlieren photography proved very useful. The last step was the PLIF flow visualisation. Unfortunately, the laser for the visualisation failed just as testing with it was about to commence and the test campaign had to be ceased without the PLIF visualisation. It was concluded that sufficient data had been obtained with the other instrumentation to enable the major objectives of the project to be achieved.

Overall, the project achieved results that demonstrate that porous injection is a promising method of fuelling scramjets.

Fuel Jet - Vortex interactions:

The research project investigation the interactions between injected fuel jets and streetwise vortices naturally occurring in scramjet engines, especially shape transitioning engines such as the REST engine is nearing completion. The PhD student Juan R. Llobet, supervised by Dr Ingo Jahn and Dr Rowan Gollan, has spent the last three years conducting numerical simulations to better characterise the vortical flow structures that are present in scramjet engines such as 2-D multi ramp engines and shape transitioning engines (e.g. REST engine) and how this vortex can be utilised to enhance fuel mixing. As our scramjet engines are typically mixing limited any improvements in fuel mixing can be translated into an increase in combustion efficiency. The research has shown that by optimised placement of the injector, approximately half way between the separation line and the core of the vortex formed by the boundary layer roll up, mixing improvements of up to 300% can be seen close to the injector. This rapid increase in mixing, can be utilised to reduce the overall length of scramjet combustor, leading to improved performance. At the same time this project has also investigated the effects on wall heat transfer of this combined fuel injection-vortex flow field. This research project will be completed with an experimental campaign in the T4 shock tunnel to validate the findings. This campaign has just commenced.
Progress Reports on Grants and Fellowships

ARC Discovery Early Career Researcher Awards (DECRA)

Three members of the Centre held ARC DECRA projects during the reference period: Vincent Wheatley, Rowan Gollan, and David Gildfind.


This project was 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 (ICF), thus its magnetic 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. Its prediction of purely oscillatory interface behaviour was verified by comparing to the results of non-linear compressible simulations. 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 interface oscillates as these waves periodically reconstruct with alternating phase as they propagate, whereas an earlier paper attributed this solely to field line tension.

A 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. A simple expression was obtained for the asymptotic interface perturbation amplitude at large times. The model has been successfully applied to predict the local interface behaviour in nonlinear simulations of plasma implosions.

With RA Pavaman Bilgi, a solver for the MHD shock refraction problem was automated and generalized. 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. Together with RA James Barth, irregular MHD shock refraction has been simulated over a broad range of parameters. The structure is more complex than originally understood, and sensitive to problem parameters. Critically, the shock refraction process always leaves the density interface vorticity free, which is the underlying mechanism for the suppression of the RMI.

With RA Daryl Bond, we have begun to examine the RMI in the far more general context of two-fluid MHD, where electrons and ions are simulated separately. We have established that for reasonable plasma parameters, vorticity is still effectively transported in the two-fluid system, but a wide range of new phenomena occur that have implications for the growth of perturbations.

The role of the RMI in another context, mixing and combustion enhancement in scramjets, was also investigated and published. Large-Eddy Simulations (LES) of axisymmetric and planar inlet-injected scramjets demonstrated that inlet injection allows the interaction of turbulent fuel plumes with primary compression shocks at the combustor entrance, triggering the RMI, which has a transformational effect on the mixing process. The mixing rate is more than doubled due to this. We also demonstrated this effect in a complex 3D scramjets. Also in scramjets, the mixing and combustion initiated by a laser induced plasma were investigated using LES and published. It was determined that the blast wave driven by the laser induced plasma was primarily responsible for ignition and drove substantial localised mixing due to the RMI.

In collaboration with RA Xin Kang, a study was conducted on the effect of viscosity and resistivity on the MHD RMI with a normal magnetic field. The main result is that increased viscosity suppressed the instability and slightly decreases the critical magnetic field strength required to prevent it from entering its non-linear phase,
while finite resistivity reduces the effectiveness of the suppression mechanism. Since resistivity allows field lines to slip across the flow, discontinuous waves do not immediately form to transport the vorticity from the interface. While the vorticity does not immediately depart the interface when the resistivity is finite, it does disperse away slowly so that the instability is still inhibited, but to a lesser extent. For these non-ideal effects to be significant, the viscosity and resistivity had to be large.

Overall, the project findings indicate that the concept of magnetically suppressing instabilities detrimental to ICF has merit, and is unlikely to be disrupted by dissipative effects. Two-fluid plasma effects were identified as a key area for further investigation.

We have developed a preliminary simulation capability for two fluid plasmas. The formulation, verification and application of this capability to conduct an initial investigation of the two-fluid plasma Kelvin-Helmholtz instability was presented at the AFMC [2]. The capability was developed to enable the effects of charge separation, plasma oscillations, differential electron motion etc. on the RMI to be investigated. Preliminary simulations reveal that the two-fluid plasma RMI differs substantially from the hydrodynamic case. The Riemann problem used to initialise the flow drives a precursor electron shock that creates substantial charge separation. The fields generated by charge separation and motion electromagnetically accelerate the electron and ion density interfaces. This drives variable acceleration RTI of the interfaces, which generate fine scale structures and increase the growth of low-mode interface perturbations. These effects are reduced for a smaller Debye length plasma. Self-generated magnetic fields are observed and the transmitted ion shock is distorted by the complex interactions with electron vortices. These results have been submitted for publication as a JFM Rapid.


Development of computer-based optimisation to improve hypersonic aerodynamic design

Next-generation launch vehicles using high-speed jet engines will make it cheaper and more reliable for humankind to engage in activities in space. This project will contribute to the technology of high-speed jet engines by developing optimised air intake systems. The research aims to advance the use of computational engineering and apply this to improve the design of air intake systems. Specifically, the project has focussed on development and application of adjoint-based optimisation in high-speed flow regimes.

The funded portion of the project on using computer-based optimisation for the design of hypersonic inlets ended in December 2016. During the initial stages of the project, it became clear that the flow solver infrastructure would need to be upgraded significantly in order to undertake the flow optimisation work. A new flow solver was implemented in the D programming language, Eilmer4. The use of the D programming language is a novel approach to building large-scale high-performance simulation codes. This novel approach was communicated to the research community at the Australian Conference on Computational Mechanics. This work appears as an archival journal paper in a special issue of the Applied Mechanics and Materials in Australia [1]. This was an unexpected development in the project plan. The newly implemented flow solver infrastructure allowed for other modelling developments that were not originally planned. Chief amongst these was the development of a conjugate wall model. This will give a more realistic boundary condition for scramjet inlet studies than what was originally proposed in the project. The work on implementing and verifying the conjugate wall model was reported in the Journal of Computational Physics [2].

In late 2015, Kyle Damm joined as a PhD student on this project. His thesis work is nearing completion and we expect an April 2019 submission. Kyle’s PhD work extends the scope and capability of the adjoint-based optimiser to both internal and external hypersonic flows. We have successfully applied the optimiser to a
hypersonic inlet test case, and will look at optimised external vehicle aerodynamics in the final phase of the project. The results of the optimised hypersonic inlet test case were presented at the 2018 conference of the Korean Society for Computational Fluids Engineering.


Dr David Gildfind. “Magnetohydrodynamic aerobreaking to enable landing of heavy payloads on Mars” (2017-2020) (DE170100263)

In the thin atmosphere of Mars, aerodynamic drag alone is not enough to land a spacecraft larger than 1 tonne. A human mission to Mars requires landing of payloads up to 80 tonne. The aim of this project is to experimentally explore how to increase vehicle deceleration by applying a magnetic field to the hot ionized gases which form around the vehicle. Interaction of the magnetic field with the ionized flow provides a path for dissipating kinetic energy and can reduce surface heating. The significance of this project is its potential to make Mars-return missions feasible by enabling greatly increased payloads. The project aims to deliver the first-ever evaluation of magnetohydrodynamic braking and heat mitigation at true flight conditions.

David’s 2015 UQ Early Career Researcher (ECR) award was used to fund the design and manufacture of a series of proof-of-concept shock visualisation and force measurement experiments. Performance analysis of UQ’s X2 facility was undertaken to identify optimum operating points for magnetohydrodynamic (MHD) experimentation using various test gases. Argon was selected as the test gas for initial experiments, since it readily ionises, and has relatively simple chemistry which will assist with initial attempts to analyse and model initial experiments. Test gas can be changed to Mars of Earth atmosphere once experimental and numerical techniques are sufficiently developed.

In 2016 and 2017 three experimental campaigns were undertaken. These experiments were based on spherical permanent magnets in 6km/s argon test flows, and involved high speed imaging, Schlieren, and spectroscopy. Three features were evident from these experiments: the shock standoff was increased, radiative intensity was also significantly increased, and that electrically insulating the model surface was required for sustained shock-stand off increase. These initial experiments validated the methodology employed, and demonstrate strong MHD interaction for a planetary entry flowfield with electrodynamically correct boundary conditions.

One finding from these initial experiments was that shot-to-shot variation was large for the insulated models. This was attributed to the surface coating choice, and in 2018 new coatings were investigated to improve consistency. A new model configuration was developed to reduce the chance of current leakage from the plasma to the support, and a new technique was developed to test for current leakage through the model coating itself. Several coatings were tested, and it was found that the ceramic coating used in the previous experiments failed the leakage test. A new high temperature thermally conductive epoxy was the only coating that passed the current leakage test, and will be used in experiments in March 2019 to evaluate if consistency is now improved. Preliminary findings of this work were presented at the AIAA Flow Control Conference in Atlanta, in 2018:


A new PhD student, Daniel Smith, was recruited in 2017 to perform the drag force experiments. He has evaluated accelerometer and stress-wave force balance (SWFB) measurement techniques. In 2018, he measured MHD drag force for a planetary entry flowfield for the first time, using the accelerometer based model. However, he has encountered significant challenges with SWFB making measurements in the
electrically conducting plasma flow field. Significant effort has been required to overcome these issues, and progress is being made. He presented his work at the AIAA Flow Control Conference in Atlanta, in 2018:


New operating conditions were developed. A significant part of the study has involved developing wind tunnel test conditions using argon test gas which produce the required shock layer properties and electrodynamic boundary conditions. In addition to this, significant computation fluid dynamics (CFD) analysis was performed to better understand the ionised flow field around the models. This work has been submitted to the AIAA Journal in February 2019:


A second PhD students was recruited to this project in October 2018, Mr Alexis LeFevre. He is investigating heat transfer mitigation for Earth re-entry, and developing MHD capability in the Centre’s CFD code collection.

We have had three conference papers accepted to present this work to the International Symposium on Shock Waves in Singapore in July 2019.

**ARC Discovery Projects (DP)**

**Professor Richard Morgan: Ablative thermal protection systems (2012-2014) (DP120102663)**

The project investigated ablative re-entry heat shields by experiments simulating hypervelocity atmospheric flight. The results will enable the design of the advanced spacecraft which are needed to extend man’s exploration of the universe.

Follow on work continued on the project in 2016-18, although the ARC funding ended in 2014. It was a very productive period, with seven journal and 11 conference papers accepted. Ten UQ and overseas PhD students did experiments relating to the grant in the UQ facilities. Collaboration between the partner institutions was strong, with eight student exchanges and two Chief Investigator (CI) visits taking place between the partners in 2015, with related experiments being performed in four of the collaborating laboratories (UQ, USQ, IRS and ECP). A UQ PhD student completed a Cotutelle exchange at ECP, on gas giant radiation, extending the capability of the ECP Plasma Torch and modelling software to include gas giant atmospheres. Three of our recent postdoctoral fellows are now employed at respected institutions in Europe, including IRS Stuttgart, EPFL Lausanne and DLR Goettingen. Dr Fabian Zander worked on the grant as a student at UQ and spent time as a postdoctoral research fellow at IRS Stuttgart, further strengthening our ties, and nine staff and student exchanges occurred in 2015. Ms Elise Fahy from UQ spent a year of her PhD at Ecole Polytechnique Federale de Lausanne (EPFL) working on related aspects of both the ESA and ARC grants; she was instrumental in integrating the numerical modelling techniques used by all the partners. IRS and ECP also developed new instrumentation for heat transfer measurements in the ECP plasma torch.

**Professor Richard Morgan, Associate Professor Tim McIntrye, Professor David Buttswoth et al Radiation and Ablation in Rapidly Expanding Flows (2015-2018) (DP150100631)**

This was a busy and productive grant. Six PhD students have completed with experimental work based on the grant, and follow on work is ongoing. Collaborative activity has been strong, with P Jacobs spending an SSP at ECP with C Laux, and Morgan and McIntrye having shorter visits. An ECP student spent 3 months at UQ working on the facilities, and another is doing a year of his Cotutelle with the group. Christopher James completed his Cotutelle secondment at ECP and is now back in the UQ laboratory working on the project and completed his PhD with joint supervision from UQ and ECP. Sangdi Gu spent a month at NASA Ames working on the grant with PI Brandis after presenting the results of his work at Scitec 2017. Two follow on AOARD/AFOSR grants have been awarded after strong interest in the project was shown from the Air Force
Institute of Technology (AFIT) who have been our collaborators on previous ARC grants, and experiments have been performed by their students on related work in the UQ labs. Subsequent to the acquisition of new hardware from an ARC LIEF grant in 2016, new experiments have been completed and published extending our spectrometry capacity into the mid-infrared spectrum, which is extremely useful for interrogating Mars entry leeward flows, which is of great current interest to NASA. Analysis of these results was the focus of Gu’s visit to AMES in January 2017. Subsequent to interest in the project being shown by Airbus Defence and Space, two Hypersonics workshops were held at UQ and ECP (now a part of the larger Paris-Saclay University unit), cosponsored by UQ, ECP the French Embassy in Canberra and Airbus. These were extremely lively and productive meetings, and a proposal to establish a CNRS sponsored ‘Laboratoire International Associee’ (LIA) was initiated based on the common research interests revealed amongst the French and Australian research groups involved. Extensive experiments were performed in the UQ expansion tubes using air and carbon dioxide gases, and the validity of the testing methodology proposed in the grant has been validated. A follow on Discovery grant application has been submitted involving most of the investigators to implement the latest developments in thermo-chemical and radiation modelling into a robust CFD code which can simulate engineering flight geometries. The validity of the code and the associated theoretical modelling will be established through a series of benchmark experiments in the UQ Facilities. Seven Journal papers were accepted in 2016, and four more are currently under review. Four conference/workshop papers were presented, and three more have been accepted for forthcoming meetings. Subsequent to discussions with National University of Singapore (NUS) researchers at the ISSW meeting in Tel Aviv, July 2015, we identified common interests in hypersonics, and a Singapore funded grant has been awarded for a collaborative research program which includes further work in the area of this current DP grant. One of our recent PhD graduates has now been recruited by NUS to work exclusively on this new grant, which we take as a strong endorsement of the methodology and value of our Discovery program. R Morgan was awarded the AIAA 2017 Hypersonic Systems and Technologies award presented at Hypersonics 2017 in Xiamen in March 2017 This award is based primarily on the outputs of this and other ARC grants by the whole team, and is more encouraging feedback of the value of the grant. Nine journal and six conference papers were presented on the work.

Associate Professor Vince Wheatley, Professor David Mee, et al Acoustic loads on hypersonic engines (2017-2019) (DP170101105)

The aims of this project are to:

- Theoretically explore how flow disturbances generate acoustic waves in scramjet engines
- Experimentally investigate acoustic wave production in supersonic flows at low-frequencies
- Experimentally measure acoustic loads in a scramjet engine under realistic hypersonic flight and fuel injection conditions
- Refine and validate an LES approach for scramjet aeroacoustics

Good progress has been made against these aims thus far in the project.

The University of Queensland has recruited three PhD students (with external scholarships) to the project and a wide variety of research is in progress. Eric Chang’s PhD thesis is initially investigating hypersonic laminar and turbulent shock boundary layer interaction with heated walls in the T4 Stalker Tube. They represent an excellent opportunity to gather data on sound generation in this canonical hypersonic flow, and to examine how/if this is affected by the wall temperature. To enable this, Eric will utilize the focused laser differential interferometry (FLDI) system funded under this project, and its first application will be to his experiments. These experiments will occur in early 2019.

Ramandeep Kaur is the second PhD student who has been carrying out and analysing Large-Eddy Simulations (LES) of the experiments involved in this project, including Eric’s, the full scramjet flow-path and the experiments conducted at UNSW. From these simulations (validated by the experiments) we hope to gain a complete understanding of the dominant sound generation mechanisms and sources of unsteady structural loading.
Ian Cartmill has also conducted Direct Numerical Simulation of a hypersonic reacting mixing layer, which is a fundamental element of scramjet flows. From this it was determined that sound is strongly preferentially radiate into the air layer, and that heat release results in reduced sound generation due to the growth of the mixing layer being inhibited. These results have been accepted for publication at the Australasian Fluid Mechanics Conference. The scramjet flowpath for the primary UQ experiments has been designed and built by an existing PhD student, Augusto Moura, and tested in the T4 Stalker Tube. This initial campaign concluded in February 2018 provides surface measurements, OH PLIF visualization of the combustion process and high speed schlieren imagery. These will help give us a detailed understanding of the flow structure which will greatly aid in understanding the acoustic signals measured in subsequent campaigns. The third PhD student recruited to the project, Ramprakash Ananthapadmanabhan, will undertake the experimental PhD topic on scramjet acoustic loading specified in the application. He will setup utilize the focussed schlieren and FLDI system to image and quantitatively measure acoustic disturbances in the scramjet flowpath.

In 2018, a series of fundamental experiments were performed at UNSW Sydney to compare with theory and to explain acoustic wave production at low frequencies. These data will be used as validation data for numerical codes and form the basis for a series of publications.

Professor Richard Morgan, Dr David Gildfind, Professor David Mee, Dr Rowan Gollan, et al. Turbulent heat transfer during Mars, Venus and Earth atmospheric entry (2017-2019) (DP171003191)

Instrumentation purchased under LE160100194 (see below) has been set up for infrared thermography and measuring surface heat transfer contours through the shock layer, using a filtering technique demonstrated by the group in single channel mode in 2015. Two PhD students have started on the project, and have developed sample flow conditions at very high Reynolds numbers in the X2 superorbital expansion tube which are suitable for the turbulent shock layer conditions required for the study. Partner investigator, Matthew McGilvray from Oxford University, has developed prototype diamond based heat transfer gauges which have the potential to give high speed and reliable heat transfer measurements in the very erosive environment of a heat shield. Prototype gauges were successfully tested in UQ’s X2 facility in 2016, using a 2D model geometry representing the centreline of the ESA IXL capsule, and compared with the outputs of adjacent thermocouple gauges. The results were published at the AIAA ground testing conference.

Two Oxford researchers (one postdoctoral fellow and one DPhil student) visited UQ testing improved models in the X2 facility in 2017. These gauges when used in parallel with the (lower speed, but improved spatial resolution) 2D infrared pyrometry will be very useful for quantifying the levels of turbulent heat transfer in re-entry shock layers that have not been reproduced in the laboratory before. Two new postdoctoral fellows spent a fraction of their time working on the project and assisting the HDR students. CI David Mee visited Matthew McGilvray at the Oxford University Engineering Laboratory, and Matthew McGilvray made short visits to UQ in December 2017 and also in 2018. CI Morgan visited OUEL twice in 2018 as part of his sabbatical in Europe, and the collaboration was very productive. JAXA obtained approval to send their instrumented Apollo re-entry capsule to UQ for expansion tube testing and PI Tanno visited UQ. Many of the group attended the ISSW in Nagoya in July 2017, and we had useful interactions there with PI Tanno and visited JAXA. At the meeting UQ was invited to host the ISSW in 2021 where we will present in detail the results of this project.

For Earth entry investigations, a blunt capsule model was built and successfully tested by PhD student Tim Cullen, with a heated strip across the front which enables infrared thermography to be obtained by looking through the shock layer. In this way we can obtain turbulent heat transfer profiles across the windward surface using non-intrusive instrumentation. This project is also relevant in regard to the Orion capsule, which is expected to make its first manned entry in 2023, and will experience Reynolds numbers of a similar order. With regards to Mars entries, Ranjini Ramesh started her PhD in 2017 on high Reynolds number shock layers representative of Mars and Venus entry trajectories. She has chosen to use the Mars Surface Lander (MSL) mission as a case study to reproduce. Because of the large diameter and mass of that capsule, it has the highest Reynolds number and ballistic coefficient of any man initiated entry to the Martian atmosphere so far, and is the most relevant mission to the objectives of this project, and is the only entry so far to have induced turbulent flow. It is also the same capsule design that is to be used for the ‘Mars2020’ mission, which is of
topical interest as there are uncertainties regarding the safety parameters for that design. Appropriate test conditions have been generated for a forthcoming test program in X2 and X3, the methodology, hardware and instrumentation developed by Cullen. PhD student Andreas Andrianatos did full scale testing in X3 of the Hayabusa entry capsule at peak heating, the first time a full scale entry vehicle has been tested like this, removing the scaling issues usually associated with laboratory testing of radiating flows. 6 Journals and 7 conference papers have been presented relating to the grant.


Flight at extreme speeds challenges the very best of our engineering abilities. The structures of high-speed vehicles are subjected to fluid-structural interactions (FSI) in which the deformation of the structure, induced by the aerodynamic loads, can in turn influence this flow field and this coupling can detrimentally deform and even catastrophically damage the vehicle.

The aims of this project are to improve our ability to accurately predict the fluid-structural behaviour and fatigue lifetime of structures subjected to such high-speed flows. This is achieved by designing and performing first-of-kind measurements of FSI in hypersonic flows and use this unique data to develop and validate our predictive codes in combination with numerical simulations to better reveal the detail of the underlying flow physics. We aim to establish the relative significance of a range of relevant parameters including Mach number, Reynolds number, dynamic pressure and stiffness (geometric and material), in isolation and in combination, in determining the severity of FSI in high-speed flows using a tightly integrated experimental and numerical approach.

In the first year of the project we have recruited a number of international students and were successful in securing UQ international APA scholarships and they are due to start shortly.

In the meantime, we have continued to develop the experimental approach with Prof Buttsworth and his group at USQ for the cantilevered plate cases, including the novel inclusion of a moving shock generator that passively oscillates in the free stream flow. In parallel to this Dr Jahn has been implementing a moving mesh capability within the Eilmer solver at UQ to simulate our FSI cases and has been testing this using the cantilever plate measurements. The capability in Eilmer has been updated from 2D to 3D to more accurately model the interactions. In addition, we have been working with CI McNamara’s group at OSU to test the ability of the surrogate modelling approach to predict the response measured in our cantilever plate FSI experiments.

Publications to date:


ARC Large Infrastructure and Equipment Fund (LIEF)

Professor Richard Morgan, Professor David Buttsworth, Professor David Mee, et al. Optical diagnostics for the investigation of high speed energetic processes (2015-2016) (LE160100194)

This was a collaborative grant between three institutions, UNSW Canberra, USQ and UQ. UNSW was the lead Institution for the grant, the equipment was intended to be shared between the three institutions. The equipment has been widely used in many experimental investigations. It continues to be fully utilised and has
proven to be a very productive acquisition, and instrumental for the success of several subsequent grant applications. The following summarises some of the outcomes:

The ability to observe highly transient processes with unprecedented spatial and temporal resolution has allowed us to experimentally verify and/or measure the existence of several previously unknown processes in high-speed flows and impact scenarios such as:

- the persistence of irregular shock reflection off ramps with concave rounded inlets
- the propagation of elastic waves in armoured metals
- the detailed opening process of diaphragms bursting under pressure
- the chemiluminescence in subsonic hydrogen flames
- the detection/measurement of afterbody radiation and temperature distributions on re-entry vehicles in hypervelocity flows

The behaviour of armoured material during ballistic impact – the burst behaviour of diaphragms was reliably quantified - the efficiency of cavity flameholders for combustion processes in subsonic and supersonic flows was determined - the most endangered zones of thermal load on a re-entry vehicle were identified, and afterbody radiation in the wake of objects flying at hypervelocity can significantly add to the heat loading of these objects and must be addressed by adequate protection.

The above contributions are important because:

- knowledge of this experimentally previously unverified behaviour has consequences for the design of protection barriers against blast waves
- the results support the development of more efficient protection systems against ballistic impact
- safety standards for vessels with diaphragm-type relief valves can be re-examined
- combustion processes in sub- and supersonic flows can be made more efficient
- the heat protection of objects flying at hypervelocity can be improved

We verified that the new instrumentation can be used for visualising very small dynamic processes like bubble collapse or deformation of microstructures. This opens new research possibilities to investigate highly dynamic and energetic processes at scales previously deemed too small for optical observation. This can also be used to investigate whether bacteria can survive hypervelocity impacts, which would contribute to the Panspermia debate (the distribution of organisms via asteroid impact). The persistence of irregular reflection in the so-called double solution domain had only been predicted analytically and numerically. The experiments conducted with the high-speed camera constituted the first time this behaviour was experimentally observed.

*Professor Richard Morgan, Dr David Gildfind, Dr Peter Jacobs, Professor David Mee Hypersonic Driver - NWTF Project (2014-2015)*

In 2014, we received a collaborative Grant from Oxford University, funded by the UK National Wind Tunnel Facility Scheme (NWTF) for $454,710 to develop what will be the fastest shock tunnel in the UK.

The structural and functional design of the facility was completed by Richard Morgan and David Gildfind, working with the team from Oxford University. Richard Morgan spent three months at the Rolls Royce technology Centre at Oxford University in 2015 working on the project. During this time, collaborative links between Oxford and UQ were strengthened, with two Bachelor of Engineering/Master of Engineering students on placement and a UQ PhD student on exchange in the Oxford laboratory. New grant proposals were developed for ARC and EPSRC projects, and Richard Morgan participated in the annual ‘Luddock day’ festivities, giving a presentation on the long-term links between UQ and OUEL.

The tunnel was commissioned in 2018, and Richard Morgan spent 2 weeks in that year participating in the process.7

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Queensland Government Funding

Dr Anand Veeraragavan” Advance Queensland Research Fellowship (AQRF) (Mid-Career): Supersonic Combustion of Hydrocarbon Fuels for High-Mach-Number Axisymmetric Scramjets (2017-2020)

Dr Veeraragavan has been awarded an AQRF that started in late 2017. This project will aim to combine the recent advancements in supersonic combustion of hydrocarbon fuels by the candidate at the University of Queensland (UQ) with the hydrocarbon fuel thermal processing capabilities at the Defence Science and Technology (DST) Group based in Brisbane in collaboration with research groups from Stanford and Illinois on thermochemistry/optical diagnostics. The success of this fellowship will position Queensland based research groups to become world-leaders in the development of hydrocarbon fuelled supersonic combustors. This will provide the basis for Queensland to become the hub of future industry activity and jobs.

DST funded projects

Development of X3R, an advanced scramjet testing shock tunnel (MYIP 5828, MYIP6303, MYIP6788) (2015 - 2018)

In response to the clear need for enhanced ground testing capability in Australia for the Mach 5 to 8 speed range, with extended test times and larger physical dimensions than can be achieved in any existing facilities, UQ is collaborating with the DST Group Applied Hypersonics branch to develop a new reflected shock tunnel, X3R. The facility is based on the existing X3 superorbital expansion tube platform, and uses the same driver and the first driven tube configured as a reflected shock tunnel. The facility will give test times in the range from 10 to 20 milliseconds, and is predicted to have useful core flows of the order of 600 mm diameter. The primary role anticipated for the facility will be for the testing of flight scale scramjet combustors for use with hydrocarbon fuels.

Progress has been good, with driver commissioning experiments completed in August 2018, thereby achieving the key technical challenge of the new facility operating mode. The project was extended with phase two funding in 2016, and the project was then expanded in November 2018 to form the cornerstone of a new five year agreement between UQ and DST Group, the “Hypersonic Enabling Technologies collaborative agreement”. As part of this agreement, X3/X3R will be relocated to DST’s new Eagle Farm site. While X3 remains the property of UQ, DST will maintain and operate the facility. As part of this agreement, DST Group will gain equal timeshare of the facility, and be able to operate it within a more suitable security environment. The benefit to UQ will be that the cost of maintaining the facility will be met by DST, and UQ will also have the benefit of operating the facility in a larger and well equipped laboratory. Furthermore, DST is establishing a collaborative space at Eagle Farm which will ensure much deeper collaboration between the groups into the future, providing immense benefit to both collaborators. Three postdoctoral researchers are currently working on the project, which is being led by Richard Morgan and David Gildfind.

Major recent achievements in this project include experimentally demonstrating the new operating conditions in August 2018, thereby confirming the analysis and development work over the preceding two years. This work has been presented at the International Symposium on Shock Waves in 2017 (winning best student paper award) and AIAA Flow Control Conference in Atlanta, Georgia, in June 2018. Driver development work was also used as a basis to develop new piston sensor technology which provided the first in-situ time-resolved measurement of piston trajectory, which was published in Shock Waves Journal in 2018:


**Professor Michael Smart. HiFiRE Postdoctoral Research Fellow A8 (2015-2016) (MYIP 6075)**

The effect of increasing wall temperature on the combustion process in scramjets operating at Mach 7 was investigated. Wall temperatures up to 2000K were considered, and the overall combustion efficiency and combustor length was of primary importance.

**Professor Michael Smart. HiFiRE Postdoctoral Research Fellow A6 (2015-2016) (MYIP 6074)**

The project performed preliminary research to determine the effectiveness of materials to emit electrons when heated. The effectiveness was referenced to a heated combustor as well as to aerodynamic heating of leading edges of a hypersonic vehicle. The research involved bench testing of the material to temperatures of 2000K.

**Professor Michael Smart. Full scale HIFiRE 8 engine testing (2017-2019) (MYIP 6993)**

As part of the HiFiRE Program, the HiFiRE 8 engine was ground tested in the T4 Stalker Tube at UQ at Mach 7, and a reduced scale compared to flight. The engine exhibited strong performance and dual-mode operation at equivalence ratios between 0.8 and 1.0 with gaseous hydrogen fuel. It is presently not known how this engine would perform at the larger flight scale. To investigate the influence of scaling, this project involved the modification/enhancement of another larger facility at UQ (X3R) to allow full-scale scramjets of interest to DST to be tested.


This project for DST involved an assessment of the current state-of-the-art in High Speed Propulsion. DST recognised the knowledge of UQ in this area, and asked that a summary be complied. The summary included all international research and development in the USA, China, Russia, Europe and Australia. Based on the summary, it was clear that the leaders in these technologies were the USA and Australia. However, China had made significant advances in the previous 10 years, and were catching up the USA and Australia at a quick rate due to significant strategic investments.

**Associate Professor Vincent Wheatley, Professor Michael Smart, Dr Anand Veeraragavan, Associate Professor Timothy McIntyre. Ethylene Fuelled Axisymmetric Scramjet Testing (2017-2019) (MYIP 6994)**

The aim of the research agreement is to extend an axisymmetric scramjet engine concept to allow the ignition and combustion of gaseous Ethylene fuel at a flight Mach number of 7.6. Experimental tests will be conducted in the University of Queensland’s T4 shock tunnel (Stalker tube) to demonstrate and characterise the engine’s performance and operability. The engine has been designed with advanced features to aid mixing, ignition and combustion while reducing losses. Numerical simulations have been conducted to estimate the efficacy of this features. The engine model has been manufactured and is presently being tested in T4.

**Associate Professor Vincent Wheatley. Large Eddy Simulation of Scramjet Fuel Array Injection (2018) (MYIP 8069)**

The aim of this project was to construct and perform Large-Eddy simulations of an axisymmetric scramjet fuel injector array. The project provided results that gave unprecedented insight into the fluid mechanics of how the injector array influences the transition to turbulence, and gave quantitative predictions of measurable quantities (both means and fluctuations) for comparison to experimental data.
Other funding

**Professor Michael Smart, Dr Vince Wheatley, Dr Anand Veeraragavan. Mach 6-8 scramjet combustion experiments using hydrocarbon fuel (Asian Office of Aerospace Research and Development) (2015-2017)**

The T4 shock tunnel is a facility designed for generation of true scramjet flight conditions (matching Mach number, velocity and altitude) between Mach 6 and 12. This research involved experiments with a relatively large scale (45mm/1.8in. diameter) axisymmetric isolator/combustor in the Mach 6-8 flight regime using gaseous hydrocarbon fuels. As well as high frequency surface pressure and heat transfer measurements, PLIF visualisations were made in the exhaust plume downstream of the combustor. This experimental set-up allowed visualisation of the combusting flow exiting an axisymmetric scramjet.

**Professor Richard Morgan, Associate Professor Tim McIntyre, Dr Anand Veeraragavan, Dr Rowan Gollan, et al... Rapidly expanding non equilibrium hypersonic flow (Asian Office of Aerospace Research and Development) (2016-2018)**

This project has done a series of experiments using a 2D compression wedge-expansion corner configuration with heated graphite surfaces, and studied the entrainment of ablative products into hypersonic shock layers, and their subsequent propagation through the non-equilibrium expansion region which forms the interface between the windward and leeward flows on entry capsules. There has been close collaboration with the Air Force Institute of Technology (AFIT), two of whose students have completed PhD’s based on experiments done under the program, with three joint campaigns performed during the reporting period for this report. A follow on grant from AOARD has been awarded to extend the collaboration into the study of wake flows.

**Associate Professor Vincent Wheatley: Magnetic suppression of instabilities in shock driven converging flows (2015-2017) (Competitive Research Grant, King Abdullah University of Science and Technology)**

This project was successfully concluded in 2017 and resulted in a following grant from the same funding source.

Hydrodynamic instabilities such as shock-driven Richtmyer-Meshkov (RM) and Rayleigh-Taylor (RT) have inhibited ignition and fusion of heavy hydrogen isotopes in inertial confinement fusion (ICF). It was shown that the RM instability is suppressed in the presence of a magnetic field. We proposed to investigate the suppression of shock-driven hydrodynamic instabilities in converging cylindrical and spherical geometries relevant to ICF: (a) investigations of cylindrical and spherical Riemann problems to determine symmetry preserving or asymmetry minimizing initial seed magnetic field configurations, (b) linear and nonlinear simulations of single and double interface RM instability investigations modelled using equations of ideal magnetohydrodynamics (MHD), (c) stability of converging MHD fast shocks, and (d) investigations into the detailed patterns of MHD shock refraction at density interfaces using a self-similar formulation of the MHD equations. These investigations enhanced the knowledge base of the plasma physics discipline. Successful suppression of hydrodynamic instabilities in ICF will have a tremendous impact and potentially pave the way to make fusion energy a reality.

The effects of uniform and saddle topology seed magnetic field configurations on spherically converging Richtmyer-Meshkov instability (RMI) in magnetohydrodynamics (MHD) were investigated using 3D nonlinear compressible simulations. Our focus was on understanding the effects of field configuration, strength and the perturbation wavenumber on suppression of the RMI and subsequently the Rayleigh-Taylor instability (RTI).

As for the cylindrical flow, all cases simulated with a seed field demonstrated suppression of the RMI and RTI. The degree of instability suppression achieved was found to increase with seed field strength and in general is insensitive to the field configuration. For strong saddle topology fields, however, a slow shock-density interface interaction occurs that causes severe low-mode distortion of the interface, resulting in substantially greater interface perturbation growth than for a uniform field. As in the planar and cylindrical cases, the mechanism leading to instability suppression is the transport of vorticity away from the location where it is baroclinically generated during the shock-interface interaction. This transport occurs roughly parallel to magnetic field lines, and thus can range from parallel to perpendicular to the interface depending on the local
field orientation. The anisotropic suppression results in perturbation growth on different portions of the interface being suppressed to different extents, with suppression maximized where the field orientation is locally parallel to the interface and minimized where the field orientation is locally normal. As in the cylindrical case, the saddle field configuration was found to introduce a lower degree of distortion from spherisymmetry in the underlying imploding flow than the uniform-field configuration, whilst having similar performance in terms of instability suppression. This suggests that the saddle field configuration is more suitable for suppressing instabilities in spherical implosion experiments designed for maximizing peak compression.

We examined whether the non-uniform suppression of the converging shock-driven RMI, due to variations in local magnetic field strength and orientation, can nonlinear simulation and the linear model for uniform and saddle fields along multiple radial rays. The model was found to provide reasonable estimates of the peak perturbation amplitude and the time this occurs at all locations investigated, making it a valuable tool for seed field design.

Associate Professor Vincent Wheatley: Investigation of Shock-driven Instabilities in Two-fluid Plasmas (2018-2021) OSR-2017-CRG6-3418, Competitive Research Grant, King Abdullah University of Science and Technology

The overall aim of this project is to fully characterise and understand the behaviour of the converging-shock driven interfacial instabilities in the presence of a magnetic field within the framework of a two-fluid plasma model. We will carry out simulations in both cylindrical and spherical geometries.

In the single-fluid MHD model, the suppression of the Richtmyer-Meshkov instability (RMI) through the application of an initial magnetic field has been theoretically demonstrated whereby the vorticity generated at the density interface during the shock interaction is transported away by MHD waves. We have now investigated the vorticity transport dynamics resulting from shock-density interface interactions over a range of plasma regimes under the two-fluid plasma approximation such that finite plasma length scale effects may be observed. To most clearly show these effects, the problem of a shock wave interacting with an inclined planar density interface was studied for the case of a very strong initial magnetic field ($\beta = 0.01$). The suppression of the RMI through the application of the initial magnetic field was demonstrated over the full range of plasma regimes investigated. At larger plasma length scales ($\frac{L}{L_D} < 0.05 - 0.01$) this suppression is due to sign reversal in vorticity, but as scales decrease vorticity is increasingly transported away from the interface. At intermediate plasma length scales ($\frac{L}{L_D} = 0.01 - 0.005$), the transport of vorticity is on widespread, continuous, oscillatory plasma waves. For smaller scales still ($\frac{L}{L_D} < 0.005$), the oscillatory wave packets begin to coalesce into narrower, steeper waves in a manner that appears to converge towards MHD like behaviour. Thus it is observed that instability suppression due to the presence of an initial magnetic field is present across all plasma regimes but with varying mechanisms and effectiveness. These findings provide confidence in the results from the more approximate MHD model and support the use of initial magnetic fields in the suppression of hydrodynamic instabilities, such as the RMI, in plasma flows. These results were published at the 2018 Australasian Fluid Mechanics Conference.

To facilitate the implementation of lower dissipation numerical method for the field equations based on a staggered-grid, constrained transport approach for divergence constraint enforcement, our two-fluid plasma solver has been ported to a new Adaptive Mesh Refinement framework, AMREX, which has native support for staggered grids. Implementation of the constrained transport approach for uniform grid patches has been completed. The approach has been demonstrated to improve the fidelity, in terms of a substantial reduction in numerical dissipation, and long term stability of simulations. The diverged constraints on the fields have been demonstrated to be satisfied to near machine precision.

Dr Ingo Jahn et al: Characterisation and control of a flap undergoing hypersonic fluid-structure interactions (2016-2018; UNSW-Canberra, USQ, Ohio State, FA2386-16-1-4024, R&D Proposal 16IOA024)

Dr Ingo Jahn is part of a collaborative team between UNSW-Canberra (Andrew Neely), USQ (David Buttsworth), and The Ohio State University (Jack McNamara) who obtained a research grant from the Air
Force Office of Scientific Research (OFOSXR) for $US160,000 to investigate the fundamentals of fluid structure interactions around control surfaces on hypersonic vehicles. The project commenced in late 2016 and the design of a first prototype for testing in USQ’s TUSQ has commenced. The project team has been successful both with developing simulation and test capabilities to look at wings incorporating both rigid and flexible actuators. These work has led to new capabilities in the Eilmer CFD solver, including capabilities to conduct Hardware in the Loop Simulations (HiLS) to investigate different control strategies and new first of its kind experimental data to support FSI research. The project was extended by 6 months until April 2019 and a continuation project is currently in preparation.

Dr Ingo Jahn: University of Queensland Early Career Researcher (ECR) Award

Dr Ingo Jahn obtained a $30,000 University of Queensland ECR award to develop a Ludweig tube based facility for testing and investigation of fundamental flow physics in supercritical CO₂ environments. Expertise from the Centre enabled Dr Jahn to preform transient tests at high pressures and high temperatures that are difficult to obtain in a steady state facility.


This project will focus on developing a fundamental understanding of how turbulent structures form and evolve in the presence of wall heating in a high-enthalpy hypersonic flow. Experiments conducted on a heated flat plate at UQ’s T4 shock tunnel, utilizing sophisticated optical diagnostic techniques such as Focused Laser Differential Interferometry will provide fundamental data. This will be analysed to inform theory and subsequent correlations that will be useful to the research community on the effect of wall heating on transition and growth of turbulence in hypersonic flows.

Dr Anand Veeraragavan, Professor Richard Morgan, Professor David Mee, Associate Professor Tim McIntyre, Dr David Gildfind, Dr Rowan Gollan, Dr Peter Jacobs, Experimental Studies of High Speed Flows. National University of Singapore (NUS)

This collaborative agreement with NUS spans across four fundamental projects: shockwave boundary layer interactions over heated plates in hypersonic flows led by Dr Anand Veeraragavan; study of heated ablative surfaces in hypersonic flows led by Professor Richard Morgan, growth of turbulence spots in hypersonic flows by Professor David Mee, and performance calculations of hypersonic test facilities by Dr David Gildfind. The work undertaken in these projects is supported by the laser diagnostics and optical measurements expertise of Associate Professor Tim McIntyre and computational fluid mechanics expertise of Dr Rowan Gollan and Associate Professor Peter Jacobs.
KPI 6 – Professional Development

Staff Development and Publications

Supervisory Skill Development

All staff, including Research Focused (RF) staff, are encouraged to be active in higher degree by research supervision (PhD and Master of Philosophy students), final year engineering undergraduate thesis supervision, and masters coursework student supervision. Staff who supervise RHD students are required to complete a program of professional development run by the University's Graduate School.

Staff can enrol in a number of courses under the topic "Maximising your RHD Advisory Skills". In addition, in 2015, the University introduced a new policy "Eligibility and Role of Higher Degree by Research Advisors". This policy sets out criteria for eligibility of principle advisors, associate advisors, and other members of the candidature team and is used as for quality assurance purposes. All principle advisors must be registered on the University's Principal Advisory Registry.

Higher Degree by Research Skill 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 Career Development Framework run by the UQ Graduate School.

Students are also encouraged to participate in the Faculty's annual Postgraduate Conference. This conference provides an opportunity for HDR 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 schools within the Faculty. Each year, the Centre for Hypersonics sponsors "The Professor Raymond Stalker Prize" for best presentation related to Mechanical and Aerospace Engineering.

The University also participates in the annual 3 Minute Thesis (3MT) competition. The 3MT is a research communication competition that challenges PhD students to communicate the significance of their project without the use of props or industry jargon, in just three minutes. This exercise develops academic, presentation, and research communication as well as supports the development of a research student to quickly explain their research in a language appropriate to a non-specialist audience leaving them to want to learn more. The School strongly encourages all PhD students to participate at least once during their studies.

Institute for Teaching and Learning Innovation (ITaLI)

The Institute for Teaching and Learning Innovation (ITaLI) provides practical support to faculties and schools to achieve and celebrate teaching excellence. ITaLI staff collect and interpret data about teaching practices to enhance learning and teaching practices and anticipate future impact and opportunities for the University. ITaLI also coordinates the student evaluation of courses and teaching (SECaT) surveys which are undertaken each semester and are used to help teaching staff improve their courses, teaching, and provision of feedback to students. Examples of projects undertaken by ITaLI include: "flipped classrooms", tutor training, electronic marking of assignments, and a new program "Teaching@UQ" which is designed to provide technology enhanced professional development to new teaching staff.

Associate Professor Vincent Wheatley has collaborated with ITaLI staff to transform the Compressible Flow module of UQ's advanced Fluid Mechanics course to a blended learning approach making use of the online content developed for the Hypersonics MOOC. This brought about major improvements in student learning, and contributed to Vincent winning an Award for Teaching Excellence at the 2017 Australian Awards for University Teaching. Centre for Hypersonics staff members Professor David Mee and Associate Professor Vincent Wheatley have since won a UQ Teaching Innovation Grant to transform three further core Mechanical Engineering courses to a blended format as part of the UQ2U Program. Vince Wheatley contributes to ITaLI
as a member of the Blended Learning Steering Committee, the eAssessment Advisory Group, and as a mentor for award and fellowship applicants.

**UQ Staff Development Program**

The University’s staff development program is run at no cost to staff. Areas of staff development activities include: “managing people”, “research skills development”, “teaching, learning and assessment”, and “OH&S and sustainability”. Some courses are compulsory, including a number of managing people and OH&S courses.

**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 3 for a list of conferences attended and publications.
Appendix 1 – History of Hypersonics at UQ

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 higher degree by research (namely MPhil and PhD) in Hypersonics. Our 100th higher degree by research student (Dr David Gildfind) graduated in 2012. Our 138th HDR student graduated in 2018, and in the three year time frame covered by this report, 18 have graduated. 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 École 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, École 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 tubes 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 HIFiRE 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 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 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 ten 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 access to space systems.

Since 2005 the group has also been involved in re-entry studies, with particular emphasis on the ablation and radiating processes occurring on thermal protection systems for spacecraft. In this area we have received five consecutive ARC Discovery grants, and many other awards from NASA, ESA and AOARD. We have developed strong collaborative links with leading researchers in the area, including NASA’s AMES and Langley Research Centers, École Centrale Paris, Institute of Space Sciences (IRS) Stuttgart and the Indian Institute of Science (Bangalore). We have recently been invited to join the NATO working group on turbulence and transition, AVT-240, and this involvement has led to a new ARC Discovery grant application in partnership with JAXA (Japanese Aerospace Exploration Agency). 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; however, the details of the re-entry and any potential observation campaigns are not released yet.

In the development of hypersonic facilities, the group continues to push the limits of technology, and has been involved in the design of the Oxford University ‘T6’ Stalker tube, and the development of a new UQ reflected shock tunnel, X3R, together with DST. Increasingly close links with DST have been a feature of recent years, and the new DST laboratory being completed at Eagle Farm, Brisbane, will house X3R and will be an international hub for collaborative research in Hypersonics.

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.
## Appendix 2 – HDR students (2016-2018)

<table>
<thead>
<tr>
<th>Name</th>
<th>Principal Supervisor</th>
<th>Program</th>
<th>Project Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sanchito Banerjee</td>
<td>Professor Russell Boyce</td>
<td>PhD</td>
<td>L1 adaptive control augmentation for a hypersonic glider. Graduated 2016.</td>
</tr>
<tr>
<td>Jorge Sancho Ponce</td>
<td>Professor Richard Morgan</td>
<td>PhD</td>
<td>Scramjet testing at high total pressure. Graduated 2016.</td>
</tr>
<tr>
<td>Zachary Denman</td>
<td>Dr Anand Veeraragavan</td>
<td>PhD</td>
<td>Optimisation of fuel-air mixing and burning in shape transitioning scramjet engines. Graduated 2017.</td>
</tr>
<tr>
<td>Steven Lewis</td>
<td>Professor Richard Morgan</td>
<td>PhD</td>
<td>Melting models of CO2, in re-entry flow conditions. Graduated 2017.</td>
</tr>
<tr>
<td>Han Wei</td>
<td>Associate Professor Timothy McIntyre</td>
<td>PhD</td>
<td>Interaction between shock layer and ablative products from heat shields during atmospheric entry. Graduated 2017.</td>
</tr>
<tr>
<td>Brad Wheatley</td>
<td>Associate Professor Timothy McIntyre</td>
<td>PhD</td>
<td>Tunable diode laser absorption spectroscopy of aerospace flows. Graduated 2017.</td>
</tr>
<tr>
<td>Sangdi Gu</td>
<td>Professor Richard Morgan</td>
<td>PhD</td>
<td>Ablative thermal protection systems for re-entry into Titan. Graduated 2018.</td>
</tr>
<tr>
<td>Will Landsberg</td>
<td>Dr Anand Veeraragavan</td>
<td>PhD</td>
<td>Optimisation of inlet and combustor fuel injection in shape transitioning scramjet engines. Graduated 2018.</td>
</tr>
<tr>
<td>Juan Llobet Gomez</td>
<td>Dr Ingo Jahn</td>
<td>PhD</td>
<td>Vortex-fuel jet interactions to enhance mixing in scramjets. Graduated 2018.</td>
</tr>
<tr>
<td>Sreekanth Raghunath</td>
<td>Professor David Mee</td>
<td>PhD</td>
<td>Boundary layer transition lengths in hypersonic flows. Graduated 2018.</td>
</tr>
<tr>
<td>Tamara Sopek</td>
<td>Associate Professor Timothy McIntyre</td>
<td>PhD</td>
<td>Fuel injection/mixing studies in hypersonic flows using advanced optical diagnostic techniques. Graduated 2018.</td>
</tr>
<tr>
<td>Tristan Vanyai</td>
<td>Associate Professor Timothy McIntyre</td>
<td>PhD</td>
<td>Scramjet accelerators investigated using advanced optical diagnostic techniques. Graduated 2018.</td>
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</table>

### Thesis submitted/under examination

<table>
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<tr>
<th>Name</th>
<th>Supervisor</th>
<th>Program</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pierpaolo Toniato</td>
<td>Professor Richard Morgan</td>
<td>PhD</td>
<td>High mach number scramjet testing in the X3 expansion tube. Submitted 2018.</td>
</tr>
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</table>

### Current HDR candidates

<table>
<thead>
<tr>
<th>Name</th>
<th>Supervisor</th>
<th>Program</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andreas Adrianatos</td>
<td>Dr David Gildfind</td>
<td>PhD</td>
<td>Radiation scaling studies in an expansion tube.</td>
</tr>
<tr>
<td>Steven Apriana</td>
<td>Professor Richard Morgan</td>
<td>PhD</td>
<td>Studying earth re-entry post shock relaxation using a mach disk.</td>
</tr>
<tr>
<td>Jamie Border</td>
<td>Dr Rowan Gollan</td>
<td>PhD</td>
<td>Walsh functions for high-resolution shock capturing and their application to expansion tube simulations.</td>
</tr>
<tr>
<td>Joseph Chai</td>
<td>Professor Michael Smart</td>
<td>PhD</td>
<td>Trajectory optimisation and control of a fly-back rocket booster.</td>
</tr>
<tr>
<td>Won Keun (Eric) Chang</td>
<td>Dr Anand Veeraragavan</td>
<td>PhD</td>
<td>Wall temperature effects in hypersonic flow.</td>
</tr>
<tr>
<td>Name</td>
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<td>Program</td>
<td>Project Title</td>
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<tr>
<td>Isaac Convery-Brien</td>
<td>Professor David Mee</td>
<td>MPhil</td>
<td>Concentrated breakdown in boundary layer transition in a hypersonic flow.</td>
</tr>
<tr>
<td>Timothy Cullen</td>
<td>Professor Richard Morgan</td>
<td>PhD</td>
<td>Infrared thermography in expansion tubes.</td>
</tr>
<tr>
<td>Damian Curran</td>
<td>Associate Professor Vincent Wheatley</td>
<td>PhD</td>
<td>Investigation of flow field manipulation, thermal compression and mode transition in a Mach 5-10 scramjet accelerator</td>
</tr>
<tr>
<td>Kyle Damm</td>
<td>Dr Rowan Gollan</td>
<td>PhD</td>
<td>Many-parameter aerodynamic optimization of a hypersonic vehicle.</td>
</tr>
<tr>
<td>Sholto Forbes-Spyratos</td>
<td>Dr Ingo Jahn</td>
<td>PhD</td>
<td>Trajectory optimisation of a partially-reusable rocket-scramjet rocket satellite launch system.</td>
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<tr>
<td>Nicholas Gibbons</td>
<td>Associate Professor Vincent Wheatley</td>
<td>PhD</td>
<td>Dynamics and simulation of hypersonic combustion.</td>
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<tr>
<td>Rory Kelly</td>
<td>Associate Professor Timothy McIntyre</td>
<td>PhD</td>
<td>Advanced imaging of rapidly expanding flows.</td>
</tr>
<tr>
<td>Jens Kunze</td>
<td>Professor Michael Smart</td>
<td>PhD</td>
<td>3D design of shape-transitioning nozzles for scramjet powered vehicles.</td>
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<tr>
<td>Yu (Daisy) Liu</td>
<td>Professor Richard Morgan</td>
<td>PhD</td>
<td>Gas giant atmospheric entry.</td>
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<tr>
<td>Pierre Mariotto</td>
<td>Dr Rowan Gollan</td>
<td>PhD</td>
<td>Radiating flows.</td>
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<tr>
<td>Ranjini Ramesh</td>
<td>Professor Richard Morgan</td>
<td>PhD</td>
<td>Transitional and turbulent heating during atmospheric entry.</td>
</tr>
<tr>
<td>Anand Ramprakash</td>
<td>Professor David Mee</td>
<td>PhD</td>
<td>Experimental investigation of scramjet acoustic loads.</td>
</tr>
<tr>
<td>Ranjith Ravichandran</td>
<td>Professor Richard Morgan</td>
<td>PhD</td>
<td>Ablation and radiation super-orbital re-entry flows.</td>
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<tr>
<td>Ramandeep Kaur</td>
<td>Associate Professor Vince Wheatley</td>
<td>PhD</td>
<td>Design of combustor for supersonic combustion of hydrocarbons in high Mach number scramjets.</td>
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<tr>
<td>Michael Roberts</td>
<td>Professor David Mee</td>
<td>PhD</td>
<td>Investigation of heated hydrocarbon fuelling in a radical farming scramjet engine.</td>
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<tr>
<td>Daniel Smith</td>
<td>Dr David Gildfind</td>
<td>PhD</td>
<td>Mars atmosphere magnetohydrodynamic aerobraking.</td>
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<tr>
<td>Samuel Stennett</td>
<td>Dr David Gildfind</td>
<td>PhD</td>
<td>Test flow optimisation and characterisation for a new large reflected shock tunnel facility.</td>
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<td>Nils Temme</td>
<td>Professor Richard Morgan</td>
<td>PhD</td>
<td>Non-equilibrium aerothermodynamics of superorbital reentry.</td>
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<td>Matthew Thompson</td>
<td>Professor Richard Morgan</td>
<td>PhD</td>
<td>Development of X2 driver conditions producing low density hypersonic test flows.</td>
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<tr>
<td>Alexander Ward</td>
<td>Professor Michael Smart</td>
<td>PhD</td>
<td>Multidisciplinary design of an accelerating hypersonic vehicle.</td>
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<tr>
<td>Ryan Whitside</td>
<td>Professor Michael Smart</td>
<td>PhD</td>
<td>Design of a variable Mach number scramjet flowpath for access to space.</td>
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**Studies interrupted/did not complete**

<table>
<thead>
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<th>Name</th>
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<tr>
<td>Kevin Basore</td>
<td>Associate Professor Vincent Wheatley</td>
<td>PhD</td>
<td>Flow physics of scramjet fuel injection through porous walls. Enrollment deferred.</td>
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<tr>
<td>Ian Cartmill</td>
<td>Associate Professor Vincent Wheatley</td>
<td>PhD</td>
<td>Withdrawn 2018.</td>
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## Appendix 3 - Publications (2016-2018)

<table>
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<tr>
<th>Publ Year</th>
<th>Book Chapter</th>
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2016  

2017  

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<tr>
<th>Publ Year</th>
<th>Department Technical Report</th>
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</table>
Appendix 4 – USQ publications (2016-2018)


Contact details

Professor Richard Morgan
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E r.morgan@uq.edu.au
W uq.edu.au

CRICOS Provider Number 00025B