Imperial College London

Institute of Shock Physics

Annual Review 2012

www.imperial.ac.uk/shockphysics

Professor Steve Rose
Founding Director

Foreword

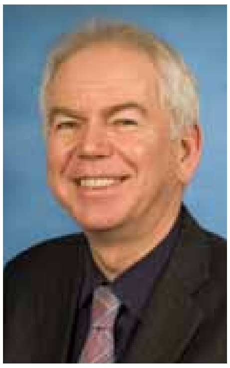
The Institute of Shock Physics (ISP) was established in 2008 with substantial investment from AWE, Aldermaston and Imperial College London and so this Annual Review marks its fifth anniversary. Although, at its start Imperial was already undertaking excellent work in the shock physics area, the establishment of the Institute resulted in very marked changes in the number of staff, research and students working in shock physics. It also saw the installation of several major new experimental facilities. This year has seen the ISP's first PhDs and MScs awarded with more expected in the coming year, showing that the Institute has become a fully operational part of the Physics Department.

Looking to the future there are many opportunities for the ISP to broaden the range of science it undertakes as well as increasing the range of national and international communities with which it interacts. I would particularly point to the new facilities being built at Imperial to study shocks generated by high-power lasers, bridging the worlds of plasma physics and shock physics to the benefit of both communities. In this Annual Review we look back on a very successful year and forward to more opportunities in the years ahead.

Contents

Cover image
Impact face of a multi target planar shock wave experiment mounted in the large bore gas launcher.

Kindly provided by
David Chapman »
ISP, Imperial College London



Professor Peter Roberts OBE
AWE Chief Scientist

Chief Scientist's comment

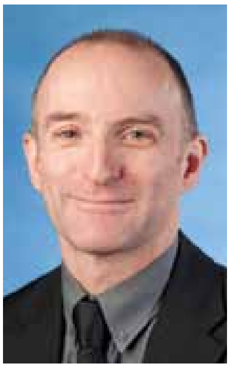
This Annual Review demonstrates the progress that has been made in establishing a community focussed on the understanding of how shock waves propagate in solids and how the relevant properties of those materials can be determined. As will be evident from the review, the ISP has established a number of training modules, at various levels, has commissioned and sponsored key experimental facilities and has undertaken and published research – vital for the long-term sustainability of the community. The establishment of the Institute is part of a wider effort, with academia, to understand how all phases of matter, including plasmas, behave at high strain rates and at ultra-high pressures, up to perhaps a petapascal. This engages other, complementary facilities, such as the new generation of light sources and the use of high power lasers, both in the UK and abroad. An additional aspect is to understand how manufacturing processes and techniques, together with related material specifications, can influence and control these dynamic properties.

Dr William Proud
Director

Director's overview

The first five years of the ISP have been ones of formation, equipment acquisition, installation and ensuring aspects of health and safety. There have also been the necessary political and diplomatic elements of networking, assurance and building-up of active links with research groups around the world. In the UK, the formation of the IOP specialist group on Shock Waves and Extreme Conditions (SWEC) provides a non-partisan platform for this field. We have also built on our strong links to the USA, Russia and China. The Royal British Legion Centre for Blast Injury Studies (CBIS) is supporting a different area of research within the ISP from that of our main funder, AWE. AWE has committed to its continued support of the ISP by signing a substantial continuation contract which assures the Institute identity and continuity until 2018. Imperial also strongly supports the ISP, which is no longer an 'unknown' amongst the staff in this very active research university.

Finally, I'd like to thank members of staff in the ISP programme office who have ensured the smooth-running of the institute with good grace; and our technicians who have kept this experimentally aggressive area supplied with high-quality components made over many hours. Those components are reduced to fragments in micro-seconds by the researchers! I hope you find interest in these pages, which describe the results of the efforts of a large number of people who have a broad and fundamental interest in this area.



Dave Chambers
AWE Hydrodynamics Division

Sponsor's comment

I am delighted that AWE's initial five year investment in the ISP has been successful in realising our vision of a centre of excellence in shock physics in the UK. The Institute now delivers technical expertise, state-of-the-art facilities and training courses that support AWE's programme. I am particularly pleased to see the first students graduate from the ISP this year. This is a clear example of how the Institute is growing a new community of shock physicists in the UK, a talent pool that AWE has started to draw upon. The interactions with AWE staff have continued to strengthen, with the large bore gas gun now delivering some of the highest quality data I have seen in novel impact experiments. This is thanks to the excellence and commitment of the Institute's staff to help AWE deliver a challenging programme of research. It is also great to see the new extreme physics laboratory open and I look forward to hearing of similar successes from the MACH facility in the future. The ISP's links with other universities is strong, with some exciting developments in experimental and theoretical physics describing a wide range of materials in extreme conditions. This integrated and joined-up thinking has delivered research that has been vital in helping AWE develop a predictive material modelling capability. A new chapter is now opening for the ISP and I hope that AWE's continued investment will allow the Institute to grow and become internationally recognised as a world class centre for shock physics research and teaching long into the future.

Strategy and outputs

Led by Imperial College London, the Institute of Shock Physics (ISP) is a world-class, multidisciplinary research organisation established in 2008 with major support from AWE and Imperial to provide a UK focus for shock physics research and training. We are pleased that from March 2013, AWE has provided further, substantial funding for a second, five-year phase of the ISP.

Shock physics focuses on the understanding of what happens to matter under extreme conditions. The research can be applied in many ways, including: analysing the effect of meteorite impacts on planets, spacecraft and satellites, understanding how tsunamis are formed and understanding the high pressure conditions that occur at the core of planets. Man-made high pressures include aeronautics and national security related applications such as: including studies on force protection, understanding how biological materials behave when exposed to shock waves and developing improved energetic materials.

In collaboration with partners from across the UK and overseas, the ISP undertakes research over multiple scales, from seconds to picoseconds and from bulk to atomistic. It does this using a range of state-of-the-art experimental platforms, diagnostics and modelling capabilities. The Institute also aims to educate the next generation of scientists and engineers in the science of shock waves, ultrafast material phenomena and matter at extreme conditions through a cohort of PhD students. Each year the ISP delivers a very popular undergraduate module in hydrodynamics and shocks, a Master's course in Shock Physics, a short course series on special topics, an annual conference and technical conferences, meetings and seminars.

Governance and management

- William Proud » Director
- Chris Thompson » Programme Director
- Ciara Mulholland » Institute Administrator
- Eva Gledhill » Administrative Assistant

The ISP is currently guided by two Boards, an Operations Management Board (OMB) chaired by our Director, Dr William Proud, which meets quarterly, and a Strategic Management Board (SMB) chaired by Professor Sir Keith Burnett, CBE, FRS, which meets annually. Day-to-day management is provided by the programme team, led by Dr Chris Thompson, located in the ISP headquarters at Imperial's South Kensington Campus. This team prepares monthly progress reports for AWE and runs a joint AWE/Imperial Technical Operating Group to review and agree solutions to technical issues relating to Imperial's large bore gas gun. For the second phase of the ISP, the SMB will be replaced by an Advisory Board. We will also introduce a Gas Gun Governance Committee.

Figure 1: Summary of AWE investment plus financial gearing.

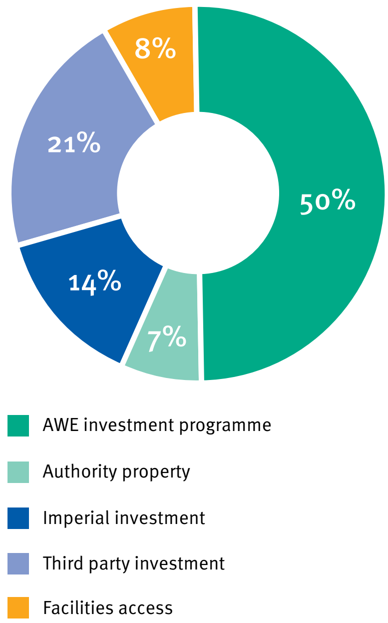
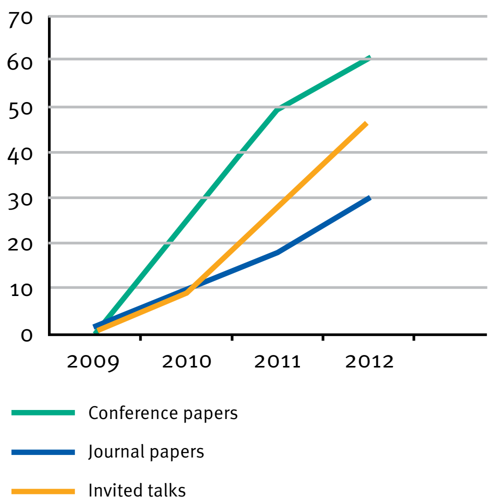


Figure 2: Cumulative total of research outputs from ISP funded staff.



Success of the Institute of Shock Physics is measured against Key Performance Indicators collected together in a Balanced Scorecard. A summary of key outputs since 2008 is as follows:

FINANCES

The AWE funding commitment of around £10 million over five years to the ISP is spread across five institutions – Imperial, University of Cranfield – Defence Academy of the UK, University College London, University of Edinburgh and University of Oxford. In order to demonstrate value for money, the ISP collects information on financial gearing across a range of categories including underpinning funding from other funders such as the UK Research Councils for staff and equipment, use of other facilities including synchrotron radiation sources worldwide, equipment donation and additional resource such as visiting researchers and fellows.

PEOPLE DEVELOPMENT

» Twenty one PhD students working at five institutions; one QinetiQ funded PhD; one funded by The Royal British Legion
» Five PhD students have completed their studies and are either writing-up or waiting for vivas; three have already been offered Research Associate positions in their respective areas of research and one has been offered a post at AWE
» Trained 30 summer interns, some are now interested in MSc and PhD courses
» Delivered 902 training days through 10 short courses
» Delivered taught Masters in Shock Physics to three cohorts totalling 14 students; the first five graduated this year; one has taken up a PhD position in the ISP; first part-time MSc

INSTITUTE CAPABILITY

» Six academic staff and five Postdoctoral Research Associates at three institutions, three technical experts and a programme office at Imperial
» Fifty-three visiting academics from 10 institutions including AWE; seven affiliate members
» 100mm-bore single stage gas gun and pulse power MACH facilities at Imperial
» Several small-scale, portable impact launchers under development ranging in bore, from 13 mm – 30 mm, delivering velocities from a few 10's ms^{-1} to ‹1000 ms^{-1}

RESEARCH OUTPUT

» **Published:** 30 journal papers, 61 conference papers and delivered 47 invited talks at prestigious meetings and organisations
» **Recent examples of conferences:** DYMAT 2012, Freiburg, Germany; 39th IEEE International Conference on Plasma Science (ICOPS) 2012, Edinburgh; IUCr Commission on High Pressure 2012, Mito, Japan
» Over 15 key AWE experiments delivered on the Imperial gas gun during 2012

"We're extremely pleased to have received the new AWE contract that assures our future for the next five years. I'd especially like to thank Toni Lilly and Stewart Stirk of AWE for enabling the contract negotiation and for their on-going and stirling support of the ISP."

Chris Thompson
PROGRAMME DIRECTOR, INSTITUTE OF SHOCK PHYSICS

Shock physics focus

One of the key aims of the ISP is to provide a UK focus for shock physics research and training. We do this by organising international conferences, meetings and events and by raising the profile of what we do through stakeholder events. In 2012 we delivered a major international conference to an audience of around 100 registered delegates, hosted on behalf of DYMAT, in New Models and Hydrocodes for Shock Wave Processes. To date we have delivered four annual meetings; the most recent in February 2013 with over 65 delegates attending; we have held five successful stakeholder events to raise awareness of the Institute at AWE and Imperial – in the last year a Facilities Showcase at Imperial and a Materials Science event at AWE resulted in several collaborative leads; and we hosted numerous visits from academia, industry and government.

Delegates at the 2013 PETER Conference.

Following a Town meeting attended by over 70 people and introduced by Ian Cullis of QinetiQ, the Institute of Physics (IOP) Groups Sub-Committee approved the formation of a Specialist Group – Shock Waves and Extreme Conditions (SWEC). SWEC aims to promote the science, engineering, technology and mathematical aspects of materials under rapid dynamic loading or at extreme conditions and covers areas from astrophysics, climatology, construction, mining, earth sciences, static high-pressures to plasmas and the core sciences of physics and chemistry. It will do this in a number of ways, for example:

- Annual conference on pressure, energy, temperature and extreme rates (PETER)
- Workshops on specific topics of interest to members
- Evening lectures
- Networking

PhD Student Prize

PhD student Will Neal (pictured) was awarded the Anne Thorne Thesis Prize for his work on 'The role of particle size in the shock compaction of brittle granular materials'. This prize is awarded annually for the best Imperial Physics PhD thesis in any area of experimental work, including the development of novel instrumentation or analysis methodology.

Imperial College London

Research

Institute of Shock Physics

- William Proud
- Dan Eakins
- Simon Bland
- Gareth Collins

Over the past few years, the ISP at Imperial has established a diverse research profile, encompassing multi-scale studies extending from MPa to Mbar pressures, from the intermediate to very high strain-rate regimes, and from kilometres to sub-micrometer length scales. The following is a brief summary of some of the exciting work being performed by our students and post-graduate researchers.

LOW STRAIN-RATE

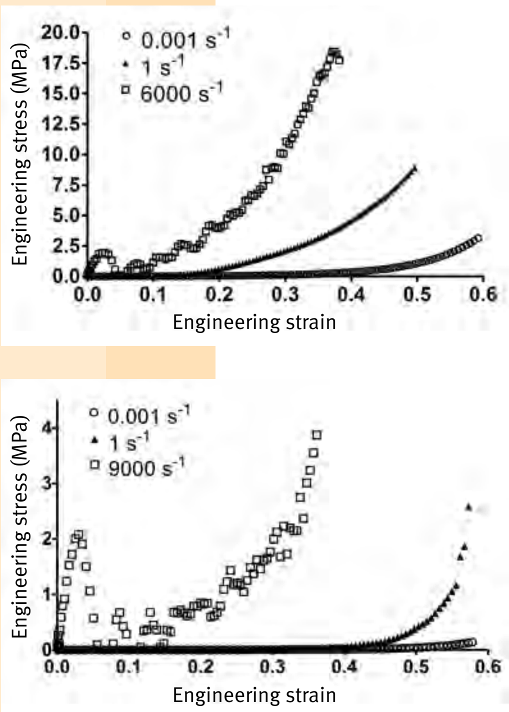
Mechanical properties of porcine skin in compression at different strain rates

- **Chiara Bo (PhD student)**
- **Jens Balzer**
- **Kate Brown**
- **William Proud**

Porcine skin is a substitute material for studying human skin due to its similarity in composition and material response. It is a heterogeneous material composed of three main layers: epidermis, dermis and adipose tissue, the dermis being most responsible for its overall mechanical response. Uniaxial compression experiments were performed on fresh porcine skin samples at different strain rates with a view to developing a constitutive model. Cylindrical skin specimens, about 8 mm in diameter, were obtained from the rump and thigh of the porcine subject using a biopsy punch. Compression experiments were performed with an Instron 5566 for the 0.001 s^{-1} and 1.0 s^{-1} strain rates, while high strain rates (6000-9000 s^{-1}) were achieved using a Split-Hopkinson Pressure Bar system (SHPB). Magnesium bars and semiconductor strain gauges were used to maximize the signal transmission to the output bar and to allow the signal measurement. We found that the mechanical response of skin in compression is strongly dependent on the strain rate of loading and on the location from which the samples were collected (figure 3). Specimens collected from the rump showed a stiffer response compared to samples harvested from the thigh.

Fitting the experimental data to the Ogden hyper-elastic model suggests that the shear stress increases as a function of strain rate, which is in good agreement with previously published data. This study represents the first reported difference in mechanical properties of skin when harvested from different areas of the animal, and is an important aspect if the material properties are to be integrated in a whole body model.

Figure 3: Average (of three experiments) stress strain curves for different strain rates for skin harvested from rump (top) and thigh (bottom).



Low to intermediate strain-rate testing of materials

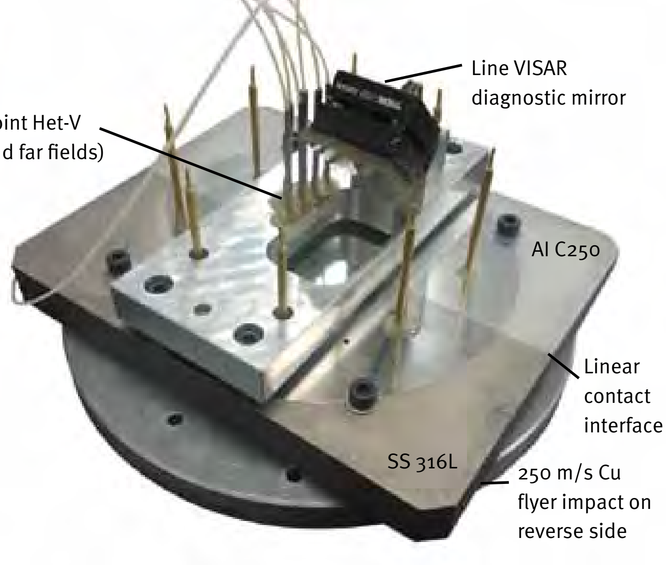
- **Jens Balzer**
- **James Wilgeroth**
- **William Proud**

The development of robust material model parameters for computer simulation of dynamic phenomena is relevant to both research programs going on within the ISP, but equally of significant importance for our industrial collaborators. With this objective in mind a number of low and intermediate strain rate tests using standard universal testing machines, drop-weight towers, and Hopkinson bar techniques have been performed. In one example a comprehensive study on a polymeric system enabled the population of a model for an otherwise uncharacterized material. Some studies merely provided a spot check for material pedigree and confirmation of model parameters.

Jens Balzer has completed an extensive study of the low and intermediate strain-rate response of aluminium 5083, Ti-6Al-4V, and high purity titanium using novel specimen geometries. In addition to standard cylindrical sample geometries, inclined cylinders were investigated, with the angle of inclination set to 5 degrees and 10 degrees to trigger failure along a predefined direction. Results demonstrated no evidence of shear localization in the aluminum samples irrespective of inclination, while in the case of the titanium samples, 5 degrees was optimum for initiating shear band failure.

Figure 4: Offset cylinder arranged for quasi-static and drop-weight experiments.

» **Figure 5:** Stainless-steel/aluminium friction target, showing piezo pins for impact tilt, 6 PDV probes for velocimetry of the far-field response, and final turning mirror for line VISAR.



The dynamic behaviour of materials at extremes of temperature

- Amnah Khan (PhD student)
- James Wilgeroth
- William Proud

An environmental chamber is being developed for use with the recently commissioned Split-Hopkinson Pressure Bar (SHPB). The combination of accurately resolved strain gauge data and high-speed imaging techniques will allow the effects of temperature on the dynamic response of materials to be investigated in detail. The environmental control system will cool samples using regulated liquid-nitrogen flow and heat specimens using thermostatically-controlled ceramic band heaters. Both techniques incorporate design features that will ensure bar movement and gauge signal response are not influenced by the testing conditions. This approach will provide a functional range of approximately -80 to 80°C, allowing investigation of the types of materials used in aerospace and defence applications at the extremes of temperature experienced in their operational environments. These studies may be extended to biological materials, i.e. Centre for Blast Injury Studies research. The data obtained from this new SHPB capability will assist the development of non-linear material models, providing greater accuracy to numerical simulation of impact events.

On the rate and temperature dependence of piezoelectric materials

- Amnah Khan (PhD student)
- William Proud

Piezoelectricity is a well-established phenomenon which occurs during deformation in some classes of materials, producing unique electrical behaviour. So-called piezoelectrics have a strong correlation between crystal distortion and electrical polarisation, allowing these materials to be used as stress and time-of-arrival sensors, or generators of mechano-electric energy. This project examines the charge output of a novel lead zirconate titanate (PZT) ceramic over a range of strain-rates and temperatures relevant to typical service conditions. PZT is known to undergo a number of phase transitions which influence its piezoelectric response, but its sensitivity to starting porosity is less understood. The response of samples of varying porosity compressed using drop-weight and SHPB apparatus at room temperature has been investigated. Future studies will use the environmental control systems being developed to investigate the role of temperature on the mechanical and electrical response, with the objective to develop a mechano-electrical model for the candidate materials.

Anisotropy across the strain rates

- Gareth Tear (PhD student)
- William Proud

Gareth's project is investigating the anisotropy of metals and porous compacts which display directionally-dependent properties across quasi-static, intermediate and shock loading strain-rates. He is utilising state-of-the-art diagnostics such as high-speed photography, stress and strain gauges, HetV, line VISAR.

HIGH STRAIN-RATE

Dynamic friction

- Mark Collinson (PhD student)
- Dan Eakins
- David Chapman
- Graham Ball (AWE)
- William Proud

The bulk dynamic behaviour of multi-component systems is often dominated by complex interactions taking place at the mesoscale, specifically along material interfaces. Research is on-going to better understand the extent to which material microstructure and strength influences relative material motion and boundary evolution under high-rate loading. New experiments allowing direct interrogation of material interfaces between stainless steel and aluminium are being performed (figure 5). Using our 100 mm light gas launcher, such targets are impacted by a copper flyer, launching oblique shock waves along the contact boundary and producing relative sliding velocities of up to 100 ms^{-1}. Time and spatially resolved velocity profiles are measured on the rear of the target surface through a multiple channel frequency shifted PDV and a line imaging VISAR system (figure 6), focussing on the far and near field responses relative to the contact interface. By comparison of these measurements against current generation hydrocode models, good agreement can be attained in the far field, with deviations in the near field indicative of the role of friction in the relative sliding response. This technique will be extended to consider steel and aluminium pairings of varying microstructure and alloy composition, allowing the roles of such properties on shock-induced sliding to be investigated.

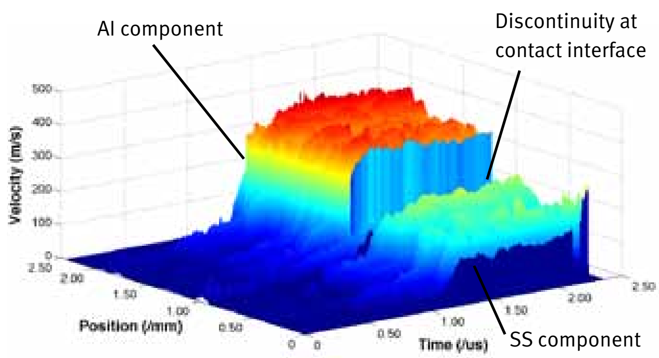


Figure 6: Line imaging velocimetry profile recorded across the interface of stainless steel and aluminium components of a multi-material target subjected to a 250 ms^{-1} copper flyer plate impact.

» Figure 7: Cylinder expansion target mounted on the 100-mm light gas launcher.

Dynamic fracture

- **David Jones (PhD student)**
- **David Chapman**
- **Dan Eakins**

The focus of the past year has been on developing a full scale expanding cylinder experiment for the ISP 100 mm light gas launcher. The main aims of this experiment were: uniform expansion of a cylinder at strain rates up to 10^4 s^{-1}; the ability to deploy multiple velocity and imaging diagnostics; and being able to control the initial temperature of the cylinder. The cylinder size is limited by the desired strain rate, a 100 mm diameter cylinder would require a velocity out of reach of the launcher and the subsequent energy involved would cause problems with fragment mitigation. For this reason the cylinder is set to have a 50 mm inside diameter, with a matching projectile consisting of a spigot mounted on the end of a standard sabot. Data is derived from multiple channels of PDV to track the radial expansion velocity of the cylinder along several points, and high speed video to track the edges of the cylinder for a strain rate distribution alongside a high speed framing camera to identify the strain at which failure initiates. Temperature control is provided by a solid steel insert which forces the expansion, rather than the classic polymer insert used previously which can only be used at room temperature. The experimental setup *in situ* is shown in figure 7, with the mirrors (right) for one side of the high-speed imaging and the PDV probes mounted below the cylinder so that they do not block the cameras.

The experiment provided a wealth of novel data, recording radial velocity for up to 200 µs, far longer than contemporary work. Strain rate was within the desired range, with a peak expansion velocity of around 350 ms^{-1}. The clear PDV data from multiple points can be used to calibrate the framing camera data and will enable calculation of failure strain vs. strain rate along the cylinder. The next stage will be to introduce the temperature control, enabling isolation and promotion of different failure mechanisms in the expanding cylinder. This can then be used to investigate how the failure type affects the fragmentation behaviour, through channels such as the energy required to fracture and the strength of the material.

HIGH PRESSURE

The determination of strength under conditions of high pressure is a core research focus of the ISP, leveraging the Institute's multi-platform multi-scale capabilities to probe the role of temperature, microstructure, and loading-rate on the onset of plastic flow under dynamic loading. This research theme in particular benefits from a number of international collaborations with colleagues from Sandia and Lawrence Livermore National Laboratories, USA, the Institute of Problems of Chemical Physics in Chernogolovka, Russia, and from the Joint Institute for High Temperatures in Moscow, Russia.

Material strength at high pressure

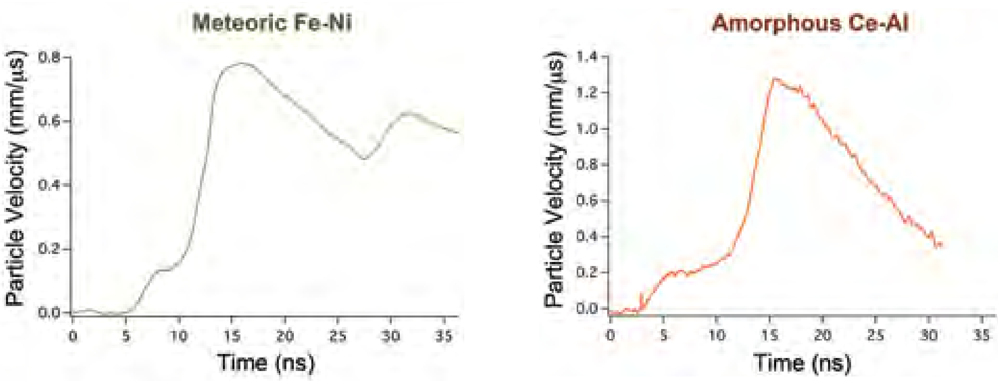
- **Laura Chen (PhD student)**
- **John Winters (PhD student)**
- **Dan Eakins**
- **Simon Bland**

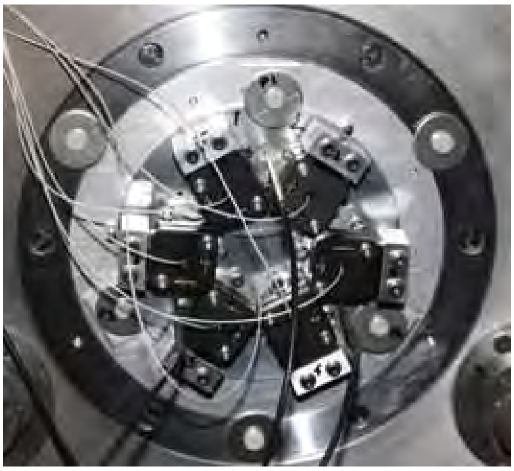
The origins of dynamic material strength are linked to processes of stress relaxation occurring at the sub-µm scale. In metals and alloys, these processes involve the behaviour of dislocations – their nucleation, mobility, and interactions with near- and far-field obstacles. For amorphous materials, particularly metallic glasses, these mechanisms are far less understood.

Presently two projects are being undertaken to explore the physics underlying material strength at high pressures. Working in collaboration with LLNL the role of crystallinity, composition, and temperature on the ultrafast deformation behaviour of Fe-Ni alloys and Ce-Al samples is being explored by Laura Chen, John Winters and colleagues on the Jupiter laser. The Fe-Ni alloys are of similar structure to those found in the core of meteorites, and the results may help explain how these break up on entry to the atmosphere; whilst Ce-Al samples can be prepared as either crystalline or amorphous forms vastly changing their internal structure.

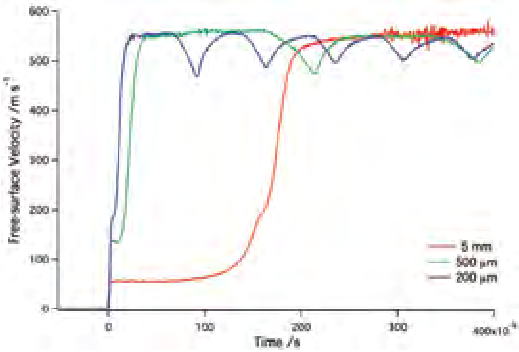
Supported shock waves are driven into targets on the order of 30-100 µms, and free surface response measured using line-imaging VISAR. Examples of measurements taken on Fe-Ni and Ce-Al are shown in figure 8, which reveals the free surface velocity measured at the rear of the samples during shock breakout. By analyzing the various wave features, the stress, strain, and strain-rate associated with different relaxation processes can be inferred. In the case of Ce-Al, which cannot relieve stress through dislocations, such VISAR measurements can reveal the onset of instabilities such as shear banding.

» Figure 8: Reduced line-VISAR measurements for (a) an Fe-Ni target sourced from a Diablo Canyon meteorite, and (b) an amorphous Ce-Al metallic glass. Important features in the Fe-Ni data include an elastic wave beginning at 5 ns leading to plastic relaxation at 8 ns, followed by spall around 27 ns. The Ce-Al shows a similar precursor feature, however this is not due to traditional slip.





» **Figure 9:** Completed magnesium multi-target mounted within the 100 mm light gas launcher.



» **Figure 10:** Free-surface velocity traces measured from Mg targets of 5 mm, 500 µm, and 200 µm thickness tested simultaneously using the 100 mm light gas launcher at Imperial. Note the clear dependence between the peak precursor state and the target thickness.

Hysteresis in the elastic-plastic compression-unloading cycle

- **David Chapman**
- **Dan Eakins**

It is known that the peak free surface velocity of a shocked elastic-plastic material should be slightly less than twice the particle velocity behind the shock front; this difference being proportional to the yield stress. The existence of precursor decay in metals is a well-established experimental observation, where the yield stress on compression may vary with time, distance of wave propagation, and on the total plastic strain value. Consequently, precise measurement of the free surface velocity can be a rich source of information on the effects of time and strain on material hardening or softening. A collaborative project with Dr Savinykh and Dr Garkushin from the Institute of Problems of Chemical Physics in Chernogolovka, Russia, and Professor Kanel from the Joint Institute for High Temperatures in Moscow, Russia, recently investigated the influence of stress relaxation kinetics on the peak state achieved during impact loading. Samples ranging in thickness from 5 mm down to 200 µm simultaneously shocked using the 100 mm light gas launcher at the ISP. Figure 9 shows the completed target mounted on the large bore gas launcher, with six PDV channels measuring redundant target thicknesses. Examples of the measured profiles for 5 mm, 500 µm, and 200 µm magnesium targets are shown in figure 10, which demonstrates a clear relationship between the target thickness and the peak elastic state in agreement with previous observations for this alloy. We also observed the more subtle hysteresis in the elastic-plastic compression unloading cycle for both materials, where qualitatively the peak free-surface velocity increased with increasing specimen thickness. Work is currently ongoing to explain the observed magnitude of hysteresis in terms of microstructural effects such as dislocation multiplication.

We have therefore demonstrated the capability for preparing thin foil targets, simultaneously loading different target thickness, and diagnosing the resulting wave profile using frequency conversion PDV. An upshift of 7 GHz was selected to facilitate the ns resolution required to diagnose shock structure in thin foil targets. This work paves the way for future experiments on thin targets to investigate ultrafast deformation behaviour of FCC and HCP materials.

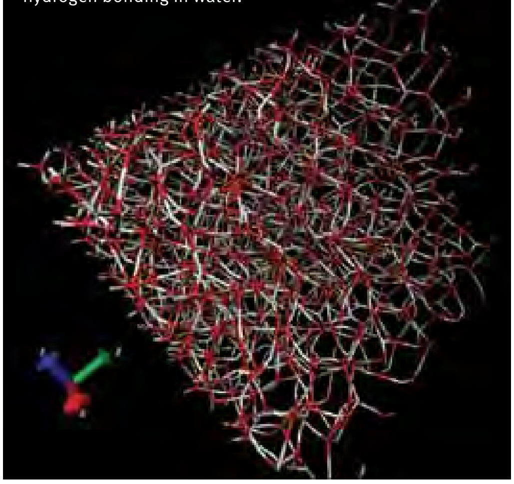
The effect of polarisation on the rapid freezing of water

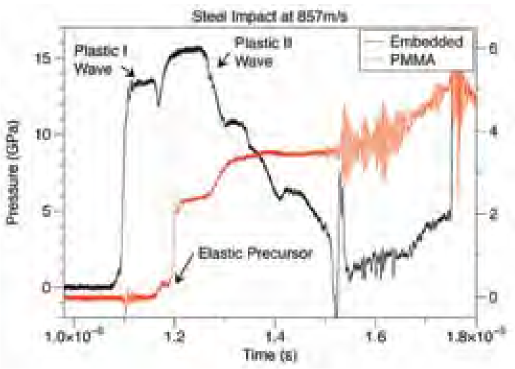
- **Samuel Stafford (PhD student)**
- **Simon Bland**
- **Dan Eakins**
- **Dan Dolan (Sandia National Laboratory)**

The melt curve of materials holds rich information concerning phase stability and coexistence, and has typically been studied through heating. Solidifying from melt under compression promises to expose new kinetics, yet is a practical challenge due to adiabatic heating which tends to keep the Hugoniot in the liquid phase. Consequently, most observations of freezing occur in quasi-isentropic experiments, where ramp waves compress a material over a relatively long time with reduced heating. This project will build on previous research on water, by investigating the influence of external electric fields on crystallisation kinetics or growth patterns.

Our experiments will apply an electric field to a sample of water during compression, to see how the alignment of the highly polar molecules can play a part in encouraging crystallisation outside of the normal phase space. To help guide the experimental design small cells of water are being modelled in the classical MD code Gromacs, with a view to moving onto the more powerful LAMMPS once initial experimental conditions are established. Experiments will take place at the Dynamic Isentropic Compression Experiment facility at Sandia National Laboratory; and on facilities in the ISP.

» **Figure 11:** MD simulations of hydrogen bonding in water.





« **Figure 12:** The multi-wave shock structure produced in a steel target subject to phase transition.

Phase changes

- **James De'Ath (AWE)**
- **William Proud**
- **Daniel Eakins**

This project has concentrated on the effect of additives and temperature treatment on the shock phase transition of steels. A series of experiments was conducted for stresses of up to 16 GPa. Gauges and velocity interferometry were used to capture the development of the shock pulse. The results indicate a strong microstructural dependence and large variation in the phase transition pressure.

Modelling granular materials at the meso-scale using iSALE

- **Will Neal (PhD student and RA)**
- **Gareth Collins**
- **David Chapman**
- **William Proud**

Building on a successful ISP funded PhD project, the in-house hydrocode, iSALE is being adapted to model granular materials at the particle level. It is hoped that this will answer some of the questions raised during the experimental series, in particular how particle size affects brittle materials under shock-wave loading. The study discovered that three distinct densification mechanisms exist during the compaction of these materials (figure 13). Each densification phase had a significant effect on the structure of the shock-wave profile that caused the wave to be unsteady and therefore constantly changing over time. This was demonstrated on the 100 mm light gas launcher at Imperial. The unsteady wave profile resulted in variation between intermittent and therefore terminal loading states. This discovery undermines the assumption that a single Hugoniot relationship can describe a granular material, something that the iSALE simulations aim to address in more detail.

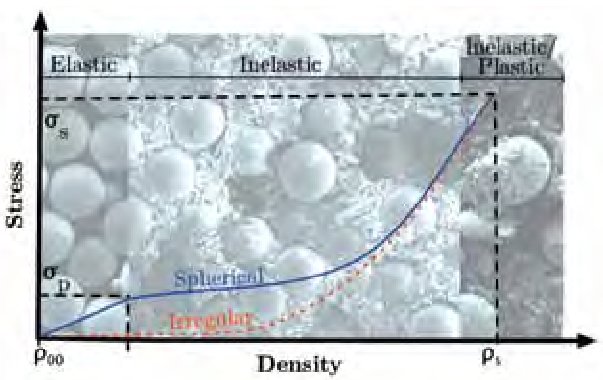


Figure 13: Regions in which three particle-densification mechanisms dominate during the stress-density response of a brittle granular material.

EXTREME CONDITIONS

Pulsed power driven neutron pulses

- **Simon Bland**
- **Kuan Hiang Kwek (Academic Visitor, University of Malaya)**
- **Krishnan Mahadevan**
- **Colt James (Alameda Applied Sciences)**
- **Ceri Clemett**
- **Jim Threadgold (AWE)**

There is significant interest from our stakeholders in sources and detectors for neutrons. One such source – the plasma focus – provides a high intensity, short pulse source; which could be used for detecting nuclear materials and possibly IEDs. Previously a 'single shot' focus built at Imperial has been used in these experiments. During 2012 a project with John O'Malley's group at AWE saw the installation of a 10 Hz plasma focus from Alameda Applied Sciences at Imperial, and the high intensity pulsed neutrons that were produced were successfully used to test a variety of new and old neutron diagnostics, examining response and dead time. A high speed framing camera was used by the Imperial team to explore all of the stages of focus dynamics. This is the first time (to our knowledge) that multiple frames have been used to analyse the action of focus' and has allowed new insights into factors affecting neutron production – in particular what limits production and why is it so variable from pulse to pulse. An example of the data taken is shown in figure 14.

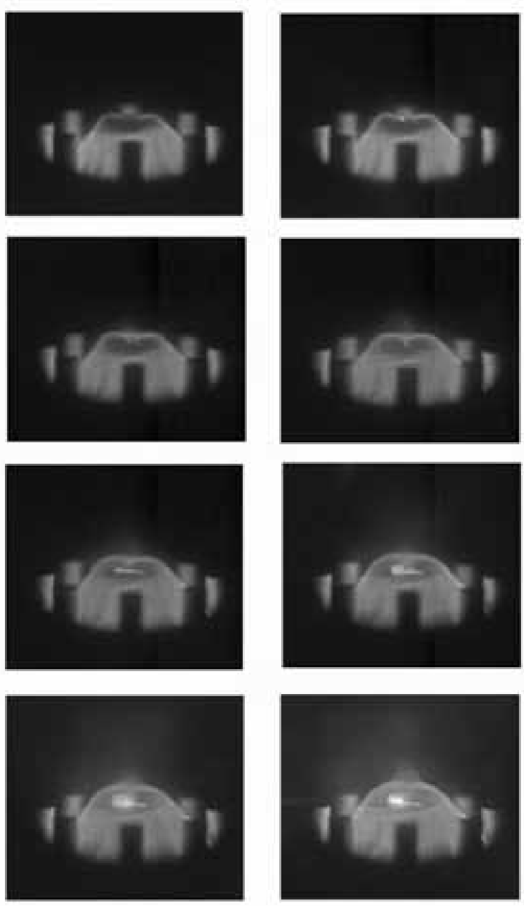


Figure 14: Framing images of plasma focus in 3.8 Torr of deuterium. Frames were 10 ns apart, 5 ns duration and show formation of tight pinch followed by breakup. Diameter of cathode posts seen in the images is ~40 mm.

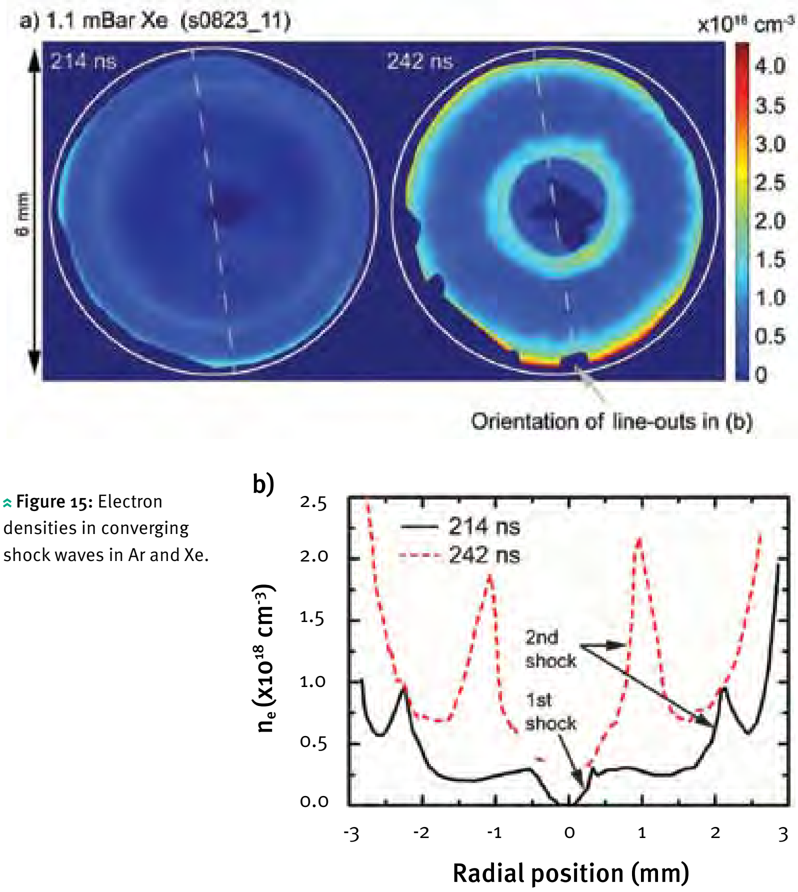


Figure 15: Electron densities in converging shock waves in Ar and Xe.

Pulsed power driven radiative shock waves

- Jonathan Skidmore (PhD student)
- Guy Burdiak (recently completed PhD)
- Sergey Lebedev
- Simon Bland

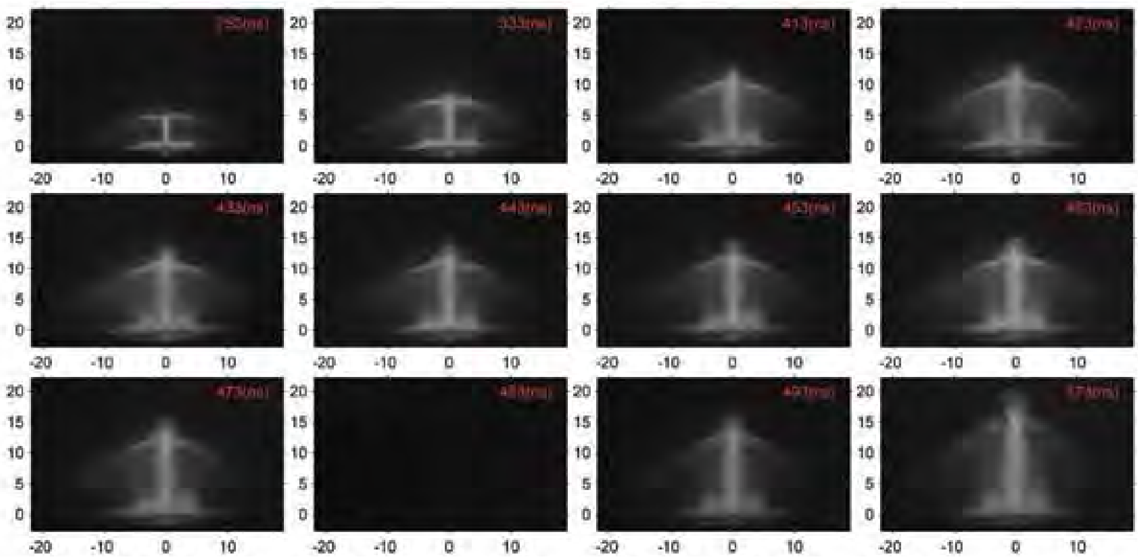
Radiative shock waves are produced when a shock is sufficiently intense that emission by material behind the front heats and ionises material ahead of it. Such conditions are found in many astrophysical phenomena – such as supernovae; whilst in the laboratory, radiative shock waves govern the implosion and heating of inertial confinement fusion experiments. Methods have been pioneered to create intense radiative shock waves in dense plasmas on the MAGPIE pulsed power facility at the cm scale over 100s of ns. In cylindrical geometries multiple shock fronts can be observed - the first shock is believed to be driven by yielding of the liner material; the second is magnetically driven, initiated by the melting of the liner; and a third shock is driven by ablation pressure. Cooling instabilities are seen following the shock waves. Such shocks and instabilities could significantly impact the heating of fuel in Magnetised Liner Inertial Fusion experiments.

In planar geometries, shockwaves with velocities ranging from 15 kms^{-1} - 50 km^{-1} have been launched from radial foil z-pinches. Evidence of thermally driven instability has been observed and a new method for controlling the velocity and shape of the shock has been suggested. Initial parameter scans looking at the effect of atomic mass and mass density of the pre-shocked medium have also been carried out.

Publication:

G.C. Burdiak, S.V. Lebedev, R.P. Drake, A.J. Harvey-Thompson, G.F. Swadling, F. Suzuki-Vidal, J. Skidmore, L. Suttle, E. Khoory, L. Pickworth, P. de Grouchy, G.N. Hall, S.N. Bland, M. Weinwurm and J.P. Chittenden
The production and evolution of multiple converging radiative shock waves in gas-filled cylindrical liner z-pinch experiments
HEDP, 9(1), p. 52–62, 2013

Figure 16: High speed framing images of radiative shock waves launched from foil.



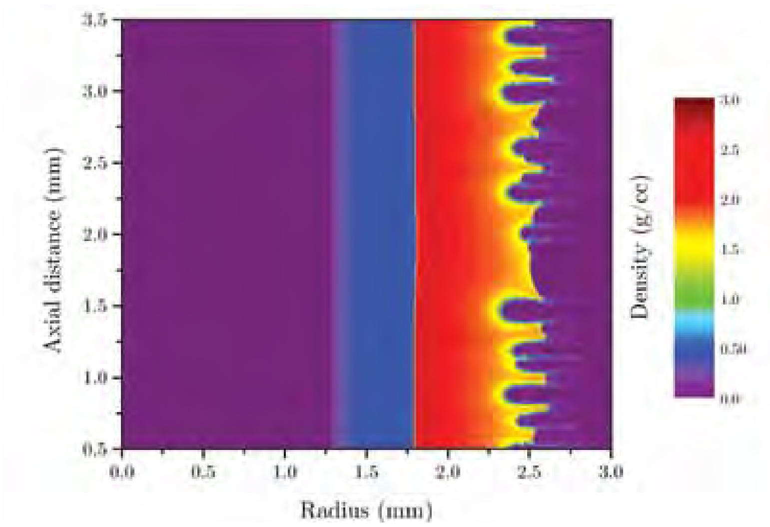


Figure 17: Profiles of density vs radius for deuterium filled liner using fictitious flow method to enable isentropic compression; and 2D simulation showing that while outside of liner displays instabilities, boundary is remarkably smooth.

Cylindrically convergent isentropic compression

- **Marcus Weinwurm (PhD student)**
- **Jerry Chittenden**
- **Simon Bland**

In the past 10 years, the use of pulsed power to drive isentropic compression experiments has produced extremely accurate measurements of EOS at pressures up to ~5 Mbar on the world's largest pulsed power facility – the 26 Mega-Ampere Z accelerator at Sandia National Laboratories using a simple 'strip line' load. Going to high pressures using strip lines requires higher currents; however a more practical way to achieve this may be through the use of cylindrically convergent target geometries. These could potentially also allow small, university-scale pulsed power facilities – such as MACH (see Facilities) or MAGPIE– to also achieve the Mbar pressures expected, for instance, in planetary cores.

Throughout 2012 methods to drive cylindrically convergent isentropic compression experiments were explored using the GORGON MHD code. Efforts concentrated on using simple 'hollow' liners, such as those presently being explored in experiments on Z, and liners filled with a target material such as cryogenic liquid deuterium. Here the difference in impedance between the (usually) metal liner and the fill can often lead to shock waves launched early in time, introducing excess heating. Several methods were developed to find the current pulse shape required to drive these loads, including a novel fictitious flow method. The resultant pulse shape appears to be significantly superior to the usual 'sine squared' current pulse of typical accelerators and could enable fermi-degenerate states of deuterium such as those present in the interior of gas giants to be obtained in the laboratory.

Modelling disperse multiphase flows using adaptive unstructured meshes

- **Christian Jacobs (PhD student)**
- **Gareth Collins**

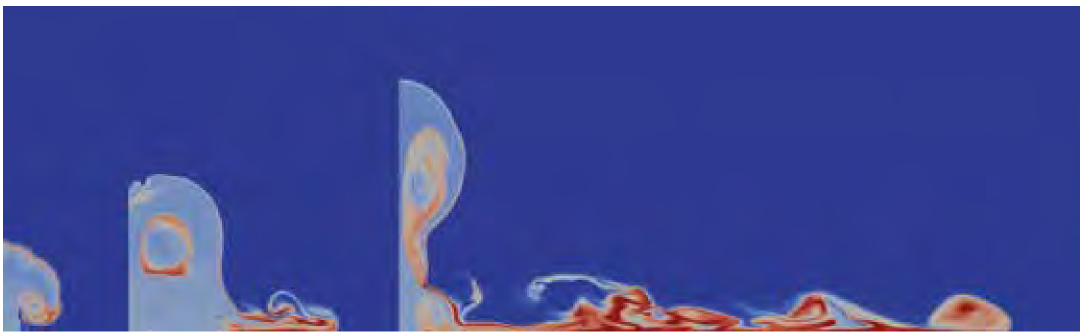
As part of an ongoing ISP funded project, the finite element model Fluidity has been extended to simulate dispersed multiphase phenomena, such as the motion of droplets, particles or bubbles within a surrounding fluid.[1] This new capability has been validated against experiments of volcanic ash particles settling through water (figure 18), which exemplify the role of vertical density currents in the rapid transportation of material from the surface to the seabed. This research has been used to establish a new criterion for the onset of collective plume settling of ash in the ocean. The unstructured mesh capability of Fluidity allows for complex geometry domains, and the adaptivity library resolves the particle plumes economically by focussing resolution only where necessary.

The multiphase model has also been extended to simulate compressible flow of the surrounding fluid and heat exchange between the particles and fluid. The compressible fluid capability was validated by comparison with experiments of shock-induced particle bed fluidisation. This functionality is required to simulate the atmospheric dispersal of hot debris produced in volcanic eruptions and meteorite impacts. Some preliminary results of a volcanic eruption simulation are shown in figure 19.

Publications

[1] C.T. Jacobs, G.S. Collins, M.D. Piggott, S.C. Kramer and C.R.G. Wilson
Multiphase flow modelling of volcanic ash particle settling in water using adaptive unstructured meshes
Geophys J Int, 192(2), p. 647–665, 201

Figure 19: Particle distribution at three times during a simulated volcanic eruption (30 s, left; 125 s, middle; 225 s right). As the volcano erupts, hot ash and air at 1,100 K enter the domain at 141 ms^{-1}, forming a cloud of particles and an overhanging vortex caused by drag effects. After this buoyant cloud of ash rises until approximately 1 km above ground level, it starts to collapse; the majority of the settling particles create a dense, ground-hugging pyroclastic flow, while some become entrained in the main eruption column.



Cranfield University

Defence Academy of the United Kingdom

Dynamic Response Group

- Gareth Appleby-Thomas
- Paul Hazell
- Mike Goff (PhD student)
- David Wood (PhD student)

A founding partner of the ISP, the Dynamic Response Group is largely research-based and currently supports two PhD students (one ISP funded). It has also published approximately 40 peer-reviewed articles since the inauguration of the ISP. In addition, numerous collaborations have ensued between Imperial, University College London and AWE – many of which are on-going. Areas explored have ranged from tissue simulants to the dynamic strength of HCP materials such as magnesium.

Our facilities include several single-stage gas-guns and, uniquely, our location and capabilities allow us carry out experiments on explosive materials. Since joining the ISP our diagnostic capabilities have expanded significantly and we are now able to deploy not only gauges and Het-v equipment, but also flash X-ray and particle-velocity (PV) gauge systems. The PV system, to be employed to track the run-to-detonation following shock loading in explosive targets, has been developed for use on two of our gas-guns using pairs of permanent magnets. In this technique, embedded wire-element gauges are picked up by an incident shock wave and flow in the target material at the particle velocity. A surrounding magnetic field means that induced currents in these gauges will be proportional to their velocity – and hence the PV itself. The use of permanent magnets as opposed to Helmholtz coils has the advantage of ensuring a stable and predictable field; maximising data quality.

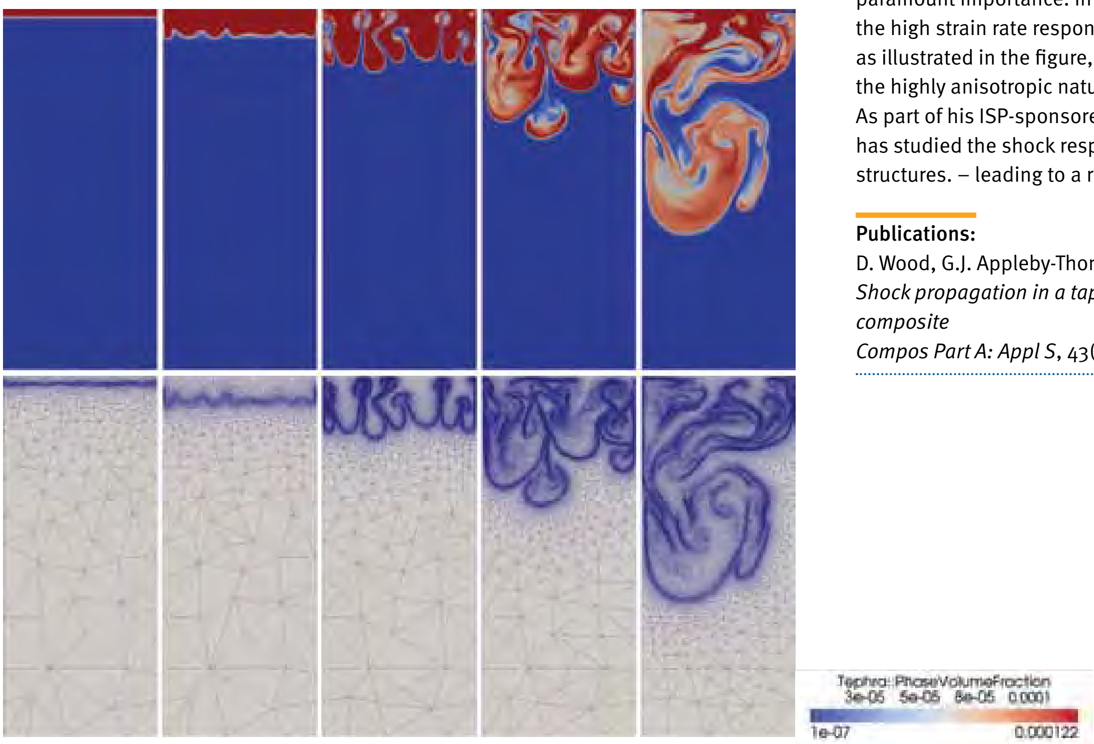
Other ISP-related work has focused on the shock response of composite systems. Carbon fibre composites have become more prevalent in structural applications in recent years. Due to the potential for such systems to be subjected to impact during their in-service lives, detailed knowledge of the material behaviour over a range of conditions is of paramount importance. In particular, knowledge of the high strain rate response is desirable. However, as illustrated in the figure, this is problematic given the highly anisotropic nature of such materials. As part of his ISP-sponsored PhD, David Wood has studied the shock response of such complex structures. – leading to a recent journal paper.

Publications:

D. Wood, G.J. Appleby-Thomas, P. J. Hazell and N. Barnes
Shock propagation in a tape wrapped carbon fibre composite
Compos Part A: Appl S, 43(9), p. 1555–1560, 2012

Figure 20: Micrograph of a tape-wrapped carbon-fibre phenolic resin showing c.a. 200 micron-diameter fibre bundles.

Figure 18: Volcanic ash particle settling in a water tank (0.3 x 0.3 x 0.7 m). 48 μm particles initially settled at approximately 0.17 cms^{-1} as predicted by Stokes' law. As more particles flux in, the particle-laden layer became unstable and plumes began to form, resulting in settling velocities over ten times greater than that of an individual particle.



University College London

Static High-P, T Research

- Paul McMillan
- Furio Corà
- Dominik Daisenberger (now at Diamond Light Source, I15)
- Richard Briggs (PhD student, now an RA at Centre for Extreme Conditions Science, University of Edinburgh)
- Melissa Cutler (PhD student)

The goal of the static high-P, T research programme at UCL has been to develop *in situ* studies and new materials synthesis to complement the shock physics activities of the ISP.

We have been engaged in a major study to investigate the high-P, T melting and crystalline transformations of tin (Sn); that is a strategic elemental material. The studies reveal some unusual behaviour. It was previously thought from shock experiments and simulations that the melting line became nearly flat above ~40 GPa with maximum values below 2500 K. Our laboratory experiments combined with *in situ* synchrotron X-ray diffraction show that the melting slope rises again above 60 GPa reaching ~6000 K at 100 GPa. This result has inspired new laser-driven ramp and shock experiments to be carried out at centres including Lawrence Livermore National Laboratory in the USA.

At lower temperature the crystalline material exhibits unusual polymorphism within the body centred structure of the γ-Sn phase that exists from 10-150 GPa. In particular there appears to be a thermodynamically impossible coexistence of two phases with closely related structures over a wide pressure range. We are applying a combination of experimental and theoretical techniques to understand this behaviour and this is leading to new models for melting and phase transformation of Sn that will affect its dynamic properties.

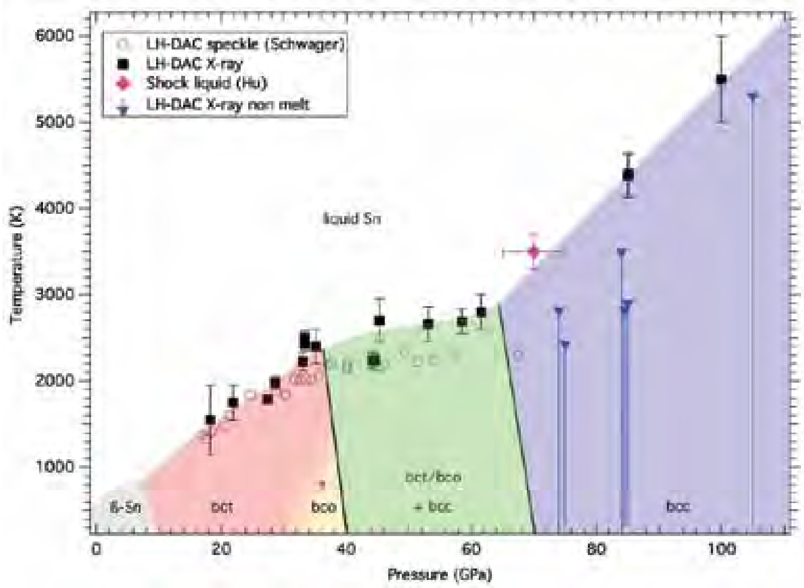


Figure 21: Phase transitions and melting data for Sn from laser heated DAC measurements combined with synchrotron X-ray diffraction and optical imaging studies. The coloured regions indicate stability ranges and transitions between beta-Sn (Sn-II; grey) and body-centred tetragonal (bct) Sn-III (peach). At P > 70 GPa the structure is body centred cubic (bcc) and at intermediate pressure the bct and bcc forms coexist (light green). This is associated with a flattening of the melting relation between 40-70 GPa followed by a rapid rise to >5500 K by 1 Mbar (105 GPa). Blue diamonds indicate laser heated runs that did not achieve melting in the bcc range.

Recent attention has focused on high-P, T melting relations in tantalum where previous shock studies and ab initio calculations were in agreement but laser-heated LH-DAC studies indicated much lower Tm values. The discrepancies extend from several hundred up to several thousand degrees in the multi-megabar range. Recent work using LH-DAC combined with synchrotron X-ray diagnostics of melting developed at the ESRF have now shown that part of the problem is due to reactions of the heated Ta metal at high pressure with C atoms derived from the diamond surfaces to cause formation of tantalum carbide (TaC). During LH-DAC experiments carried out at the APS we investigated the melting relations of TaC as a function of pressure that help us understand the tantalum-carbon phase diagram under static and dynamic compression conditions.

During our studies of Sn melting we applied a thermodynamic model based on co-existing polymorphic domains based on a previous study of Xe, that can contain interleaved hexagonal (hcp) and face-centred cubic (fcc) close-packed structures at high pressure. However recent theoretical studies indicate that earlier results reporting the Xe melting relation were incorrect. We have now carried out a LH-DAC study of Xe melting at high-P, T using synchrotron X-ray diffraction and are analysing the data to aid interpretation of static and shock experiments.

New synthesis studies are being focused on high-density materials in the C-N-H system using static and dynamic techniques. Laboratory synthesis experiments are providing precursors derived from designed chemical reactions. These are then treated under high-P, T conditions using LH-DAC and shock recovery techniques to be implemented at Imperial or Shrivenham ISP facilities.

Finally our static high pressure group has begun to investigate the behaviour of biomaterials under static and dynamic pressurisation. One project supported by the Leverhulme Trust (UK) and Sloan Foundation (USA) seeks to understand the survival and adaptability of organisms under extreme high-P conditions. Related to this work shock recovery experiments have been carried out using the gas gun facility at Shrivenham following design of specialised targets at Imperial. In other work we are collaborating with the Shrivenham group to study the behaviour of plant seeds and other biomaterials under static pressurisation conditions to complement their programme of shock studies.

University of Edinburgh

Figure 22: The DAC is a versatile tool that is routinely used by researchers to study material properties to millions of atmospheres. ISP projects in Edinburgh and UCL rely heavily on this type of capability.

Publication

S.G. MacLeod, B.E. Tegner, H. Cynn, W.J. Evans, J. Proctor, M.I. McMahon and G.J. Ackland
An experimental and theoretical study of Ti-6Al-4V to multi-mbar pressures
Phys Rev B, 85, 224202, 2012

New phase of dense hydrogen: graphene-like mixed atomic-molecular state

- **Ross Howie (PhD student)**
- **Eugene Gregoryanz (Edinburgh)**

In March 2012 Ross published the seminal paper (Howie et al., PRL 108, 125501, 2012) on a new phase of solid hydrogen (phase IV), the first solid phase of hydrogen discovered in the past 25 years. This phase is quite unusual structurally and chemically as it represents an intermediate state between common molecular and monatomic configurations. However, even though that paper mapped the P-T domain where the phase IV of hydrogen exists many questions about the low temperature behaviour of phases IV of both hydrogen and deuterium remained unanswered. Using in situ optical spectroscopy, Ross has investigated temperature stability of the phases IV of dense deuterium and hydrogen. He observed phase III to IV transformation, imposing constraints on the P-T phase diagrams of both elements. The spectral features of the phase IV-III transition and differences in appearances of the isotope's Raman spectra strongly indicate the presence of proton tunnelling in phase IV. The changes in optical spectra above 275 GPa might suggest the presence of a new solid modification of hydrogen (deuterium) closely related structurally to phase IV. The extrapolation of the combined band gap yields 375 GPa as minimum transition pressure to metallic state of hydrogen (deuterium).

Publications

R.T. Howie, T. Scheler, C.L. Guillaume and E. Gregoryanz
Proton tunneling in phase IV of hydrogen and deuterium
Phys Rev B, 86, p. 214104, 2012

A.F. Goncharov, J.S. Tse, H. Wang, J. Yang, V. V. Struzhkin, R.T. Howie and E. Gregoryanz
Bonding, structures, and band gap closure of hydrogen at high pressures
Phys Rev B, 87, p. 024101, 2013

University of Oxford

Molecular dynamics simulations of shock-induced phase transitions in silicon

- **Gabriele Mogni (PhD student)**
- **Justin Wark (Oxford)**

The aim of this project is to gain a better understanding of the mechanical response properties at the microscopic lattice level of certain crystalline solids under the effects of dynamic compression. For this purpose we rely on an interplay between *ab initio* modelling via computational simulations on one hand, and laser-based experimental investigations on the other. Of particular interest to us in recent times has been the behaviour of crystalline silicon subject to shock and ramp loading as observed in classical Molecular Dynamics simulations, especially in the context of its pressure-induced solid-solid polymorphic phase transitions. As can be observed in the figure below, multi-million atom simulations of shock-wave propagation in a single-crystal sample of silicon predict the onset of a high-pressure mixed-phase region ensuing directly after the initial elastic response, consisting on one hand of nearly-hydrostatically compressed cubic-diamond crystal structure (orange), and on the other of phase-transformed material lying in a high-pressure stable phase (red). By analysing the resulting banding structure, we are able to formulate a complete model for the relief of shear stress across the plane transverse to the shock-propagation direction which is consistent with the interatomic potential.

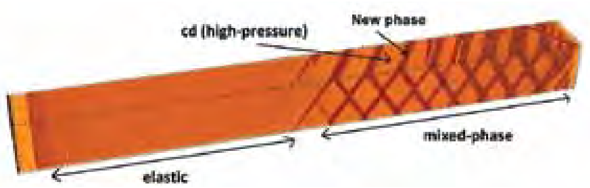


Figure 24: Multi-million atom Molecular Dynamic simulation of shock wave propagation in single crystal silicon.

Centre for Blast Injury Studies

Force blast protection

- William Proud
- Kate Brown (Austin, Texas and Cambridge)
- Chiara Bo (PhD student)
- Thuy-Tien Nguyen (PhD student, CBIS)
- James Wilgeroth (CBIS)
- Andrew Jardine (Cambridge)

The Royal British Legion Centre for Blast Injury Studies (CBIS) at Imperial College London is the result of a £5 million five-year award by the Royal British Legion to promote innovative inter-disciplinary research into blast injury causation, treatment, mitigation and prevention. The Centre is a collaboration between military and civilian clinicians, scientists and engineers.

Blast Force Protection, led by Dr William Proud of the ISP, is one of three research themes within the Centre. It builds on work undertaken by Dr Jens Balzer and PhD student, Chiara Bo and deals with the interaction of the blast wave with the materials and structures around the human body. Much of the work is aimed at ensuring that the stress pulses applied to biological materials are representative of those experienced in the real world environment. In order to achieve this, the theme will develop sensors, study the interface between materials, develop physically based models for materials used in protection and measure the load produced by the blast. This theme is being taken forward in collaboration with Dr Andrew Jardine and Dr Kate Brown from the University of Cambridge.

Development of split-hopkinson pressure bar system for cell monolayer experiments

As part of a body of work being undertaken by ISP PhD student, Chiara Bo, and Research Associate, Sam Godfrey (CBIS), a confinement chamber previously developed for the Split Hopkinson Pressure Bar (SHPB) system to study the effects of pressure waves on biological samples (cells in suspension) has been further modified to allow experiments on cell monolayers. Adherent cells are grown on a plastic coverslip, which is then mounted on support bars (figure 24) using polymeric screws. The support bars themselves are then inserted into the confinement chamber, which is held within a supporting frame and mounted on a rail carriage. This arrangement allows for accurate alignment of the support bars with the input and output bar of the SHPB system. Liquid medium is inserted in the chamber as in previous experiments and the chamber is then sealed with an o-ring and retention screw. The aim of the project is to gain better understanding of the effects of controlled pressure delivery on a wide range of cell-types, including nerve cells and osteoblasts.

A post-experimental morphological damage assessment is performed using fluorescent microscopy, which allows damage mechanisms to be related to pressure-time parameters (calculated from strain gauge signals). Finally, this experimental approach provides improved sterility to the system. The chamber and support bar assemblies can be prepared in a microbiology safety cabinet and simply inserted in the chamber support without exposing the samples to potential contaminants.

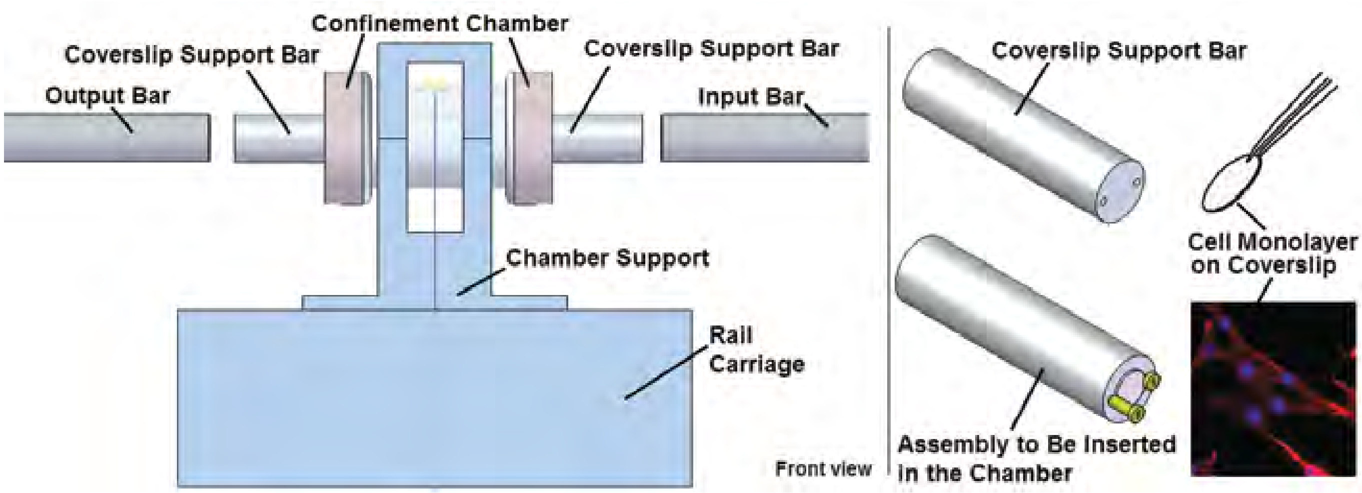


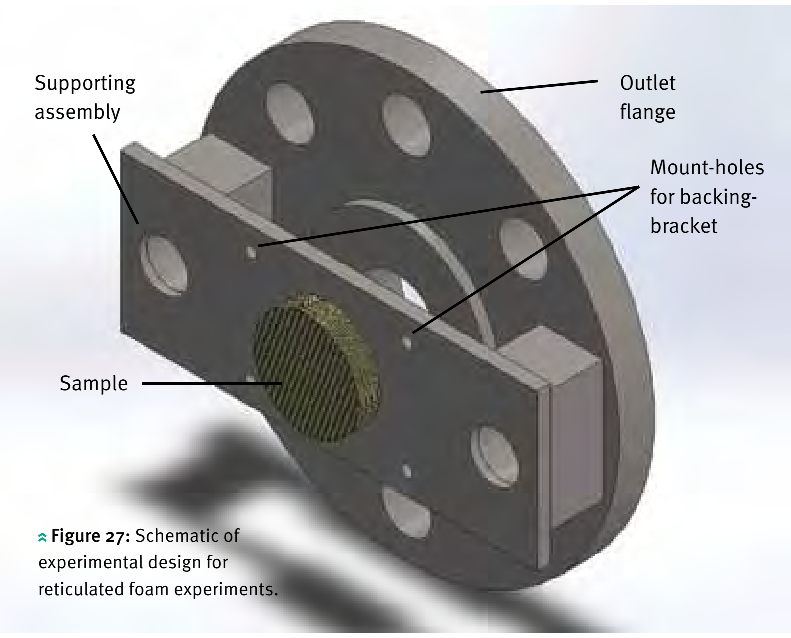
Figure 24: Schematic of the confinement chamber setup for cell monolayer experiments.

⌃ **Figure 25:** ISP/CBIS shock tube apparatus.

Performance characterization of a shock-tube system

This project seeks to characterize the performance of a shock tube system to be used in a number of research avenues within the ISP and the Centre for Blast Injury Studies at Imperial. The relationship between diaphragm rupture and pressure evolution within the system has been an area of key interest to date. However, methods which will allow the user to alter the pressure profile in terms of intensity, shape, and duration are in development. This will permit study of a wide range of blast conditions on biological and blast-mitigating materials within the respective centres. Materials of interest include lung tissue, cell cultures, and reticulated (open cell) foams. The shock tube system is illustrated in Figure 25. The pressurised section, i.e. the driver tube, is typically separated from the ambient section of the system using either a single or double aluminium or Mylar® diaphragm arrangement. Sudden rupture of the diaphragm(s) creates a blast wave (a shock-front of compressed gas) which propagates towards the shock-tube outlet and target area. Future research areas related to the performance of the shock-tube apparatus include:

- The study of stress distribution and shock flow around samples of differing size and shape
- Using metallic meshes and granular materials inside the tube to alter shock flow
- Examination of shock interactions using high-speed photography with birefringence and Schlieren methods
- Development of finite-element simulations for studying shock wave formation, loading of irregular shapes (e.g. mouse lung)



⌃ **Figure 27:** Schematic of experimental design for reticulated foam experiments.

⌃ **Figure 26:** Examples of aluminium diaphragm bulge and rupture.

The interaction of blast wave with reticulated foam

Injuries to the tympanic membrane (ear drum) and inner ear are particularly common in individuals subjected to blast overpressure, such as military personnel engaged in conflict. Consequently, there is a demand for improved auditory protection systems, which are capable of both preventing this type of injury while providing maximum situational awareness to the user. An experimental design allowing for a number of reticulated (open cell) foams to be subjected to dynamic compression using the shock tube within CBIS has been developed by James Wilgeroth. Specific effects of porosity; relative density, which is determined by the ratio of cellular material to solid material from which the foam is made; sample thickness; incident pressure; and shock pulses of varying timescale upon the evolution of peak overpressure behind foam samples are of key interest. In addition, the use of Schlieren imaging techniques will allow for detailed examination of gaseous flow at the rear surface of shocked foam samples.

Training

Industry, agencies and government increasingly require access to expert knowledge and innovative well-educated recruits in many and varied research fields. The ISP provides education across a wide spectrum of activities and target groups. A non-exhaustive list includes:

1 HOUR

Research talks

Institute staff and students give numerous talks, seminars and lectures aimed at researchers, funders and the public. These provide a good route for reporting, networking and raising awareness, for example, PhD student Chiara Bo has been invited to give a talk at the 2013 SCCM/APS meeting.

1 DAY

Continuous professional development

ISP staff deliver short consultancy projects, problem solving and short refresher-update sessions for research organisations in the public and private sectors. This enables research challenges to be resolved by consulting with experts either through focussed discussion or general overviews of a research field.

2 DAYS

Annual conference

Aimed at ISP members and colleagues in related research areas. This provides an excellent opportunity to discuss research, find out what has been achieved and find inspiration from fellow scientists and engineers.

10 WEEKS

Undergraduate course 'Shock Waves and Hydrodynamics'

Many university degrees allow for a degree of selection and specialisation in the latter years of the curriculum. Imperial's Department of Physics is no exception. With the founding of the ISP, the fourth year option 'Shock Waves and Hydrodynamics' was entered onto the list of options. Jerry Chittenden who leads the option has found that it has great resonance amongst the undergraduates, with up to 40% of the students opting for this course. This has made it the most popular undergraduate option for all the years it has run.

3 MONTHS

BSc/short projects

Aimed at established researchers and undergraduates. The undergraduate Physics degree course leading to BSc includes a three month-long project. In the ISP these projects have included shear band formation in metals and the flow of granular materials. There is also a steady flow of visitors from academic and research institutions who spend a few months in the summer at the ISP, this provides opportunities for close networking and also for exposure to new ideas and research cultures.

6 MONTHS

Masters projects

Aimed at undergraduates and postgraduates. To obtain the award of an MSci, students need to undertake a long research project. The ISP hosts several of these every year. In the summer of 2012 Thuy-Tien Nguyen undertook a project involving the characterisation of a shock tube for use by CBIS. She investigated the rupture of the diaphragms in the system during operation and also the propagation of the shock pulse throughout the system.

1 YEAR

Extended projects

Aimed at active researchers and postgraduate students. The ISP has established a one-year MSc course in Shock Physics (with a two-year part-time option), which gives recent graduates essential background knowledge and exposes them to current research through projects and seminars given by acknowledged experts in this field. The course is in-line with the Bologna Accord and quality is assured through internationally accepted monitoring. In addition it is not unusual for some research students to spend significant time at other research centres. In 2013, the MSc students are heading out to the Technical University of Pardubice for blast range training.

Some of the first graduates in MSc Shock Physics, May 2012.

Short courses

The ISP delivers short courses aimed at recent recruits as well as established researchers to provide background knowledge and/or latest research findings or techniques. A short course on a general topic can provide a time-efficient opportunity to cover both these aspects through lectures by experts in the field. On average the ISP organises two of these sessions per year around topics of wide interest (e.g. energetic materials, modelling, diagnostic techniques etc.). More specialised sessions can also be arranged.

3 DAYS

Nuffield projects

Aimed at 16–18 year olds. The Nuffield Foundation along with other Charities provides the funding for bursaries for the 'brightest and best' to spend part of their summer holidays in a university working on small research projects. The aim is to allow them to experience, and be enthused by real research. In the UK, physics is now amongst the top 10 most popular subjects studied at A-level; the ISP is pleased to be able to play its part in the careers of these students by hosting Nuffield projects.

6 WEEKS

Undergraduate research opportunity programme projects

Imperial operates a scheme where undergraduates can work with a research group during the summer break and obtain experience of research. This year the summer at Imperial was dominated by the London Olympics and Paralympics but this did not prevent UROPs!

8 WEEKS

2 YEARS

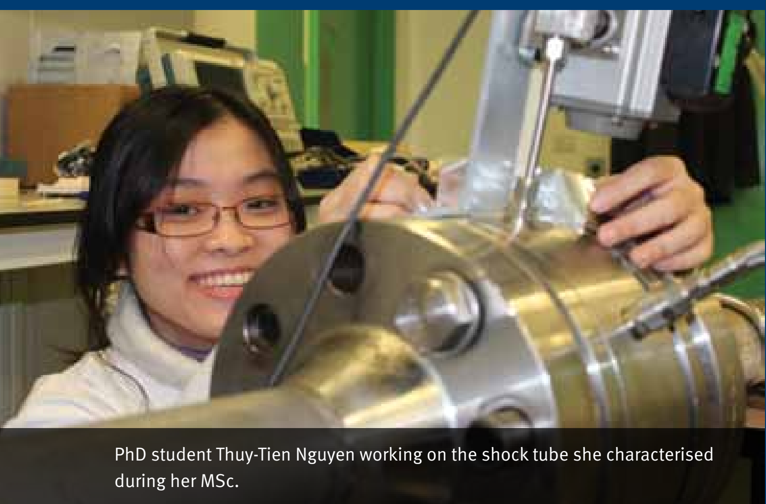
Postdoctoral contracts

For active researchers. Having staff with research experience is fundamental for both their own development and that of their group. In many ways they provide the back-bone of the research effort, often bringing knowledge from other fields.

3 YEARS

PhD studies

For graduate researchers. A doctoral degree provides the standard entry-level qualification to research. The ISP has hosted 23 PhD students so far, including one funded by QinetiQ and one funded by The Royal British Legion.



PhD student Thuy-Tien Nguyen working on the shock tube she characterised during her MSc.

UROP students, Ernest Lo and Qufei Gu briefly describe their research into the dynamic breaking of metal wires and the use of resistance measurements and high-speed photography to determine the failure process:

"One of the early experiments which established the field of dynamic properties of materials was performed by John Hopkinson in the mid-19th century. This involves using a falling weight to pull a wire.

One conclusion of our experiment is that the dynamic strength is larger than the static strength. The experiment used 5 m long wires of 5 mm diameter (or, more precisely, their Imperial equivalent). In a series of studies we produced a smaller version of the system with a range of wires, 1 m long and 0.2 – 0.5 mm diameter. We measured the resistance of the wire and took high-speed photography of the impact process. Under these loading conditions the resistance-time measurements showed the deformation of the wire was virtually identical in static and dynamic cases. The combined effect of loading pulse duration and wave speed in the wire produce a pseudo-steady load to be exerted on the wire and the fracture process results in a similar form of the wire fracture surface.

Comparison of the data from the 19th century and the 21st century indicates the importance of the interplay of the wave speed, impulse duration and dimension in these systems."

Facilities

Imperial College London

Technical support is provided to ISP research:

Imperial College London
- Steve Johnson
- Mark Grant
- Alan Finch
- Physics instrumentation workshop

Cranfield University
- Andrew Roberts

University College London
- Ed Bailey
- Steve Firth

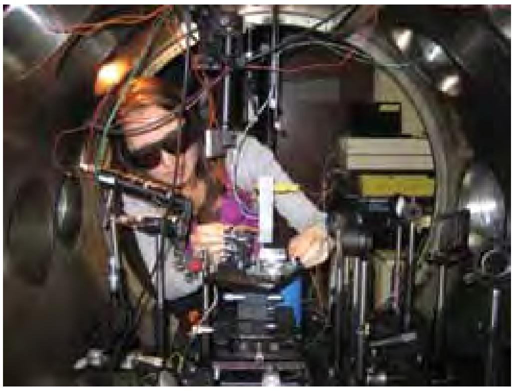
The strength of the Institute of Shock Physics at Imperial College London resides in its multi-scale loading platforms and broad diagnostic suite. The application of these cutting edge diagnostics to well-established and evolving loading methods enables the determination of material properties with an unprecedented confidence.

Large-bore single stage gas launcher

The single-stage gas launcher at Imperial is the largest compressed gas impact system in the UK. Using highly compressed helium, the gas launcher can launch 100 mm diameter projectiles at velocities in excess of 1400 ms^{-1}, generating pressures and temperatures of up to 70 GPa and nearly a thousand degrees upon impact.

Commissioned in February of 2011, the ISP gas launcher is now a mature world class facility. The 2 m diameter experiment tank permits both bulky targets and complex diagnostic systems (e.g., heating/cooling stages, free-space optical elements), allowing a combination of elaborate experiments and precise measurements. The launcher is also fitted with an extended soft-capture tube to recover targets following impact for materials characterisation. One of the primary features of the launcher is the ability to simultaneously test multiple samples in a single impact experiment. By ensuring the same loading into the target package, any differences in measured response are due exclusively to sample variations (see high pressure section page 8). This provides a key capability to directly compare material behaviour, and can help correlate testing performed between different platforms.

A comprehensive proven diagnostic suite is available on the facility, including; an 8 channel multi-generation PDV system (optical velocimetry), time of arrival sensors, pressure transducers, high speed imaging including; video (100k fps), framing (200 Mfps), and streak cameras. Additionally, an adjacent dedicated diagnostics table allows setup of more complex diagnostics; a line-imaging VISAR has been constructed to spatially resolve the non-uniform motion of heterogeneous surfaces (see dynamic fracture in research section page 8). Future developments will include time-resolved spectroscopy and pyrometry techniques.

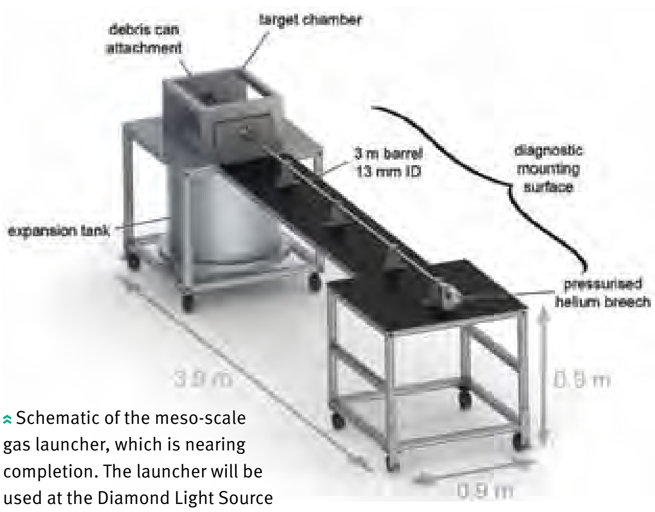


The ISP also benefits from access to facilities through collaboration. PhD student Laura Chen (pictured) spends time on the Janus facility as part of a collaboration with LLNL.

The 100 mm bore gas launcher at Imperial has performed over 100 experiments studying topics ranging from EOS, high-pressure strength, distended materials, and fragmentation.

Small-scale impact facilities

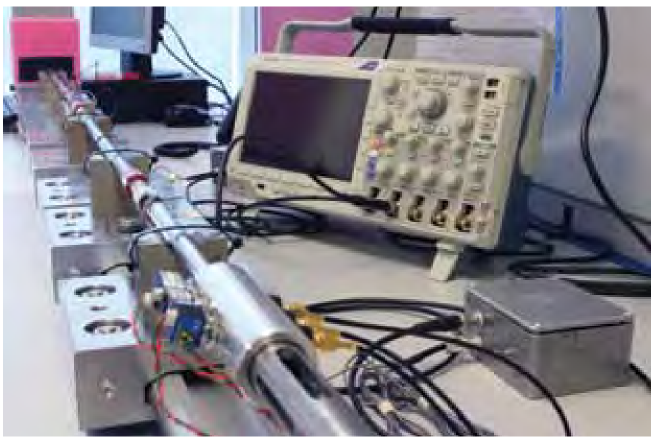
A number of small-scale impact launchers are under development at the ISP. These facilities range in bore, from 13 mm – 30 mm, and expected performance, with velocities from few 10s ms^{-1} to <1000 ms^{-1}, and are designed with flexibility and portability in mind. Suitable for small-scale ballistics studies and materials characterisation such as Taylor impact tests, these launchers can also be used for diagnostic development, are readily accessible training tools for undergraduate and postgraduate students, and are potentially portable for off-site studies. Additionally, these meso-scale facilities bridge the spatial, temporal, and pressure scales between the main experimental platforms of the laser-shock driver, MACH and the large-bore gas launcher, continuing ISP's theme of multi-scale research.



Schematic of the meso-scale gas launcher, which is nearing completion. The launcher will be used at the Diamond Light Source during the 2013 allocation period.

Split Hopkinson Pressure Bar

The Split-Hopkinson Pressure Bar (SHPB) apparatus used by both the ISP and the CBIS is a rail-mounted system allowing for accurate alignment of both the chosen projectile and functional bars. Projectile velocity is measured using a photodiode array whilst wave profiles within the (Titanium or Inconel) bars are monitored using type AFP 500-90 semiconductor gauges which are manufactured by Kulite Semiconductor Products INC. The complimentary rail and precision rail-slider design offers flexibility to the system and for bars of differing length and material composition to be interchanged with ease.



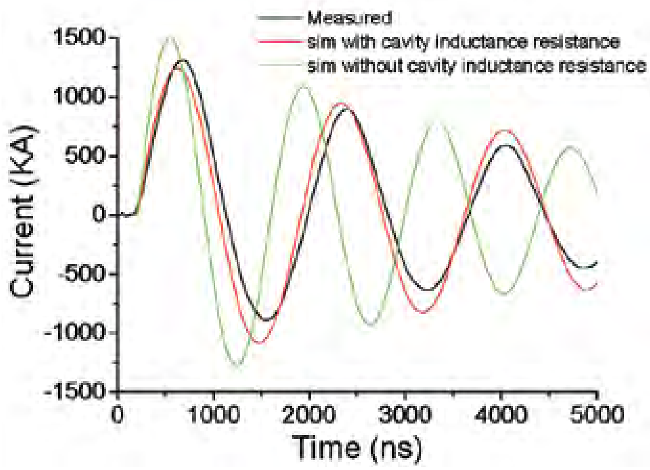
Split Hopkinson Pressure Bar in the Centre for Blast Injury Studies.

MACH pulsed power platform

MACH is a 2 MA, ~300 ns rise time pulsed power facility based on cutting edge Linear Transformer Driver technology. Unusually for a Mega-Ampere generator, MACH incorporates no oil, no water and no SF6 insulation gases; this allows for an extremely low maintenance, 'fast turnaround' system.

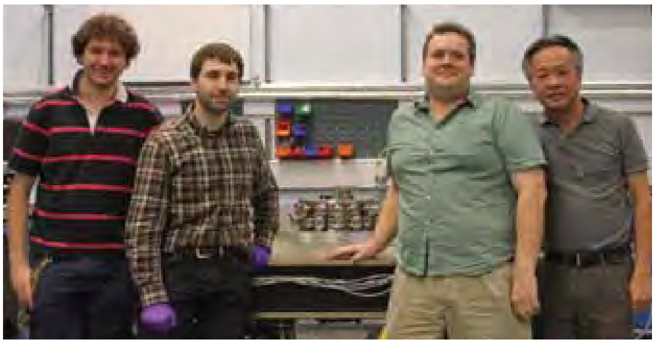
Throughout 2012 experimental hardware has been developed for MACH, ready for use in isentropic compression experiments. An ultra-low inductance transmission line and low cost, easy to manufacture load have been developed, with all machining done in-house by the Physics instrumentation workshop. The distribution of current in the stripline has been modelled, allowing the effect of its shape on magnetic pressure to be explored. An 8 channel third generation PdV system has been built to analyse the pressure across targets in these experiments, and soon a two-line VISAR system will enhance the facilities capabilities.

Towards the end of 2012, the MACH facility moved to its new home in the Extreme Physics Laboratory. The move was accompanied by the successful firing of several initial test experiments, allowing better modelling of behaviour of isentropic loads and a series of final adjustments to be made to load hardware.



MACH current vs simulated current.

Simple stripline experiment, before and after.



(Top) Double height pulsed power bay (~8x8 m) showing MACH, along with the line VISAR system (optical table to left), crane, and desks for electronics, vacuum systems and diagnostics.

(Bottom) The pulsed power team, finally in their new home of the Extreme Physics Lab.

Extreme Physics Laboratory

The newly built Extreme Physics Laboratory in the Blackett building is a high quality space dedicated to producing extreme pressures, densities, and temperatures in materials for a variety of research purposes. The laboratory is linked by a series of large diameter beam pipes to enable high power, high energy laser beams to pass to and from MAGPIE and the laser consortium, where the Cerberus laser is housed. The project represents collaboration between three of Imperial's research groups – Plasma Physics, Quantum Optics and Laser Science, and the ISP, and was funded by an internal infrastructure grant of ~£1 million.

Construction of the laboratory commenced in March 2012, and took ~7 months; during which time the MACH pulsed power platform moved to a temporary home to carry on its research. The finished laboratory has four sections: a dedicated high-bay and crane, to house MACH and other large scale pulsed power based experiments; a semi clean room with re-enforced floor to stably house large laser amplifiers; a laser target area; and a capacitor room. Whilst we apply for grants to see the building of the Cerberus extreme laser, these sections have been outfitted for research projects including laser-gas jet interactions in high magnetic fields, a dedicated space for developing fibre optic velocimeters and interferometers, a calibration station for XUV spectrometers for use in both laser and pulsed power driven high energy density physics research, and the MACH facility has both been installed and fired approximately 50 test shots to establish new experimental hardware.

Laser-driven shock system (spring 2013)

The ISP is working with the Blackett Laser Consortium to construct a new laser-based experimental platform for studying the ultrafast response of materials at Mbar pressures. Following a successful Wolfson bid to the Royal Society, the Huxley 147 laboratory was completely refurbished to house a dedicated area for ultra-fast imaging of extreme states of matter. The works included placing a number of new beam tubes to connect the main Cerebus laboratory, and reinforcing the floor to support the weight of the new target chamber. Work on the room was completed early February, with plans to install the target chamber by mid-February. Using former components from AWE, Aldermaston's HELEN laser, the Cerberus laser will be upgraded to deliver a 50 Joule, 1.4 ns long-pulse in a uniform 1 mm^2 area, with future upgrades expected to achieve 500 J in a 4 ns shaped pulse. The system is being designed to rapidly compress very thin targets, on the order of tens of micrometers in thickness, at strain-rates between 10^8-10^{10} s^{-1}. The result will be a new ISP experimental platform dedicated to the study of dynamic material behaviour at short length and time scales (several to tens of micrometers, sub-ns to nanoseconds). Study at these fine scales provides a unique view to the early processes responsible for bulk behaviour.

The long-pulse laser shock system will incorporate a number of key capabilities:

- Direct structure-property correlation, via testing of expensive single-crystal or ultra-high purity samples
- Multi-step loading profiles, to allow successive target conditioning and probe waves for excited state characterization
- Target heating and cooling stages, to achieve temperatures between 100 – 1000 K, and isolate or frustrate thermally activated processes
- Line-imaging VISAR for diagnosing shock front planarity and target response

The laser driver is a complementary loading platform for the ISP, allowing the seamless investigation of various phenomena from their origins (laser) through to their meso-scale (MACH) and bulk conclusions (gas launcher).

The newly refurbished Huxley 147 laboratory and former RAL target chamber, which will be host to Imperial's first long-pulse laser shock experiments in summer 2013.

Cranfield University

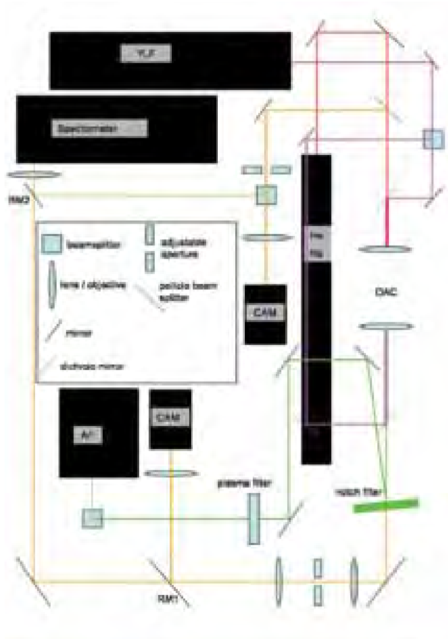
The lab at Cranfield University (Shrivenham) is furnished with several gas guns ranging in calibre from 22 mm to 75 mm. Much of the core work is carried out using 50 mm gas guns; one gas gun is dedicated for working on explosives; and one gas gun is reserved for inert materials. Diagnostics include piezo-resistive gauges; heterodyne velocimeter and high-speed imaging. Split Hopkinson Pressure Bars and drop-weight towers are also installed to interrogate the dynamic behaviour of materials at lower strain-rates. In particular, the ISP has access to a 4-channel Flash X-ray 300 kV system that allows interrogation of dynamic in-material events at micro-second time resolution. The figure below shows this system fitted to one of the 50 mm bore gas guns.

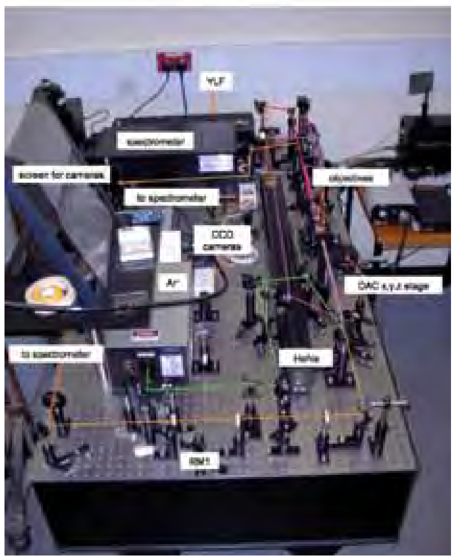
Flash X-ray on the blue target chamber.

University College London

We have developed capabilities for diamond anvil cell (DAC) compression experiments into the Megabar regime combined with laser heating up to temperatures of 6000-7000 K.

ISP funding has supported a high pressure gas loading system allowing compressed N2, Ar, He or H2 to be loaded into membrane driven DACs providing quasi-hydrostatic or reactive compression environments. Those experiments are complemented by our other facilities funded by EPSRC and UCL, including large volume press devices that we use for materials synthesis and *in situ* studies up to 4-25 GPa and T = 2300 K. To complement our laboratory spectroscopy and light scattering experiments we carry out synchrotron X-ray studies at the European Synchrotron Radiation Facility (Grenoble, France), Diamond Light Source on the Harwell Research Campus near Didcot, UK, and the Advanced Photon Source (Argonne National Laboratory, USA).





» Schematic (top right) and photograph (bottom right) of ISP Diamond Anvil Cell and laser facility. Green lines represent 514.5 nm line of argon ion laser, red lines represent 633 nm line of HeNe laser, magenta lines represent 1053 nm radiation from YLF laser and orange lines represent scattered radiation/ thermal emission/imaging pathways (dashed and dotted lines on the photograph represent vertical laser paths and laser paths below main optical axis respectively).

Translation

Industrial engagement

Working with corporate partners has always been part of the Imperial way of working. The 1907 Charter states that the objectives of the university shall be

> "to provide the highest specialised instruction and most advanced training, education, research and scholarship in science, technology and medicine, especially in their application to industry"

and that philosophy is very much at the heart of the strategy for the ISP. As an AWE-sponsored institute, the ISP is a very good example of how a corporate partnership with the College works in practice. Building on this relationship, we are pursuing our aim to become the UK Centre for Shock Physics by establishing links, and developing programmes with other industrial groups as well as partners in universities and other research laboratories. During the last year, the ISP has hosted numerous visits by potential industrial partners.

We are particularly pleased to have established a very successful partnership with Thales UK over the last year.

Thales is a global technology and engineering company with a heritage in the defence sector. The missile electronics business of Thales UK provides a range of specialist fuzing and safety and arming systems for use in the latest guided weapon and missile systems. These systems cover hard target fuzing, lethal payloads, safety, arming and fuzing systems, rocket motor ignition and ordnance research activities.

In particular Thales's hard target fuzing systems provide the functionality and performance for weapon systems to penetrate very hard and deeply-buried targets such as concrete bunkers. They are specifically designed to withstand the extremely severe environments that are encountered during deployment and operation. Hydrocode modelling is used extensively in the development of system survivability.



Thales – Institute of Shock Physics collaboration

- **Laurie Turner (Thales)**
- **Darren White (Thales)**
- **Jens Balzer**
- **David Chapman**
- **James Wilgeroth**
- **Amnah Khan (PhD student)**
- **Dan Eakins**
- **William Proud**

Thales routinely uses epoxy resin-based encapsulates to protect electronic components used in high-g shock environments. While the gross response of these materials has been shown to provide good shock resistance, their detailed behaviour is not fully understood, especially at extremes of temperature. For example, one of the epoxy materials appears to behave as a very high viscosity fluid rather than a solid when under high compression.

Future requirements are likely to include multiple high frequency shocks, and so it is important for Thales to improve its understanding of these materials. This is being achieved by exposing samples to controlled high-velocity impacts at different temperatures and monitoring the bulk and surface strains. This data will then be used to define parameter values for LS-Dyna material models used in simulations.

The experiments include dynamic mechanical analysis (DMA), Instron testing and Split Hopkinson Pressure Bar (SHPB) experiments, each performed over a range of temperatures, and which collectively cover the required strain-rates. The experiments have been chosen to obtain data needed to populate a rate- and temperature-dependent constitutive model for polymers – for example, the Mulliken-Boyce model.

QinetiQ –The degradation behaviour of complex hybrid propellants

» **Ruth Tunnell (QinetiQ, PhD student)**
» **William Proud**

Over the past year, my PhD has encompassed four main areas of work which are as follows:

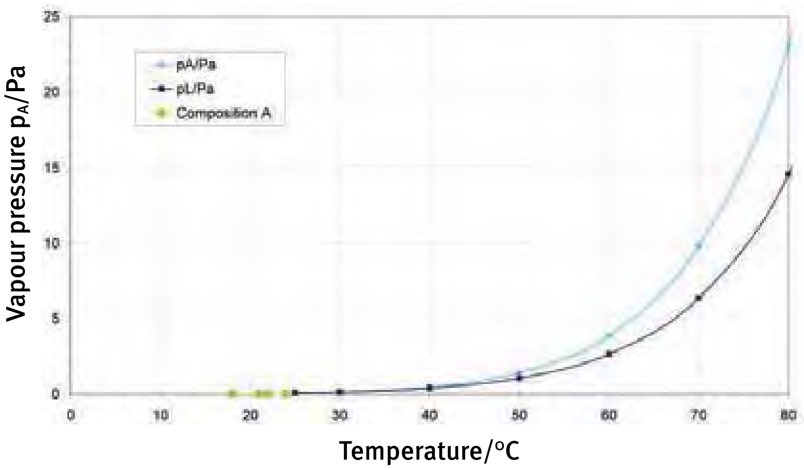
- Understanding the fundamental ageing mechanisms of a particular complex hybrid propellant
- Looking at the effect of ammonium perchlorate with regards to ageing behaviour
- Investigating whether the chemical and mechanical properties of a particular propellant are affected by ageing in an environment where there is limited oxygen and water
- Measuring the process of Nitroglycerine migration from complex hybrid propellants

I have presented the results from all four areas of work at several conferences meetings and conferences:

- The use of Analytical Methods to Understand Complex Hybrid Propellants, presentation to the Institute of Shock Physics Annual Meeting, March 2012. I was also invited to give the same presentation at a meeting at the Diamond Light Source in June 2012
- Measurement of the Vapour Pressure of Nitroglycerine above Propellants, 43rd International Conference of the ICT, Germany, June 2012

Vessel used for vapour pressure measurements.

Nitroglycerine partial pressure, p_A, generated from antoine constants and p_L, langmuir equation vs temperature



Comparison of initial data with literature values.

Defence Science and Technology Laboratory, (Dstl)

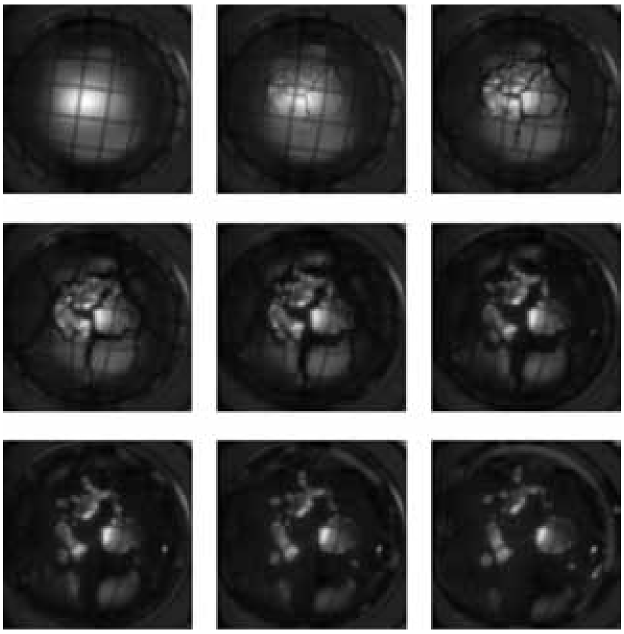
» **Andrew Laing (Dstl, Research Fellow)**
» **Roland Smith**
» **William Proud**

We are delighted that Dr Andrew Laing has chosen to undertake his (Dstl) research scholarship with the ISP. He is currently conducting research into a miniature thermal history sensor that can survive high shock environments.

National Physical Laboratory – Knowledge Transfer Secondment project funded by the Engineering and Physical Sciences Research Council

» Ian Robinson (NPL)
» Andy Knott (NPL)
» Stephen Downes (NPL)
» David Chapman
» Stephen Johnson
» William Proud
» Simon Bland

The National Physical Laboratory (NPL) has recently completed a Knowledge Transfer Secondment (KTS) project where staff from NPL were seconded to the ISP to develop a new facility to investigate the speed of opening of burst diaphragms used to generate shock waves in shock tubes. This study supports on-going research at NPL which is aimed at developing a shock tube-based technique for determining the dynamic response of pressure transducers that are used in applications such as turbine and internal combustion engine development. The new facility consists of a gas-filled cylindrical vessel (equivalent to the 'driver' vessel in a conventional shock tube) that is connected directly to a housing that is capable of holding diaphragms either singly or in a 'double-diaphragm' configuration. The driver vessel is constructed from PVC tubing that has a 76 mm nominal internal diameter and is capable of operating at pressures up to 1.4 MPa. The vessel pressurisation is controlled using solenoid valves and is monitored using a pressure sensor that is connected close to the gas inlet of the vessel.

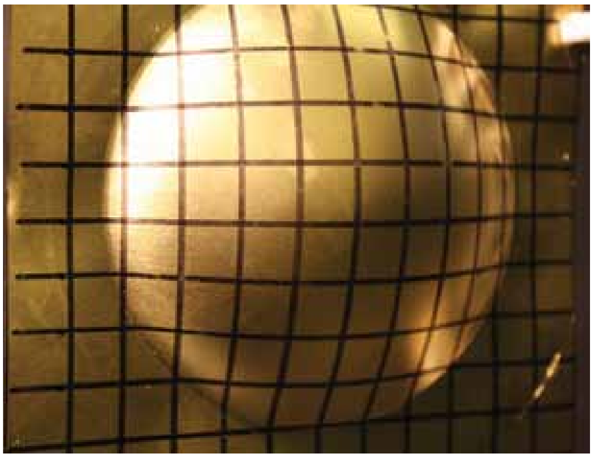


0.025 mm thick brass diaphragm during bursting – the frames were taken at 16.5 μs intervals.

The new facility, which has been built as part of this KTS project, has been used to investigate the bursting characteristics of brass diaphragms similar to those used in the NPL shock tube. The diaphragm material failure 'mode', and the rate at which it opens, may affect the quality and intensity of the generated shock wave and thereby affect the accuracy of the measurement of the dynamic performance of a test sensor. A high-speed camera (a Phantom V7.3) was used to take a series of time-lapsed images of the bursting of diaphragms made from 0.025 mm brass shim material. The figure shows both an un-burst diaphragm (colour) and a sequence of time-resolved images of a diaphragm as it was bursting. The opening time was found to vary from around 160 μs for material that fragmented (as shown in the figure) to around 250 μs for diaphragms that opened by a tearing/ripping process.

NPL and the ISP hope to take this work further by correlating the observed opening times with the downstream events that are experienced by a pressure sensor mounted on the end-wall of the 'driven' vessel in the shock tube. Such a study would include the thicker diaphragms, other diaphragm materials (e.g. aluminium) and different preparation processes (e.g. scored diaphragms) that are needed to generate suitable shock pressures for various industrial applications. It would also be advantageous to add a transparent driven section to the shock tube so that schlieren photographic methods might be used for direct observation of the formation of the shock front.

A 'marked-up' diaphragm that withstood the maximum pressure allowed in the tests with inelastic deformation.



Outreach

One of our primary aims is to educate and inspire the next generation of scientists and engineers in the science of shock waves, ultrafast material phenomena and matter at extreme conditions. We do this through open days, talks and one-to-one discussions with the emphasis very much on accessibility of our staff for open discussion. In the last year, we organised a very successful stand at the Natural Sciences Facilities Showcase and also hosted numerous visits.

About the Atomic Weapons Establishment (AWE)

AWE plc plays a crucial role in the defence of the United Kingdom by providing and maintaining the warheads for the country's nuclear deterrent. It is a centre of scientific and technological excellence, with some of the most advanced research, design and production facilities in the world.

Through our links with industry and institutions such as universities, professional bodies and government agencies, we build upon and share knowledge for mutual benefit.

About Imperial College London

As the only UK university to focus entirely on science, technology, engineering, medicine and business, Imperial College London offers a critical mass of international research expertise and a vibrant home for innovation and enterprise.

Sustained support for research at multidisciplinary centres like the ISP is a sound investment in the UK's economy and in developing the next generation of pioneers, researchers, innovators entrepreneurs in the field.

The ISP acknowledges support and funding from AWE plc and Imperial College London.

ISP partners

The Institute of Shock Physics has a number of partner organisations with which it has Memoranda of Understanding or legal agreements to enable joint working. We also have a number of visiting academics who spend time working in the ISP. Over the next year, we will be moving to a membership model that will welcome many more organisations into our network.

Contact

If you are interested in working with us by carrying out research or providing teaching, funding us, accessing our training programmes or collaborating with our excellent researchers and technical staff, please contact:

Chris Thompson
Programme Director
Email: c.thompson@imperial.ac.uk
Tel: +44(0)20 7594 7396

Ciara Mulholland
Institute Administrator
Email: c.mulholland@imperial.ac.uk
Tel: +44(0)20 7594 1343

www.imperial.ac.uk/shockphysics