NEW DISCOVERY

Showcasing excellence across AWE

AWE

In this issue:

Profiling our people
Sharing knowledge
Inspiring future generations
Cutting-edge expertise
Protecting our borders

Autumn/Winter 2018/19

AWE plays a crucial role in the defence and national security of the UK

If you have any feedback or suggestions for future articles, we would love to hear from you!

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Dame Sue Ion is Honorary President of the UK National Skills Academy for Nuclear. She was Chairman of the UK Nuclear Innovation Research Advisory Board (NIRAB) until March 2017.

She represents the UK on a number of international review and oversight committees for the nuclear sector including the European Union Euratom Science and Technology Committee which she chairs. She is the Chair of the Science Advisory Board for the Canadian National Nuclear Laboratory.

Dr Ion spent 27 years with British Nuclear Fuels Ltd rising to the position of Chief Technology Officer in 1992, a post she held until the company was wound up in 2006.

She was a non-Executive Director on the Board of the Laboratory of the UK Health and Safety Executive from 2006-2014. She has been a member of the ONR's (Office for Nuclear Regulation) Technical Advisory Panel since September 2014.

She is Deputy Chair of the Board of the University of Manchester, on which she has served since 2004, and holds a visiting Professorship at Imperial College London.

Dame Sue writes about the parallels between civil defence and nuclear energy in this edition of *New Discovery.*

The **parallels** between **civil defence** and **nuclear energy**

The UK's journey to becoming a nuclear power in its own right and to being a developer of civil nuclear energy systems began when Clement Attlee's government decided that Britain required the atomic bomb to maintain its position in world politics.

In the early days of atomic energy, as it was called, the then defence mission drove the entire programme, so to have talked about parallels between the defence and civil missions would have been anathema to the pioneers working in the sector at the time.

Astonishing progress was made in a small number of years. William Penney and John Cockcroft returned to the UK after collaborating with the US during WW2 and led the newly established laboratories AWRE and AERE at Aldermaston and Harwell, respectively, and Christopher Hinton was appointed to lead the Industrial Group for Atomic Energy. By 1950 the Windscale piles had been loaded with the first fuel, aluminium clad uranium bars made at the newly developed Springfields works in Lancashire and the first reprocessing plant built at Windscale. Then in 1952 the first UK test took place at Monte Bello off the west coast of Australia.

However, thereafter the civil and defence programmes diverged significantly. The civil programme, enthusiastically driven by Cockcroft, concentrated on the development of large scale economic generation of electricity. The defence programme, having acquired the materials it needed, concentrated on evolving and improving the design of several versions of the deterrent and in later years, developing the well-established programme of validation and verification required to assure the product and its overall system in the absence of the ability to carry out any tests.

Throughout the 1970s and 90s the two nuclear sectors, civil and defence, operated in largely parallel universes with very little in the way of substantive interaction between the two communities at the industrial level but both underpinned in terms of a significant generic science base within what was the UKAEA and the significant university research it contracted. However, the privatisation of the electricity supply industry and the restructure and privatisation of most of the UKAEA in the mid 1990s, led to a catastrophic decline in the research base of both civil industry and the university sector in respect of actinide chemistry and metallurgy/materials science and engineering involving uranium and plutonium.

It was not until the late 1990s that it was realised that a fundamental rethink and regeneration of capacity and capability was essential to the national interest for both civil and defence purposes. Discussions between EPSRC, AWE and what was then BNFL (now the NNL) led to collaborative or synergistic programmes of work which continue to this day, focussed particularly in the area of waste management, where the generic underpinning science was the same, as were the tools and techniques and assessment methodologies.

Whilst based on fundamental analytical techniques that would be familiar to researchers of old, these programmes have seen the development of much more sophisticated and capable detectors and computers.

This is not to say that nothing has changed. We do have quicker, cleaner, more sensitive techniques. For example, the separation of americium isotopes such as Americium-241 has been difficult for many years, due to its tremendous similarity to the Lanthanide elements. However, a new family of extractants developed through collaboration between AWE and the University of Manchester have proven to be very adaptable for analytical scale separations.

Dame Sue says "The fact is fundamental understanding of the metallurgy and materials science of uranium and plutonium, in matters such as clad pick up, oxidation and corrosion and the impact of modern and evolving manufacturing processes amongst others, is essential for the development of advanced Generation IV reactor systems. That is also true for the assurance, validation and verification of the deterrent and common cause in threat reduction means that ongoing interaction between the civil and defence sectors at the basic science level will continue to be important in the years to come."

A further area of recent common interest has been the use of muon tomography. The civil world had been interested for some time in exploring the use of this technology to interrogate the interiors of containers/structures that cannot be probed by more traditional methods (e.g. X-rays) and thus enable the detection of special nuclear material.

"This area of research is an important step in the nuclear industry's efforts to protecting our borders and keeping our country safe"

Dr Dame Sue Ion FREng FRS

Working together to improve skills

AWE is leading the way in connecting with schools through educational charities like the Education Business Partnerships (EBP) and Basingstoke Consortium, to create a greater impact in helping improve students' skills.

We support pupils from a young age – as evidence has shown that early interventions are a cost-effective way to raise young people's aspirations and help develop a future pipeline.

In Basingstoke, AWE works with Basingstoke Consortium, who are leaders in their field, to ensure that we are providing the right encounters at the right time to young people. Basingstoke Consortium provides us with opportunities to proactively connect young people to the world of work through business by educating, inspiring and preparing them for the future.

CEO of Basingstoke Consortium and EBP South, Cath Longhurst, says, "It is important that young people are inspired by businesses like AWE into different careers to allow them to make informed decisions about options, career paths to ensure they are choosing the right subjects and gaining the skills needed by industry. We need to make the variety of occupations more visible so that young people know about them and can aspire to them.

"Opportunities provided by us include attending large interactive events like TeenTech – an annual event in which AWE takes part – which aims to educate young people about careers in STEM (science, technology, engineering and maths). It is important that AWE attends these events, as by the age of 15-16 one third of their career interests lie in just 10 occupations."

"We value our long-standing partnership with the Basingstoke Consortium not only through TeenTech, but also through other outreach events as we share the same vital goal – which is about inspiring future generations of scientists and engineers"

Philippa Kent
AWE community engagement manager

Courtesy of the Basingstoke Consortium

Collaborating with our international partners

Our international partnerships are a vital aspect of AWE's exchanges and obligations on matters relating to nuclear treaties.

Established in 1995, the International Liaison Office (ILO) is central to AWE's work on facilitating international exchanges and providing advice to MOD, and other UK government departments, relating to international treaties.

The 1958 US-UK Mutual Defence Agreement represents the majority of our interactions, through which the well-established Joint Working Groups (JOWOGs) and other exchanges take place – involving the US nuclear laboratories and plants.

The agreement enables cooperation between the two countries in the fields of nuclear weapon technology, nuclear propulsion and nuclear threat reduction – for mutual benefit.

AWE head of international relations, Gareth Price, says, "Not only does the ILO give advice and guidance to our main partners – the US and France – we also provide support when undertaking exchanges with countries such as Australia, New Zealand and Canada."

"Our collaboration with France falls under a treaty between the British and French Governments, signed in 2010, referring to Teutates, a project concerning joint radiographic facilities – EPURE in France and the Technology Development Centre at AWE.

"The scope of the ILO is vast and ever-evolving as our international collaborations continue to grow for the benefit of supporting the UK nuclear deterrent now and in the future – and keeping our country safe," says Gareth.

Profiling our people

Ed

Head of the Programme Management Office

I've got a great job! I help safeguard the UK while working with remarkable people, in unique facilities, on extraordinary and complex products. Coming to work is easy! It's about working hard, learning lots and – critically for me – making a difference. I get to deliver the programme that provides a central role in national defence, through cutting-edge expertise, inspiring stars of the future and working with international partners. And I do all this by leading the Programme Management Office (PMO) at AWE.

Running the PMO provides a unique perspective of AWE's business and operations. We get to interface with all parts of the work we deliver and it affords me an oversight of the whole organisation. This includes our expert scientists and engineers; maintenance of critical nuclear facilities; once-in-a-generation infrastructure projects; a nuclear threat reduction programme; and the leadership that binds it all together.

We have three primary roles within the PMO

1 **Oversee the delivery and management of the contracted scope of work. This has to be done within a fixed budget, a challenging programme and high expectations across the business**

2 **Plan future years of the programme. This is the exciting bit, as we're moving into a new era with new capabilities and a modern infrastructure**

3 **Report performance. We provide a critical role in updating our stakeholders on how we are progressing and where we need help; our key stakeholders include the Executive team, our shareholders and the MOD**

So how did I get here?

If you're expecting me to say it's a result of meticulous planning in striving for a clearly defined objective it's not. But it's not luck either. The conventional A-Levels took me on to study aerospace engineering at the University of Manchester. From there I landed a job in the Defence Evaluation and Research Agency working on lethality and complex weapons, and the vulnerability of UK air platforms. Through the privatisation of QinetiQ I gained more experience of Weapon System Integration, and in the early 2000s I started working on strategic systems. Firstly supporting the 2006 deterrent white paper and then working at the MOD (in DE&S) on the newly formed Future Submarine Integrated Project Team.

As AWE was thinking about the future I supported the systems engineering team in options studies, eventually taking a role in that area. Following that I worked in strategy development and then as a technical adviser to our CEO, Iain Coucher.

Although I've actually only worked for two companies (QinetiQ for 11 years and AWE for nearly seven), I've been lucky enough to have a range of jobs where I've gained experience in technical, programme and business disciplines. I also completed an MBA through the Open University, and am a Fellow of the Royal Aeronautical Society.

None of my career has been planned – but I have taken opportunities as they have presented themselves. The decisions I've made are based on my values and a small set of criteria. I started with the obvious ones: work in jobs where you can make a difference, work hard in doing that role, and learn lots while doing it.

But it's more than that. We spend too much time at work, at a personal level it mustn't be a chore. There are hundreds of studies that show happier people are healthier; having fun improves communication and it breeds creativity amongst a number of other benefits.

Every day I learn something new in the PMO helped by a dynamic and vibrant environment. I'm incredibly fortunate to be surrounded by dedicated and knowledgeable people who also enjoy a sense of fun and camaraderie. We need this to deliver our commitment to the UK's national defence programme now and in the future.

Historical Insights

Hand in hand: AWE and Polaris

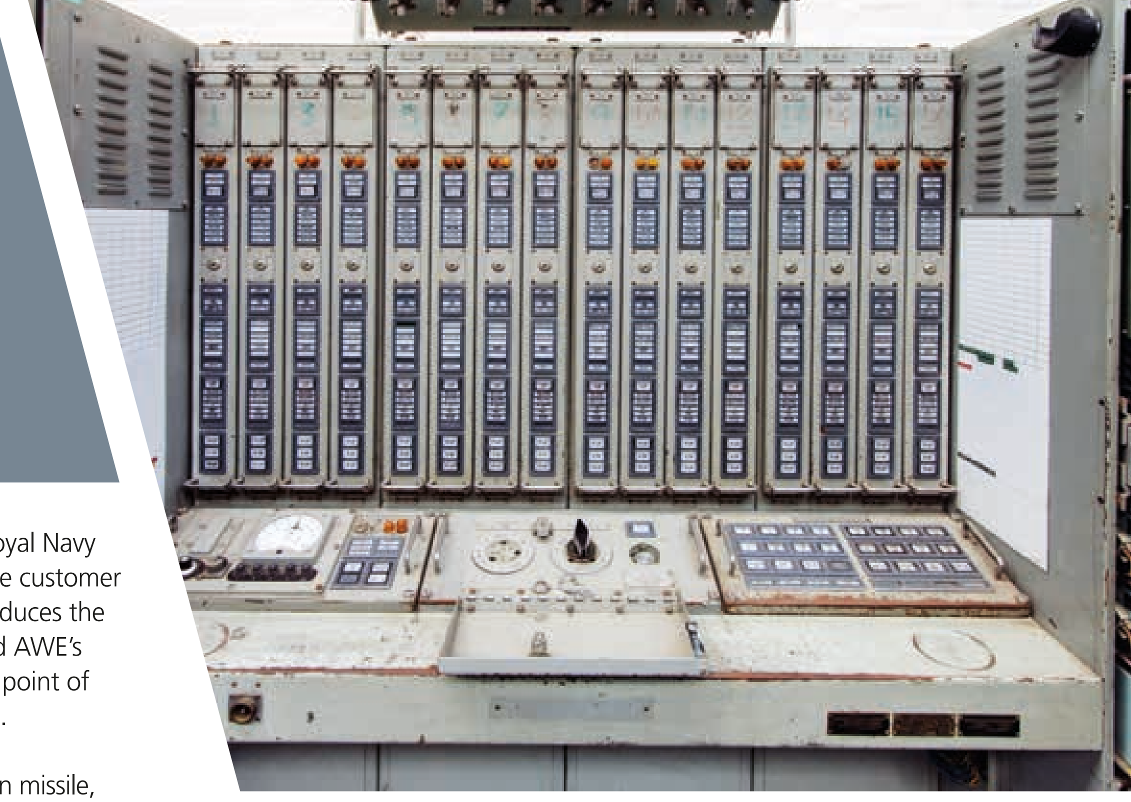
Polaris was the Royal Navy's first submarine-launched nuclear ballistic missile system and it entered service 50 years ago, in June 1968, when HMS Resolution embarked on her first deterrent patrol. Previously, British strategic nuclear weapons had been carried by manned bomber aircraft, and formal responsibility for the deterrent passed from the Royal Air Force to the Navy a year later when the second of four Polaris submarines became available and a continuous series of patrols could begin.

Secretary of State for Defence Denis Healey made a low-key announcement in the House of Commons:

> **Responsibility for the United Kingdom's contribution to NATO's strategic nuclear deterrent forces was transferred from the Royal Air Force to the Royal Navy on 30th June 1969… I should like to pay tribute to the way in which the officers and men concerned at all levels in the Royal Air Force have discharged their responsibilities for the last 12 years, and to express full confidence in their successors in the Royal Navy.[1]**

AWE's predecessors at Aldermaston, Burghfield and Coulport played important parts in the Polaris programme, designing, manufacturing, fitting and maintaining warheads and re-entry vehicles. The Resolution class submarines continued to provide Britain's deterrent until the 1990s, when they handed over to the current Vanguard class, armed with Trident missiles. The Royal Navy remains AWE's frontline customer today. This article introduces the Polaris programme and AWE's contribution up to the point of Resolution's first patrol.

Demonstration and Shake-down (DASO) launch of a Polaris missile from HMS Revenge, 1983
Photo: US Navy



Polaris was an American missile, originally designed and built by Lockheed for the US Navy. Under Chief of Naval Operations Admiral Arleigh A Burke, the US Navy conceived Polaris in the 1950s as a retaliatory, 'second-strike' system. Burke's idea was that, instead of having to build more and more bombers and defend their bases at prodigious cost, the United States should deploy a deterrent force under the ocean where it couldn't be found. Polaris came to be seen as the best guarantee of a minimum – but nevertheless unacceptable – level of damage to the USSR in retaliation for any attack on the US.

To drive Polaris delivery, Burke created a Special Projects Office (SPO) and put Admiral William F Raborn in charge. Raborn was passionate and single-minded, and he carried Burke's so-called 'hunting licence.' This was the sort of document project and programme managers dream of: "if Admiral Raborn runs into any difficulty with which I can help, I will want to know about it at once… if more money is needed, we will get it. If he needs more people, these people will be ordered in."[2]

Success came because Polaris had a unique strategic role; the US Navy won over potential critics, such as the head of the nuclear propulsion programme, Admiral Rickover; they introduced new technology incrementally, and ruthlessly prioritised programme schedule; and they cleverly introduced and used new programme-management tools. The 'hunting licence' also helped. Above all, "the Polaris was devised and built by true believers."[3]

The British Admiralty knew about Polaris all along, and First Sea Lord Admiral of the Fleet Lord Mountbatten was a particular enthusiast, keeping up a long correspondence on the subject with Burke. Other Royal Navy officers were much more cautious, fearing that a British Polaris programme would be controversial and expensive, and draw resources away from higher priorities, especially aircraft carriers and hunter-killer nuclear submarines.[4]

In December 1962, however, external events forced the Navy to put aside its scepticism. President Kennedy cancelled the American air-launched ballistic missile Skybolt, which British politicians had been counting on to arm the RAF's strategic bombers in future. Prime Minister Harold Macmillan was in trouble over Skybolt as he flew to Nassau, the capital of the Bahamas, for a scheduled meeting with Kennedy.

The Nassau meeting was quite a drama; indeed, Macmillan made sure that it was. Eventually Kennedy agreed to offer Polaris missiles in place of Skybolt. They would be fitted with British warheads, carried on British submarines, and assigned to NATO "for the purposes

1. House of Commons debates, written answers 3 July 1969, vol. 786, col. 136

2. Harvey Sapolsky, The Polaris system development: bureaucratic and programmatic success in government (Harvard UP 1972), p. 36; Graham Spinardi, From Polaris to Trident: the development of US Fleet Ballistic Missile technology (Cambridge UP 1994), p. 25
3. Sapolsky, The Polaris system development, p. 159
4. Richard Moore, The Royal Navy and nuclear weapons (Frank Cass 2001), ch. 5

of international defence of the western alliance in all circumstances, except where Her Majesty's government may decide that supreme national interests are at stake".[5] This remains the basis on which Trident missiles are made available by the US to the UK today.

At the Atomic Weapons Research Establishment (AWRE) at Aldermaston, options were suddenly needed for a Polaris warhead. Some information on the US Mk.47 warhead, used on the original Polaris A-1 missile, had been made available to AWRE in 1958 during the earliest discussions under the new US-UK Mutual Defence Agreement or MDA. Four years later, however, new versions of the missile were being developed. John Challens, AWRE's chief of warhead development, led a visit to the Livermore laboratory in California to find out more about the associated warheads.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A larger UK technical mission was sent to the US in March 1963 to look specifically at Polaris A-2 and A-3. Leslie Williams of the Ministry of Aviation or MOA (essentially what is now the MOD Defence Equipment and Support organisation) led this team, and Challens represented AWRE. A-3 was effectively a new generation missile: bigger, longer-range, with improved guidance and now not just one warhead in one re-entry vehicle but a re-entry system of three warheads, in three re-entry vehicles of a new, smaller design. A-3 was unproved: test flights had only begun in August 1962 and eight of the 10 so far, including one witnessed by Williams and Challens at Cape Canaveral during their visit, had been problematic.

A detailed Polaris Sales Agreement (PSA) was drawn up and signed in April 1963. The US negotiating team was headed by the US Navy's Judge Advocate General, Admiral William C Mott, a highly trained patent lawyer, and included many staff from SPO. The UK Admiralty also fielded a strong team including RAdm Hugh 'Rufus' Mackenzie, whose job it was going to be to set up a Polaris Executive organisation, equivalent to SPO, in the UK.

SPO was anxious to maintain the greatest possible commonality between the US and UK Polaris systems, to maximise UK procurement from US companies, and to have its advice on quality and reliability accepted and not questioned by the UK. This was for good professional reasons: SPO wished to preserve its own delivery reputation and to protect US commercial interests and intellectual property. The UK team readily agreed that "identicality was one of the keys to a speedy transfer of information and assistance" and that this consideration outweighed dollar savings or any other, less tangible advantages of home-produced or UK-unique equipment.[6] Thus the PSA envisaged the sale of a system as close as possible to that of the US Navy, meaning for example the same number of missiles in each submarine, and the same navigation, fire control and other systems. A 5% levy on the purchase price was agreed to cover US research and development costs.


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A Royal Navy officer in the MOA, RAdm Frederick Dossor, was made responsible for the warhead and re-entry vehicle to Mackenzie as Chief of the Polaris Executive, and a US-UK Joint Re-entry Systems Working Group (JRSWG) was set up to manage missile/warhead interface issues.

AWRE worked on the warhead with the US Atomic Energy Commission and US laboratories under MDA auspices. As with any complex organisational arrangement, this appears to have worked well as long as the personnel involved were sympathetic to each other's concerns. As Mackenzie took the trouble to make clear, in drafting terms of reference for the JRSWG, his concerns were "the timescale of the British [naval ballistic missile] programme… [and] the basic philosophy of making only essential alterations from a current US system."[7]

Ministers decided in June 1963 to buy the A-3 missile and re-entry system, in line with this philosophy. The US Navy would be keeping it in service for longer and so commonality would be preserved for longer. AWRE was therefore initially directed to produce a close copy of the planned US warhead, the Mk.58. Variations from this design would be allowed only for clear safety or reliability reasons, or if manufacturing difficulties would be such as to threaten programme delivery dates.

Over the course of the next nine months, as it turned out, clear reasons to vary the warhead design

5. Joint statement on nuclear defence systems, 21 Dec 1962 (online at http://www.presidency.ucsb.edu/ws/index.php?pid=9063)
6. Peter Nailor, The Nassau connection: the organisation and management of the British Polaris project (HMSO 1988), p. 16.

7. Undated (Apr 1963) draft, Mackenzie to Adm Galantin USN (AWE archive document)

did emerge. In early 1964, a case was made to the Secretary of State for Defence, Peter Thorneycroft, that a warhead incorporating important elements of British design should be used, instead of a close copy of the Mk.58. Thorneycroft agreed, and this warhead design, known to AWRE as Reggie and to the MOA as ET317, was used on the UK Polaris missile in service. It is a tribute to the people involved, including still John Challens at AWRE, that this new warhead decision was made without particular controversy and without threatening the overall programme timescale. UK Polaris warheads and re-entry vehicles were delivered on time from the Royal Ordnance Factory at Burghfield for HMS Resolution's first patrol.

The Royal Navy Armament Depot at Coulport along with new shore facilities at the nearby Faslane naval base and elsewhere in the UK, formed another important part of the Polaris programme.[8]

Work on a Polaris armament depot was helped considerably by the US Navy which shared information, layouts and drawings of the equivalent facilities at Charleston, South Carolina and Bangor, Washington. Building requirements were submitted to the Ministry of Works by August 1963 and work started in earnest about a year later. By spring 1966, permanent staff were stationed in a former private house just outside the depot perimeter and recruitment of local staff, many of them shipped and bussed in daily from the south bank of the Clyde, started in earnest. Bunkers were needed for storing missiles and warheads; and workshops for fitting re-entry vehicles and electronics to missiles before loading on board. Sophisticated test facilities were also created, for example to X-ray rocket motors and monitor delicate guidance equipment.

Work at Coulport was always made difficult by poor access roads and hard ground, and in January 1968 hurricane-force winds damaged the new missile guidance test building and other facilities and left Coulport inaccessible for several days. Nevertheless HMS Resolution sailed on time, under Cdr Michael Henry RN, for her first Demonstration and Shake-down or DASO missile firing in February 1968, and later her first patrol.[9] To the Royal Navy's great credit, Mackenzie's Polaris Executive, like its role model SPO in the United States, had delivered the Polaris programme on time, cost and quality. Aldermaston, Burghfield and Coulport, among many other organisations in the UK, had played their parts well.

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In future editions of *New Discovery*, we intend to cover the operation of the Polaris system and life on board, and the major role AWRE played in the Chevaline upgrade programme, which kept Polaris credible into the 1990s.

8. Andrew McLeod, 'The Royal Naval Armament Depot', in Capt John Moore RN, ed., The impact of Polaris: the origins of Britain's seaborne nuclear deterrent (Richard Netherwood 1999), ch. 28
9. Cdr Michael Henry RN, 'A CO's story', in Moore, ed., The impact of Polaris, ch. 34

Handing over the gavel

After chairing AWE's Warhead Safety Committee (WSC) for many years, Jim West MBE has finally passed over the gavel to his successor Graham Hughes.

The WSC provides independent advice to AWE's projects and to the Executive on all aspects of nuclear warhead safety. It also advises the Defence Nuclear Organisation, and in particular the Nuclear Weapon Approving Authority, on warhead design, which relates to operational usage across the lifecycle phases of the UK nuclear enterprise.

Membership of the WSC is composed of subject matter experts from across the company together with external independent members. The WSC works closely with the AWE Nuclear Safety Committee, which deals with facility and operational safety. Both committees provide oversight of our nuclear deterrent responsibilities.

Reflecting fondly on his time as chairman, Jim says, "It has been a privilege to work with the members and technical specialists on many detailed aspects of our nuclear warhead designs, making sure that AWE's projects meet the stringent safety requirements of the MOD and regulators."

Although the business of the committee has often been complex and serious, Jim has always tried to maintain a sense of pragmatism and informality, trying his best to put presenters at ease. The gavel became a symbol of his chairmanship in keeping order, but stopping short of using it for actual physical reprimand!

Jim intends to continue to use his vast experience as member of various committees to provide insight into nuclear safety matters across AWE and the MOD.

Good luck and best wishes to Graham in his tenure of looking after a committee that first sat in 1958!

Making an 'explosive' connection

AWE explosives modelling experts, Nick Whitworth and Caroline Handley, gave a tutorial to an international delegation at Dstl Porton Down, as part of sharing knowledge in the area of explosives modelling and simulation, to support UK nuclear deterrence.

The tutorial centred on understanding and using CREST, a model developed by AWE scientists for use in hydrocode simulations. CREST is a reactive burn model that is capable of reproducing a range of shock initiation and detonation behaviour in explosives. This is achieved by using a reaction rate that depends on a function of entropy rather than pressure. Owing to the importance of this technique, the tutorial attracted leading numerical simulation engineers from the US Army, Navy and Airforce laboratories, who see the UK as an important collaborator in the field of energetics simulation.

Caroline says, "We are pleased to have been given this opportunity to teach staff at Dstl and the US Department of Defense laboratories about the CREST model. They are keen to use CREST in hydrocodes provided by the US Department of Energy (DOE) laboratories. The tutorial will undoubtedly be useful in our future interactions with the DOE labs."

The course was organised by Bob Dorgan from the US Air Force Research Laboratory (AFRL) Eglin, who has been based in the UK since July 2017. He has spent over a year seconded to the structural dynamics team at Dstl, before he is due to join AWE in the near future for a secondment, to focus on explosives modelling.

"We look forward to welcoming Bob to our team to help develop and apply CREST to various applications."

Caroline Handley
AWE explosives modelling expert

Courtesy of Dstl

The future looks bright for high pressure experiments

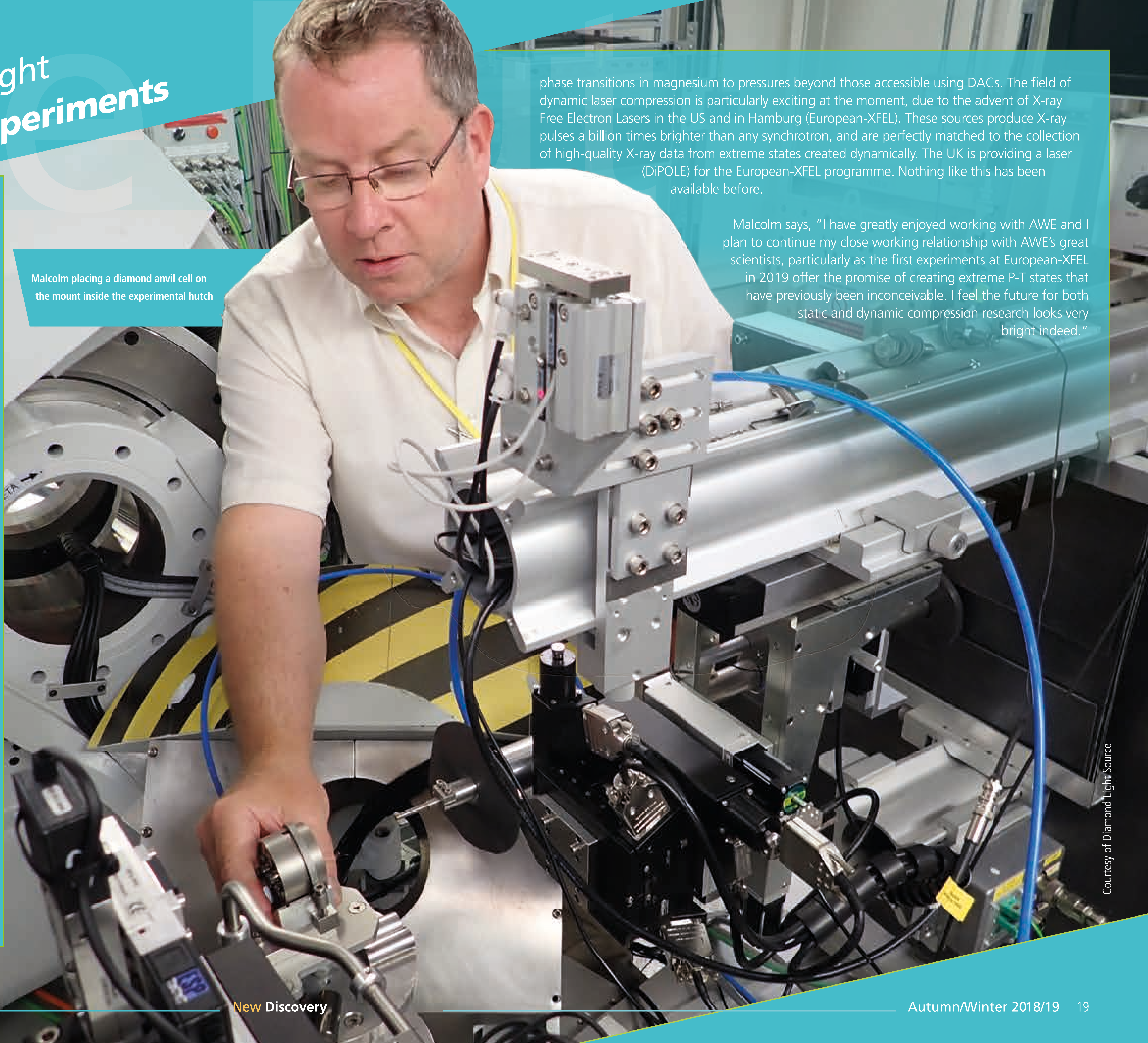
The behaviour of matter at extremes of pressure and temperature is of great interest and significance to AWE scientists, to support our understanding of the UK's nuclear deterrent – as well as to those who specialise in diverse areas such as planetary interiors or biological organisms.

Such material states can either be created statically, where microscopic samples are compressed in a diamond anvil cell (DAC), or dynamically, where extreme states can be generated for nanosecond durations by irradiating samples with intense laser pulses. The crystal structures of the compressed materials can then be studied by illuminating them with X-rays, either from a synchrotron or from a short-lived plasma X-ray source created via a pulsed laser.

Malcolm McMahon is professor of high pressure physics in the School of Physics and Astronomy at the University of Edinburgh, and has been a William Penney Fellow (WPF) since 2012. Prior to starting his fellowship he specialised in combining DACs with X-rays to investigate the structural behaviour of elements. He has continued this work in collaboration with AWE. One particular highlight is the uncovering of previously unknown structural relationships for the lanthanide elements that are relevant to the actinide series of metals. Much of this research has been conducted at the Diamond Light Source synchrotron facility in the UK. Most recently, Malcolm was awarded UK funding to extend DAC studies to higher pressures using "sculpted" DACs.

Malcolm has also used his fellowship to extend his research into the use of dynamic compression, using AWE's Orion laser, and the Omega and NIF lasers in the US. A recent campaign at NIF has studied the phase transitions in magnesium to pressures beyond those accessible using DACs. The field of dynamic laser compression is particularly exciting at the moment, due to the advent of X-ray Free Electron Lasers in the US and in Hamburg (European-XFEL). These sources produce X-ray pulses a billion times brighter than any synchrotron, and are perfectly matched to the collection of high-quality X-ray data from extreme states created dynamically. The UK is providing a laser (DiPOLE) for the European-XFEL programme. Nothing like this has been available before.

Malcolm says, "I have greatly enjoyed working with AWE and I plan to continue my close working relationship with AWE's great scientists, particularly as the first experiments at European-XFEL in 2019 offer the promise of creating extreme P-T states that have previously been inconceivable. I feel the future for both static and dynamic compression research looks very bright indeed."



Malcolm placing a diamond anvil cell on the mount inside the experimental hutch

Courtesy of Diamond Light Source

It's a noisy business

The Comprehensive Test Ban Treaty (CTBT) verification process utilises a number of technologies to detect covert nuclear weapons explosions, should they occur, around the world.

Such an explosion leaves a number of traces by virtue of the energy released (such as seismic, infrasound, hydro-acoustic and radionuclide). The CTBT verification process attempts to detect these signatures by different means, and then determine important details about it, such as location and magnitude.

A typical explosion releases mechanical energy by effectively "pushing" the air around it, or the ground below. In the atmosphere, this initially creates a shock front (pressure discontinuity) close to the source. The shock front dissipates as it moves away from the source, eventually reducing in amplitude and steepness to produce linear, acoustic (sound) waves if the explosion released enough energy initially.

Owing to the changes in atmospheric temperature with altitude, linear sound waves curve upwards into the atmosphere. This curvature, known as refraction, causes the sound propagation path to pass through atmospheric regions where "high" frequency components are rapidly absorbed, leaving the low frequency "infrasonic" components to propagate onwards. This refraction means that it is not a simple matter to state whether a signal will be received at a given station. This gives rise to the counter intuitive notion that you could be standing relatively near to an explosion, but not hear it.

By infrasound, we mean sound waves with frequencies typically in the range 0.1-10 Hz, which are generally inaudible to us. At ground level, these waves have wavelengths as long as 3.5 km, and because of this, they are not usually disturbed by geographical features and, due to the atmospheric conditions, will often propagate for thousands of kilometers. The first recorded observation of naturally occurring infrasound was from the enormous eruption of Krakatoa in 1883. Infrasonic waves, produced by the volcanic explosion, circled the globe several times, broke windows that were hundreds of miles away from the volcano, and were recorded worldwide.

There are almost 60 Comprehensive Test Ban Treaty Organisation infrasound monitoring stations worldwide, and at each one will be an array of precision micro-barometers (pressure detectors). Each micro-barometer is connected to a wind reduction mechanism that ensures that short wavelength noise from wind does not pass through to the detector.

Until recently, AWE did not have the capability to tell, in detail, whether a given monitoring station would receive a signal from a source at a known location. Such information is critical in deciding where such monitoring stations should be placed to best capture signals from sources at any location in the world.

Recent research at AWE into atmospheric infrasound propagation has added to existing analysis technologies, with the aim of providing higher fidelity information when combined with other technologies. This work has enabled the development of a suite of computer codes, aptly and collectively named 'NOISE' (or the **N**ormal m**O**de **I**nfrasound **S**olv**E**r), which reflects the mathematical method (commonly known as the normal mode method) by which the sound propagation is calculated.

Although still in a state of development, this suite of codes can already make predictions of signal responses, from a given source with a known yield, at a given detector station (see Figures 1 and 2). These calculations also reveal the complex nature of sound refraction in the atmosphere (see Figures 3 and 4), which is further complicated by non-linear effects in the thermosphere (between 90 km and 500 km), and the interaction of slow moving atmospheric gravity waves (propagated by the buoyancy of the air) with infrasound propagation (see Figures 5 and 6). The asymmetric effects of the background wind can be seen in Figure 7. AWE applied mathematician, Pete Spence, says "This work is challenging, but very rewarding in many ways. Almost everyday is an opportunity to learn!"

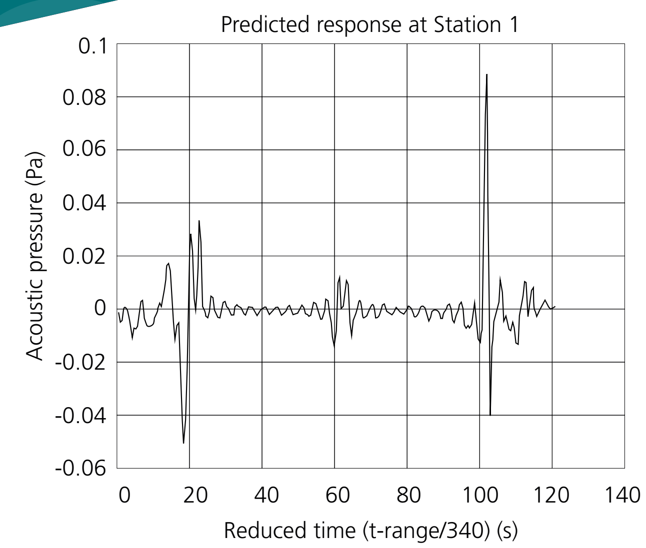


Figure 1. Predicted detector response at detector Station 1 from a large explosion centred 75 km away. The predicted pressure is very low, indicating that this signal would be barely visible. Reduced time is the actual time minus the time taken for the signal to reach the station, if it had not refracted (i.e. as if it has travelled the shortest path to the station)

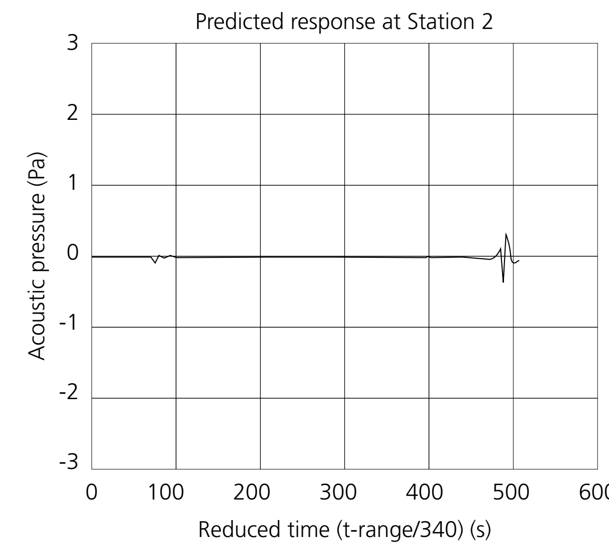


Figure 2. Predicted detector response at detector Station 2, which is 320 km from the same explosion, and inclined at a different angle to the source location. The predicted signal magnitude is higher, but the signals appear to be much smoother. This is due to the sound having travelled high into the atmosphere and back to ground, with higher frequency components absorbed. Real signals are noisier than this

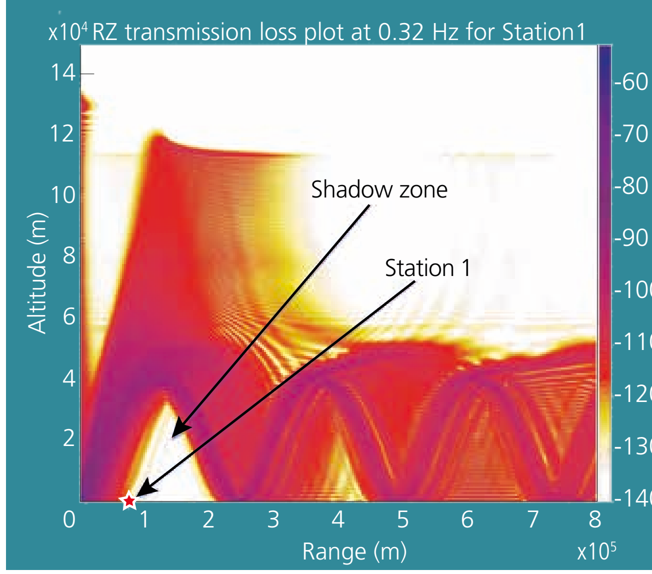


Figure 3. A corresponding plot to Figure 1 showing the transmission loss (a logarithmic measure of drop in sound pressure from source) as a function of distance from the source and altitude, for a single frequency (0.32 Hz – the highest magnitude component in the predicted blast wave spectrum) in the frequency domain. The patterns reveal propagation paths and are formed by the complex nature of the atmospheric refraction. The small red star to the bottom left represents Station 1, relative to the source (located at zero), and clearly shows that it is situated in a shadow zone, hence the low pressures in Figure 1

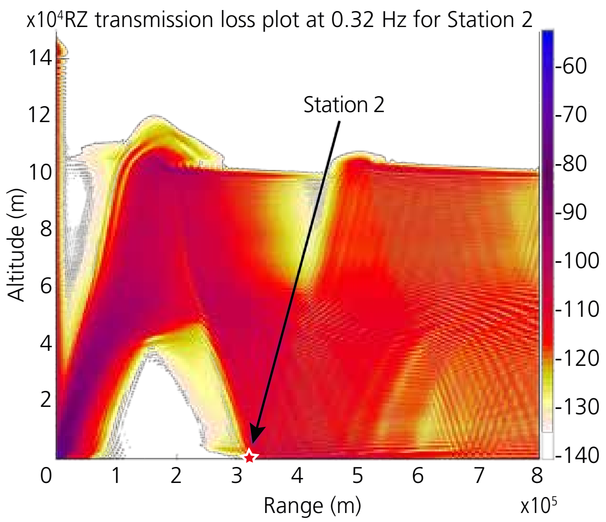


Figure 4. A corresponding plot to Figure 2 showing the transmission loss as a function of distance from the source and altitude, for a single frequency in the frequency domain. The detector location (small red star) represents Station 2, relative to the source (located at zero), and clearly shows that Station 2 is likely to receive a signal, hence the higher pressures than in Figure 1

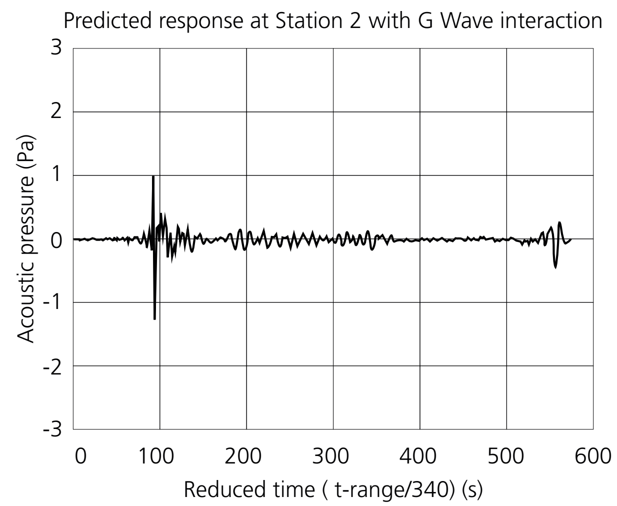


Figure 5. Predicted detector response at Station 2 from the same explosion, but with the effects of atmospheric gravity waves included. The presence of gravity waves causes multiple reflections from layers in the atmosphere giving rise to a more realistic signal

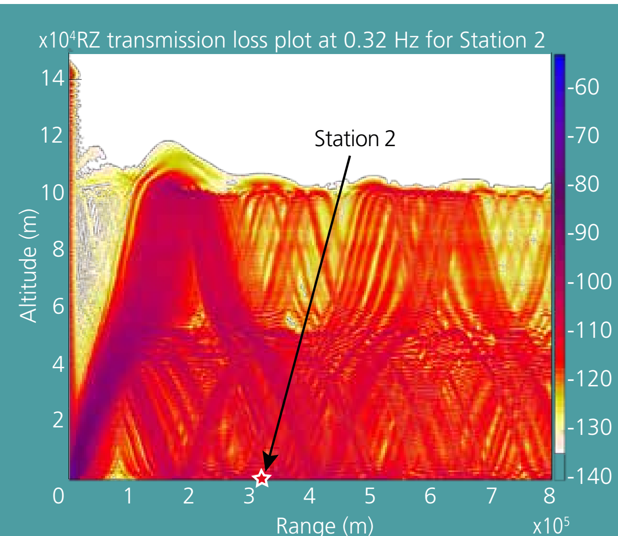


Figure 6. A corresponding plot to Figure 5 showing the transmission loss for the frequency 0.32 Hz, but including the effects of atmospheric gravity waves. The structure is more complex than in Figure 4, and gives rise to the more complex signal in Figure 5

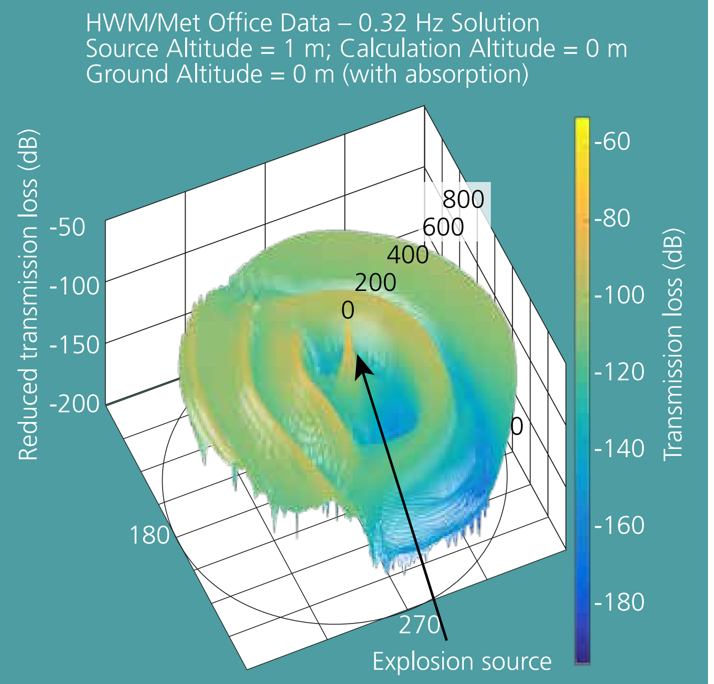


Figure 7. A representation of the transmission loss with direction at ground, for an explosive source located at the centre of the picture. The asymmetry is caused by the asymmetric wind in the atmosphere. The deep troughs are the shadow zones

Systems thinking: thinking outside the box

AWE recognises the importance of systems thinking and is investing in this area across the company to support our mission in national defence and security.

It's not just for engineers

There are two commonly encountered myths about systems thinking: that it is new idea and that it is only for systems engineers.

Systems thinking is not a new concept. The foundational ideas have long been advocated by such notable minds as The Buddha, Leonardo da Vinci, Aldous Huxley and Albert Einstein, to name but a few. The decision, therefore, that AWE will be promoting systems thinking across the enterprise was a natural development from its desire to continuously improve systems engineering within the organisation. Unlike the technically focused skills for systems engineering, those required for systems thinking are widely held and beneficial in all aspects of modern life.

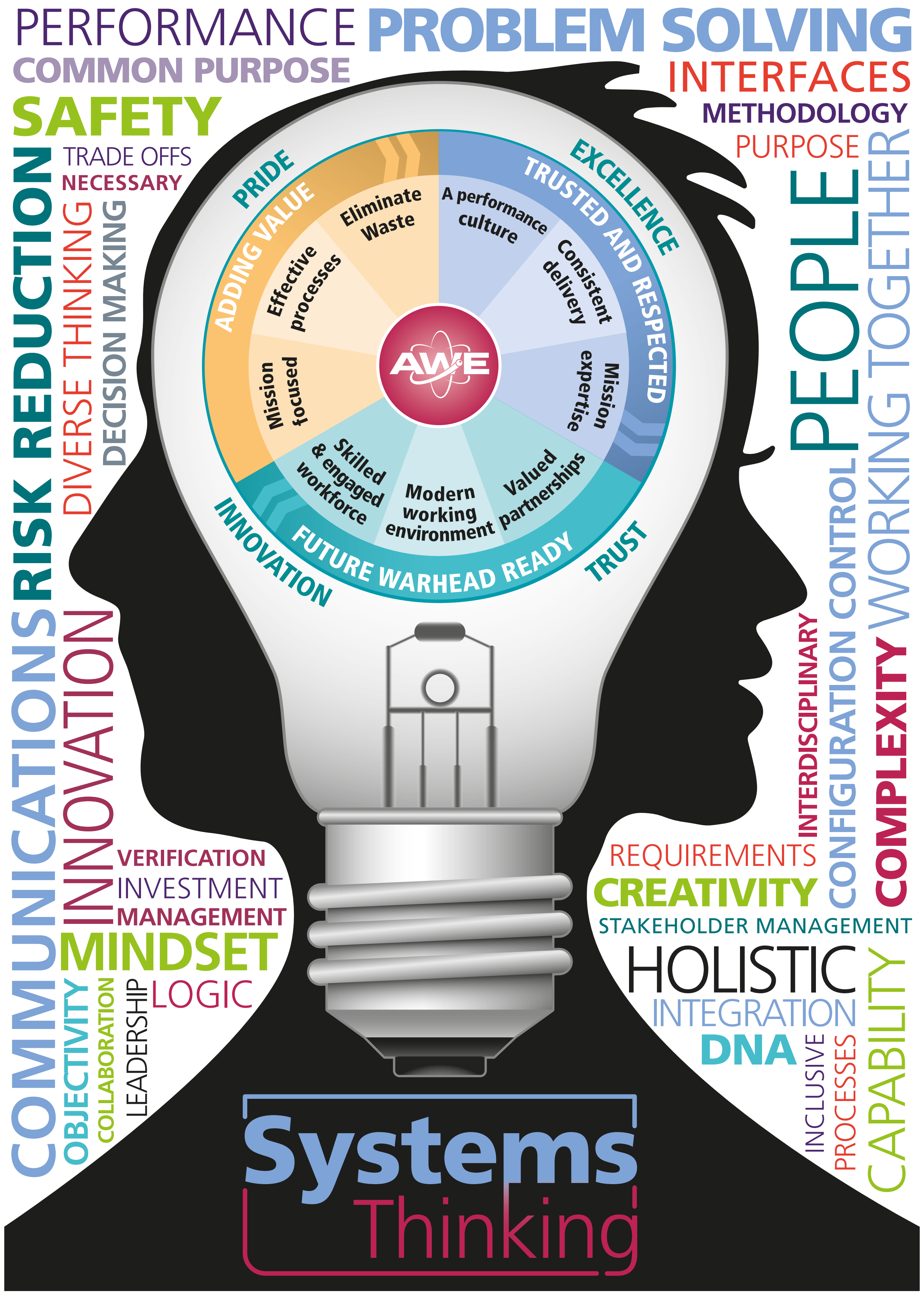
The team who organised the AWE Family Day, held in September 2017, used systems thinking to successfully deliver this event to over 4000 visitors. This was an example of systems thinking in a non-engineering domain. The application of many of the habits of a systems thinker such as 'changes perspective to increase understanding' and 'considers how mental models affect current reality and the future' were pivotal in dealing with multiple stakeholders and issues.

Most highly successful individuals are natural systems thinkers. They consider not just the problem in front of them, but also the context of the problem and the impact of potential solutions. In doing so, they identify potential 'curve balls' or pitfalls that are likely to occur as they work through their problem and are able to take mitigating action in advance, thereby saving time, money, effort and/or frustration. At AWE, we draw on a strong network of support for this activity. We are promoting close ties with both Lockheed Martin and the International Council of Systems Engineering to ensure that we have the best possible approach to propagating systems thinking behaviours across the enterprise.

Spreading the word

AWE head of profession for systems engineering, Cliff Cheesman, together with the systems thinking team, led by Gary Vonderlinden – a Lockheed Martin secondee – have been running workshops across AWE.

The workshops are focussed on raising awareness of systems thinking principles through interactive exercises designed to bring out the 'systems thinkers' in all of us. It starts with the acknowledgement that your perception of any system will differ dependent on your point of view – through working on changing your perspective – to ensure that all aspects of a



system are considered before tackling a problem.

Cliff says, "The question that the team had was how to embed this mindset in the organisation. AWE has adopted Prosci's five-step model to establish and embed change: ADKAR (Awareness, Desire, Knowledge, Ability, and Reinforcement).

"We therefore needed an offering that would appeal broadly, raise awareness and create desire in the business for a systems thinking approach.

"It was at this point that we came across the '14 Habits of a Systems Thinker' developed by the Waters Foundation – an organisation dedicated to systems thinking education, especially for schoolchildren. It wasn't difficult for our team to design a course around this and the result was the Systems Thinking Workshop (STW). We have now delivered over 35 STWs and have enjoyed the company of over 625 AWE staff. I have been fortunate to facilitate the majority of these sessions and have gained immense pleasure and pride from them. It's great to see how engaged people are with the ideals of systems thinking and I learn so much from the variety of perspectives on offer."

"I believe systems thinking is essential to deliver AWE's mission to the appropriate standard of quality, on time and on budget. Essentially it is a means to improve communication and enhance collaborative working and understanding"

Dave Chambers
AWE director, science, engineering and technology

Flash X-ray radiography: can lasers improve our image quality?

Hydrodynamic experiments at AWE are used to provide data on the properties of thick, dense materials subjected to high strain rates via extreme temperatures and pressures. These experiments help us to understand the safety, performance and reliability of nuclear warheads.

High energy flash X-ray radiography is used to diagnose these challenging and unique experiments (**see figure 1**). Current techniques employ giant high-energy pulsed power X-ray machines, developed by AWE for this specific application (**see figure 2**). These flash X-ray sources exhibit very high X-ray doses (one million times the dose received from a standard dental X-ray) in a single pulse of less than one millionth of a second.

An intense X-ray beam of very short duration is used to penetrate the explosively driven thick, dense object, freezing the motion of the dynamic object of interest to produce a snapshot in time of the material behaviour. The quality of the radiographic image obtained is dependent upon the X-ray machine dose, spot size and energy spectrum as well as the motion blur produced by the rapidly moving object.

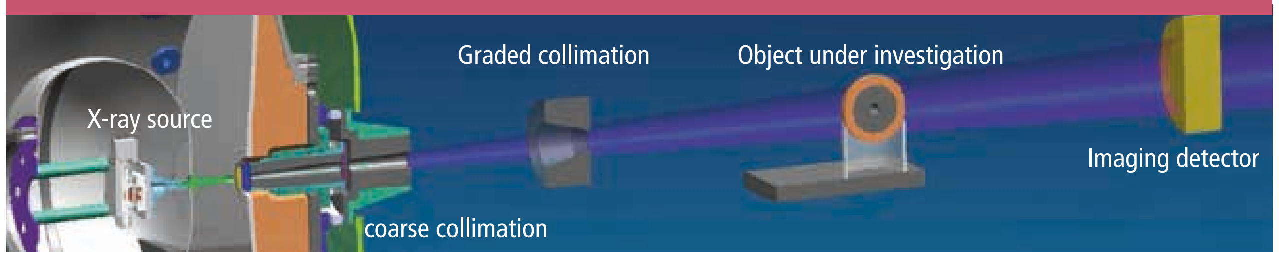
The large X-ray spot sizes of these flash X-ray sources (a few millimetres in diameter) can lead to blurring of the resulting radiographic image.

It is well known that high-energy X-rays can be generated from the interaction of intense laser light, produced by a petawatt (10^{15} watts) type laser (such as those at the world-leading Orion laser), with a suitable heavy metal target[1]. Laser light can be focussed to very small spot sizes in very short duration single pulses (one hundredth of a millimetre in less than a billionth of a second). These properties can significantly outperform current high-energy flash X-ray sources, reducing the effects of source and motion blur.

The imaging potential of such an X-ray source has been evaluated from a number of collaborative campaigns, with staff from the Commissariat à l'énergie atomique et aux énergies alternatives (CEA, France's defence laboratories), using the Omega EP petawatt lasers at the Laboratory for Laser Energetics (LLE), Rochester, Unites States[2] and the Orion laser.

During these collaborative campaigns, radiographic diagnostic techniques designed by AWE for hydrodynamic experiments were used to record radiographs of test objects in order to characterise the laser generated X-ray source spectrum, dose and imaging resolution. A tungsten step wedge of known thickness (and hence X-ray attenuation) was used to infer the X-ray spectrum and dose produced by the petawatt laser. A resolution test object provided information regarding the X-ray spot size and imaging resolution achievable with the laser driven sources. Each of these test objects, along with an imaging plate (used to record the radiograph), were loaded into a Ten-Inch Manipulator (TIM) suitable for insertion into either the Omega EP or Orion laser target chambers.

Figure 1. Schematic of typical radiographic chain for hydrodynamic experiments



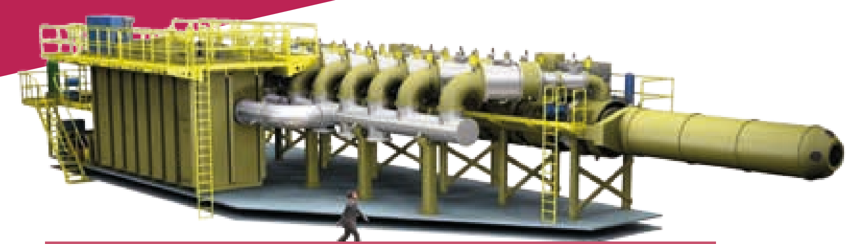


Figure 2. AWE pulsed power X-ray machine

These static object radiographic experiments have demonstrated the potential of a laser driven X-ray source to resolve artefacts of less than 0.1 mm buried inside an object as thick as 10 cm of steel (**see figure 3**). This significant improvement in static X-ray imaging resolution, coupled with the potential removal of motion blur (due to the ultrafast laser pulse), could lead to at least a factor of five improvement in image resolution over current AWE systems. This improvement can be likened to the superior image detail afforded by the use of current 4k high definition television compared with the typical cathode-ray tube TV of the 1990s.

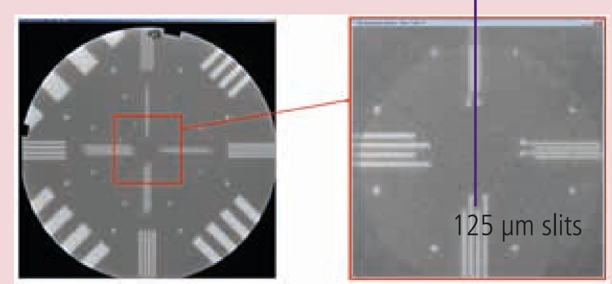
Higher resolution images obtained from AWE hydrodynamic experiments will lead to improvements in our current understanding of material properties subjected to high strain rates, making the laser driven X-ray source an attractive successor to the pulsed power X-ray machines.

The thick, dense materials requiring investigation at AWE can be challenging because they far exceed the equivalent thickness of steel. An order of magnitude increase in the X-ray dose would be necessary to penetrate the object of interest.

AWE principal scientist in radiography, Chris Aedy, says, "Results from the experiments performed at LLE and Orion have demonstrated that a laser's X-ray dose output is a function of laser energy and intensity. Future near-term improvements to the US National Ignition Facility (NIF) and the French PETAL lasers would yield sufficient laser energy and intensity to produce the dose levels required. This would help elevate laser driven X-ray sources to be an attractive high resolution successor to current pulsed power machines for AWE hydrodynamic experiments. Once these facilities come online, further X-ray radiography experiments will be proposed.

"It is also worth noting that current off-shoots of these types of petawatt lasers in the form of multi-pulse, high repetition rate lasers could potentially be used to provide ultra-high resolution imaging for non-destructive testing and medical physics applications. AWE is currently exploring the possibility of collaborating with the US laboratories to investigate the properties of this type of laser driven X-ray source."

Figure 3. Resolution Test Pattern image obtained with an image plate fielded inside and outside the laser chamber demonstrating better than 0.125 mm resolution



1. C Courtois et al. High resolution multi-MeV x-ray radiography using relativistic laser solid interaction. Physics of Plasmas 18, 023101 (2011)
2. C Courtois et al. Characterisation of a MeV Bremsstrahlung x-ray source produced from a high intensity laser for high areal density object radiography. Physics of Plasmas 20, 083114 (2013)

The eyes of the engineer

A problem for the engineer and scientist is how do we know that a material or component is structurally 'sound'? We cannot just cut it open, we need some means to look inside to check its integrity and we do not have the superpower of X-ray vision!

Non-destructive evaluation (NDE), or non-destructive testing (NDT) methods, can provide the answer and be the 'eyes' for the engineer and scientist. Using NDE techniques and technologies, we can obtain valuable information about the state of materials and components highlighting any defects or abnormalities without affecting the material under inspection.

At AWE, we employ NDE techniques to ensure the integrity and safety of our unique materials in our challenging environments.

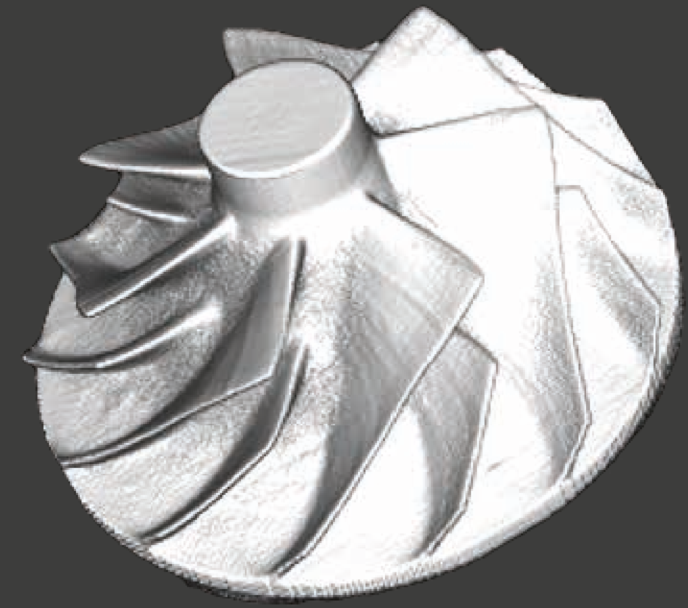
Ultrasonic, eddy current, magnetic particle, acoustic emission and radiographic techniques are used throughout the manufacturing and assembly processes at AWE and throughout the lifecycle of the nuclear warhead.

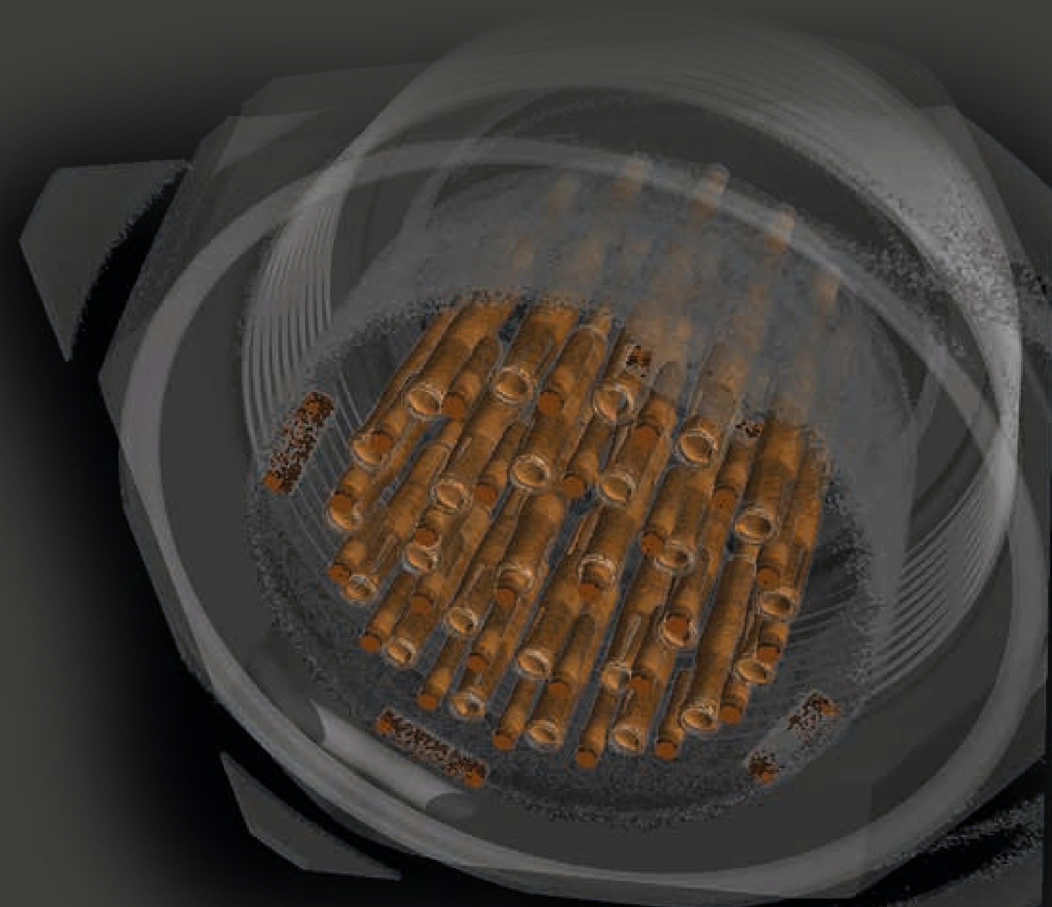
X-ray Computed tomography (XCT) in particular is used in many applications providing three-dimensional digital X-ray radiography images, which can be reconstructed to provide 3D volumetric data and enable a virtual reality 'walk through' of a component. XCT has the advantage of being a non-contact inspection assessment, allowing 'sensitive' materials to be inspected in controlled conditions.

Caroline Bull , whose background is in NDE at AWE and is president of the British Institute of Non-Destructive Testing, says, "The resulting NDE data feed. product assessments, aids in understanding the reliability of components and most importantly contributes to, and can, underpin safety assessments.

"Employing NDE techniques can save AWE time and money, reducing risk and ensuring that the material or components meet the required quality standards, thus increasing safety, integrity and reliability of materials and manufacturing techniques, helping to validate and verify processes and products."

Engineers and scientists at AWE may not have X-ray vision but they can use X-rays and other NDE techniques to examine internal features of objects and be their 'eyes on the inside' to give invaluable information about materials, components and assemblies.





Simulating a hostile environment

Of the two surviving aircraft hangars left on the Aldermaston site at AWE, most people will have no idea what sort of work is performed inside these old WWII buildings. Their days of housing aircraft which participated in the D-day landings are long gone, but since the late 1960s the hangars have been home to many specialist machines, known as radiation effects simulators designed to support warhead research.

These machines, with such names as Mini-C, Splattlet, IT, Dumbo, Speed and EROS (Energetic Radiation Of Systems), were designed and built to simulate some of the effects of Initial Nuclear Radiation (INR) produced from a nuclear weapon detonation. These effects form what is termed a 'hostile environment.'

Some of the INR outputs are intense x-rays and gamma rays. These short-lived radiation fields, in the order of nanoseconds (billionths of a second), can affect electronic systems. These effects on electronic systems were discovered in the 1960s and are still being addressed by engineers of modern designs. Design engineers of our military systems, both conventional and nuclear, need to assess the susceptibility of their systems and mitigate the potential effects from foreign nuclear powers. This area of work is known as Hardening & Vulnerability (H&V). The use of computer modelling is now fundamental when designing these systems; however the modelling needs to be validated to provide confidence in the system design as part of the certification into service. Since the cessation of underground nuclear testing, the use of radiation effects simulators, such as those previously mentioned, have become the primary method of validating these models. Without model validation and system testing the effects on equipment such as the Challenger 2 main battle tank, Typhoon fighter aircraft and our nuclear deterrent could not be fully assessed, which could impact their operational use.

Of these simulators only EROS has survived. It was designed and built on site, the majority of the workforce being AWRE staff. It was commissioned in 1969 for an estimated two-year life! However, nearly 50 years on, EROS remains the UK's peak gamma test facility able to meet the NATO nuclear hardening specification requirement for equipment.

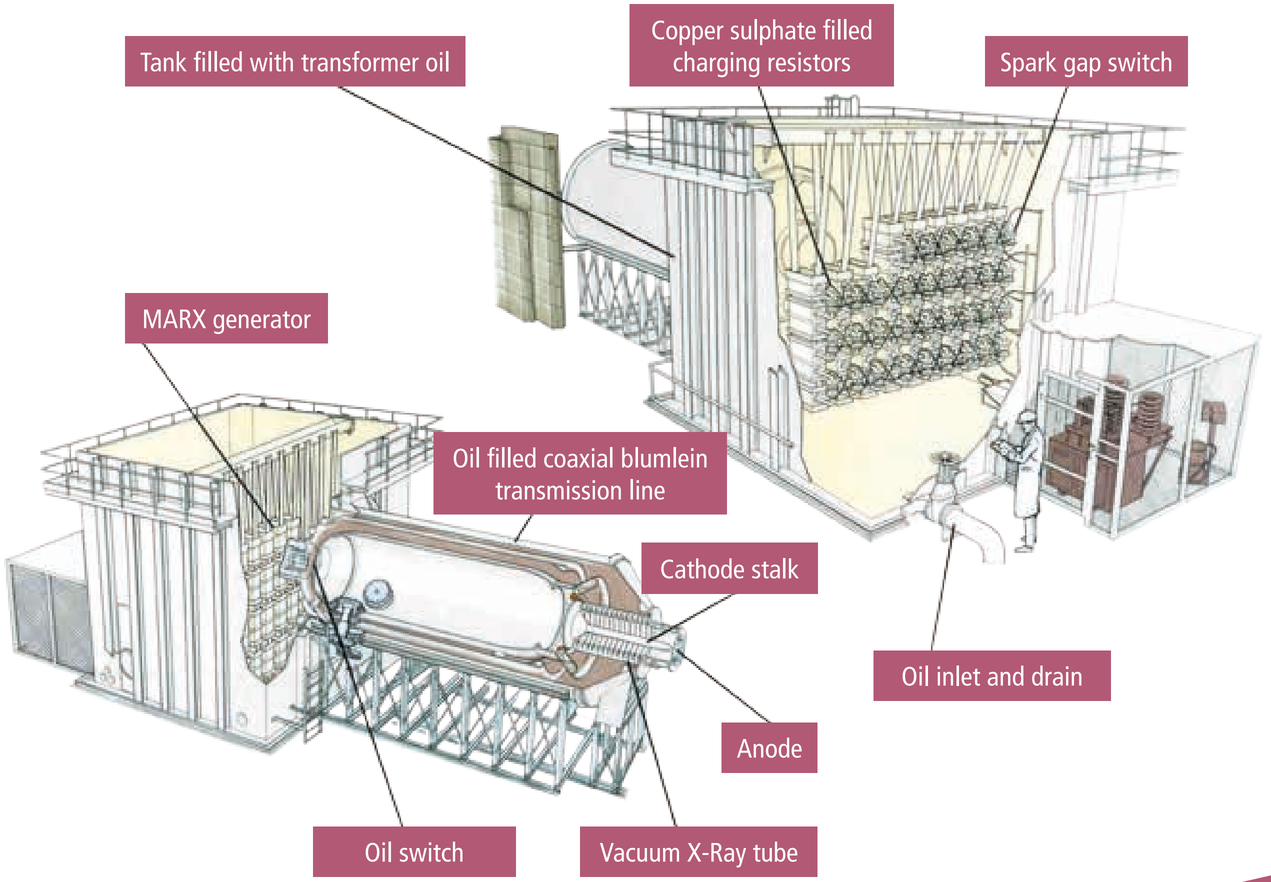
AWE operations manager for EROS, Kevin Webb, says, "We will shortly be celebrating the 40,000th shot fired on EROS, which is a remarkable achievement given its age. This has been accomplished by the dedication and hard work of many science, engineering and operational staff over five decades.

"Plans are underway for a replacement simulator, EROS 2, estimated to be in service around 2025 but until that time it is 'business as usual' for one of the sites oldest facilities."

EROS (Energetic Radiation Of Systems)

EROS is an electron beam generator it consists of three main building blocks: the Marx generator, coaxial transmission line, and vacuum X-ray tube. The Marx generator consists of 66 x 1.33 microfarad capacitors that are charged in parallel from a power supply to a set voltage. When fully charged the capacitors are switched in series by virtue of 33 gas filled spark gaps, therefore the charge on the output of the Marx is the sum of all the capacitor voltages. The resulting megavolt output is applied to the Blumlein coaxial transmission line, which acts as a temporary store and when fully charged, generates an output of desired amplitude and shape. This output is terminated at the end of the transmission line by a load, the vacuum X-ray tube.

The tube contains the diode consisting of a hemispherical carbon cathode that sits on the end of a stalk. Cold emission electrons from the cathode are absorbed by a tantalum anode plate, producing a pulse of Bremsstrahlung X-rays. Alternatively, the tantalum anode can be replaced by an aluminium foil offering a reproducible electron beam for direct energy deposition on target materials.



Profiling our People

Lisa

Control and instrumentation apprentice

I joined AWE as a control and instrumentation apprentice in 2017. I have always had an interest in mechanical machining – thanks to my dad. I would go to the garage that he worked at every Saturday to help out and earn pocket money!

When I was at school deciding what career path to take, engineering was never really an option. At the time engineering and similar trades were not seen as a “career for girls.” I was encouraged to pursue a more “traditional” career such as childcare.

Before I joined AWE I worked at Basingstoke hospital. I got to a point in my career where I couldn’t climb the ladder any higher without further training. Due to funding, all training would have to be self-funded with unpaid leave. Being a mother of three boys and having a mortgage, this just wasn’t an option for me.

After a close family friend recommended the AWE apprenticeship scheme I decided to apply. The company had a good reputation and I knew it would give me the skills to start a whole new career. And it was great to see that they accepted mature students!

A typical day for me involves working in the training academy building electronic circuits, learning how they work as well as gaining knowledge and understanding of the electrical and electronics industry. The best thing about my job is learning how things work and why. One big advantage is learning through both practical and theory work. I also have a great rapport with my colleagues and we all help each other out.

Once I have successfully completed my apprenticeship I will earn a position within the business where I can further develop my skills and knowledge. After a few years of on-site experience I would like to come back to the academy to work. I love helping people, so to come back to teach new apprentices and handing over the knowledge I have learned would be really rewarding.

Changing my career path was a big decision but I’m so pleased I did. It has shown my children that no matter how old you are, you can study at any age and start a whole new career. There is a misconception that apprenticeships are just for school leavers – I wish someone had told me sooner how varied the age range is!

New Discovery
Issue 3, October 2018

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