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Nuclear Magnetic Resonance

The Role of Human Factors in Organisational Safety

Debris Shield and Sacrificial Mirror Debris Mitigation Schemes

AWE's Outreach, Major Events and Collaborative Activities

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I'm very grateful for this opportunity to introduce the latest edition of Discovery. It gives me the opportunity to share my first impressions of science and technology at AWE, having just joined the Company as Chief Scientist in September.

Overall I have been very impressed and I have to say pleasantly surprised by the quality and breadth of the science and engineering I have found at AWE. Before joining, I worked for nearly 25 years in the civil nuclear sector, and in my experience much of the science and engineering at AWE is invisible from the outside looking in. Now that I've joined the Company, I've been able to see at first hand, as it were, the breadth and depth of the science and engineering that is being undertaken.

The breadth is particularly impressive. AWE's science and technology covers the full bandwidth of physical sciences and engineering from chemistry, physics, materials and all forms of engineering, through to modelling and simulation. Some of the research areas are distinctly special to the Company, such as hydrodynamics, photonics, nuclear physics, energetic materials, metallurgy etc. This portfolio of science, engineering and technology makes AWE, in my view, a truly unique company in the UK.

During my first few months I have also had the pleasure to attend internal technical events such as poster sessions, conferences, lectures and awards ceremonies. These have illustrated to me the recognition and importance that AWE places on people and communication across its wider technical community. Alongside all of this, of course, is the Discovery magazine.

Issue 18 of Discovery highlights the breadth of the science and technology activities undertaken at AWE. The work on debris shields for short pulse laser systems is especially important for our new Orion laser; the effects of ageing on plutonium reports our increasing awareness of the complex behaviour of this relatively recently discovered material; the developments in nuclear magnetic resonance highlight its role as a characterisation tool capable of supporting a range of AWE programmes, and the work on the helium driven gas gun and the influence of human factors on the safety of an organisation highlight the variety of our approaches to all aspects of safety. Finally I am particularly pleased to see a summary of some of the highlights of AWE's conferences and Strategic Alliance activities during 2008.

In closing, I'd like to return to my starting comment above about the science and engineering at AWE being largely invisible from the outside looking in. Some of this necessarily has to be the case for security reasons. Nonetheless, there is still the increasing scope for AWE to extend and strengthen its links outside in science and engineering, particularly with universities. The paybacks to AWE are both intellectual and financial. Amongst other things it brings access to know-how, innovation and skills, as well as peer review of our own work.

Professor Richard Clegg
Chief Scientist

Nuclear Magnetic Resonance: Principles and Applications to Materials Research

Nuclear Magnetic Resonance (NMR) has in recent times emerged as an invaluable tool for chemists and materials scientists providing high fidelity information on the chemical composition and micro-structure of materials that cannot be readily accessed by any other techniques. AWE has used NMR to characterise products resulting from a variety of synthetic chemistry and replacement materials programmes and to characterise changes in materials as a consequence of ageing.

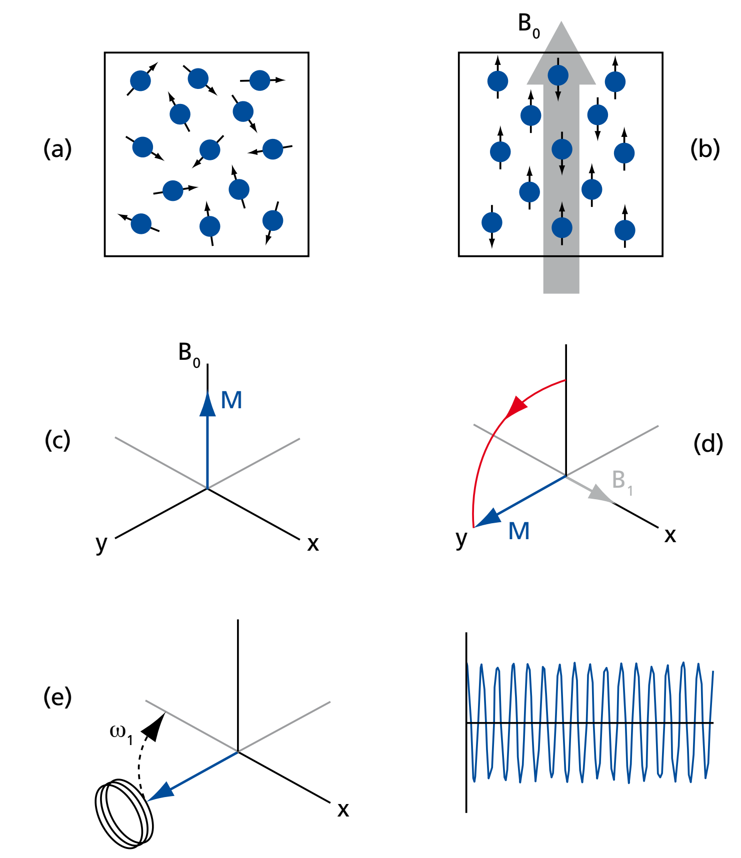
Quantum theory states that nuclei possess intrinsic angular momentum, or spin, which may only take certain discrete values. Nuclei also possess charge, which when combined with their intrinsic spin confers on the nucleus a magnetic dipole moment.

When placed in a large polarising magnetic field, each of the magnetic dipoles, or spins, within a system aligns either parallel or anti-parallel to the magnetic field direction; by convention, defined as the z-axis. An excess of spins in the lower energy level, aligned parallel to B_0 produces a bulk magnetisation **M**, which can be described as a classical vector. The basic NMR experiment shown in Figure 1, involves the application of a small radio frequency pulse which produces a small magnetic field B_1 along, say the x-axis. The result of this pulse is that the magnetisation tips away from its equilibrium position (aligned with B_0) down to the xy plane where its rotation about the z-axis, or precession, generates the NMR signal in a nearby small coil of wire, through the process of electromagnetic induction.

Figure 1(a) simulates nuclei in random orientations at thermal equilibrium. In 1(b) the nuclei, polarised in a magnetic field B_0, align parallel or anti-parallel to the direction of B_0. Figure 1(c) demonstrates an excess of nuclei aligned parallel to B_0 producing a net magnetisation described by classical vector, **M.** In 1(d) the magnetisation may be tipped away from its equilibrium position through the application of a small transverse magnetic field B_1. In 1(e) the Larmor precession of the magnetisation generates the sinusoidal NMR signal in a nearby coil of wire through electromagnetic induction.

The phenomena of NMR was discovered in 1946 by two independent groups: one led by Felix Bloch working on liquids at Stanford,[1] the other led by Edward Purcell working on solid materials at Harvard.[2] They discovered that when placed in a magnetic field, the ^1H nuclei within the sample precessed at a frequency proportional to the strength of the

FIGURE 1



The basic NMR experiment.

magnetic field. This effect is described by the Larmor equation:

$$\omega = -\gamma B_0$$

Where ω is known as the Larmor frequency, γ is the gyromagnetic ratio, which is an intrinsic property of each nucleus and B_0 is the effective magnetic field at the nucleus. As a consequence, each isotope with a non-zero nuclear spin has a unique resonance frequency. Since the magnetic field of a superconducting magnet is fixed and stable, the conventional 1-D NMR experiment provides information about a species under study in three separate ways:

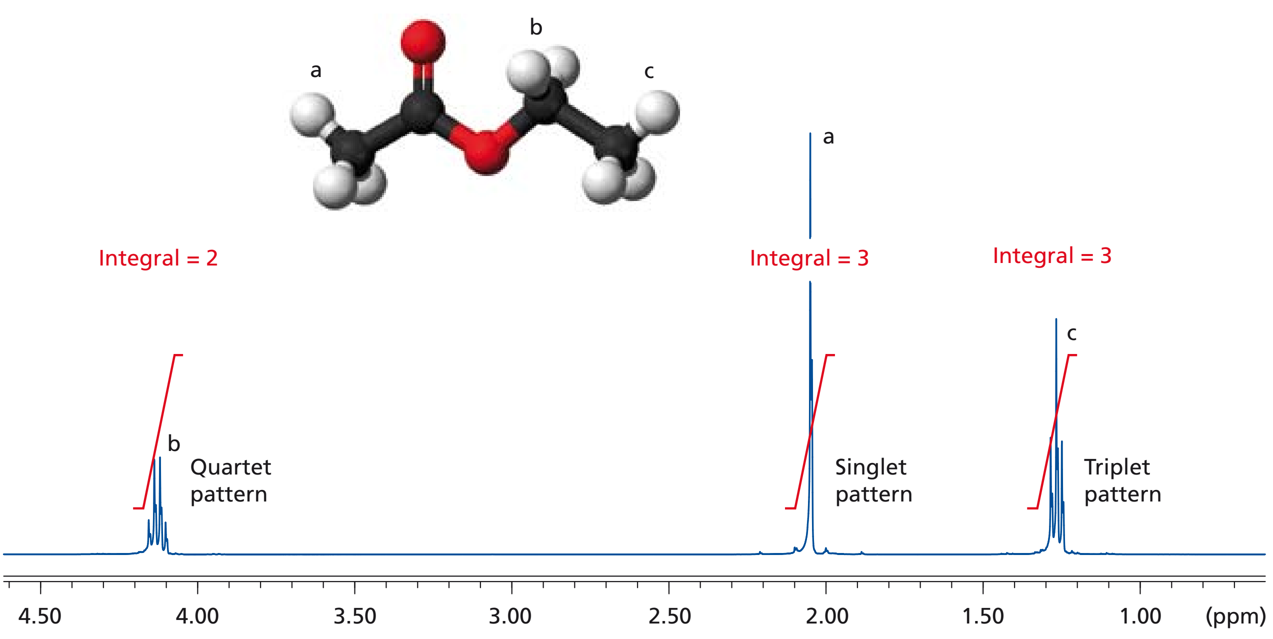
- For each nuclei in a magnetically equivalent environment within a molecule, a single resonance peak will be observed in the NMR spectrum. The difference in frequency between this resonance and that of a standard reference compound, such as tetramethylsilane for ^{1}H and ^{13}C NMR, is termed the chemical shift. The chemical shift provides information on the local electron distribution within a molecule.

- For each distinct resonance frequency, the intensity of the signal is directly proportional to the number of nuclei resonating at that frequency provided a sufficient time between pulses is applied to allow the system to relax back to thermal equilibrium. By integrating each peak in an NMR spectrum, the numbers of nuclei present in each environment can be calculated.

- When spinning nuclei in a molecule are in close proximity and in magnetically non-equivalent environments, they can cause perturbation of the signals of adjacent nuclei. The resonances contain coupling and are consequently split from a single distinct resonance peak to multiplets which contain two or more peaks. The structure of the multiplets and the separation between the fine splitting of the parent peak provides short and long range structural information about the molecule under study.

Through these three processes, the information gathered from the NMR signal allows determination of complex structures. An example of a 1-D conventional

FIGURE 2



Spectrum of ethyl acetate (inset) in solution, produced by a conventional 1-D NMR experiment. The integrals indicate the relative number of protons in each environment.

FIGURE 3

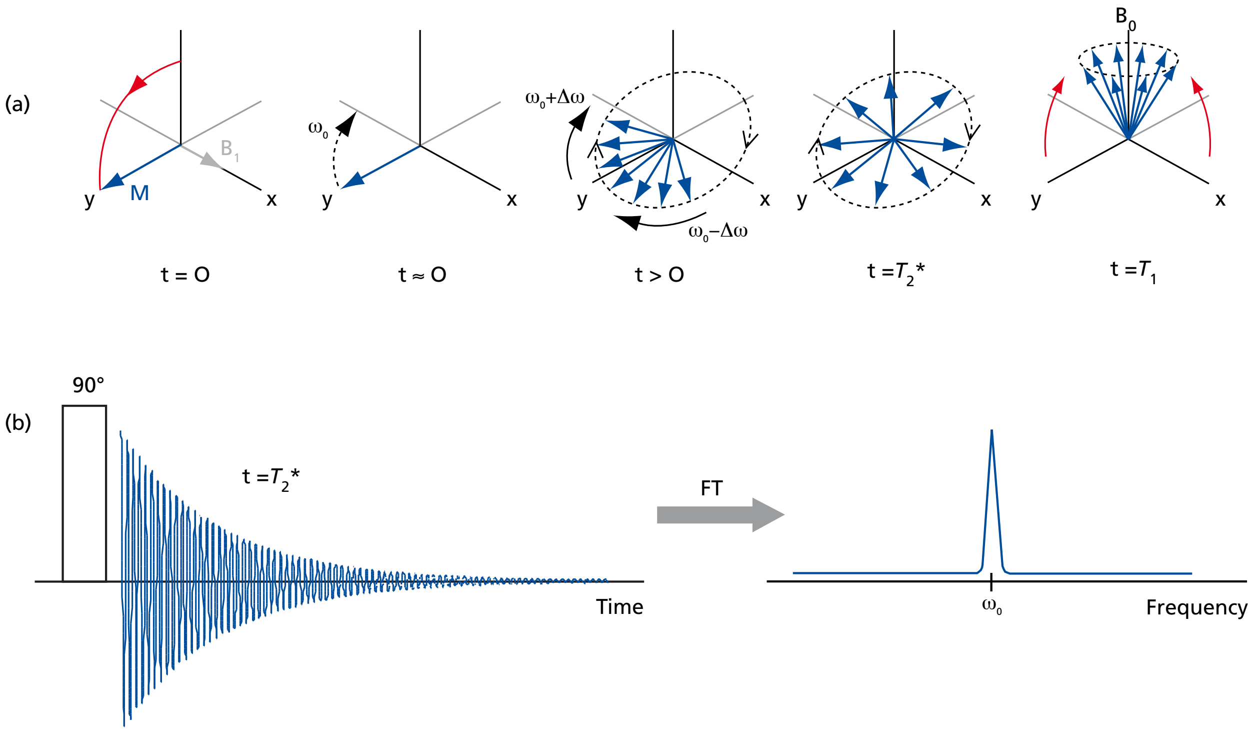


Figure 3. (a) Evolution of the nuclear magnetisation during the processes of relaxation. (b) The observed NMR signal in the time domain and the frequency domain following Fourier transform.

NMR experiment on a sample of ethyl acetate in solution is shown in Figure 2.

Over time any nucleus excited in an NMR experiment relaxes back to thermal equilibrium by dispersion of the excited energy back to the surroundings. The mechanisms for relaxation in NMR are well characterised and proceed via two pathways:
(i) The longitudinal or spin-lattice relaxation time T_1, which results from an exchange of energy between the magnetic dipoles and their local environment, and
(ii) the transverse or spin-spin relaxation time T_2, which corresponds to an exchange of energy between the individual spins in the system.

The total energy is unchanged in this instance but the phase coherence between the individual spins which constitute the total bulk magnetisation reduces to zero. Figure 3(a) shows the evolution of the nuclear magnetisation undergoing relaxation processes and

"NMR relaxation can be applied to the analysis of crosslinking density."

Figure (3b) shows the resulting NMR signal in the time and frequency domains. The observed NMR signal is seen to decay with a time constant $1/T_2^*$, broadening the resonance peak in the frequency spectrum.

The mechanisms of relaxation in solids lead to a general trend that more rigid materials have lower T_2 values than in mobile systems. As a consequence, NMR relaxation can be applied to the analysis of crosslinking density, chain entanglement and physical junctions within polymers. T_1 relaxation does not demonstrate relationships with rigidity in such a straightforward manner but it may be predicted. The T_1 value is used to set the delay between subsequent experiments to ensure

Box 1

Magnetic Resonance Imaging (MRI)

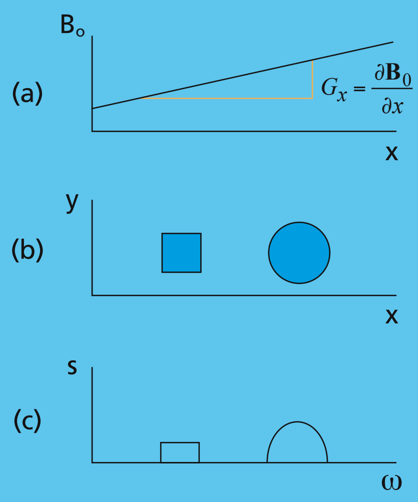
A magnetic field gradient is simply a magnetic field that varies with position, according to:

$$\mathbf{G} = \frac{\partial \mathbf{B}_0}{\partial x}$$

In the presence of a linear magnetic field gradient, the Larmor equation is modified to:

$$\omega_0 = \gamma \mathbf{B}_0 + \gamma \mathbf{G} x$$

and the relative positions of protons (or other spinning nuclei) within a material becomes encoded in the frequency domain. The principle of NMR imaging, or MRI is shown in the Figure below.



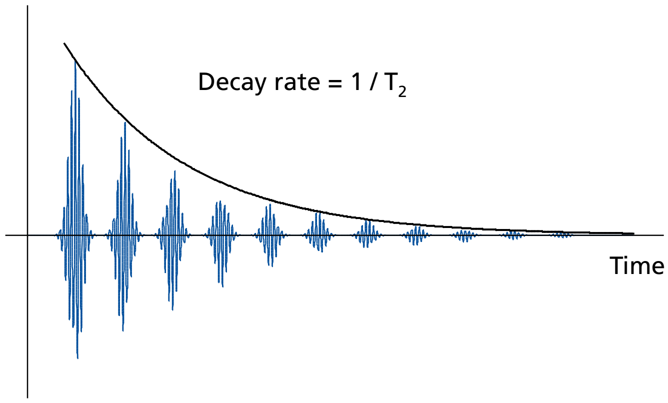
(a) The magnetic field varies linearly across the sample by application of a magnetic field gradient G_x in the x-direction.
(b) Sample shapes in the two dimensional xy plane.
(c) The NMR spectrum acquired in the presence of a magnetic field provides a projection of the sample. The signal amplitude S, is proportional to the number of nuclear spins at a given value of the magnetic field.

For a linear space dependence of the Larmor frequency, the spatial resolution Δx is related to the spread in Larmor frequencies $\Delta\omega_0$ according to:

$$\Delta x = \frac{\Delta \omega_0}{\gamma G_x} :$$

therefore the larger the line width, the worse the spatial resolution. Liquids exhibit narrow line widths of the order of 1 Hz, providing a good spatial resolution. However, due to strong dipolar interactions, line widths in solids may be up to 100 kHz resulting in poor resolution. Soft matter, such as elastomers exhibit sufficiently narrow lines between 10 Hz and 3 kHz that resolution is acceptable, i.e. between 10 and 100 µm in one dimension.[8]

FIGURE 4



The true T_2 relaxation time is determined from the decay rate of a spin-echo chain generated through a typical CPMG experiment.

the magnetisation has time to fully recover. The T_2 time is measured using the Carr-Purcell-Meiboom-Gill (CPMG) experiment which utilises a succession of 180° pulses to refocus the magnetisation after each decay, creating spin-echoes.[3,4] This technique reverses any inhomogeneity in the magnetic field and/or differences in magnetic susceptibility across the sample and allows the true spin-spin relaxation to be calculated from the decay rate of the spin-echoes, Figure 4.

Magnetic Resonance Imaging (MRI) is a non-invasive technique that is capable of imaging NMR observable parameters through optically opaque objects. Images are obtained by encoding spatial information directly into the frequency domain which is accomplished by applying magnetic field gradients across the sample, see Box 1. For each magnetic field gradient, only discrete regions, or 'slices' of the sample satisfy the resonance condition and therefore each slice can be selectively excited. Magnetic field gradients can be applied in any orientation, allowing a 3-dimensional image to be built up. Contrast in NMR images primarily originates from the processes of relaxation such that images are weighted by the density and mobility of the spin active nuclei.

NMR microscopy is a high resolution variant of MRI and has many practical uses in materials science. Recent advances in hardware allow resolutions comparable to those obtained by

FIGURE 5

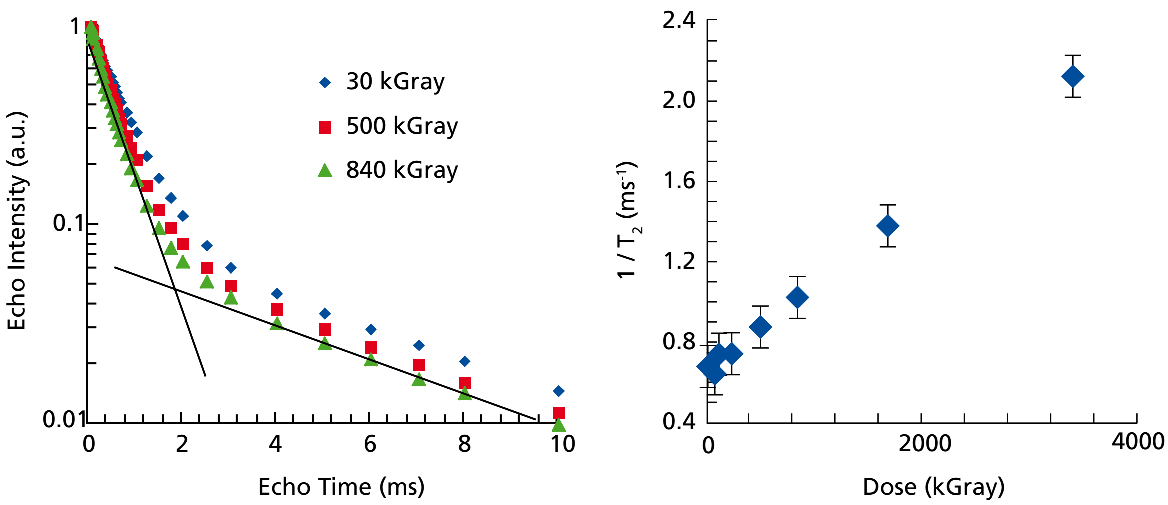
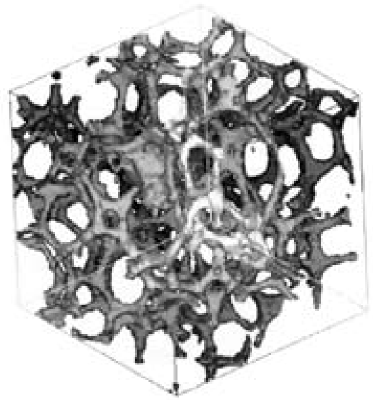


Figure 5 (a) Spin-echo decay curves for samples of filled polydimethylsiloxane which have undergone accelerated ageing through exposure to γ-radiation, (b) Short component T_2 relaxation times, with γ-radiation dose, calculated from two component exponential fits to the decay curves shown in (a).

FIGURE 6



A 3-D NMR image of a piece of flexible polyurethane foam immersed in water. The spatial resolution is 15 μm.[7]

x-ray computer tomography, making the technique uniquely powerful in providing chemical specific information on samples with defined micro structures.

At AWE, ^1H NMR relaxation studies have been used to investigate the degradation of polysiloxane elastomers as a result of ageing and radiation damage.[5] The main mechanisms for structural modifications seen in polymers that have been irradiated with high energy γ-radiation result from chain scission, crosslinking and chain-end linking reactions. These modifications affect the segmental dynamics within the polymeric system and therefore change the T_2 relaxation time. Such studies have been shown to correlate with changes in mechanical properties.[6]

Figure 5(a) shows the spin-echo decay curve for samples of a filled polydimethylsiloxane polymer system which has undergone accelerated ageing through exposure to ^{60}Co γ-radiation.[5] For many polymeric systems, the decay in the spin echo intensity may be satisfactorily described by a two component exponential of the form:

$$S(t) = A\exp\left(-t/T_2^A\right) + B\exp\left(-t/T_2^B\right)$$

FIGURE 7

Figure 7. The NMR suite at AWE comprising a 400 MHz system dedicated to solid-state spectroscopy and NMR imaging (left) and a 400 MHz system with automatic sample loading and tuning for solution state spectroscopy (right).

"The NMR MOUSE is a portable, single-sided magnet and therefore has none of the sample size limitations associated with conventional NMR."

Exact assignment of the two components is often difficult, but is it well accepted that the short component A corresponds to the crosslinked network species which represents the bulk of the polymer structure whilst the longer component B corresponds to low molecular weight network separated species, such as the silica filler and dangling chain ends.

Figure 5(b) shows the short component T_2 relaxation times for samples after varying radiation doses, calculated from two component exponential fits for spin-echo decay curves displayed in Figure 5(a).

The results show that increasing radiation dose leads to a more rapid decay of the short T_2 component. This decay is indicative of an increase in the rigidity within the polymer and hence an overall increase in crosslink density. The corresponding decrease in segmental motion would produce an increase in viscosity, shear modulus and elastic modulus and can therefore be supported by mechanical analysis.

FIGURE 8

The NMR MOUSE is a single–sided, portable magnet used for measurements of relaxation phenomena and molecular diffusivity. It is shown alongside a two pound coin for scale.

Figure 6 shows a 3-D NMR image of flexible polyurethane foam immersed in water.[7] The mobile protons in the water have a strong NMR signal, whereas the polyurethane foam is so rigid that it produces no signal on the NMR timescale. The difference in mobility between the two proton environments provides a high degree of contrast.

Contrast in polymeric systems is usually less than in systems with a high water content. However, images weighted by the density and/or mobility of an NMR active species may be routinely recorded. Novel techniques have made additional contrast filters available which allow magnetisation density, flow velocity, self diffusivity and chemical selectivity to be spatially mapped.

"NMR has proved a powerful characterisation tool providing unique data to support many AWE programmes. Relaxation experiments have been used to characterise subtle changes in materials resulting from ageing, which have been correlated with changes in physical properties."

NMR capability at AWE

AWE has a full suite of NMR instrumentation designed to provide data to support both lifetime prediction and new materials development programmes. This suite, pictured in Figure 7, comprises two 400 MHz magnets – one dedicated to the study of samples in solution and the second dedicated to solid state NMR and NMR microscopy – both are capable of high resolution 1-D, 2-D and 3-D spectroscopy. The liquid system features an automatic sample changer and fully automated tuning, whilst a low-gamma attachment for the solid system allows access to all spin active nuclei in the periodic table.

The NMR microscopy functionality enables spatially resolved information of soft polymer materials to be acquired with an achievable resolution of 5 μm in three dimensions. Multiple sample handling capabilities mean that it is possible to study samples from 2×12 mm up to 40×65 mm in size.

In addition to the two 400 MHz magnets, the suite also comprises a small device known as the NMR MOUSE (MObile Universal Surface Explorer), Figure 8, which is capable of non-destructively measuring bulk samples from the surface to a depth of around 5 mm. The NMR MOUSE is a portable, single-sided magnet and therefore has none of the sample size limitations associated with conventional NMR. However, due to the inhomogeneity of the magnetic field, chemical shifts cannot be measured, although relaxation and diffusion constants are readily accessible for materials characterisation. The NMR MOUSE will be exploited as a characterisation tool in manufacturing and surveillance.

Conclusions and Future Work

NMR has proved a powerful characterisation tool providing unique data to support many AWE programmes. Relaxation experiments have been used to characterise subtle changes in materials resulting from ageing, which have been correlated with changes in physical properties. These experiments have provided invaluable input into lifetime prediction models. NMR imaging has been applied to materials that have microscopic structures and has been proven to provide structural data on samples such as foams with high spatial resolution. AWE has an excellent NMR capability provided by state of the art equipment to fully exploit the technique in support of ongoing materials programmes. New NMR devices such as the MOUSE will be integrated into production and assembly/disassembly facilities to provide data on components.

Recent advances in NMR such as diffusometry will be developed to measure pore size and distribution. Spatial mapping of phenomena such as fluid ingress and associated polymer swelling will also be developed.

Acknowledgements

This article includes the work of many people within the organic materials area of the Materials Science Research Division. Principal contributors, both past and present, include Mogon Patel, Jenny Cunningham and Steve Black.

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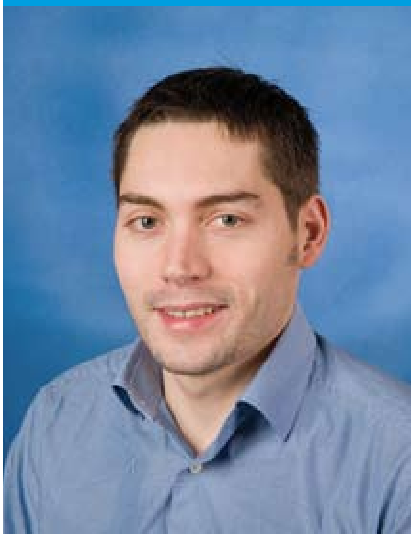
AUTHOR PROFILE



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Simon • graduated from the University of Hertfordshire in 2002 with a BSc in Astrophysics. This was followed by studies at the University of Surrey for a MSc in Radiation & Environmental Protection (completed 2004) and a PhD in Magnetic Resonance Profiling of Acrylic Adhesives. He remained at the University of Surrey, completing a short post doctoral research fellowship sponsored by Unilever developing new methods of using magnetic resonance profiling to monitor the transport of emulsions across biological barriers.

Simon joined the polymer development and characterisation team at AWE in spring 2008 and currently maintains the magnetic resonance facility. He is currently involved in a number of collaborations with members of the materials community within AWE and externally with The University of Warwick. His current area of interest is developing new techniques for polymer characterisation using magnetic resonance.

The Role of Human Factors in Organisational Safety

Achieving safety in any large organisation is by no means simple or straightforward and we can never underestimate the associated difficulties. Designing work systems to remove risks or control them is a major challenge for those organisations involved in high-risk or high-consequence operations.

Research has shown that in various domains, such as aviation, the oil, gas and nuclear industries, healthcare and the military, success or failure of safety often hinges on controlling and understanding the human factors involved at different levels of the organisation.[1] People are naturally prone to variability in their performances, especially when adapting to new challenges, varying conditions or competing demands, so there are always risks to safety from the human factor. Acknowledging the limitations of human ability and recognising that human performance depends largely on the opportunities provided to them by the system in which they work is a major step toward safer systems.[2] However, gaining an awareness of the problems of safety alone is not sufficient to improve or maintain it. Organisations also need regulation, organisational learning mechanisms, and a strategy to deal with human factors throughout current and future systems. For this, organisations need to draw upon various theories and methodologies, particularly in respect of human factors.

Human factors is the field of study that deals with the relations between people, their work and their environment.[3] Its focus is on how these relations influence the process and output of a work system, in terms of efficiency, quality, reliability, and safety. It is both an academic and applied discipline, which bridges research and practice. There is a broad landscape of the human factors discipline available to apply in the organisational safety context: it may input to hard engineering and design or deal with the more social or structural aspects of people working together. Its object of analysis will also vary and may include the study of the individual, the study of the group, or the study of the organisation as a whole. Human factors therefore encompasses physical, cognitive, and environmental ergonomics, human-machine, human-computer interaction and communications (see Box 1). In spite of this range of disciplines, human factors practitioners will have a common aim to help achieve and maintain safety while enhancing performance capability.

> "Organisations also need regulation, organisational learning mechanisms, and a strategy to deal with human factors throughout current and future systems."

In this article, we consider the theory that organisations can achieve and maintain safety by adopting the principles of high-reliability and by applying a systems approach to safety. Our specific aims are to show where human factors might fit and translate into this theory and to raise awareness of the emerging role of human factors in organisational safety within and outside the Atomic Weapons Establishment (AWE).

The Paradox of Organisational Safety

"To tackle these issues, researchers have formulated the theory of the high-reliability or resilient organisation, and describe certain principles for building safety in organisations."

One recognised theory suggests that major accidents are a normal consequence of an organisation's cycle of change and that we can never be certain about safety.[4] Paradoxically, we should perhaps feel rather cautious and tentative about safety when we are most confident in claiming to have achieved it. There are various reasons why organisations become less stable over time and experience disturbance within, which compromise the stability of their systems.[5] In spite of increasing technology and automation in organisations, safety depends heavily on people to fill engineering gaps and control complexity. It is often the case that automation has not entirely removed the human factor from a system, but simply shifted the human from one position of control to another. More opaque and complex systems of work emerge from these shifts of control with the risk that a single error may have more significant consequences. This is evident in the supervisory control of complex systems such as the nuclear power station control room. It is also evident where remotely controlled and robotic operations are gradually replacing manual operations in industry. Complexity within large organisations also emerges subtly as interactions across groups or disciplines through information technology become increasingly distributed. For long-lived organisations, the loss of domain knowledge and expertise through the succession of people may also affect the stability of its systems. It follows that such disturbance to systems and the emerging

Box 1

Performance Shaping Factors

A brief categorisation of the main factors shaping human performance at work

Individual factors

- Ability, knowledge, skill, attitude, competence, traits, personal thresholds and motivations.

System factors

- Organisational reward systems, structure, culture, training, external regulation and self-regulation,
- Team design, composition, skills-mix, structure, task-design, clarity of roles, group identity and behaviours,
- Work environment, lighting, noise, temperature, humidity, hazards, spatial configuration,
- System hardware, infrastructure, technological and physical resources, information technology, interface design,
- Process design, task-demands, informational flows, standard operating instructions, procedures and protocol.

properties of complexity within them will lead to unpredictable consequences for safety.[6] In view of these disturbances, we cannot be confident that the means of achieving past success in safety will apply to future operations and conditions. We must therefore look cautiously to the future in designing safe systems of work. To tackle these issues, researchers have formulated the theory of the high-reliability or resilient organisation, and describe certain principles for building safety in organisations.

Theory of Organisational High-Reliability

High-reliability or resilient organisations are typically found in aviation, the nuclear industry, rail, the utilities and the military.[7] High-reliability organisations are characterised as complex organisations, which may often face uncertainty and continual change in their operations, yet hold exemplary safety records. They achieve this principally through safety culture, safety mechanisms and systems design. They recognise the likely precursors of accidents and deal with them proactively rather than look to blame people retrospectively for not coping with whatever demands system design places upon them. These organisations have a constant preoccupation with failure and recognise how system design affords or constrains safe behaviour. Rather than 'fire-fight' safety problems, they deliberately seek to absorb future change and disturbance before it compromises safety. This means the high-reliability organisation is generally reluctant to simplify its operations and is constantly engaged in contingency planning. They engineer diversity and redundancy in their operational systems and command tight control on systems. Hierarchical structure and training lever safety into place, steering and supporting operators to work within established boundaries of safety. Rules, procedures and protocol guide effective behaviour, but at the same time operators have the autonomy and capacity to respond to unforeseen events and any conditions compromising safety. These organisations have stable internal structures, which allow for a continual succession of personnel, without detriment to operations.

> "Rather than 'fire-fight' safety problems, they deliberately seek to absorb future change and disturbance before it compromises safety."

In short, high-reliability organisations implement safety from the top-down, so that it can drive from the bottom-up. They balance centralised and decentralised control and their structures and processes enable stability and adaptability over time, even generations. There are several other means for an organisation to implement high-reliability:

- Regulation and the safety case assessment,
- Organisational learning, memory and feedback,
- A proactive systems approach to operational safety.

In the following, we consider where the human factors discipline features in these three requisites of the high-reliability organisation and highlight some of the current problems facing the given organisation.

Regulation and the Safety Case Assessment

The Nuclear Installations Inspectorate of the UK's Health and Safety Executive demands that for nuclear sites to operate they must qualify a statement that they are safe to do so, which depends on a thorough and rigorous substantiation of safety. This is an ongoing process of analysis, of application and of regulation over the full life cycle of a plant and a careful application

> "Organisations need to gather information from all quarters and levels to identify where and how to direct resources to enhance safety."

of hard engineering and human factors analysis. The predominant medium for this process is the 'safety case' - a document delineating the processes of an operation, facility or plant. The safety case specifies the parameters of safety and the safeguards in place to prevent or mitigate its threats. It specifies engineered hard systems, the control of various hazardous substances, radiological controls and environmental measures.

Currently, the main input to safety cases from human factors is the assessment of the adequacy of the system to support human performance, the provision of evidence concerning predictions of human error, and a descriptive account of the human factors potentially compromising safety. While it is essential to control, quantify, and eliminate human error in high-risk domains in this structured way, this is not the sole strategy for the high-reliability organisation to achieve and maintain safety. Collated estimates of human error probability are unlikely to account for the network of human factors influencing safety. Moreover, error-analysis methods will not adequately describe the non-linear interactions occurring in complex systems, particularly communications. Operators are not likely to learn, develop and refine their skill and performance from models of error. They need to learn from effective models of performance displayed by others and in the context of high-risk work, these models should also account for the ergonomics of operator tasks and their environment. This indicates that composing work systems from the bottom-up is as important as de-composing them for the risk analysis from the top down. In other words, to achieve safety, organisations must seek to find a balance between criteria-driven, human error quantification and performance enhancement objectives.

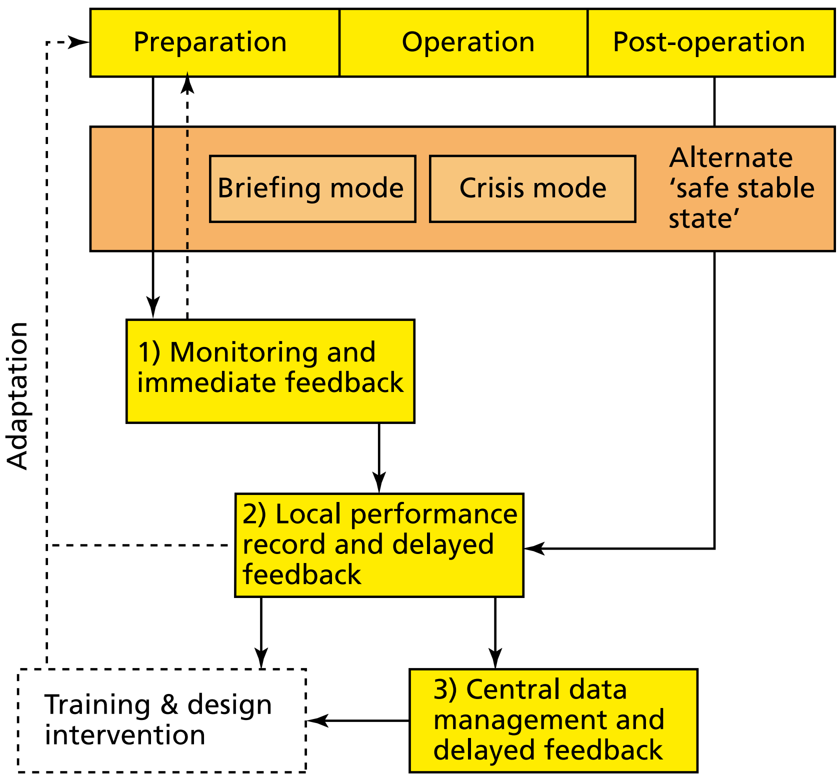
It is not yet clear where this balance lies; it will probably depend on the products, risks and resources unique to the given organisation. Even within the nuclear domain where organisations share similar properties in their products and processes, the human factors input to the safety case versus its input to performance enhancement strategies varies considerably.

Organisational Learning, Memory and Feedback

Organisational safety will also depend on the development of the mechanisms of learning, memory and feedback, which serve both top-down and bottom-up safety initiatives. Obtaining a clear picture of what is going on in an organisation across its functions is a necessary, yet very difficult, task for ensuring organisational safety. Organisations need to gather information from all quarters and levels to identify where and how to direct resources to enhance safety. Abnormal event or critical incident recording systems serve to capture data from the operational level of the organisation for such purposes. There are systems in the US and UK operating at the national level, for example the Rail Standards and Safety Board CIRAS (Confidential Incident Reporting and Analysis System), the National Patient Safety Agency critical incident reporting system, the NASA reporting system and the US Naval and Marine Human Factors Failure Analysis Systems. These mechanisms allow for the adaptation needed to maintain and improve the safety of operations and to absorb disturbance and organisational change.

Designing effective reporting systems is not easy. They depend largely on timely and effective data collation, analysis and rapid feedback of the results to different levels of the organisation, and strategic follow-up on subsequent actions. These self–reporting systems are important for organisational adaptation because they store, compute and communicate information about past performance. Figure 1 illustrates a schematic representation of feedback and regulation for hazardous operations, operating at different levels of an organisation. Monitoring and immediate feedback serves to regulate normal operations as they occur and contingencies allow operators to shift to different behavioural modes to maintain a safe stable state in the event of any deviation from safety. Operators or managers may log data concerning performance issues as feedback for learning purposes and/or send that information on to a central organisational data management system for further analysis. This serves as an organisation-wide learning mechanism to inform intervention for future operations, thereby closing the loop of adaptation to build reliability and resilience.

FIGURE 1



A schematic representation of feedback and regulation for hazardous operations, operating at different levels of an organisation. The solid line represents the feed forward information regarding performance and the broken lines the feed back information regarding performance.

Human factors practitioners might help develop learning systems, with modelling and statistical analysis or help select the most effective streams and means of communication for the lessons learned. However, these data systems rely on information that is usually limited in its depth of analysis and reports are prone to bias. It follows therefore, that organisational safety demands multiple methods of analysis and a triangulation of various data sources. Methods include accident and incident investigation, interviews, observations, and workplace assessments. Together, these provide a fuller picture of why safety might have failed. However, data management systems and their complementary methods will only be as effective as the modelling of system performance to which they contribute. This modelling must take account of our current understanding of human factors in general. Translating the lessons learned into practice is yet another challenge for the organisation and is a particularly important function for the human factors practitioner.

"At AWE, the Human Factors team has applied a range of methods to improve safety and capability across the organisation. We have recently developed a programme for assessing and improving safety culture for its facilities."

A Proactive Systems Approach to Operational Safety

Organisations are now recognising the importance of teams for translating and applying the principles of high-reliability.[8] To integrate safety strategies, it is necessary to focus on particular objects of analysis. The unit might be a facility, or a function or group of people, which reflects the constituent parts of the organisation within which it operates. An ideal unit is the team which might operate a single facility of processes or might provide functions across an organisation from a single place or as a distributed entity across several places. Teams connect the organisation and their potential characteristics are particularly relevant to safety. Teamwork rather than individual work is most likely to make the parts of an organisation cohere even if those parts are distributed. When people work together, they have the potential to achieve synergy. For the high-risk or high-consequence organisation, this synergy can amount to safety and reliability.

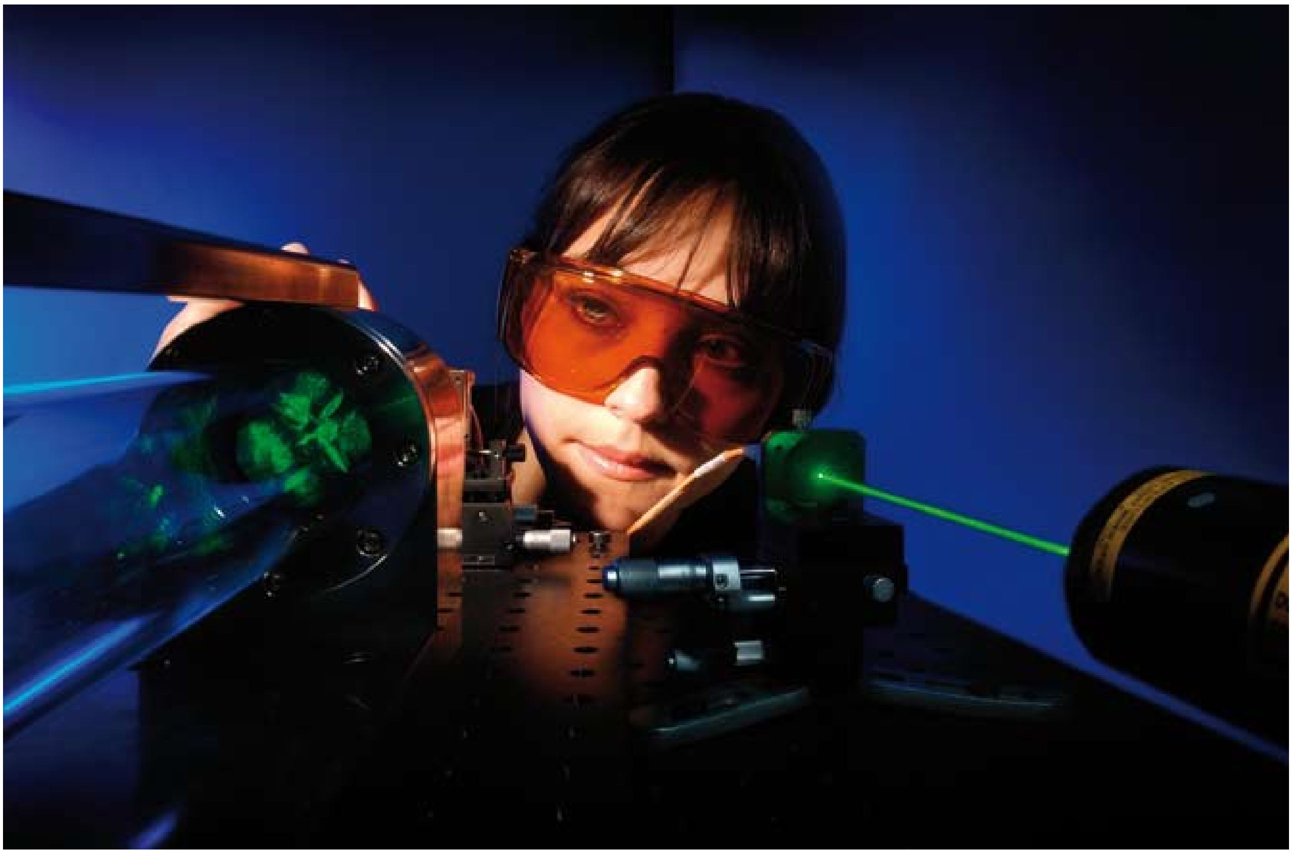
However, a group of people working together, even in the same place, does not make a team; and neither will simply telling them to act as one. Teams, unlike groups, share the costs and benefits of success and failure and their performance will depend on an effective structure, which is consistent with their given function and appropriate resources. The basic model of team performance, often adopted by researchers and practitioners follows the basic principles of an input-process-output system. Team output, in terms of efficiency, quality and safety is in direct relationship to its processes, in terms of behaviours, problem sharing, communication, support and co-ordination of activity. Team process, in turn, depends on the team input factors such as infrastructure, team composition, task design, and environment. By modelling team performance this way, it may be possible to incorporate different strategies for implementing safety: it also provides a common framework for analysing error and for developing new models of working. There are various means to achieve these aims, including team training in simulation, the development of communication and the modelling of professional competence.

Human Factors at AWE

At AWE, the Human Factors team has applied a range of methods to improve safety and capability across the organisation. We have recently developed a programme for assessing and improving safety culture for its facilities. There are four phases to the programme. In phase one, we measure the safety culture of a facility or function using a comprehensive questionnaire, which measures the five aspects of safety culture: leadership, communications, experiential learning, teamwork and individual behaviours. In phase two, we feed the results back to the facility in a focus

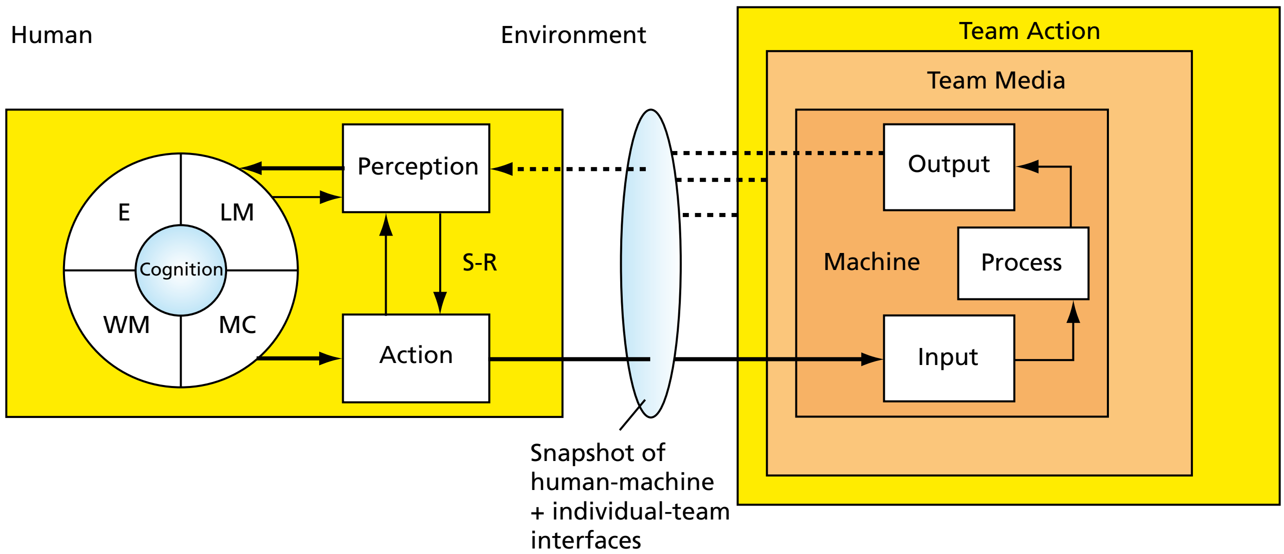
FIGURE 2

(a) Pressurised breathing air suit.



(b) Laser operations.

FIGURE 3



A model of a human-machine interface embedded in a complex system, comprising teams and their media

E = Executive, higher-order cognition, including attention, awareness, decision-making, and calculation

LM = Long term memory for objects, places, events, plans, etc., and behavioural programmes, including sensory-motor skill

WM = Working memory to support higher-order cognition and functions, such as place and task navigation, and response to uncertainties

MC = The higher order cognitive control of motor-action in view of LM, WM and stimuli presented from moment to moment

Adapted from Healey and Benn[9] (in press)

group to stimulate a discussion and to identify particular issues influencing any safety culture problems. In phase three, we run workshops to identify specific solutions to the problems previously identified, in order to generate a consensus on resolutions and specify actions for staff to implement, with mechanisms to assess the effect of those actions. We also offer one-to-one coaching for managers to enable them to coach their own staff. In phase four, we re-assess safety culture to determine the effectiveness of the interventions implemented; determine any impact on bottom-line measures and identify the priority areas to improve upon. This programme provides a team strategy for direct intervention on safety culture, while at the same time indirectly facilitating safety culture improvement by getting people together to focus on, and learn about safety issues in general.

At AWE, the Human Factors team has also carried out ergonomic analysis of difficult and complex work (see Figure 2). This has included assembly and disassembly tasks, hydrodynamic experiments, plasma physics and laser operations, material movement and processing, waste management, pulse reactor operations and decommissioning. We have developed guidance for immediate operational feedback by providing clearer understanding of what it is that operators should monitor throughout their work. The information captured related to the specification of tasks and their clear translation into usable manuals, guidelines, and operating instructions. Other work has included human reliability assessment, human factors integration and shift-working pattern assessment.

These examples demonstrate an increasingly proactive role of human factors in safety at AWE. This trend is growing across domains, as case studies provide growing evidence of the human factors discipline improving organisational safety and efficiency by the ergonomic and usable work and design that it helps to produce. Consistent with a proactive approach, the Human Factors team will soon be supporting an Engineering and Physical Sciences Research Council Doctoral research studentship over four years, in partnership with the UK's Manchester University. The student will research nuclear decommissioning methods, to address the gradual change to decommissioning methods in general and to evaluate whether current engineering approaches to risk reduction are adequate for optimising those methods. The research focuses on the use of remote versus manual operations of the same or similar decommissioning tasks in the foreground of human-machine interface models (see Figure 3).[9]

The Human Factors team is also collaborating with the US Sandia National Laboratories Human Factors Group on issues including the reliability of safety-critical measures, such as checking and inspection, which is a common problem for safety across domains. There seems insufficient research to address associated failings, in spite of an intended function in providing the last line of defence against unsafe acts, conditions or process failures. The team is collaborating with training managers within AWE in order to incorporate human factors into tooling design. The team is also proposing to develop human factors on the following themes:

- Tooling, glove box and control room design,
- Improving integration within AWE's project delivery process,
- Safety culture assessment and coaching for organisational change,
- Development of human factors methods within safety assessments,
- Developing clearer guidelines and operating procedures for operators.

Our future work might follow that of other organisations applying a systems approach to safety and the Human Factors team may develop the following themes:

- Analysis of system communications,
- Safety control research and development,
- Analysis of the shared working environment,
- Team ergonomics and performance modelling,
- Accident, critical and potential event investigation,
- Integration of human factors into operator training,
- Simulation training for high-risk tasks or crisis management.

"We have developed guidance for immediate operational feedback by providing clearer understanding of what it is that operators should monitor throughout their work."

Conclusions

The most serious accidents derive from a range of human factors and so organisations must deal with those factors to prevent future accidents. However, if the ultimate measure of success for human factors practice is the absence of accidents, then once that is achieved it is more difficult to demonstrate its value as a preventative force. However, high-reliability organisations do not believe their future safety is guaranteed from past success: changes occur within an organisation that may influence system performance and compromise safety. Consequently, high-reliability organisations remain stable and resilient to change through various means, particularly regulation and the safety case assessment, organisational learning, memory and feedback mechanisms and a proactive systems approach to operational safety.

"The Human Factors team is also collaborating with the US Sandia National Laboratories Human Factors Group on issues..."

Logic dictates that human factors should be an integral feature in organisational systems from beginning to end. If high-reliability theory is correct in its assumptions, we might predict human factors will therefore have an increasingly proactive role in the modelling, design and integration of organisational systems. We might also predict that human factors will become increasingly specialised to meet the demands of emerging organisational diversity. More research on the application of human factors in organisational safety will be helpful in determining its future position, utility and value.[10]

Box 2

Key Messages

- Achieving and maintaining safety in high-risk/consequence organisations is a major theoretical and practical challenge,
- Current high-reliability theory suggests that organisations achieve safety by adopting a certain set of principles and by developing certain characteristics,
- The application of human factors is valuable to organisational safety and should be measured,
- The disciplined application of human factors by qualified practitioners helps organisations achieve high-reliability,
- The ideal application and position of human factors in any given organisation is unclear and varies considerably;
- Theoretical issues in organisational safety may inform the future application and position of human factors, but we should test that theory.

Acknowledgements:

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Debris Shield and Sacrificial Mirror Debris Mitigation Schemes

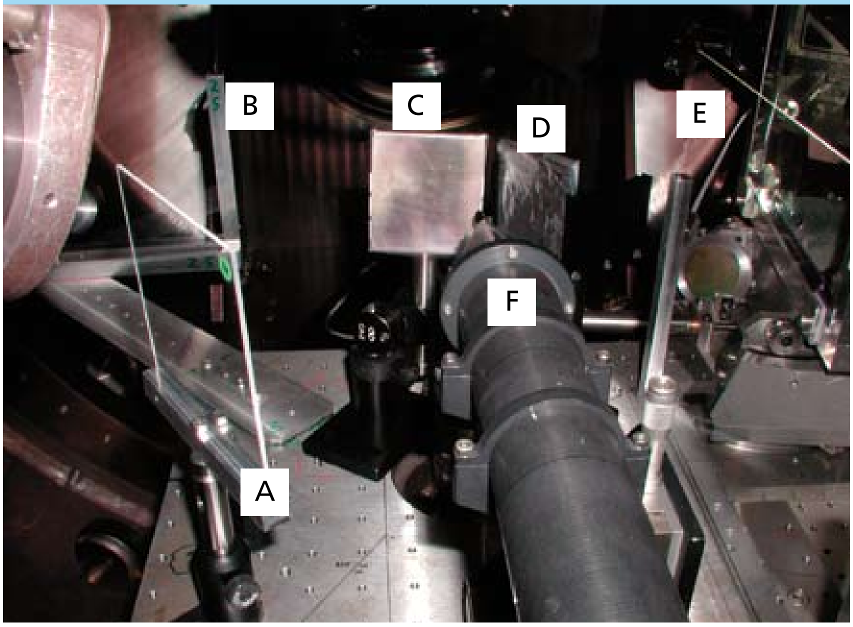
Laser-target debris production and mitigation is of concern to existing and future laser systems. Whereas the use of debris shields is well established for long (nanosecond) pulse systems there is less consensus on mitigation schemes for short (femtosecond to picosecond) pulse systems. Orion poses the challenge of protecting optics and diagnostics from both regimes, sometimes simultaneously.[1-2] It was the purpose of these experiments to explore possible Orion mitigation schemes on the Helen laser and allow potential solutions to be critically evaluated.

Helen CPA Beam Baseline Performance

The interior of the target chamber and the experimental configuration for this study is shown in Figure 1. The key elements of the arrangement are: (A) a 4 inch square, 2 mm thick fused-silica debris witness plate; (B) a 253 mm x 205 mm x 0.55 mm D263T borosilicate glass debris witness plate; (C) an aluminium plate to prevent debris hitting the CPA turning mirror and long-pulse optics (at times this was fitted with a removable polymer sheath for debris collection); (D) a radiochromic film stack with aluminium anti-fogging foil; (E) a witness plate as for B; (F) an X-ray pinhole camera. The CPA beam enters from the left and the target foil was at the chamber centre between (F), (C) and (D). A 10 micron thick tantalum foil was used as the target material and an X-ray pinhole camera was used to obtain data on the focal spot uniformity. A stack of 50 mm square segments of radiochromic film (RCF) (Gafchromic HD810) was used to monitor proton emissions from the target. In addition, several glass debris witness plates were used around the target to both monitor target emissions and protect the short-pulse turning mirror and the long-pulse optics.

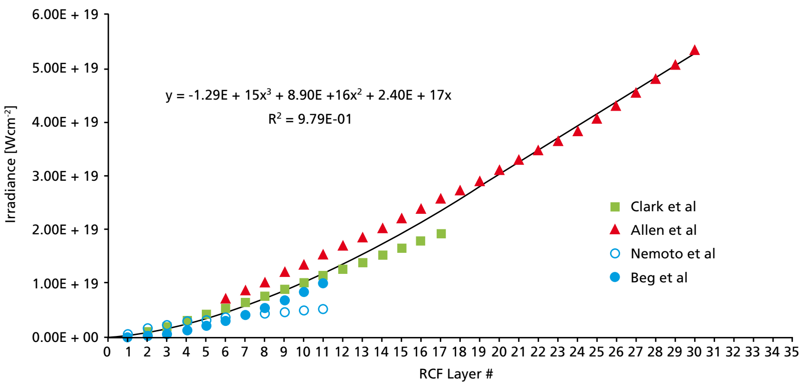
When CPA (chirped pulse amplification) pulses interact with thin metal foil targets, protons are produced if the incident irradiance is sufficiently high. The resulting emissions can be measured by exposing a stack of many layers of RCF. A number of studies have been performed with short-pulse laser beams to investigate this phenomenon[3-6] and we have used this work as a means to evaluate the peak laser irradiance via the number of film layers that show a response to the proton beam. The higher the laser irradiance, the higher the maximum proton energy and therefore the greater the penetration of the charged particles into the layers of the film stack. Figure 2a illustrates the data derived from references 3-6 and a polynomial fit that was used to relate the number of exposed layers of RCF to laser irradiance at the target. Figure 2b shows the target irradiance of the Helen CPA beam when measured by this method.

FIGURE 1

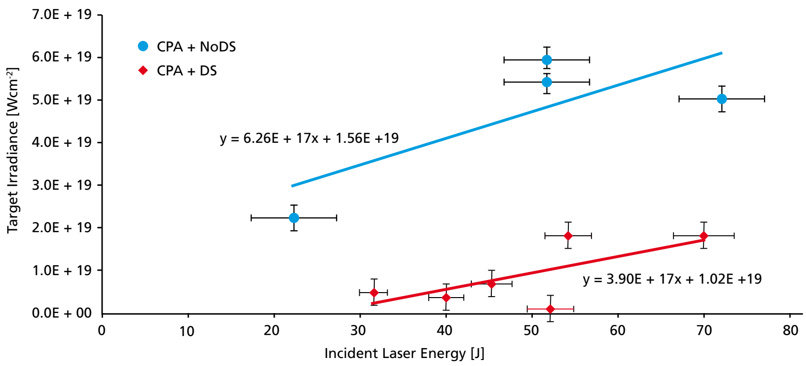


The experimental arrangement for the study of the baseline performance of the Helen CPA beam, viewed from east.

FIGURE 2



(a) The relation between maximum penetration of protons into RCF layers versus maximum laser irradiance incident onto the target foil. A best-fit cubic equation with a high correlation coefficient is drawn through the data from the four referenced studies.



(b) Target irradiance on 10 micron thick tantalum foils as a function of laser energy incident into the target chamber with (red symbols & trend line) and without (blue symbols & trend line) a parabola debris shield in place. The shield was formed from 2 mm thick BK7 glass.

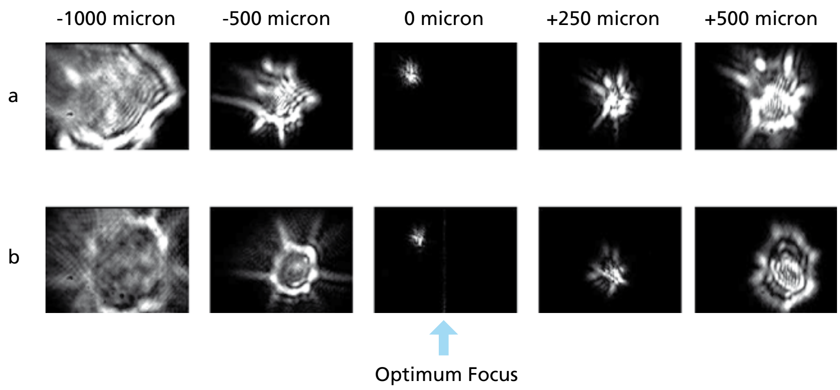
It can be seen that with a debris shield in place the beam irradiance was degraded. The proton-production threshold was about 26 J. At higher laser energies (~60 J) the irradiance was a factor of four lower than when no debris shield was used. There are insufficient data and too much scatter to obtain a good estimate of the threshold energy for proton production without a debris shield. Taking the maximum slope of the data, an intercept is given at ~5 J confirming previous observations at AWE and giving trend-data that shows that the threshold performance is quite different but that the slope of the data in both cases is similar. This suggests that the low-intensity properties of the beam are different and that the effects of laser power are secondary and the linear aberrations of the shield need to be improved.

The CPA beam is normally optimised by observing the focal spot of a low-power alignment beam with a microscope inside the Helen target chamber. The position and orientation of the focussing mirror and any debris shield is then optimised to give the smallest spot size at the target chamber centre. This alignment procedure was followed for the cases above of illumination with and without an off-axis parabolic mirror debris shield. In addition, the far-field light distribution was also measured either side of the optimum focus to determine how the light distribution varied along the optical axis of the focussing system. Figure 3 illustrates the data collected from five positions with respect to the optimum focus. The absolute position of optimum focus is different with respect to the parabola surface when a debris shield is used

> "The CPA beam is normally optimised by observing the focal spot of a low-power alignment beam with a microscope inside the Helen target chamber."

and when it is not. The data in Figure 3 qualitatively indicate that the spot size is larger when the debris shield is used and not as symmetrical as the spot from the parabolic mirror alone. Image saturation, the need to adjust neutral density on each frame capture and the need to take higher-magnification pictures near focus prevented a quantitative analysis of the debris-shield-induced aberrations in the time allowed within this experiment. This should however be further studied to determine if mount-induced, inherent material or polishing aberrations are the main cause of concern.

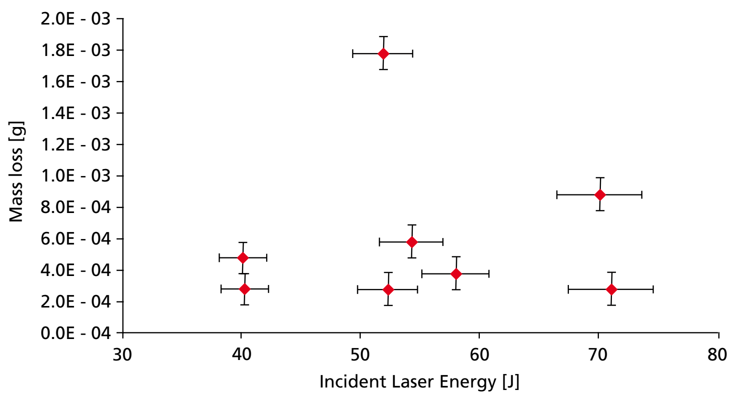
FIGURE 3



Laser spot size as a function of position (a) with a debris shield and (b) without a debris shield protecting the off-axis-parabola focussing mirror of the Helen CPA beam. The width of the image frame is 200 microns.

Each of the targets used in the above studies was recovered for inspection after the laser shots. The 10 micron thick foils had ragged-edged holes formed in them of varying sizes and were often buckled and generally tilted away from the incident face. The ejection of material during the laser interaction was sufficient to cause these mechanical effects. Figure 4 indicates the mass loss identified for the 10 mm diameter, 10 micron thick foils by comparing post-shot masses of the damaged targets with the mass of unfired foils. There appears to be little correlation with incident laser energy in this limited set of data by comparison with thicker aluminium foils studied previously.[1, 2] Most targets exhibited a mass loss in the range 0.2 – 0.8 mg but one lost as much as 1.8 mg of material.

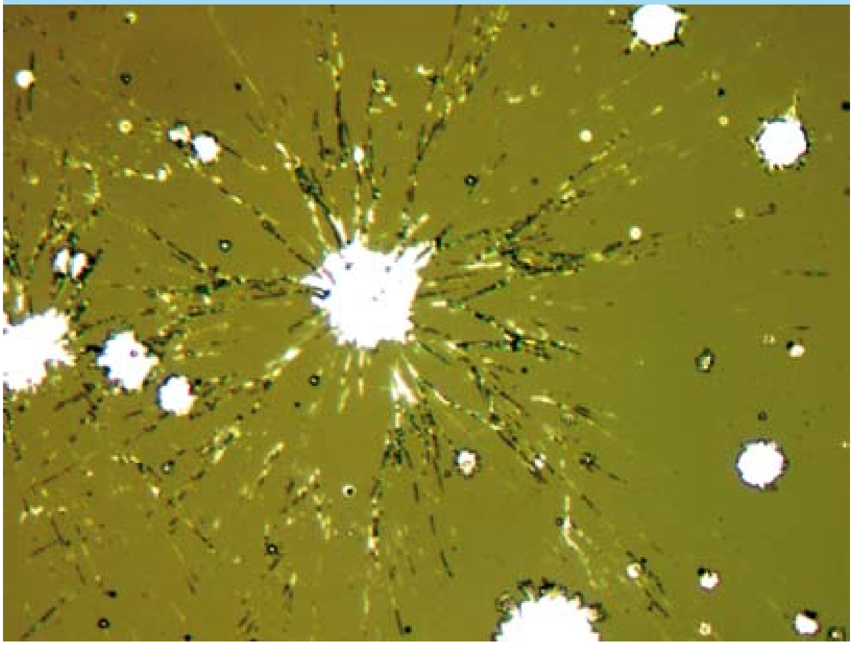
FIGURE 4



Mass loss from 10 mm diameter, 10 micron thick foils as a function of laser energy.

The material lost from the target was collected by witness plates for subsequent study. Debris features observed in these experiments ranged in size from sub-micron to millimetres. Figure 5 shows material from a target collected on a 4-inch square fused-silica witness plate. The central feature is typical of a high-velocity impact with material radiating away from the point of impact. The largest material area in Figure 5 is ~ 45 microns in diameter but thin ray features (a few microns) extend out to a diameter of 400 microns. The smallest features shown in this view are ~ 2 microns in diameter. The spatial

FIGURE 5



Target-generated debris captured on a fused-silica witness plate. The frame width of this view is 375 microns.

distribution of the debris can be very non-uniform: debris patterns appeared unique to a given shot because they probably depend on many parameters for example target material, incident energy, focal-spot intensity distribution and microscopic nature of the target material. All these parameters are subject to variation from shot-to-shot. With sufficient observations it may be possible to draw some general conclusions or at least guidelines for minimising any contamination or damage that the debris may cause.

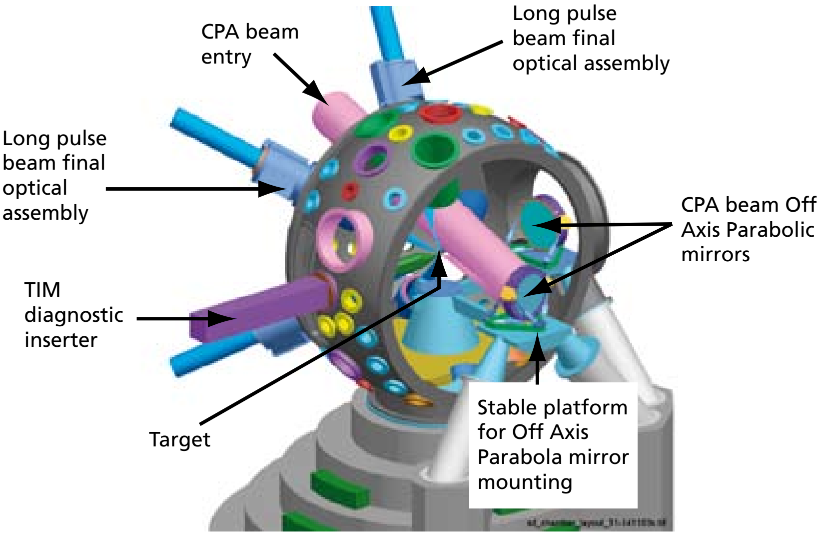
Evaluation of sacrificial mirrors

The concept of using a sacrificial mirror arose from the desire to protect the parabolic mirrors in the Orion target chamber shown schematically in Figure 6a. Debris and shrapnel can be generated readily from both targets and diagnostics in a laser target chamber and the resultant contamination adheres to optical surfaces easily. The contamination can reduce the transmittance of optical coatings, increase scattering and act as initiating points for laser damage. Shrapnel impacts lead to permanent damage to optical components. In long-pulse (nanosecond) laser systems, the use of debris shields between the aspheric focussing lens and the target is common practice. Many users of CPA laser systems are reluctant to use transmitting shields because of concerns over non-linear refractive-index effects causing a reduction in focal irradiance at the target. A possible reflective debris-shield solution is the use of a sacrificial mirror. Figure 6b illustrates how this may be achieved on Orion. A small mirror intercepts the focussing beam and diverts it through 90 degrees onto a target.

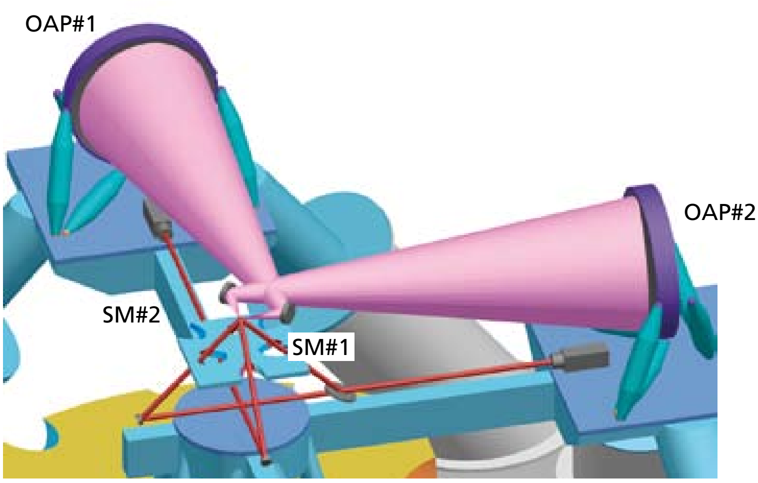
Debris emissions from the target that travel back along the path of the incoming laser beam only hit the sacrificial mirror and not the parabolic mirror. The sacrificial mirror is small, inexpensive and of short delivery time. By contrast, large-aperture parabolic mirrors are expensive (tens of thousands of pounds) and have delivery times of about one year. A disadvantage of this

"Debris emissions from the target that travel back along the path of the incoming laser beam only hit the sacrificial mirror and not the parabolic mirror."

FIGURE 6



(a) The proposed Orion target chamber utilising 10 long-pulse beams in two cones of 5 beams and 2 Petawatt-class beams. One of the CPA beams is along the axis of one of the long-pulse cones. The other CPA beam is orthogonal to its sibling (see also Figure7).



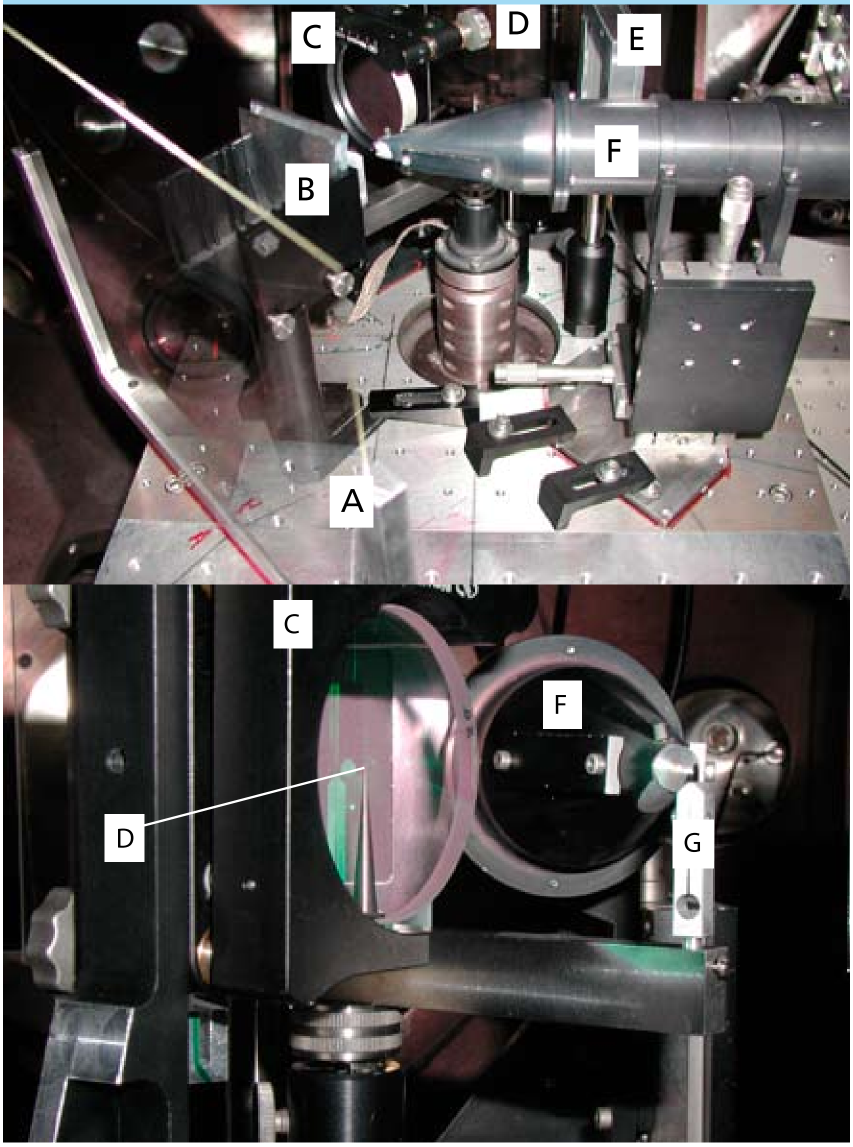
(b) The orthogonal Orion PW laser beams illuminating a target via two sacrificial mirrors. Beam one is delivered to the target by off-axis parabolic mirror 1 (OAP#1) and sacrificial mirror 1 (SM#1). Beam two is delivered to the target by parabolic mirror 2 and sacrificial mirror 2.

approach is that the sacrificial mirror is sacrificed on one shot in two ways, first it is covered with target debris from short range and secondly the laser fluence at its surface is above the damage threshold so the sacrificial mirror is in itself a source of debris, albeit not in a direction towards the main short-pulse optics. It is also possible that the sacrificial process itself could reduce the beam irradiance at target by using energy inefficiently or causing beam aberrations. The arrangement of optics, diagnostics and target used for the sacrificial-mirror investigations is shown in Figure 7.

It was desirable to simulate the Orion conditions in terms of beam irradiance at the sacrificial mirror but this implied that mirror position, aperture and in particular mirror-mount diameters would encroach on the CPA beam path from the final plane turning mirror to the parabolic focussing mirror. It was therefore necessary to reduce the beam area (and consequently energy) by a factor of 2 to ensure the hardware did not encroach on the short-pulse beam. These considerations led to the positioning of the mirror surface 50 mm from target chamber centre in the parabolic-mirror direction with the target 71 mm from chamber centre.

Because the target was no longer at the chamber centre by many 10s of millimetres and all the

FIGURE 7



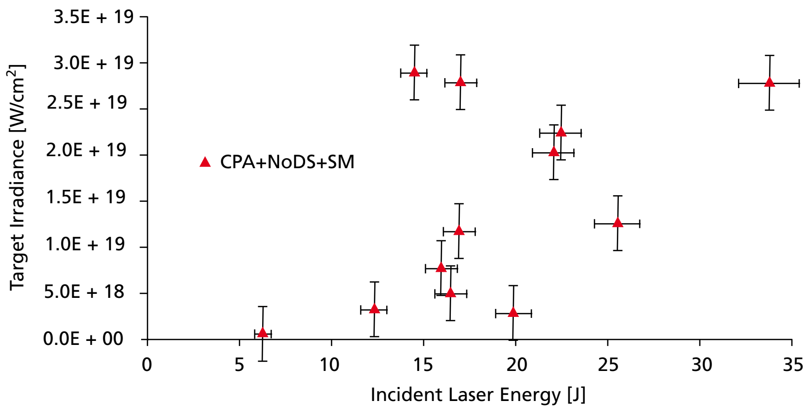
Sacrificial-mirror experiment, viewed from east (above) and south (below). (A) D263T witness plate; (B) RCF stack; (C) sacrificial mirror and mount; (D) reference spike at chamber centre; (E) pyro-electric detector; (F) X-ray pinhole camera and (G) target and its clamp mount.

conventional alignment aids and diagnostics were mounted to look at the chamber centre a number of difficulties had to be overcome in the execution of the experiment. The position of the various components and diagnostics were initially marked on the mounting table to allow ease of location. The sacrificial-mirror mount was set in position with the aid of the table markings (Figure 7a). A mirror was inserted in the mount and centred by observation of an alignment beam on the mirror surface.

A new target mount was utilised that could sit in the existing target manipulator but allowed a reference spike to be placed at chamber centre whilst holding the target in its desired off-centre position. The orientation of the sacrificial mirror was then adjusted to observe an alignment beam on the centre of the circular foil target. The parabolic-mirror focus was then optimised by the use of an insertable far-field microscope (as used for the data in Figure 3) with respect to a fiducial wire on a target. The X-ray pinhole camera was adjusted to be in the correct position by using its own reference spike to obtain the correct distance from the target. The reproducibility of the process was checked a number of times by removing and replacing the sacrificial mirror in its mount and found to be satisfactory. All these operations were initially performed at atmospheric pressure. It is well known that the alignment changes when the chamber is pumped down to vacuum so further alignment checks were necessary prior to firing a laser shot. The final alignment step was to check for a retro-reflection from the target to ensure it was at the focus of the parabolic mirror. The strength of this signal was somewhat variable but was sufficient in all cases to check the focussing.

Two shots were fired with a gold mirror. The mirror was a commercially available dielectric-protected, optically-thick gold layer. The mirror substrate was synthetic fused silica of 51 mm in diameter and 8 mm thick with a surface flatness of $\lambda/10$ at

FIGURE 8



Proton-beam and RCF-derived target irradiance as a function of incident laser energy. The pulse width = 500 fs. The beam area is reduced by a factor of two compared to the standard CPA beam.

633 nm. The objective of using a metallised mirror was to track where the coating went after the sacrificial process occurred. Gold plasmas from laser targets usually form pink and blue coatings on witness plates and identify debris patterns readily.[1] Fused silica was the choice of substrate material as there were potential concerns over proton-activation issues with BK7 glass. Two shots were also fired with a dielectric-coated silver mirror. The mirror was a commercially-available, dielectric-enhanced, optically-thick silver layer. The mirror substrate was of the same specification as the gold mirror.

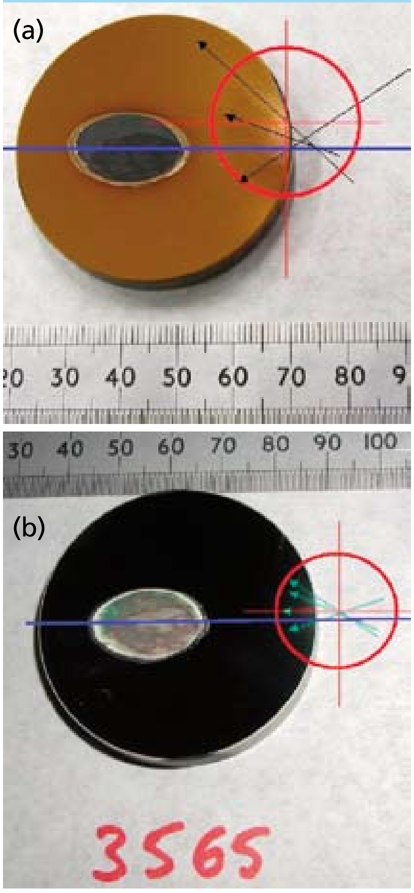
The use of a silver mirror was to compare a different metal to gold to see if there was any difference in behaviour and if the debris pattern was easier to identify as in the atmosphere silver usually blackens readily to silver oxide. Eight shots were fired with a 45 degree angle of incidence, high-reflectivity dielectric stack formed from alternating layers of high- and low-refractive-index materials. The mirror substrate was of the same specification as the gold mirror. Because of the higher reflectance available from dielectric mirrors and their superior damage threshold this is the coating most likely to be utilised for sacrificial mirrors.

> "Fused silica was the choice of substrate material as there were potential concerns over proton-activation issues with BK7 glass."

A range of pulse energies was used in the shots to examine the influence of laser irradiance on surface damage morphology, debris distribution and proton production from metal foil targets.

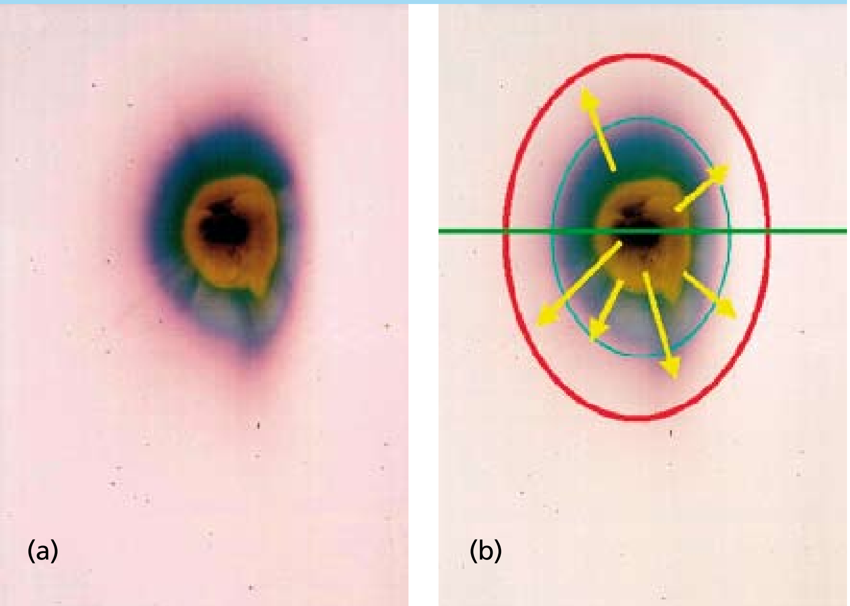
Figure 8 shows the RCF-derived target irradiance for the targets illuminated by the CPA beam with no parabola debris shield and using a sacrificial mirror. The energy threshold for proton beam production was ~6 J. The highest irradiances derived were 2.8 and 2.9 x 10^{19} Wcm^{-2} from the

FIGURE 9



CPA-laser-beam-damaged surface and target-debris patterns on (a) a gold sacrificial mirror (Shot 3561) and (b) a silver sacrificial mirror (Shot 3565).

FIGURE 10



(a) A scanned image of D263T witness plate 12 fielded on Shot 3561, 17 J incident energy with a gold sacrificial mirror.

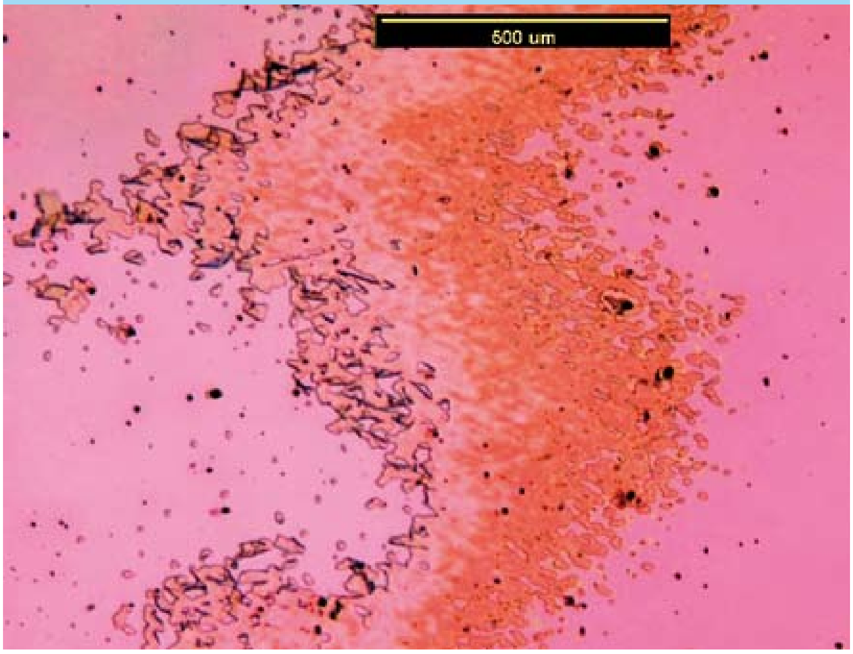
(b) An annotated and enhanced image of the witness plate.

two shots with the gold sacrificial mirrors. Post-shot photographs of a gold-coated and a silver-coated sacrificial mirror are shown in Figures 9 (a) & (b) respectively. They both show the damage caused to their surfaces by the incident CPA beam. The elliptical footprint of the surface damage was measured as 21.0 mm for the major axes and 13.7 mm for the minor axes. This implied that the range of average "on-surface" power densities used in the experiments were from 5.2 TWcm^{-2} to 28.5 TWcm^{-2}. This is clearly in excess of the manufacturer's quoted damage thresholds for the coatings, of 50 MWcm^{-2} at 10 ns pulse lengths. The debris patterns arising from the target emissions were also visible at the edges of the sacrificial mirrors. If a conical distribution from a point source is assumed it is possible to measure a cone angle for the debris field from these observations.

In Figure 9(a) the full cone angle is 20.4 degrees with the axis of the cone tipped vertically up by 3.9 degrees. The corresponding data for Figure 9(b) are 17.4 degrees and 1.0 degrees respectively. The blue line indicates the plane of the beam axis and chamber centre. The red circle indicates the extent of the debris field and the arrows indicate ray structures in the debris field that extrapolate to a common source. The upward tilt is probably explained by the use of a manual clamp mount for the foil and the target not being precisely vertical.

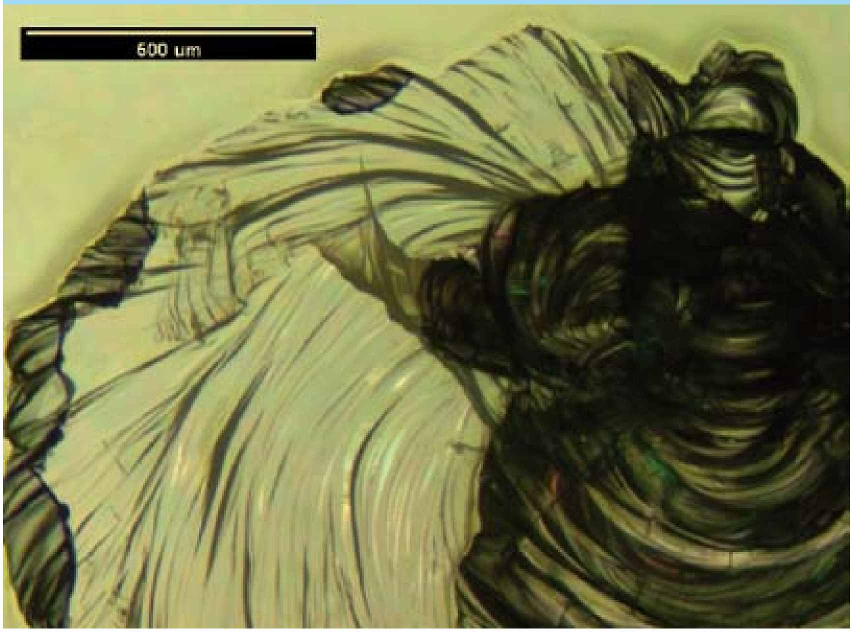
Similar analyses can be performed for the mirror-coating debris in Figure 10 but in this case it is obvious that the debris source is not a point but the damage ellipse on the mirror surface and the divergences are different

FIGURE 11



Reflected light micrograph of a multi-layer dielectric high reflectivity stack used as a sacrificial mirror on HELEN.

FIGURE 12



Exit face damage crater on a multi-layer dielectric high reflectivity stack used as a sacrificial mirror on HELEN: incident laser energy 22J.

in the horizontal and vertical planes. The green line indicates the plane of the beam axis and chamber centre. The red ellipse indicates the maximum extent of the debris field and the arrows indicate ray structures in the debris field that extrapolate from a common source of the strongest colouration of debris material (blue ellipse). Two angles Φ and γ were defined that indicate the divergence in the vertical and horizontal planes respectively. Using these definitions, the size of the damage patch, the dimensions of the debris signature on the witness plate in Figure 10 and the distance between the mirror and the witness plate, Φ was derived as 21.8 degrees and γ as 13.6 degrees for the maximum extent (outer ellipse) for the gold mirror. For the smaller, more heavily-coated region (inner ellipse) Φ = 13.2 degrees and γ = 7.6 degrees.

A similar analysis for the silver mirror with an incident laser energy of 34 J yielded Φ = 28.4 degrees and γ = 21.0 degrees for the maximum extent of the mirror debris. The smaller, more heavily-coated region had values of Φ= 8.6 degrees and γ = 3.2 degrees.

The energy transmission of the mirrors was monitored to give some information on the efficiency of the beam delivery. Because of uncertainty over the damage threshold of the pyro-electric sensor used it was decided to measure the small amount of transmitted light rather than the larger amount of reflected light. Regardless of mirror type or incident energy the mirrors transmitted about 3% of the incident laser beam. Microscopy of the mirror surfaces after the experiment showed that the main cause of damage for all the metal mirrors was complete removal of the coating. In the case of the dielectric mirrors it was more difficult to establish if all or only part of the coating was removed. Figure 11 shows a reflected light micrograph of a multi-layer dielectric high reflectivity stack used as a sacrificial mirror on HELEN with the less damaged part of the surface on the right. More layers of the stack are

"In addition there were a few craters in the surface of some mirrors that may have been caused directly by the laser beam or indirectly by shrapnel impact."

progressively damaged towards the left of the micrograph where the beam irradiance was higher. The dark lines in the left half of the view indicate material from layers that were delaminated and are aligned orthogonal to the surface. The dark oval features are probably shrapnel damage from the foil used in the experiment. In addition there were a few craters in the surface of some mirrors that may have been caused directly by the laser beam or indirectly by shrapnel impact. In either case the craters also had debris features imprinted on them and therefore the cratering must have occurred more rapidly than the slowest of the debris arrivals. On a small number of the mirrors there was a crater on the rear face (Figure 12) always corresponding to the centre of the beam-damaged area on the incident face – it is likely that this damage must be laser-induced rather than caused by shrapnel.

Conclusions

The performance of the Helen short-pulse CPA laser beam has been studied with and without a debris shield via its effects on proton production. It appears that the existing debris shields are causing a reduction of the maximum irradiance on the targets by a factor of ~4. As a consequence the energy threshold for proton production is moved from 6 J to 25 J by the use of the current form of debris shield. The main contribution to this is believed to be the conventional optical aberrations of the shield rather than a non-linear optical effect in the material.

The potential of transmissive debris shields, of the same specification as used on HELEN, for Orion may be limited to setting-up experiments when maximum intensity is not required, given the reduction in achievable intensity on target. Improvements to the wavefront-transmission specification that can extend the usefulness of this technique may be possible.

The use of sacrificial mirrors has been investigated, albeit at reduced beam area and energy. The results are encouraging, as they have produced similar irradiances to that of the unprotected CPA beam. Target-debris distributions arising from laser interactions have been observed and cone angles measured. The same is true for debris produced by the sacrificial-mirror coating. These data can be used in conjunction with a CAD model of the Orion chamber to determine the best use of sacrificial mirrors as a debris-mitigation scheme as well as defining any areas of risk from contamination by either target or mirror debris. The sacrificial mirror is destroyed in the process and therefore is only usable for a single shot. A suitable method for changing between shots is required. Alignment methods will also require further development.

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Andrew Comley •Andrew studied for his MSci in Physics at Imperial College graduating with first class honours. He joined the Imperial Laser Consortium studying X-ray and fast-ion production from the interaction of high-intensity laser pulses with liquid microdroplets. Gaining his PhD in 2001, he remained at Imperial researching laser-cluster interactions. He spent four years in the semiconductor industry where he developed and patented laser and extreme-ultraviolet light sources for next-generation lithography systems. In 2005 he joined AWE where, in addition to his work on HELEN, he has developed experimental platforms at the US OMEGA laser facility collaborating with LANL, in preparation for forthcoming radiation transport experiments at the National Ignition Facility. He is also responsible for the delivery of backscatter diagnostics and target illumination and viewing systems for the AWE ORION laser facility.

AWE's Outreach, Major Events and Collaborative Activities

Welcome to this new and exciting feature packed with all the news and stories covering AWE's outreach, major events and collaborative activities across a range of scientific, engineering and technological disciplines.

2008 has been another busy and successful year for conferences and exhibitions at AWE, in support of our outreach activities nationally and internationally. Conferences, exhibitions and awards ceremonies are an important feature of our company. The 1958 Mutual Defense Agreement followed the successful conclusion of the Grapple series of nuclear tests. In May 2008, the 50th anniversary of the '58 Agreement was marked at AWE with a stunning exhibition depicting the key highlights and exchanges of the Agreement between the UK and US governments relating to the two nations' partnership in nuclear strategy. The exhibition started its journey at AWE before moving to the Ministry of Defence (MoD) in Whitehall, then on to the Forrestal Building in Washington, and subsequently to the Atomic Test Museum in Las Vegas before finally returning to AWE.

Other major events in 2008 included the Science, Engineering & Technology Awards 2007, reported in Discovery 17, the Project On Nuclear Issues (PONI) Conference, the Strategic Alliance Partners Conference, the Plutonium Futures Meeting and the 50th Annual Meeting of the American Physical Society Division of Plasma Physics.

Nuclear debate

AWE successfully hosted the UK PONI Conference, in October 2008. PONI is a forum managed by the US-based Center for Strategic and International Studies (CSIS), on behalf of, and supported by, the US Department of Energy and Department of Defense – both the MoD and AWE also take part. PONI was set up in 2003 with the aim of building and sustaining a community of promising nuclear experts on policy and planning issues. It is attended by individuals from UK and US nuclear laboratories, the military, industry, academia and the policy community. Members in the early stages of their career are encouraged to present personal views and ideas on nuclear issues and the ensuing discussion is guided by experienced nuclear experts.

AWE managing director, Dr. Don Cook, opened the event and said: "PONI is strongly supported by our customer, the UK MoD, who hosted last year's UK conference in London. These conferences clearly exploit the opportunity to bring together representatives from the UK and US communities to focus on common interest and purpose – this stems from the very heart of PONI's mission."

The two-day event was attended by approximately 100 delegates from the UK and US and included some lively and thought-provoking debate on key issues around nuclear strategy and the global landscape. A wide spectrum of UK and US PONI members delivered presentations on common areas of interest, further demonstrating the strong partnership between the two nations. Subjects discussed included maintaining and sustaining the US nuclear deterrent, the future of arms control and disarmament, UK strategy and posture, proliferation prevention, nuclear forensics, and a view on the international approach to reducing global nuclear danger.

Prof. Richard Clegg, recently appointed as AWE's chief scientist, said: "AWE clearly understands the required technical growth, but we also need to extend AWE's development beyond the technical platform. AWE needs staff that can support HMG's nuclear technical-policy debates

"Members in the early stages of their career are encouraged to present personal views and ideas on nuclear issues and the ensuing discussion is guided by experienced nuclear experts."

FIGURE 1

Address by Prof. Richard Clegg, AWE chief scientist.

and who can engage on a wider international stage, in support of AWE's outreach programme. We thus need to ensure AWE has sufficient staff to be able to engage in this arena, with confidence and knowledge. Without PONI, we would be unable to support the transfer of experience and understanding of the important nuclear issues from one generation to the next. All of you here today will help to nurture this process".

FIGURE 2

PONI delegates.

For this reason, AWE has established the Nuclear Weapons Policy Discussion Programme (NWPDP) forum, formed of some thirty staff from across AWE, which meets on a regular basis to debate the 'big issues' facing the world, and especially those with nuclear overtones. All NWPDP members are also members of the PONI forum. The group plays a pivotal role in the knowledge exchange and sharing of nuclear issues, but also provides a development opportunity for existing and new contributors to the group ensuring a virtuous cycle of talent and expertise.

Special guest Prof. Sir Peter Knight, senior principal at Imperial College and member of the Science and Technology Advisory Committee at AWE, said: "AWE is a world leader in the promotion of science, engineering and technology. I am keen to support the next generation as they add value to the UK's deterrent programme so that we continue to be perceived in this way by the international community."

Sir Peter also repeated his belief in the importance of the kind of interaction between the US and UK which PONI is designed to foster. His thoughts were echoed by MoD's, deputy director strategic technologies, Dr. Mike Baker, who said: "The purpose of PONI is to ensure that there is a next generation of policy makers with expertise in the nuclear arena, as well as a community of technical experts who are policy aware."

"AWE's mission means that it undertakes some unique science, engineering and technology work. However, because of the

FIGURE 3

Steve Henry, deputy assistant to the Secretary of Defense on Nuclear Matters, addressing PONI delegates on US nuclear strategy and posture in the 21st century.

nature of AWE's business, we also need to be able to support MoD studies and thinking associated with nuclear policy and nuclear strategy," said David Holder, chair of the NWPDP at AWE.

More information on CSIS/PONI can be found at their website (www.csis.org/isp/poni).

Academic Alliance

For the first time, in September 2008, AWE brought together leading academics from the UK's top universities to discuss ways to maximise AWE's Strategic Alliance partnerships. Academics from the University of Cambridge, Cranfield University, Heriot-Watt University and Imperial College joined AWE scientists, engineers and technologists at the Strategic Alliance Partners Conference, hosted by AWE and supported by MoD, held at Wokefield Park, Mortimer.

Gary Burnell, AWE's Technical Outreach senior manager said: "AWE's Corporate Technical Outreach programme engages with relevant parts of the UK's science, engineering and technology (SET) community in order to add value to AWE's programmes." AWE has always had strong links with the academic community, but our Strategic Alliances offer a more strategic way of partnering with key institutions. The partnerships offer enhanced collaborations, secure financial leverage and maximise contact with high calibre scientists and engineers. A Strategic Alliance with AWE enables both parties to collaborate – to their mutual benefit – in areas of science and engineering, including the use of the other party's facilities, and the development of staff."

"The formulation of a Strategic Alliance with a university is based on a firm partnership and commitment between AWE and the whole university organisation, and not just with a specific department, faculty or group of individuals."

Partners are selected based on rigorous criteria, and once accepted, a rolling programme of research is developed and supported through the lifetime of the alliance. The inaugural conference provided a key platform for discussions in order to spur the exchange of ideas, and discuss opportunities for enhancing collaborations in the SET arena.

AWE managing director, Don Cook, opened the event and said: "It is clear to see that we have formed excellent links with the UK's top universities to address AWE's future research and development requirements through studentships, fellowships and project sponsorship. It's

> "For this reason, AWE has established the Nuclear Weapons Policy Discussion Programme (NWPDP) forum, formed of some thirty staff from across AWE..."

FIGURE 4

Vince Osgood, associate director of Economic Impact, EPSRC.

platforms like this that promote the kind of interaction that AWE strives for in order to develop the academia-industry exchange."

Prof. Peter Littlewood, head of the Cavendish Laboratory at the University of Cambridge, provided a personal insight of his views on the strategic alliance programme. In the area of advanced computing and simulation, he suggested that with nuclear energy as a future energy option for the UK, AWE could play a leading role in re-establishing core nuclear engineering knowledge and skills. Within high performance computing, he commented on the need for good software engineering practices: another area where potentially AWE could take the lead. Peter's general observation was that AWE is in a unique position to influence the debate surrounding the UK's drive in this area and should perhaps 'stamp its authority'.

Prof. Ian Wallace, head of the Department of Environmental and Ordnance Systems at Cranfield University, presented some thoughts for future improvements in the alliance. These included addressing the insularity between different groups at AWE, potentially altering the relationship between AWE and the strategic partners. This novel approach would enable the partners, as a unified force, to support AWE thus improving the visibility of the strategic alliance ethos.

With increased UK Government funding over the last decade in science research, Vince Osgood, associate director of Economic Impact, from the Engineering and Physical Sciences Research Council, argued that the UK had an enviably healthy research base. Vince discussed the EPSRC's goals for the future, which included increasing the focus on the key challenges for society and bringing about more transformative research. He concluded that the importance of linking research and innovation, in promoting collaboration in the UK is fundamental.

Prof. Chris Hankin, deputy principal of the Faculty of Engineering at Imperial College, gave an insightful overview of Imperial's collaborations with AWE, including the recently created and AWE funded Institute of Shock Physics. He noted, as a side point, that a subsidiary goal would be for the Institute to attract physicists, in particular trained shock physicists to AWE. In the area of new materials modelling research, Chris explained the concept of a joint workshop with AWE that had been used to help identify new interactions. He suggested that it would be beneficial to hold similar workshops, in the future, across all SET disciplines at AWE.

> "One of the key benefits to AWE, he commented, was that the university is keen to pursue new ideas quickly and easily."

"The discussions have undoubtedly spotlighted new applications and fresh sources of funding, painting an optimistic future for partnerships, at all levels, with AWE."

Prof. Julian Jones, deputy principal for Strategy and Resources at Heriot-Watt University, commented that multi-disciplinary and inter-institute science, engineering and technology would be instrumental in solving some of the world's challenges: energy, environmental and climate change, infrastructure and transport, the interface between life and physical sciences, modelling, and risk. Julian also noted that the Scottish Funding Council had provided funding incentives for universities to plan their research collaboratively.

With a long history of collaboration with AWE, Julian stated that the university had developed an established process for interacting with AWE. One of the key benefits to AWE, he commented, was that the university is keen to pursue new ideas quickly and easily. He added that Heriot-Watt's PhD students were now beginning to regard AWE as an employer of choice.

Julian said: "You can usually do more together than separately.

FIGURE 5

Strategic Alliance Partners Conference delegates.

"The combined efforts of everyone in the partnerships will undoubtedly help AWE to realise its vision..."

Regarding the partnership between Heriot-Watt and AWE, I believe it is one of knowledge exchange rather than the knowledge transfer process and that we (Heriot-Watt) should learn as much as they (AWE) do."

Bernard Marr, a global authority in strategy management and partnerships and chief executive and director of research at the Advanced Performance Institute, facilitated the conference. He also gave an after-dinner address, entitled 'Managing and Improving Partnership Performance'.

Gary Burnell concluded: "The combined efforts of everyone in the partnerships will undoubtedly help AWE to realise its vision, through sustained research and development collaborations thus ensuring that the UK proudly remains at the forefront of cutting-edge science, engineering and technology achievement. The discussions have undoubtedly spotlighted new applications and fresh sources of funding, painting an optimistic future for partnerships, at all levels, with AWE."

The alliances are a great model for how AWE can plan and grow its SET capabilities for the future and strategically work with relevant skills outside of the Company. Based on the success of the conference and the opportunities for the future, AWE looks forward to the next event.

Further information on AWE's Technical Outreach activities is available on AWE's website (www.awe.co.uk).

European Affair

AWE chief scientist, Prof. Richard Clegg, was among a delegation from AWE at a high-level conference held in Europe for the first time. The Plutonium Futures Meeting, chaired by Dr. David Geeson (group leader, Actinide Materials), took place in July 2008, at the Palais de Congrès in Dijon, France, attended by 375 people from across the globe. The event discussed and debated issues relating to condensed matter physics, materials science, surfaces, interfaces, colloids, corrosion, actinide chemistry, fuel cycle issues and, speciation and detection.
"We were one of three co-hosting and sponsoring organisations alongside Commissariat à l'Énergie Atomique (CEA) France and the Institute for Transuranium Elements (ITU) Germany," said events and communications manager, Paul Sagoo. "A good delegation attended from the actinides community within AWE – supporting safe and secure nuclear research as part of the world energy mix."

The French high commissioner for Atomic Energy, Bernard Bigot, gave the opening welcome speech for CEA and Didier Haas, head of the EURATOM Work Programme, represented ITU and the European Commission Joint Research Centre, while Richard delivered a speech on behalf of AWE and the UK. Richard later sat on the panel of experts for the first of two Round Table Sessions that was entitled 'Plutonium and Global Security'.

AWE speakers at the conference included Prof. Ian Donald, Brian Metcalfe and Dr. Gordon McGillivray who talked about actinide waste issues and corrosion. David Geeson, heading AWE's corrosion and plutonium metallurgy ageing programmes, chaired one of a number of sessions alongside materials chemists, Dr. Marina Dawes and Dr. Paul Roussel. Marina was also AWE coordinator for the conference.

"I was delighted with the technical content and AWE delegation at this event," said Richard, former director of Manchester University's Dalton Nuclear Institute. "The bringing together of experts and those in the early stages of their careers from the wider actinides community will, I am sure, further raise the profile of our research in this important area working with our European colleagues."

David said the senior American members of the Steering Committee were very impressed with the first European-hosted Pu Futures conference (the event had previously always been held in the US).

"There were multiple parallel sessions comprising plenary, invited and contributed talks and poster sessions."

Materials science papers from the conference will be published in the Journal of Nuclear Materials and a selection of chemistry papers will appear in Radiochimica Acta. The next conference in the series will return to America, scheduled to take place in September 2010 at Keystone, Colorado.

Plasma Physics Forum

Members of AWE's Plasma Physics Department (PPD) attended the 50th Annual Meeting of the American Physical Society Division of Plasma Physics in Dallas, Texas, in November 2008, at which over 2000 delegates were present. This unique international forum covered all aspects of plasma physics including fusion (both magnetic and inertial confinement), high energy density physics, astrophysics and laser-plasma interactions. There were multiple parallel sessions comprising plenary, invited and contributed talks and poster sessions.

AWE members presented a number of papers, and PPD co-authored several others given by their collaborators in the UK and US. The PPD-led papers covered asymmetrically-driven implosions, shock-sphere interactions and z-pinches, which all generated significant interest at the conference. As the National Ignition Facility (NIF) laser project in the US nears completion, inertial confinement fusion was, as expected, a hot topic at the meeting. The meeting also provided the opportunity for PPD staff to hold side discussions with their collaborators to address plans for further experiments at UK and US facilities, including NIF.

AWE is already fast preparing for a number of high profile events in 2009 – once again focussing on an exciting range of scientific endeavours and applications – some pioneering and others building on current capability. These include the Science, Engineering & Technology Awards 2008, the 'people's awards at AWE', to be held in mid 2009, and the Polymer Degradation Discussion Group (PDDG) Conference in Sestri Levante, Italy, in September 2009. Look out for news and conference highlights in future editions of Discovery!

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Exhibit created to celebrate the 50th anniversary of the 1958 Mutual Defence Agreement, between the United Kingdom and the United States.

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