THE BANG BEHIND THE BUCK

Replacing the UK's Nuclear Warheads

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OCCASIONAL PAPER

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Other papers within this series include a discussion of the practical implications of a move away from continuous submarine patrols; a discussion of the UK's approach to replacing its nuclear forces; and an analysis of the role of UK's co-operative nuclear relationships in this process.

Each paper presents these factors within their historical context, and examines both the political and technical issues that drive them. Their role in shaping the future of the UK's nuclear forces is then discussed with reference to archival sources, research interviews and technical studies.

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The Bang Behind the Buck: Replacing the UK's Nuclear Warheads

Amidst the political soul-searching over the future of the UK's nuclear forces, the renewal of its ageing *Vanguard* submarines has dominated the public debate. Given the funds required to replace them, this is only natural. However, an important point has been neglected. The submarines are only one element of the UK's nuclear forces, which incorporate Trident D5 missiles and the nuclear warheads that arm them. Just as submarines age and require replacement, the UK's nuclear warheads also deteriorate over time and may eventually need replacing themselves.

Brought into service in 1994, the UK's current arsenal of nuclear warheads will celebrate its twentieth anniversary this year. While there are few concerns about its current effectiveness, it is unclear whether it will continue to age gracefully. The complex array of interconnected components that make up the UK's warhead deform and decay over time, affecting its behaviour and thus the reliability of the warhead. To date, the UK has been able to maintain its warheads by replacing and refurbishing these components with US assistance through the 1958 Mutual Defence Agreement (MDA), which is due for review and possible extension this year.[1]

However, it is not clear how sustainable this approach is. Eventually a fault may arise that cannot be easily remedied, and replacing original parts with alternatives gradually alters warheads from their original tested design, introducing uncertainty into their functioning and effectiveness. And most importantly, the UK may not always be able to rely upon the US for the provision of relevant materials and expertise. The future of the US nuclear arsenal is currently uncertain and, as will be argued below, the UK will likely be unable to decide the future of its own arsenal until the US has done so – no matter what condition its warheads are in.

The most recently published estimate of the longevity of the UK's nuclear arsenal suggests that gradual refurbishment and maintenance can keep it in service at least until the late 2030s.[2] However, if indications emerge that the arsenal could not survive beyond this projected timeline, then the UK would have to develop a replacement or accept that its nuclear force would eventually become ineffective. The 2013 Trident Alternatives Review suggests that replacing the UK's nuclear warheads would take approximately seventeen years for the first unit at an estimated cost of around £4 billion in 2012 prices.[3] As such, the next Parliament may have to start considering a replacement towards the end of its term if a replacement were to be needed by the latter half of the 2030s.

Despite being pivotal to the long-term operation of the UK's nuclear force, very little information has been made available as to what replacing a nuclear arsenal actually involves and how a replacement decision will ultimately be made. This is because most details of the UK's nuclear arsenal and the methods used to maintain it are understandably classified. This paper draws upon what open sources are available to shine some light onto this issue by outlining the composition and status of the UK's nuclear arsenal, and describing how it might ultimately be replaced or renewed.

In doing so, it argues that making such a decision purely on the basis of projected reliability will be very challenging. With limited understanding of warhead ageing and without recourse to nuclear testing, it is extremely hard for the UK to quantify the confidence that can be held in any assessment of a warhead's longevity beyond its initial planned service life, which is often conservative. Indeed, reflecting US policy, the UK may not even attempt to quantify such confidence. Bearing the financial and political burdens of replacing the UK's nuclear arsenal in the face of such uncertainty may dissuade the government from making such a choice unless compelling projections of unreliability emerge. In the absence of an obviously fatal flaw in the existing warhead, the fate of the UK's nuclear arsenal may actually depend more upon external than internal factors.

Ultimately, the dynamics of the UK's relationship with the US nuclear programme, rather than any assessment of UK warhead reliability, will dictate any decision to retain or replace the UK's nuclear arsenal. Technological change and the development of missile defences may force the US, and subsequently the UK, into upgrading or abandoning their nuclear arsenals. Similarly, a radiological or even nuclear accident may generate such fear in the public that both parties may have to fundamentally revise the safety features of their warheads. Finally, if the US abandoned the Trident D5 missile in favour of an alternative, the UK would most likely have to pursue a new warhead to fit a new missile. Unfortunately, the UK may have no more luck predicting the future of the US nuclear programme (whose greater resources make it far more agile) than it does the reliability of its own nuclear stockpile.

Building a Nuclear Arsenal

The origin of the current Trident warhead, and indeed most of the UK's past nuclear warheads, can be traced back to the 1958 MDA with the US. This agreement, forged in the shadow of the Soviet Union's burgeoning intercontinental ballistic missile (ICBM) capability, ended twelve years of nuclear separation between the former wartime collaborators and gave the UK access to more advanced nuclear expertise and capabilities from across the Atlantic. Following this agreement, the two partners strengthened their collaboration with the 1963 Polaris Sales Agreement, which provided the

UK with Polaris submarine-launched ballistic missiles to carry domestically manufactured (but collaboratively developed) warheads to their targets.[4]

When it became clear in the late 1970s that the US would phase out the Polaris missile over the 1980s, the UK was faced with an important choice. If it wished to retain the domestically designed upgrade (known as Chevaline) to the Polaris warhead, it would also have had to generate a domestic source of missile parts to maintain its existing arsenal without US assistance. On the other hand, if it chose to abandon the Polaris missile in favour of the Trident missile under development in the US, it would also have had to develop a new warhead that would be compatible with the characteristics of Trident.[5]

In June 1980, the UK chose to phase out the Chevaline system at the beginning of the 1990s in favour of Trident missiles, armed with a new warhead and carried by a new generation of *Vanguard*-class submarines.[6] Drawing upon initial option studies and US efforts to develop its own Trident warhead, development of the UK's warhead began in earnest later that same year with the 'Dutchess' test explosion at the US Nevada Test Site.[7] After nine more development tests between 1980 and 1987, the Trident warhead likely entered production in the late 1980s.[8] Following three final explosive tests at the Nevada Test Site in 1989, 1990 and 1991,[9] the new warhead entered into service in late 1994 and armed the first *Vanguard* submarine patrol in early 1995.[10] In total – and taking into account initial studies prior to the 1980 Trident decision – the UK's Trident warhead was brought into service over a period of around sixteen to seventeen years: the same duration anticipated for a replacement warhead.

The UK's Current Nuclear-Warhead Stockpile

Today, the UK retains an estimated stockpile of up to 225 Trident warheads.[11] The majority of these warheads are held aboard active submarines and are periodically removed for servicing at the Royal Naval Armaments Depot in Coulport, close to the Royal Navy Clyde Naval Base at Faslane. Before entering a patrolling cycle, submarines dock at a covered pontoon at Coulport to be armed with warheads. These are brought down from their stores and 'married' to the submarine's missiles. When submarines are removed from the patrolling cycle this process (which can take a number of days) is reversed.

The UK's total stockpile is steadily being reduced to no more than 180 warheads, and is split into two portions. The largest portion contains those kept 'operationally available' for the *Vanguard* submarine fleet and contains no more than 120 warheads. Submarines entering the patrolling cycle are now each equipped with eight active Trident D5 missiles, which are in turn armed with forty warheads between them.[12] This operationally available inventory represents a full complement of warheads for three of the UK's four *Vanguard* submarines. On average, each missile would be loaded with five warheads: less than half its total capacity. However, it is highly unlikely that these warheads will be spread evenly amongst all eight missiles. It has been suggested that some missiles may contain only a single warhead to serve a 'sub-strategic' role,[13] which can demonstrate the will to escalate to a large-scale strike.[14] While the UK avoids referring to a sub-strategic role, accepting that any use of nuclear weapons would be unavoidably strategic, the capability to deliver a relatively limited nuclear strike remains in place.[15] To keep these warheads in operation, a small number are occasionally returned to the UK's Atomic Weapons Establishment (AWE) in Berkshire for examination, maintenance and refurbishment.[16] To accommodate this gradual maintenance without reducing operationally available stocks, a second portion of the total stockpile serves as spares.

By reducing the number of its operationally available warheads, and subsequently the amount of spares required for maintenance and refurbishment, the UK will eventually bring its overall stockpile down to no more than 180 warheads. The monitoring of warhead convoys between Coulport and AWE suggests that this reduction process is currently underway – something the UK Ministry of Defence has confirmed by stating that warheads are being disassembled and processed in a way that prevents their reassembly.[17]

The Anatomy of a Nuclear Weapon

In order to consider the impact of component degradation, it is worth briefly considering the design of the UK's warhead. As detailed information on the UK's Trident warhead is highly classified, it is not possible to give a description of its actual composition. The basic principles of nuclear explosives, however, are relatively well known at an unclassified level. It is therefore possible to outline the main components of the UK's nuclear warhead with a reasonable level of confidence. (For a more detailed description please see Appendix 1.)

At the warhead's heart lies a spherical 'pit' of plutonium which, when compressed to several times its normal density by a shell of high explosives, generates a fission reaction in which the splitting of one atom causes other atoms to split. This process is boosted by the injection of lighter elements into the core of the imploding pit, which fuse together and release energetic particles that destabilise the heavier atoms in the pit, prompting them to split as well.

To reach yields of approximately 100,000 tons of TNT (100 kilotons, or kT), the UK's warhead harnesses the energy produced by this fission pit (or 'primary') to spark fusion in a larger, separate 'secondary' reservoir of light elements. Rather than using the explosive power of the primary to compress the secondary (which would be torn apart by the force), a heavy metal radiation casing reflects 'soft' radiation from the primary reaction around the interior of the weapon while allowing more energetic radiation such as

X-rays and gamma rays to escape. The 'momentum' carried by this softer radiation quickly compresses and heats the secondary (before the explosion tears it apart) until fusion is again ignited. The energy produced by this secondary can then be used either to spark more fission – serving, in a sense, as a larger-scale 'booster' – or can be released as a fusion component of the nuclear explosion.

To hold all these nuclear components in place within the radiation casing and to channel soft radiation smoothly around the secondary, the void between the primary and the secondary is filled with an extremely light but strong inter-stage material, thought by some to be a material called 'fogbank'.[18] This collection of nuclear components (including the primary, secondary, and inter-stage materials) is often referred to as the 'physics package', as it carries out the core physical processes of a nuclear explosion. The UK can tailor the yield produced by its warhead by including or excluding certain stages in the physics package. For instance, the UK could avoid 'boosting' the primary, or disrupt the radiation implosion of the secondary in order to reduce the warhead's yield.

Non-Nuclear Components

While the physics package represents the nuclear 'explosive', there are a number of components that integrate this explosive into a deliverable and serviceable weapon that will detonate only at the correct time. For example, the neutron generator that triggers fission in the primary is held outside of the physics package for ease of replacement. For similar reasons, the gas transfer system that injects tritium 'boost' gas into the primary is also stored outside of the physics package. Finally, the mechanisms which ultimately arm, fuse and fire (AF&F) the weapon – such as radar fuses, safety and security devices, detonators and batteries – are installed around the physics package and integrated into the weapon casing. In the case of the Trident warhead, this weapon casing is a heat-proofed conical shell that protects the warhead during atmospheric re-entry and ultimately brings it to its target.

Many of these non-nuclear components are supplied to the UK from the US under the MDA, and it was also known early in development that the Trident warhead would depend upon the US for spare components, training and missile-test facilities, along with supporting technical information and services.[19] For instance, the UK has upgraded its warheads with the US-supplied Mk4 re-entry vehicle and its accompanying AF&F system,[20] external neutron generators and gas transfer systems.[21]

Monitoring a Nuclear Arsenal

The fission and fusion processes described above all take place in a matter of nanoseconds, requiring components to work in perfect harmony and with exact timing. As such, each element of a warhead must be engineered with great precision and manufactured to exacting standards. As warheads age, however, their components change. The plutonium in the pit will oxidise, creating a rust-like layer on its surface and interfering with the link between the pit and its high explosives. Meanwhile, it will radiate neutrons and energy, interfering with other components and altering the way its internal structure behaves during implosion. Furthermore, the polymers that hold the high explosives in shape can degrade and deform. Adhesives and plastics can similarly deform, shifting components out of place. Over time, these defects can accumulate to such a point that a weapon loses potency, predictability or even operability.

In some cases, these ageing processes can be predicted and dealt with through the periodic replacement of components. For instance, the tritium gas used to boost the primary and the batteries powering the AF&F mechanisms degrade at a known rate and are periodically replaced without interfering with the sensitive physics package at the weapon's core.

Defining Reliability

Unfortunately, the ageing processes of other components are not so well known and must be studied to ascertain the ultimate reliability of the weapon. While the UK has not explained how it defines the reliability of its warheads, the US has released a definition that can reasonably be assumed to resemble the UK's approach. According to a laboratory publication, US warhead reliability is based upon the probability that a weapon will deliver a certain yield, at the right moment, without being affected by the environments it passes through.[22] Interestingly, this definition encompasses the risk that a warhead might detonate prematurely, but not lower-level safety risks such as the release of radioactive materials – which depends more upon external factors (such as handling accidents) than the age of a warhead.

The traditional method of testing these reliability criteria is no longer available to the UK. Having ratified the Comprehensive Nuclear Test-Ban Treaty (CTBT) in 1998, the UK cannot simply fire a nuclear weapon and monitor its effectiveness. Instead, the UK has developed a warhead-science programme to recreate the complex processes and systems of a nuclear warhead in a virtual environment.

Assessing Reliability

The details of this programme, which was developed in the early 2000s, have been laid out by three nuclear-weapon scientists in the journal *Nature*.[23] At its heart, this programme relies upon a collection of virtual models developed by AWE that recreate the processes and systems that go into producing a nuclear explosion. These models are built upon a foundation of background physics (such as the hydrodynamic characteristics of imploding plutonium and the application of radiation pressure to create fusion) and detailed designs of the original Trident warhead. The models are then integrated together into a virtual model of the original Trident warhead that can then be detonated and validated against the archived results of past explosive tests.

This approach has many benefits for the UK. Aside from violating the CTBT, carrying out a single explosive test consumes a huge amount of time and money. In comparison, a virtual model can be detonated many times over in a variety of different configurations and contexts. However, for it to provide useful information about the current and future reliability of the UK's stockpile, this model must reflect the physical reality of today's arsenal and the ageing processes it undergoes.

To maintain the link between this virtual warhead and its real-world counterpart, the UK periodically removes a number of warheads from its stockpile for surveillance.[24] According to former Foreign Office official Dr John Walker, the UK removes approximately one warhead a year from its stockpile for 'breakdown and examination'.[25] These examinations likely take a number of forms. For instance, 'Stockpile to Target Sequence' trials recreate the mechanical and thermal environments a warhead experiences by shaking, shocking, compressing and heating warheads and their subsystems (including both radioactive and explosive components). The structural and radioactive responses of a tested warhead are carefully recorded, compared with the accepted tolerances and fed into the numerical models.[26]

Similar surveillance tests examine samples of ageing high explosives;[27] subject weapon casings to flight tests;[28] or record the implosion of samples of aged plutonium[29] – all to feed more experimental data into these evolving models. Indeed, it is probable that all materials, components and sub-systems of the Trident warhead are tested in some way, compared against design tolerances provided by the UK or US supplier, and then fed into numerical models.[30] Aside from refining the numerical modelling of a nuclear warhead, these surveillance activities also likely serve to identify any emerging reliability issues, and to subsequently inform future surveillance priorities and any necessary engineering solutions.[31]

The Reliability of Today's Arsenal

By drawing upon this information, the UK's virtual warhead can be updated and modified to reflect its current physical state and a number of possible future states. By detonating this virtual warhead in a variety of conditions and scenarios, AWE is able to build a picture of how its reliability might change over time.

But how much reliability is enough? Presumably there is a threshold at which the UK would consider its warhead intolerably unreliable, at which point it would have little faith that it would deliver the required yield to the right place at the right time. Unfortunately, there is no unique level at which to set this threshold. With only one nuclear system and a relatively small number of warheads, the UK may well take a more conservative approach to establishing reliability than its nuclear partners in the US,[32] which operates nuclear-armed submarines, bombers and silo-based missiles, all of which can draw upon at least two different warheads.

Wherever this threshold of reliability lies, any indication that the UK's warhead may become unreliable will create great pressure to either refurbish existing warheads or develop a replacement. However, without full knowledge of how individual components might age over time (and little chance of an explosive test), there will always be uncertainty over when this moment might come. Quantifying this uncertainty – which, after all, arises from a multitude of imperfect tests and measurements – has proven so challenging that the US stopped trying over a decade ago.[33] It is highly unlikely that the UK has had any more luck.

The difficulty in assessing reliability is well demonstrated by public assessments of the longevity of the Trident warhead. When the Labour government announced in 2006 that it planned to develop a Trident-based successor to the *Vanguard* submarine, it reassured the public that the accompanying warhead could last into the 2020s with 'relatively minor upgrading and refurbishment'. However, it was uncertain whether continued upgrades or refurbishment could hold off age-related unreliability much beyond that point.[34]

Only four years later, the 2010 Strategic Defence and Security Review offered a far more confident assessment. As concept work continued on a replacement submarine, the government announced that the warhead could stay in service at least into the late 2030s, adding another ten years to its predicted lifespan.[35] This extension suggests that either the 2006 assessment might have overestimated the impact of age-related degradation or that AWE's assessment procedures had improved over these four years to allow more long-term predictions.

With evidence that the Trident warhead will remain reliable up to the late 2030s, there is little pressure on the current government to determine the fate of its nuclear stockpile. Instead, when the next government comes into power after 2015, it will have to make its own assessment as to the future of the UK's nuclear stockpile.

The next government will therefore have two main options: either it can continue the status quo and mitigate the ageing process by refurbishing the existing warhead; or it can begin the long process of developing a replacement.

Replacing a Nuclear Arsenal

If the current maintenance programme is capable of extending the life of the Trident warhead until the late 2030s (when it will become the longest-serving warhead in the UK's nuclear history) it may be able to possibly extend its life further. Studies into the degradation of plutonium suggest that it is remarkably resilient to ageing,[36] and while the UK can acquire the original components of the Trident warhead it may be confident in its longevity.

However, maintaining the status quo may not always be possible. Sources of original components and materials are sometimes cut off (through obsolescence or loss of manufacturing capability), and introducing alternatives often involves more uncertainty. Indeed, even the words 'new, improved version' or 'drop-in replacement' are said to strike 'terror' into the hearts of AWE engineers.[37] The implementation of 'relatively minor upgrading and refurbishment' may eventually have a relatively major impact on assessments of the UK's warhead. In light of these difficulties, abandoning original components and developing a replacement warhead may seem like a more attractive choice.

Very little has been said about this option, and what has been said provides little insight into what replacing a warhead actually involves. Thankfully, the UK is not the first nuclear state to contemplate developing a replacement warhead without recourse to explosive nuclear testing. In 2004, the US Congress initiated the Reliable Replacement Warhead (RRW) programme, which over four years developed a design for a new nuclear warhead that could replicate the capabilities of the existing US stockpile in a more robust, advanced and reliable package.[38]

If the UK were to replace its existing stockpile, it would likely aim for a similar goal. However, US experience suggests that the UK might be tempted to aim higher. After its creation, the RRW programme grew in size and incorporated a number of other changes to the US stockpile such as additional safety and security mechanisms as well as changes to the weapons complex that maintained it. Fears have already been raised that the UK might seek to develop a replacement warhead with a wider range of potential yields to make the stockpile more usable against small targets.[39] Similarly, the UK might take the opportunity to add to its current nuclear capabilities by, for instance, developing robust warheads that can penetrate hardened bunkers,[40] or developing enhanced radiation weapons. Indeed, the UK was able to observe, and even participate in, many elements of the US RRW programme through its nuclear collaboration with the US under the MDA,[41] and any pursuit of a replacement warhead will follow most of the procedures and processes adopted by the US.[42]

The ambition of any UK replacement programme may ultimately reach beyond its technical and financial grasp. Between 2007 and 2008, the US Congress blocked all funding requests to advance the new warhead beyond the design phase into development engineering, arguing that the programme as it stood went ‘far beyond the scope and purpose’ of its original formulation.[43] While the UK warhead programme enjoys comparative shelter from parliamentary oversight, it has historically operated within stricter budgetary constraints. Moreover, AWE would not want to risk undue political attention by making the same mistakes as the US. Furthermore, many of the non-nuclear components within the UK’s current warhead are supplied by the US under the MDA, and the UK presently lacks the capability to develop domestic alternatives. The Trident Alternatives Review suggests that the UK would not seek to develop domestic non-nuclear components if it were to pursue a replacement warhead for the Trident missile, thereby avoiding a step that would multiply costs considerably, add at the very least two years to production timescales, and jeopardise broader aspects of the Anglo–American nuclear relationship.[44]

If the UK retains US-supplied non-nuclear components, development of a replacement warhead would necessarily focus on the indigenous elements of the UK’s warhead, namely the physics package. In this case, the UK’s domestic sources of plutonium, highly enriched uranium, high explosives, and lithium-deuteride fusion fuel provide it with some flexibility.[45]

Despite this flexibility, any changes to the physics package would have to retain compatibility with US-supplied non-nuclear components. Doing so would prevent any changes that would greatly increase the dimensions or disturb the weight distribution of the physics package. For instance, there is only limited space within the Mk4 re-entry vehicle; therefore, increasing the volume of the primary to accommodate more robust explosives would force a corresponding reduction in the size of the secondary.[46] Any resulting loss of yield might subsequently force the UK to reconsider how many warheads it would need for a strike, and backtracking on warhead reductions made to date would come with significant political costs.

This dependence would also prevent any changes to the primary and secondary as they would disrupt the vital interfaces between the physics package and the US components that trigger its detonation. Neutron generators are tailored very precisely to a particular physics package, and it is quite possible that the reliability of a warhead would be severely affected if this physics package were to change. For instance, while the US operates two warheads for the Trident missile (the W88 and the W76, the latter bearing the closest resemblance to the UK’s warhead), the non-nuclear components from one cannot easily be used in the other.

This creates an important trade-off in any replacement warhead. If the UK retained the non-nuclear components it currently acquires from the US, any significant changes to the physics package would entail greater uncertainty about its compatibility with US components. Rather than risk disturbing the important interfaces between nuclear and non-nuclear components, any replacement warhead may eventually be limited to only minor adjustments to the physics package. In this case, making even minor adjustments to this key component without the ability to conduct a full explosive test may generate risks that greatly outweigh any reliability benefits such a limited change might offer.

The UK may be able to find more room for improvement if it were to procure different non-nuclear components from the US, such as those used in the W88 warhead. Although this might require a drastic change to the UK's physics package, such a change could be supported by the exchange of expertise through the MDA and could result in a replacement warhead design grounded in explosive nuclear tests (albeit to a lesser extent than the current design).

Across the Pond and into the Future

The future of the UK's nuclear arsenal is therefore inextricably linked to that of the US. Even if its warhead were to age gracefully, the UK would have little option but to pursue a fully domestic replacement if the flow of non-nuclear components and expertise from the US were to dry up. In this event, the current £4 billion price tag for a replacement would need to be revised upwards by a significant margin. If the reliability of the UK's nuclear stockpile were to take a turn for the worse, any easily affordable replacement would depend heavily upon the non-nuclear components the UK could acquire from the US.

Yet the future of the US nuclear stockpile remains in flux. After abandoning the RRW programme in favour of continued refurbishment and upgrades (bundled into packages referred to as Life Extension Programs), the stewards of the US arsenal have been developing a long-term strategy for its future.

The '3+2' strategy outlined in the 2014 Stockpile Stewardship and Management Plan aims to transform the four warheads that arm US land- and sea-based ballistic missiles into three 'interoperable' warheads that can be easily exchanged between the two missile types. As part of this effort, the US recently completed a scoping study that evaluates the use of 'common [physics packages] and common and adaptable non-nuclear components',[47] which may ease the UK's sensitivity to future changes in the US stockpile.

Through the exchanges enabled by the MDA, the UK's arsenal may be able to undergo a similar transformation, which will both remedy any emerging age-related defects whilst simultaneously reducing the risk that the loss of any one non-nuclear component would render the arsenal unsustainable.

Unfortunately for UK nuclear planners, it is not at all certain that this plan will be allowed to go ahead. On a technical level, the '3+2' strategy may not be achievable without recourse to explosive nuclear testing. On a financial level, the anticipated $60 billion price tag may be too much for strained US defence and energy budgets to swallow. At the operational level, both the US Navy and US Air Force have been unenthusiastic about the concept of warhead interoperability. More importantly, the plan may not be politically feasible for either the president (who has pledged not to develop 'new' nuclear weapons) or Congress, which learnt from the RRW programme to be wary of ambitious and hazily defined goals.[48]

Indeed, while an official outline of the '3+2' strategy by the US Department of Energy states that it is 'absolutely essential and must be accomplished', it also acknowledges that the strategy may be derailed by mandatory funding reductions, emerging issues within the stockpile or geopolitical events that might alter US priorities.[49] Moreover, if the '3+2' strategy were to go ahead despite these obstacles, there would still be no guarantee that its results would ultimately be compatible with the UK's domestically produced physics package.

The UK may feel comfortable that despite sustained pressure from the US nuclear-weapon complex, the path of the US warhead programme is unlikely to depart markedly from the status quo. As the RRW programme indicates, neither the US Congress nor the executive has the appetite for big-ticket reforms of the nuclear complex in the absence of a clear need for change. This comfort might be misplaced. As mentioned above, technological change (such as developments in missile defence or the retirement of the Trident D5) or political change may force the US to swiftly reappraise its nuclear priorities. Furthermore, any sea change in the US nuclear complex, whose larger budget affords greater responsiveness, might easily outstrip the UK's ability to keep up. If the UK cannot predict the future of the US arsenal with greater certainty than that of its own arsenal, it may yet suffer an expensive shock to the system.

The Future of the UK's Nuclear Stockpile

If indications emerge within the next parliament that the UK's nuclear stockpile may not survive past the late 2030s, the government at the time will be faced with a dilemma. Without a clear steer from the US, the UK may have to choose between developing a replacement warhead with an uncertain supply of components (and over time, missiles), or retaining an arsenal of suspect reliability. In the case of the former, the UK might embark on a pathway that, at best, produces limited results, and, at worst, risks jeopardising the much-valued exchange between the two nuclear partners. Given this tough choice, pressure to replace the UK's warhead may meet equal and opposite pressure to delay until a clear pathway can be developed in collaboration with the US.

Delaying such a choice may indeed be the best option available to the UK: the continuation of upgrades and refurbishment has so far proven successful in the US and may continue to be successful in the UK. From both political and financial perspectives, the costs of developing a substantially new replacement warhead are best avoided if possible. This sentiment is confirmed by an article in AWE's in-house journal, which states that there is 'always a major incentive to extend the life of warheads beyond the very conservative timescales' defined by their original design and maintenance processes.[50] And from a technical perspective, it is very difficult to say whether the gradual refurbishment and replacement of components *cannot* extend the life of the UK's arsenal beyond previously defined timescales. As discussed above, it is extremely challenging to quantify the uncertainty of assessing stockpile reliability and it is probable that, reflecting US practice, the UK makes no effort to do so.

As successive governments consider the future of the UK's nuclear stockpile, the health and predictability of its ongoing nuclear relationship with the US will weigh heavily upon the minds of nuclear decision-makers. This relationship played a central role in the genesis of today's stockpile, and continues to play such a role in its ongoing maintenance. Any dramatic change in the US nuclear complex will have unavoidable repercussions for the UK. For instance, if the US were to pursue replacements or alternatives to its warheads and their non-nuclear components, the UK would have to choose whether or not it wished to follow in American footsteps or take on the burden of developing its own approach. While reliability assessments will play an important role in determining the fate of the Trident warhead, this role may ultimately be subservient to that of the US nuclear complex and its deep ties with the UK.

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Notes and References

1. 'UK's Strategic Nuclear Deterrent', Memorandum submitted by the Ministry of Defence to the House of Commons Defence Select Committee, HC 835, 19 January 2006, Annex A.

2. HM Government, *Securing Britain in an Age of Uncertainty: The Strategic Defence and Security Review* (SDSR), Cm 7984 (London: The Stationery Office, October 2010).

3. HM Government, *The Trident Alternatives Review* (TAR), (London: The Stationery Office, July 2013).

4. For a more detailed discussion of US–UK nuclear co-operation see Hugh Chalmers and Malcolm Chalmers, 'The Future of the UK's Co-operative Nuclear Relationships', RUSI Occasional Paper, June 2013.

5. The National Archives (TNA), DEFE 19/275, Duff-Mason report on factors relating to the further consideration of the future of the UK nuclear deterrent (commonly known as the 'Duff-Mason report'), December 1978, pp. 8–9.

6. Kristan Stoddart, 'The Special Nuclear Relationship and the 1980 Trident Decision', in Jennifer Mackby and Paul Cornish (eds), *US–UK Nuclear Cooperation after 50 Years* (Washington, DC: CSIS, 2008), p. 95.

7. Troy E Wade II, 'Nuclear Testing: A U.S. Perspective', in Mackby and Cornish (eds), *US–UK Nuclear Cooperation after 50 Years*, p. 206. It is possible that initial phases of development had begun before the Trident decision was made (through preliminary discussions and exchanges with the US over its own plans for the Trident missile).

8. TNA, DEFE 25/434 E59, p. 1.

9. Wade, 'Nuclear Testing: A U.S. Perspective', p. 207.

10. Royal Navy, 'HMS Vanguard', <http://www.royalnavy.mod.uk/The-Fleet/Submarines/Ballistic-Submarines/Vanguard-Class/HMS-Vanguard>, accessed 7 March 2014.

11. Robert S Norris and Hans M Kristensen, 'The British Nuclear Stockpile, 1953–2013', *Bulletin of the Atomic Scientists* (Vol. 69, No. 4, July/August 2013).

12. HM Government, SDSR, para. 3.10.

13. Michael Quinlan, 'The Future of United Kingdom Nuclear Weapons: Shaping The Debate', *International Affairs* (Vol. 82, No. 4, July 2006).

14. Statement by Commodore Tim Hare, House of Commons Defence Select Committee Minutes of Evidence, 28 March 2006, <http://www.publications.parliament.uk/pa/cm200506/cmselect/cmdfence/986/6032802.htm>, accessed 23 November 2013.

15. House of Commons Defence Select Committee, 'The Future of the UK's Strategic Nuclear Deterrent: The White Paper – Government Response to the Committee's Ninth Report of Session 2006–2007', HC 225-1, 27 February 2007, pp. 2, 18.

16. *BBC News*, 'UK to be "More Open" about Nuclear Warhead Levels', 26 May 2010.

17. Rob Edwards, 'UK's Nuclear Weapons being Dismantled under Disarmament Obligations', *Guardian*, 11 August 2013.

18. Rob Edwards, 'Trident Missiles Delayed by Mystery Ingredient', *New Scientist*, March 2008.

19. TNA, DEFE 25/325, 'M E Quinlan DUS(P) to PS to Secretary of State ANNEX A', 3 October 1980.

20. *Hansard*, HC Debates, 28 March 2007, Col. 1524W.

21. There is little evidence to suggest that the UK has a domestic capability to produce neutron generators and gas transfer systems. In written evidence to the House of Commons Defence Select Committee, Greenpeace suggested that the UK's warhead utilises the 'MC4380' neutron generator produced by Sandia National Laboratories in the US. See House of Commons Defence Select Committee, 'The Future of the UK's Strategic Nuclear Deterrent: The Strategic Context', Eighth Report of Session 2005–06, 20 June 2006, Annex B, 'Memorandum from Greenpeace', <http://www.publications.parliament.uk/pa/cm200506/cmselect/cmdfence/986/986we13.htm>, accessed 23 November 2013.

22. R L Bierbaum et al., 'DOE Nuclear Weapon Reliability Definition: History, Description, and Implementation', Sandia Report, SAND99-8240, April 1999, <http://www.wslfweb.org/docs/usg/reli99.pdf>, accessed 23 November 2013.

23. Keith O'Nions, Robin Pitman and Clive Marsh, 'Science of Nuclear Warheads', *Nature* (Vol. 415, February 2002), pp. 853–57.

24. *Ibid*., p. 854.

25. Correspondence between John Walker and Brian Burnell, nuclear-weapons.info, We177 entry, footnote 172.

26. Carole Reece, 'Trials and Testing at AWE', *Discovery* (No. 5, July 2002), pp. 8–15.

27. Dr Annette Lewis and Dr Tim Goldrein, 'Strain Measurement: Techniques in Explosives', *Discovery* (No. 3, July 2001), pp. 26–43.

28. Charles Kernthaler, 'Joint Test Programme: Model Based Assurance', *Discovery* (No. 1, March 2000), pp. 36–39.

29. Peter Sankey and Andy Fox-Boudewijn, 'Experimental Hydrodynamics', *Discovery* (No. 5, July 2002), pp. 2–7.

30. Lewis and Goldrein, 'Strain Measurement', p. 36.

31. The US adopts a cyclical approach to surveillance activities, which may reflect the approach adopted by the UK. For more information, see US Department of Energy, 'FY2014 Stockpile Stewardship and Management Plan', June 2013, Section 2.2.2.

32. Indeed, AWE's in-house publication argues that the presumed lifespan of a warhead design is 'very conservative'. See Lewis and Goldrein, 'Strain Measurement', p. 38.

33. Bierbaum et al., 'DOE Nuclear Weapon Reliability Definition', p. 20.

34. HM Government, *The Future of the United Kingdom's Nuclear Deterrent*, Cm 6994 (London: The Stationery Office, December 2006).

35. HM Government, SDSR.

36. Bruce T Goodwin, 'Plutonium at 150 Years: Going Strong and Aging Gracefully', *Science and Technology Review* (December 2012).

37. Norman Godfrey and Wilhelm Huck, 'Alternative Materials: New Routes to Old Materials – The Alternative to "Alternatives"', *Discovery* (No. 6, January 2003), pp. 38–45.

38. Jonathan Medalia, 'Nuclear Warheads: The Reliable Replacement Program and the Life Extension Program', CRS Report for Congress, 3 December 2007, p. 3.

39. Mark Townsend, 'Secret Plan for N-bomb Factory', *Observer*, 16 June 2002.

40. Such as the 'robust nuclear earth penetrator' explored by the US. See Jonathan Medalia, '"Bunker Busters": Robust Nuclear Earth Penetrator Issues, FY2005–FY2007', CRS Report for Congress, 21 February 2006.

41. Interview with John Harvey in Mackby and Cornish (eds), *US–UK Nuclear Cooperation after 50 Years*, p. 296.

42. In response to a written question, former Defence Secretary Lord Hutton stated that AWE adopts a similar approach to the US in the 'management of research' and the

'assessment of technology readiness'. See *Hansard*, HC Debates, 2 March 2009, Col. 1370W.

43. Jeffrey Lewis, 'After the Reliable Replacement Warhead: What's Next for the U.S. Nuclear Arsenal?', *Arms Control Today*, December 2008.

44. HM Government, *Trident Alternatives Review*, p. 37.

45. For details of the UK's domestic stockpiles of plutonium and uranium, see 'Global Fissile Material Report 2013', Seventh annual report of the International Panel on Fissile Materials, <http://fissilematerials.org/library/gfmr13.pdf>, accessed 23 November 2013.

46. John R Harvey and Stefan Michalowski, 'Nuclear Weapons Safety: The Case of Trident', *Science and Global Security* (Vol. 4, 1994), pp. 261–337.

47. US Department of Energy, 'FY2014 Stockpile Stewardship and Management Plan', Section 2.6.2.

48. For an independent report into the '3+2' strategy, see Lisbeth Gronlund et al., 'Making Smart Security Choices: The Future of the US Nuclear Weapons Complex', Union of Concerned Scientists, October 2013, <http://www.ucsusa.org/assets/documents/nwgs/nuclear-weapons-complex-report.pdf>, accessed 23 November 2013.

49. US Department of Energy, 'FY2014 Stockpile Stewardship and Management Plan', Section 2.6.2.

50. Lewis and Goldrein, 'Strain Measurement', p. 36.

Appendix: The Anatomy of a Nuclear Weapon

The detailed design of the UK's Trident warhead is highly classified, and it is not possible to give a description of its actual composition. The basic principles of nuclear explosives, however, are relatively well-known at an unclassified level. It is therefore possible to outline the main components of the UK's nuclear warhead with a reasonable level of confidence.

The Primary

At its heart, the UK's nuclear warhead is powered by a spherical 'pit' of plutonium metal. The atoms within this metal are not entirely stable and occasionally split spontaneously into two energetic fragments, releasing uncharged sub-atomic particles (known as neutrons) and a powerful burst of radiation.[1] To translate these products into a full-scale nuclear explosion, the neutrons released by one split can be used to disturb other atoms into splitting, thereby releasing more energy and neutrons to create a powerful chain reaction which quickly spreads throughout the pit.

To initiate this 'fission' chain reaction, the detonation of an outer shell of polymer-bonded high explosives compresses the pit to several times its normal density, which allows few neutrons to escape the pit without disturbing other atoms. At the optimal density, the pit is bombarded with neutrons from an external generator (see below) to 'trigger' the first links in the chain. To prevent the energy released by this reaction from prematurely expanding the pit – thereby reducing its density and interrupting the chain reaction (known as a 'fizzle') – a 'tamper' shell of dense metal (possibly beryllium) between the explosives and the pit serves to briefly contain the force of the exploding core and its neutrons. This tamper greatly increases the efficiency of the chain reaction, and reduces the amount of plutonium required for any given level of explosive power.

These four components – the pit, tamper, high explosives and neutron generator – are collectively known as the 'primary'.[2] Many of the UK's earlier nuclear weapons utilised only this fission process, and the US was able to use it to produce explosions equivalent to 500,000 tons (500 kT) of TNT.[3] However, achieving higher yields with fission alone required collecting an unstable and unsafe quantity of fissile material together in one place.[4] To efficiently achieve higher yields, modern thermonuclear weapons use the huge energy released by fission to spark a more complex and powerful process known as fusion, in which light elements are forced together into heavier elements.

Fusion 'Boosting'

The heat and pressure generated by the Trident warhead primary is likely used to ignite a small fusion reaction to 'boost' the fission process. To do so, light elements (such as tritium) are injected into the centre of the imploding pit just before its temperature and pressure peak. Here the elements fuse together, releasing yet more energy and a burst of highly energetic neutrons. These energetic neutrons then disturb the heavier, more stable isotopes within the pit and its tamper (which are less affected by fission neutrons) into splitting. This boosting process therefore consumes much more of the fissile pit, increasing the efficiency of the primary and allowing a further reduction in fissile material and tamper weight, whilst simultaneously reducing its tendency to 'fizzle'.

The Secondary

The Trident warhead likely uses this 'boosted' fission process to spark fusion in a physically separate 'secondary' device.[5] This secondary stage recreates the intense heat and pressure of the primary boosting process above, but is not constrained by the amount of fusion fuel that can be used within the imploding pit. Instead, a large quantity of solid fusion fuel of light elements (typically a substance known as lithium-6 deuteride) is collected in what is referred to in the US as a 'canned sub assembly', or CSA.

Rather than utilising the explosive force of the primary to compress and heat the CSA (which would be ripped apart in the process), the secondary stage exploits the faster-acting radiation released by the exploding primary. While this radiation is not solid, it can still be said to have a 'momentum' that can compress and heat the solid fusion fuel, and therefore spark fusion. To contain this radiation within the weapon and ensure that it compresses the CSA evenly, the primary and secondary stages are housed within a heavy-metal (possibly depleted uranium) radiation casing. This casing contains 'soft' lower-energy radiation throughout the interior of the weapon, whilst allowing higher-energy radiation (such as X-rays and gamma rays) to escape. This channelled 'soft' radiation compresses and heats the CSA from all sides until fusion is ignited.

Once ignited, the fusion process within the secondary releases even more neutrons and energetic radiation. These secondary products can then either become a second fusion aspect to a nuclear explosion or be used to spark fission in another reservoir of uranium (in this sense becoming a larger-scale 'booster'), or even possibly to ignite fusion in a third stage. Theoretically, the achievable yield through this two-stage design is unlimited and has been proven capable of producing a yield of fifty million tons of TNT: one hundred times the maximum power ever produced by a fission-only device.[6]

To hold all these nuclear components in place within the radiation casing and to channel soft radiation smoothly around the CSA, the void between the primary and the secondary is filled with an extremely light but strong inter-stage material, thought by some to be a material called 'fogbank'.[7]

This collection of nuclear components (including the primary, secondary and inter-stage materials) is often referred to as the 'physics package', as it carries out the core physical processes of a nuclear explosion. The UK can 'tailor' the yield produced by its warhead by including or excluding certain stages in this physics package. For instance, the UK could avoid 'boosting' the primary or disrupt the radiation-driven implosion of the secondary in order to reduce the warhead's yield.

Non-Nuclear Components

While the physics package represents the nuclear 'explosive', a number of components integrate this explosive into a deliverable and serviceable weapon that will detonate at a specified time. To facilitate simple replacement the neutron generator that triggers fission in the primary is held outside of the physics package. For similar reasons, the gas transfer system that injects tritium 'boost' gas into the primary is also stored outside the physics package. Finally, there are the mechanisms that ultimately arm, fuse and fire (AF&F) the weapon, such as radar fuses, safety and security devices, detonators, and batteries. These AF&F mechanisms are installed around the physics package and integrated into the weapon casing, which, in the case of the Trident warhead, is a heat-proof conical shell that protects the warhead during atmospheric re-entry and ultimately brings it to its target.

As stated earlier in the paper, many of these non-nuclear components are supplied to the UK from the US under the 1958 MDA. It was known early in development that the Trident warhead's composition and maintenance would depend upon the US for spare components, training, missile test facilities, along with supporting technical information and services.[8] For instance, the UK is known to have upgraded its warheads with the US-supplied Mk4 re-entry vehicle and its accompanying AF&F system,[9] external neutron generators and gas transfer systems.[10]

Notes and References

1. This fission process releases at least *ten million* times the energy of a conventional explosion per atom. For basic physics of fission explosives, see Robert Serber, *The Los Alamos Primer* (London: University of California Press, 1992).

2. In the past the UK used to name these primaries, with the primaries for the Red Beard and WE177 nuclear bombs being known as 'Peter' and 'Katie', respectively. See Richard Moore, 'The Real Meaning of the Words: A Pedantic Glossary of British Nuclear Weapons', UK Nuclear History Working Paper, The Mountbatten Centre for International Studies, <http://nuclear-weapons.info/Working_Paper_No_1.pdf>, accessed 23 November 2013.

3. See ‘Mk-18’, Strategic-air-command.com, <http://www.strategic-air-command.com/weapons/nuclear_bomb_chart.htm>, accessed 23 November 2013.

4. See ‘Violet Club’ (which contained enough enriched uranium to initiate, if not necessarily sustain, a chain reaction *without* being imploded) at nuclear-weapons.info, <http://www.nuclear-weapons.info/vw.htm#Violet%20Club/www.nuclear-weapons.info>, accessed 23 November 2013.

5. For the basic physics of fusion explosions, see Friedwardt Winterberg, *The Physical Principles of Thermonuclear Explosive Devices*, Fusion Energy Foundation Frontiers of Science Series (New York, NY: Fusion Energy Foundation, 1981).

6. Staged weapons have been proven to be capable of producing a yield of fifty *million* tons of TNT: 100 times the maximum power ever produced by a fission-only device. See the Tsar Bomba; Viktor Adamsky and Yuri Smirnov, ‘Moscow’s Biggest Bomb: The 50-Megaton Test of October 1961’, *Cold War International History Project Bulletin* (No. 4, 1994), p. 3, <http://www.wilsoncenter.org/sites/default/files/ACF1B7.pdf>.

7. Rob Edwards, ‘Trident Missiles Delayed by Mystery Ingredient’, *New Scientist,* March 2008.

8. TNA, DEFE 25/325, ‘M E Quinlan DUS(P) to PS to Secretary of State ANNEX A’, 3 October 1980.

9. *Hansard*, HC Debates, 28 March 2007, Col. 1524W.

10. There is little evidence to suggest that the UK has the domestic capability to produce neutron generators and gas transfer systems. In written evidence to the House of Commons Defence Select Committee, Greenpeace suggested that the UK’s warhead utilises the MC4380 neutron generator produced by Sandia National Laboratories in the US. See House of Commons Defence Select Committee, ‘The Future of the UK’s Strategic Nuclear Deterrent: The Strategic Context’, Eighth Report of Session 2005–06, 20 June 2006, Annex B, ‘Memorandum from Greenpeace’, <http://www.publications.parliament.uk/pa/cm200506/cmselect/cmdfence/986/986we13.htm>, accessed 23 November 2013.

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