The SCIENCE of NUCLEAR WARHEAD ASSURANCE

This information leaflet describes the key elements of a programme that will underpin future assessments of the safety and reliability of the UK's nuclear warheads. It is part of a series of leaflets that outline some of the novel scientific research MOD is involved in.

The Nuclear Warhead Assurance Panel:

In addition to MOD staff led by the Chief Scientific Advisor (Prof Sir Keith O'Nions), this leaflet was written in consultation with eminent scientists from UK industry and academia.

Prof Sir Den Davies CBE, FREng, FRS: Former president of the Royal Academy of Engineering. Until recently, chairman of the Nuclear Research Advisory Council - a public body responsible for the independent scrutiny and review of the UK Nuclear Research programme.

Dr Clive Marsh CBE: Chief Scientist of the Atomic Weapons Establishment, Aldermaston.

Prof Philip Burke CBE, FRS: Emeritus Professor of Mathematical Physics at Queens University Belfast. His research interests include atomic, molecular and optical physics and their application in astronomy and laser physics. He is also interested in the scientific application of supercomputers.

INTRODUCTION

As a responsible nuclear weapon state, the UK regards safety and reliability as central to the maintenance of their nuclear warheads. We define these concepts as follows:

- ***A safe warhead is benign in all situations other than deliberate detonation.***
- ***A reliable warhead will act in prescribed manner when detonated.***

Between 1952 and 1992 the UK carried out 45 explosions involving a nuclear yield to verify theoretical principles and to study the properties of warhead materials. The primary purpose of the tests was to demonstrate and verify scientific understanding rather than test the operation of the warheads themselves.

During each explosive test, a large amount of data was collected using a suite of sophisticated instruments. The information gathered during the nuclear tests was crucial in providing the UK with the necessary confidence in the safety and reliability of its nuclear warheads.

However, the UK is now committed to the Comprehensive Nuclear-Test-Ban Treaty and no longer conducts nuclear-weapon-test explosions or any other nuclear explosions. To address nuclear warhead assurance in the 21st Century, therefore, the UK has developed a programme of leading-edge research that does not require such explosions .The research will provide necessary confidence in safety and reliability by further developing our understanding of the fundamental processes involved.

This factsheet outlines the UK's approach to nuclear warhead assurance and describes the key areas of the research programme.

THE UK's NUCLEAR DETERRENT

Over the last decade the UK has taken action to reduce its stockpile of nuclear warheads. Polaris - a submarine launched ballistic missile (SLBM) system - has been decommissioned; similarly the nuclear bombs that were in service with the RAF have been dismantled.

Today, the Trident SLBM (introduced to service in 1994) is the UK's only nuclear weapon system. Trident is fitted with a UK warhead developed at the Atomic Weapons Establishment (AWE) Aldermaston, a 670-acre site in rural Berkshire. An overview of the principles behind a modern nuclear warhead is presented in Box 1.

Historically, nuclear weapons (including Trident) have been designed and underwritten through a combination of theory, computer simulations, laboratory experiments and the judicious use of underground nuclear tests. Nuclear tests provided the ultimate validation of the safety and reliability of the UK's nuclear warheads.

In 1998, the UK ratified the Comprehensive Test Ban Treaty and is careful to conduct its warhead assurance programme in compliance with international treaty obligations. New research into fundamental warhead science is necessary to understand more completely the processes involved. Probing and testing this understanding is crucial to maintaining a high level of confidence in the safety and reliability of the Trident warhead without recourse to nuclear testing.

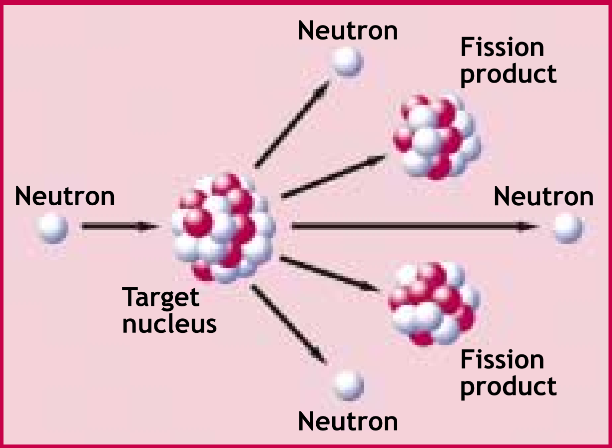
Established in 1950, AWE is the UK's centre for warhead-related research activity and is responsible for maintaining a safe and serviceable warhead through Trident's lifetime. This research is performed by AWE on behalf of the Ministry of Defence.

Box 1: How a Modern Nuclear Warhead Works

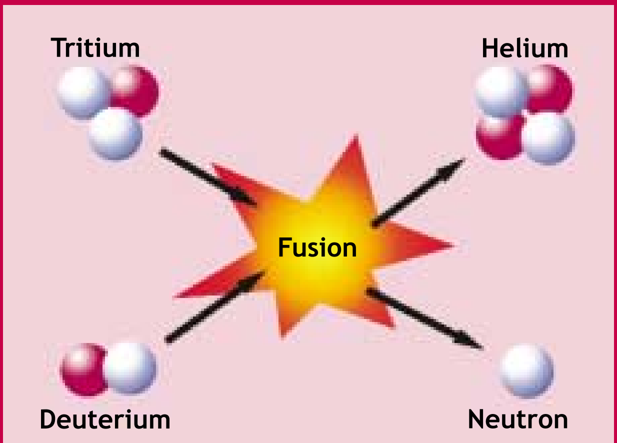
In common with chemical explosions, nuclear explosions occur when a large amount of energy is released in a very short period of time. Nuclear explosions begin with the initiation of nuclear fission when heavy atoms like plutonium are split into smaller fragments by the impact of a neutron. During fission, energy is released and further neutrons are emitted that initiate fragmentation of other plutonium atoms. This process can continue in a rapid chain reaction with the release of large amounts of energy. The very high temperatures and pressures generated can be used to initiate nuclear fusion reactions in which the nuclei of light atoms, for instance a mixture of deuterium and tritium (isotopes of the hydrogen atomic nucleus) fuse together - again releasing large amounts of energy and further neutrons. The energy that fuels the sun is derived from nuclear fusion.

Modern warheads use both fission and fusion reactions. While the precise design details of individual warheads are classified to prevent proliferation, generic principles are widely known. Modern warheads usually incorporate two distinct elements, conventionally referred to as the primary and secondary stages. When the warhead is detonated, chemical high explosives are used to compress the primary stage, which comprises a core containing plutonium-239, which undergoes rapid and uncontrolled nuclear fission. Fission is further enhanced by 'boosting' the reaction. Boosting involves the addition of a deuterium-tritium mix, which undergoes fusion due to the high temperature and pressure conditions generated by the supercritical plutonium-239. The exploding primary stage is then used to initiate a secondary stage, which consists of both fissionable and fusionable materials. The majority of the overall energy or 'yield' released during a nuclear explosion is derived from the secondary stage.

Nuclear Fission: **a large atomic nucleus can be fragmented into smaller fission products by the impact of a neutron. More neutrons - and energy - are also released.**



Nuclear Fusion**: tritium and deuterium collide and fuse to form a helium atom. The reaction also produces a neutron and releases energy.**



THE UK's WARHEAD ASSURANCE PROGRAMME

The primary goal of the UK's programme of warhead assurance is to maintain a high level of confidence in the safety and reliability of the Trident warhead. To do this, AWE scientists must be able to demonstrate their understanding of the physical and chemical processes that occur within the warhead. In addition, age-related changes must be investigated and the implications understood. Computer simulations are used to predict the effect of future changes and warheads are routinely withdrawn from the operational stockpile for forensic examination, which further improves the accuracy of these simulations. However, there are a number of challenges presented by the warhead assurance programme:

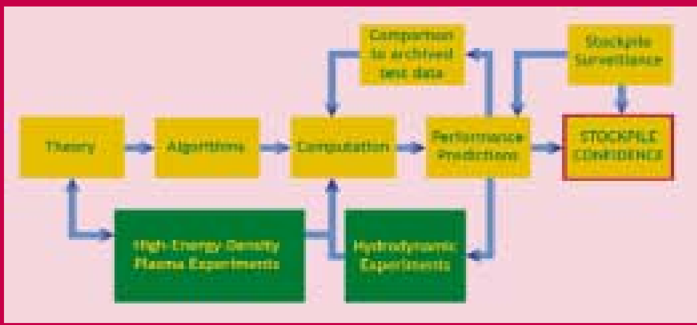
- **The extreme temperature and pressure conditions that occur at the heart of a nuclear explosion are difficult to generate via alternative means.**
- **The interactions between the various components of a warhead are highly complex and hard to characterise.**
- **Some of the materials used in nuclear warheads exhibit very unusual properties.**

The UK’s response to these issues is the warhead assurance programme (illustrated below).

Box 2: The UK's Warhead Assurance Programme

There are four main areas of research undertaken as part of the UK's programme to address warhead assurance, namely:

- **Computer simulation**
- **Hydrodynamics**
- **High-energy-density plasma physics**
- **Materials ageing**



Experiments and models are used to test theoretical understanding of the scientific principles and processes involved. Confidence in the safety and reliability of the UK's nuclear warheads is based on the accuracy of computer models when compared with experimental data. Historical test data and detailed examination of warheads withdrawn from the stockpile also provide information to validate the models. Each of these areas of research is described in this information leaflet.

COMPUTER SIMULATION

To simulate the behaviour of the Trident warhead, computer models have been developed. Refining these models to improve the accuracy of the simulations is central to AWE's programme. High-fidelity models require a good understanding of the fundamental physics, material properties and reactions that occur during a nuclear explosion. With modern supercomputers, it is becoming possible to design and run detailed 3-dimensional models that represent those processes that are pertinent to warhead research. In common with other branches of research science - from atmospheric chemistry to zoology - warhead models are rooted in theory and tested through carefully designed laboratory experiments. In addition to the experimental data obtained by UK studies, the programme benefits from long-standing collaboration with US scientists, which takes place under the auspices of the Mutual Defence Agreement, signed in 1958. The UK and US share certain information regarding test data and results from their respective research programmes.

Box 3: Computer Power

Massively powerful supercomputers are necessary to run the complex models that simulate the physical and chemical processes of a nuclear warhead. To run these computer models from start to finish can take days, or even weeks.

During 2002, AWE will substantially upgrade its computing facilities and establish itself as one of the leading computer installations in the world. The new system will increase the existing computer power 30-fold and deliver 3 teraflops - the capability to perform 3 million million calculations per second. To put this in perspective, if the 6 billion inhabitants of the earth were each given a calculator, they would need to carry out 500 calculations every second to keep pace!

HYDRODYNAMICS

When the primary stage of a nuclear warhead is explosively compressed, components (including the plutonium core) experience extremely high rates of strain causing them to behave like fluids. The behaviour of materials under such conditions is known as 'hydrodynamics' and is actively being studied at AWE. Experiments carried out at AWE involve explosive compression of materials to observe how compression and shock waves develop and how materials behave at interfaces between components. Explosive experiments take place within robust facilities that are specially designed to contain the experiment safely. Simulant materials such as tantalum or lead are normally used in these experiments, but due to the unique properties of plutonium a small number of experiments necessarily involve plutonium itself. In these cases the amount of fissile material used is far below the quantity necessary to produce nuclear yield. As a further precaution, tests involving toxic or fissile materials are completely contained within a further leak-tight vessel made of thick submarine steel. In addition to experiments planned at AWE, complementary experiments are being carried out in collaboration with the US weapons laboratory, including some at their facilities in Nevada.

To study the movement of shock waves through the high-density material, AWE has developed a technique that uses powerful X-ray machines to record snapshots of an experiment. Other research establishments also use this method, but currently the facility at AWE is unique in operating two X-ray machines together. The facility can provide information in one of two configurations:

- **Capturing simultaneous images of an experiment along different axes provides an insight into 3-dimensional phenomena.**
- **Recording two images at different times during the experiment means that the evolution of shock waves in the material over time can be studied.**

Data obtained from the dual X-ray configuration is valuable, but it is limited because only two radiographs can be taken of each experiment. Utilising UK expertise in this area, AWE is now designing a new hydrodynamic research facility that could include up to five X-ray machines. Data from this facility would be processed to produce 3-dimensional, time-sequenced representations of the experiment.

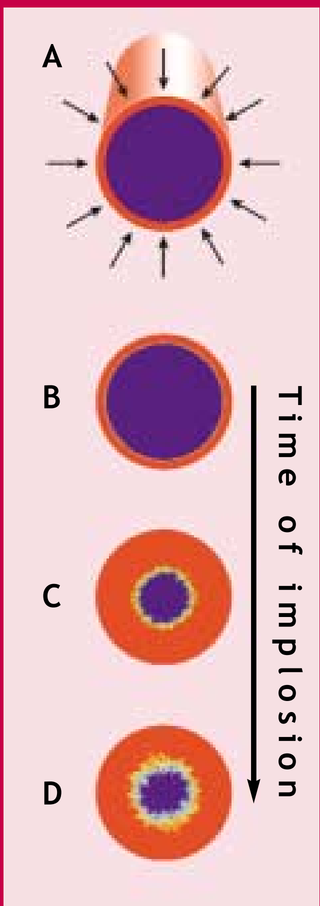
Turbulent mixing plays a major role in the functioning of a nuclear warhead. Conditions can exist where mixing between materials either side of an interface affects overall warhead performance. An important case is a phenomenon called the Rayleigh-Taylor instability (below), which can result in surface break up and mixing of materials at the interface.

Box 4: Turbulent Mixing and Rayleigh-Taylor Instability

Turbulence is an everyday occurrence visible in the movement of water and in cloud formation and weather patterns. However, for such a well-known physical process turbulence is poorly understood. The search for a theory to fully explain turbulence has not yet provided a complete answer, even though detailed 3-dimensional models can be run using modern supercomputers and there is significant University research in the area. AWE scientists are investigating specific aspects of turbulence - one of which is known as Rayleigh-Taylor instability. A simple model that illustrates Rayleigh-Taylor instability is the implosion of a metal tube containing a material of much lower density (right).

Inward pressure on the cylinder walls cause it to implode (A). As the implosion proceeds, material inside the cylinder is 'squeezed' inwards. The interface between the two materials becomes progressively unstable, which leads to turbulent mixing of the materials (B-D). In this experiment very small random imperfections exist on the otherwise smooth interface. These imperfections grow rapidly with time as a result of the surface instability. The area and extent of turbulent mixing increases as the implosion proceeds, from the small imperfections at B to the large mixing area in D.

The issue facing AWE scientists is to model the overall effect of Rayleigh-Taylor instability on mixing and its impact on warhead performance rather than the fine detail of the mixing zone. This is analogous to predicting the weather over an area, rather than for a specific location.
3-dimensional numerical models are used to simulate turbulent mixing processes in conjunction with experimental studies to investigate relevant mixing processes.



LASER PHYSICS

To understand more fully those processes that occur during a nuclear explosion, fundamental data about the materials involved must be obtained - under comparable temperature and pressures. However, it is difficult to replicate the extreme temperatures and pressures that occur during a nuclear explosion by alternate means. The method of choice at AWE is to use ultra-high power lasers.

If high-power laser beams are focused into a small volume (less than 1mm^3) for a very short time period (about 1 nanosecond or 1 thousand millionth of a second) it is possible to generate temperatures above 1 million ^oC. This provides conditions that approach those at the centre of a nuclear explosion and is sufficient to perform useful experiments on material properties.

One of the main aims of the laser physics programme is to investigate 'radiative opacity', a measure of how much materials impede the flow of radiation. A simple example is the 'flow' of visible light (which is a form of radiation) through different materials. It is obvious through experience that some materials (like glass) impede the transmission of light less than others do (like wood). AWE is primarily interested in high-energy radiation and the opacity of materials in the plasma phase, where free electrons and positively charged ions co-exist.

Radiative opacity varies with the nature, temperature and density of a material. Over the past 15 years, the 1-terawatt (1 million million watts) HELEN laser at AWE has made it possible to collect meaningful data on radiative opacities. However, even this powerful laser cannot generate the temperatures and pressures experienced within a nuclear warhead. Currently, opacity values for warhead conditions are generated using computer models. In order to validate predicted opacity values, the UK is pursuing a two-pronged approach:

1. The UK is working with the US on a giant laser currently under construction in the US: the National Ignition Facility (NIF). When operational, NIF will deliver 600-terawatts of laser power and provide a platform for opacity experiments under realistic conditions. NIF will also provide the opportunity to achieve thermonuclear fusion under controlled laboratory conditions.

2. AWE are assessing the feasibility of developing a new laser facility in which to fire short-pulse lasers at targets pre-compressed using a long-pulse laser. It is a promising new technique that could generate temperatures and pressures far greater than those currently achievable; reaching into the conditions pertinent to a nuclear explosion.

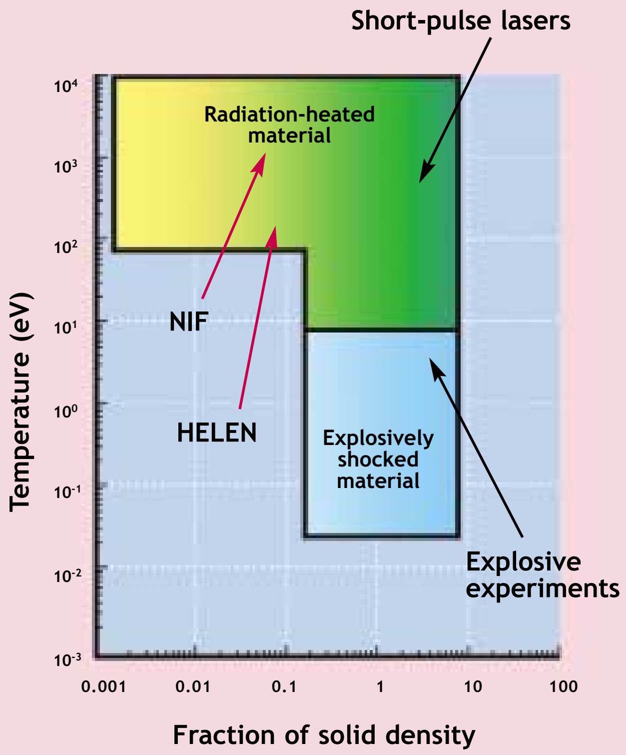
Box 5: Conditions Inside a Nuclear Explosion

The intense temperature and pressure conditions generated during the operation of a nuclear warhead are illustrated (right).

In this chart, temperatures are expressed in electron volts, where 1eV = 1.16x10^4 ^oC. Ambient room temperature, 20 ^oC, is equivalent to about 3x10^{-2}eV. Pressures are represented by fraction of solid density.

Conditions achieved using explosive experiments and the 1-terawatt (10^{12} watt) HELEN laser at AWE are also shown, as is the giant 600-terawatt NIF laser currently under construction in the US.

In the future, lasers with very short pulse lengths (about 1x10^{-15} seconds) might provide an alternate route to accessing suitable temperature regimes.



MATERIALS AGEING

The design of modern nuclear warheads is necessarily complex and involves the use of many different components. In terms of safety, the Trident warhead contains an array of robust features that prevent accidental detonation.

A large number of materials (such as metals, rubbers, high explosives and inorganic salts) are utilised in the Trident warhead, all of them selected for certain characteristics. Some of these materials are very unusual. To maintain warheads in a safe and reliable state throughout their in-service lifetime any age-related issues must be identified as early as possible. Once identified, the implications of each problem must be understood - and solutions developed if necessary. A further complication is that some components used within the warhead are no longer available, either due to legislation (e.g. the Montreal Protocol on Substances that deplete the Ozone Layer) or cessation of manufacture for other reasons. Before introducing any new component its properties must be fully characterised.

In addition to basic materials research, warheads are periodically withdrawn from the stockpile, dismantled and subjected to forensic examination to check the health of the stockpile. Some components known to have a limited life are located outside of the sealed nuclear package. Replacing these components is relatively straightforward - for example, tritium decays over time (half-life = 12.3 years) and is routinely replaced at planned intervals.

However, replacing components located within the nuclear package presents a far more difficult challenge. In response to this, the possible degradation of materials within the nuclear package (such as plutonium and chemical high explosives) is the subject of ongoing research. Several ageing mechanisms have been identified for plutonium:

- **It is chemically reactive and susceptible to conventional corrosion that affects most metals.**

- **Plutonium undergoes internal degradation that occurs due to radioactive decay. Over time, plutonium-239 decays to uranium-235 (half-life = 24,400 years) generating a helium ion.**

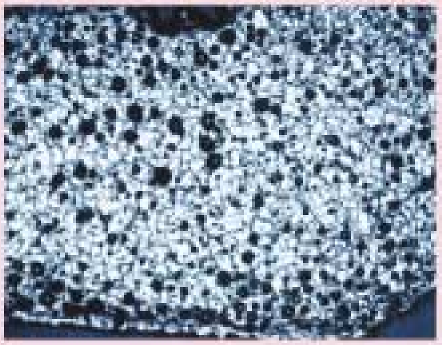
The energetic release of positively-charged uranium and helium nuclei causes considerable modification to the internal structure of plutonium. However, measurements of aged plutonium show that the overall crystalline structure is preserved in samples over 30 years old, due to an apparent self-annealing of the plutonium.

Given the unique nature of plutonium (see Boxes 6 and 7) more investigation is required to probe the behaviour of this most unusual of materials even further.

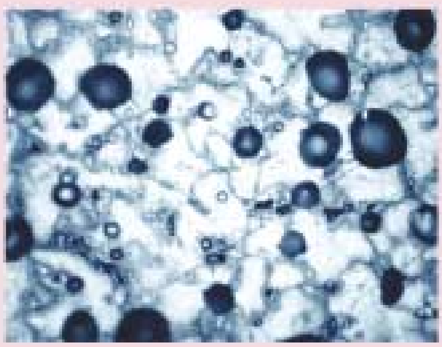
Box 6: Helium Bubble Growth Within Plutonium Metal

It has been estimated that 2500 plutonium atoms are displaced by each energetic uranium nucleus that is released due to radioactive decay. These uranium atoms bludgeon a path through the crystal structure and create 'holes' in their wake. This has such a significant effect that on average, each plutonium atom will have been jogged from its original site within 10 years. Helium ions also modify the internal structure of the plutonium, albeit in a more subtle manner. Following the capture of two electrons from the plutonium metal, helium atoms are created which diffuse and combine with others to form bubbles of gas within the metal.

Under a microscope helium bubbles of a comparable size (≈100μm) to plutonium grains are visible after this plutonium sample was held at 500 °C.



a) Plutonium sample magnified by approximately 60 times

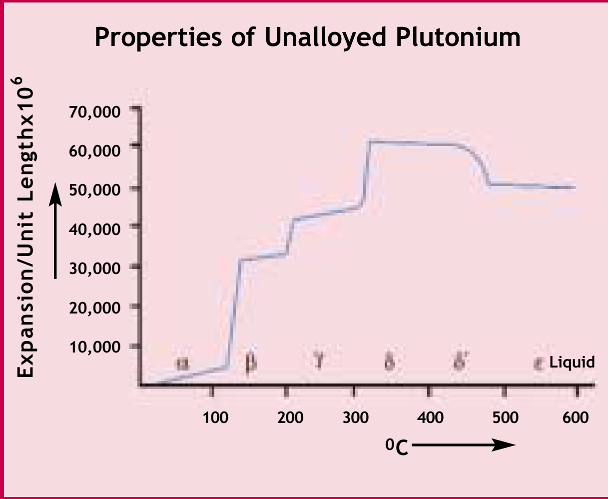


b) Plutonium sample magnified by approximately 300 times

Box 7: Plutonium - a Most Unusual Material

Plutonium, the 94th element in the Periodic Table, can be produced from uranium-238 in a nuclear reactor. It is a unique metal with very unusual properties. Consequently, investigating its nature and attempting to understand the relevant physics and metallurgy is very challenging. In addition to being fissile and radioactive, plutonium is toxic and chemically reactive, meaning that special handling techniques are required.

Relatively small changes in temperature, pressure or chemistry can alter the electronic configuration of plutonium, and hence its physical properties. One particularly abnormal characteristic is that solid plutonium displays 6 different phases when heated from room temperature prior to melting at 650 ºC (see chart, right). Each phase is distinct and has, for example, a different crystal structure, density and resistivity to its counterparts. This can present enormous difficulties in fabricating and storing plutonium. However, it has been found that if small amounts of gallium (under 10%) are added to molten plutonium, the highly ductile δ-phase can be cooled to room temperature making it possible to form and cast the metal into the desired shape.



ASSURANCE INTO THE FUTURE - THE WAY FORWARD

This information leaflet sets out the key issues involved with assuring the safety and reliability of the UK's nuclear weapons and describes the scientific research carried out at AWE in response to this challenge.

While the UK is working towards the ultimate goal of global, verifiable nuclear disarmament, it is committed to maintaining a nuclear weapon system as the ultimate deterrent for as long as this is required. To maintain a safe and reliable warhead, it is imperative that an assurance programme be performed. For the warhead assurance programme to be effective a vibrant science base at AWE must be preserved and further links forged with the wider research community. Recent years have seen a shift in emphasis towards active research in fundamental science. The elements of this research are being brought together and interpreted using high-fidelity 3-dimensional computer models.

The proposed hydrodynamic research facility and new laser installation will provide scientists at AWE with state-of-the-art facilities with which to conduct leading-edge research. Continued collaboration with academic and industrial colleagues in the UK and warhead scientists in the US will enable specialists at AWE to push forward the frontiers of nuclear warhead science.

The scientific research and assessment programme outlined here, combined with surveillance of sample warheads, has been developed to provide the necessary level of confidence in the safety and reliability of Trident for as long as it is required.

FURTHER INFORMATION

Some of the scientists responsible for compiling this information sheet have also published an article in the scientific journal *Nature*. This covers some of the topics outlined here in more scientific and technical detail. See *Nature*, vol 415, pp 853-857, 2002. Figures contained in Boxes 5, 6 and 7 are based on those that appeared in the *Nature* article.

AWE publishes a science and technology journal called *Discovery* that highlights the research achievements at AWE.
For details contact:
The Corporate Communications Office,
Building F6.1,
AWE Aldermaston,
Reading,
Berkshire RG7 4PR.
AWE also has a website that describes its programme, www.awe.co.uk

For further information on science within the MOD please visit the MOD website at www.mod.uk. Other science information leaflets - covering topics such as Genomics and Nanotechnology - are also available from the MOD.

If you have any specific queries about this information sheet or its contents, feel free to e-mail the Director of Strategic Technologies at dstrattech@gtnet.gov.uk.

Alternatively you can write to us:
Director of Strategic Technologies,
Room 5/18 MOD Metropole Building,
Northumberland Avenue,
London WC2N 5BP.