NIS Nuclear Information Service

Extreme circumstances

The UK's new nuclear warhead in context

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Front cover image:
Timelapse of MIRV re-entry paths from a 1986 Peacekeeper missile test.
Credit: US DOD.

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Executive summary

Introduction
The United Kingdom (UK) Government's programme to build a new nuclear warhead is the latest stage in the Ministry of Defence plan to replace all three parts of the UK's nuclear weapon system: the submarine, missile and warhead. The new warhead will be deployed on the UK's Trident missiles which are leased from the United States (US). It will be a 'parallel' programme to the new US W93 Trident warhead currently being developed.

The UK is unique amongst the nine nuclear-armed states in fielding a single nuclear weapons system, using only submarine-launched missiles with no ground or air-launched weapons. It has the smallest nuclear weapons stockpile amongst the five nuclear-armed states recognised by the 1968 Nuclear Non-Proliferation Treaty (NPT). As a party to that treaty the UK is committed to eliminating its nuclear weapons. In March 2021 the government abandoned plans to reduce the UK's warhead stockpile limit to 180 and instead announced an increase to 260, a reversal of trends established towards the end of the Cold War.

This report investigates the current status of the UK's Replacement Warhead Programme to try and understand why it is going ahead, what strategic thinking underlies the decision, and what can be inferred about its likely characteristics from all available sources. Much of the key source material is comprised of US public documents about the W93 and related programmes.

UK Replacement Warhead Programme
The new warhead programme was announced in February 2020. It entered its 'readiness phase' in the financial year 2019-20, and the government spent £214m on the project up to the end of financial year 2020-21. The project is currently at a stage analogous to the first phase of the W93 programme and is yet to settle on a single chosen design. The government has not provided an official cost estimate and timetable for the project, but the warhead is likely to come into service some time in the late 2030s or early 2040s.

In September 2020 the government announced that the Atomic Weapons Establishment (AWE), where the UK's nuclear warheads are designed and produced, was being brought back into public ownership. This was partly due to the poor value for money, regulatory and programme delivery performance under the previous contract, but the government's desire to exercise greater control over AWE as the warhead project commenced was also a major factor.

W93 and Mk7
The US W93 programme was revealed by the Trump administration in February 2020. The warhead will be housed within the Mk7 aeroshell, which is designed to protect the warhead as it re-enters earth's atmosphere. The Mk7 has a separate budget, and is run as a separate, but closely related, project alongside the W93.

In Fiscal Year 2021 the project entered an initial phase where a range of potential warhead designs are evaluated against various desired attributes, characteristics and constraints. After this it will transition into a second phase where the warhead concepts will be reviewed and developed into a series of design options that will eventually be winnowed down to a single proposed design. The current planning estimate cost for the W93 is $13.4bn to $15.5bn, equivalent to between £10.9bn and £12.6bn. This figure is expected to change as the design matures.

The two factors that appear to have played a significant role in the decision to build the W93 are an ambition to revitalise the US nuclear weapons industrial base, and the desire for an additional type of submarine-launched warhead in case of a technical problem in one of the two current designs.

Active US-UK cooperation on this new generation of nuclear weapons pre-dates the February 2020 announcements of the W93 and UK replacement warhead. Since 2016 the two countries have been working together on the Joint Technology

Demonstrator (JTD) project, developing demonstration warhead systems that could potentially be deployed in a number of future warheads.

The UK's 2021 Integrated Review

The most significant change to the UK's nuclear posture in the 2021 Integrated Review (IR) of Security, Defence, Development and Foreign Policy was a reversal of a decades-long trend of reductions in the UK nuclear stockpile. Instead of the planned reduction of the stockpile ceiling from 225 to 180 by the mid 2020s, it was increased to 260. The IR also reversed the policy of providing information about the numbers of operational warheads and the number of deployed warheads and submarines.

These changes will allow the number of deployed warheads to increase with no accountability or democratic challenge. There are two broad goals that this could be intended to achieve: either to increase the overall number of warheads that would be used in a full nuclear strike, or to increase the range of different strike options available by fielding missiles carrying different numbers of warheads. Some missiles could also potentially be carrying a lower-yield version of the warhead.

The most likely explanation for this decision is a change in what the government determines to be 'credible' in terms of its nuclear capabilities. While the process of devising the IR will have involved detailed and careful analysis, that does not mean the final decision, taken by the Prime Minister, would have been characterised by careful deliberation. Suggestions that the decision was driven by a desire for the UK to be more assertive about its nuclear weapons possession are more convincing than the justifications given in the IR.

Analysis of convoys carrying nuclear warheads from AWE to Scotland, where the UK's nuclear-armed submarines are based, suggest that warhead numbers were reduced by around 12 between 2010 and 2015, then returned to their 2010 levels around 2017 or 2018, with substantial increases in warhead numbers in 2019 and 2020. The possibility that the stockpile rose above the government's self-imposed stockpile limit of 225 during 2020 cannot be ruled out. These increases call into question public assurances that the previous reductions were irreversible.

The UK appears to be in breach of several of its commitments under the NPT, including commitments to unilaterally reduce its nuclear arsenal, to increase transparency and that reductions would be irreversible.

UK Replacement Warhead characteristics

The UK Replacement Warhead is very unlikely to differ substantially from the design of the US W93 warhead. The UK warhead will depend on US-made components and will need to have an identical weight distribution and shape to the W93. The UK could incur substantial additional costs to produce a warhead that would be considered less reliable, due to the difficulties in providing assurance that all the components would work as intended throughout the life of the warhead.

Unless the difficult decision is taken for the two designs to diverge, the Replacement Warhead is likely to follow the W93 in having an explosive yield somewhere between the two current US strategic Trident warheads: the 100kt W76-1 and the 455kt W88. The yield is unlikely to be as high as the W88 due to the increase in the accuracy of the system since that warhead was designed, but this report argues that the new UK warhead can be expected to have a yield that is significantly higher than the current UK warhead, which is based on the US W76-1 warhead and thought to have a similar explosive yield.

Evidence presented in this report also suggests a lower-yield capability will be available from the new warhead. Part of the initial production run for the new UK warhead could even be adapted to explode with this lower yield. It is also likely the design process will anticipate the warhead being hosted on missiles carrying different numbers of warheads, allowing for a range of strike sizes.

The UK replacement warhead will be based on existing US warhead designs that have been tested, although it may incorporate elements from more than one design. Some of the warhead's components will be based on those already used in existing US nuclear weapons. The UK warhead will be housed in the Mk7 re-entry body, supplied by the US, and is almost certain to incorporate technologies being developed under the JTD project to increase safety and security.

The warhead will be designed to work with the current Trident missile stock. The missile has been upgraded once and is now planned to undergo a second life-extension upgrade. It is very likely that the future capabilities of the missile will be taken into account during the warhead design process.

Conclusions

Although both the W93 and UK Replacement Warhead are yet to reach the stage of selecting a final design, key decisions are happening now, in a political context where the security doctrines of each country are willing to countenance a widened role for nuclear weapons. The impact of this may prove to be long-lasting, as the warheads are likely to remain in service well into the second half of the 21st century.

This report makes the case that the W93 and the UK Replacement Warhead should be seen as being driven by political considerations, rather than technical factors. The major factor in the decision to go ahead with the warheads is the internal pressure to sustain infrastructure and capabilities within the nuclear weapon programmes in both the US and UK. This is a clear demonstration of the limitations of a model of disarmament whereby nuclear-armed states make incremental reductions in their arsenals at a pace determined by their political convenience.

The need for negotiated disarmament agreements to reduce international tensions is greater than at any time since the end of the Cold War. Recent developments have diminished the prospects for international cooperation, but the stark reality of the alternatives means that the nuclear-armed states have to find the political will to advance towards their shared objective of a world without nuclear weapons. That goal is as relevant and urgent as it has ever been.

From being the NPT nuclear-weapon state that could claim to be the closest towards achieving disarmament, the UK is developing a new weapon that will likely have a larger explosive yield, and is now increasing warhead numbers and broadening the circumstances in which it would countenance a role for nuclear weapons in its security doctrine. While the internal processes that lead to these decision will have involved detailed deliberation, the final decision by the Prime Minister appears to have been guided by a desire for the UK to be less 'apologetic' about its continued possession of nuclear weapons.

The increase in the UK's warhead stockpile and the probable increase in capabilities from the UK Replacement Warhead are likely to further weaken the NPT treaty regime which is already struggling with a loss of credibility, and with accusations of bad faith levelled at the nuclear weapon states. As the programmes are at an early stage in development, these harms can be avoided with sufficient political will and leadership. Specifically, the UK should declare that the new warhead will not involve any upgrade to its offensive capabilities.

The moves away from transparency and accountability in the UK militate against this outcome. The political will to make progress on disarmament is unlikely to emerge without more scrutiny of the nuclear weapons programme, which should be provided by parliament. The UK would also need to exercise influence over the US to ensure that the parallel W93 and Replacement Warhead Programmes do not jeopardise the UK's disarmament commitments. The slim chances of success do not absolve the UK of its disarmament obligations

Recommendations

1. If the UK Replacement Warhead Programme goes ahead, despite the known drawbacks, the Government should make a public statement to the effect that the programme will not result in any change to the UK's nuclear capabilities, and any changes to the warhead design will be solely focussed on:
   a) Improvements to safety and surety.
   b) Ease of verifiable dismantlement, using lessons learned in the UK's disarmament verification research.
   c) Easy replacement and life-extension of components, in order to eliminate any technical pressures for new future warhead designs while the UK remains a nuclear weapons state.

2. The UK government should release a detailed justification for the recent increase to its warhead stockpile cap, in order to allow public debate about the merits of the change.

3. This justification should include a statement about the status of any lower-yield capability on the UK's current warhead and a timetable for the permanent phase-out of this capability, in keeping with its commitments to the 2000 and 2010 NPT Review Conferences.

4. The UK should abandon its doctrine of strategic ambiguity. It has the potential to confuse decision-making in a crisis and any strategic benefit it might provide is outweighed by the harms done to democratic scrutiny, accountability and strategic stability.

5. The UK government should immediately make public the size of its operational warhead stockpile, as well as the maximum number of missiles and warheads carried on each submarine. It should commit to updating parliament on any changes to these numbers.

6. The UK's nuclear weapons programme, particularly the Dreadnought submarine programme and the Replacement Warhead Programme, should be subject to detailed parliamentary scrutiny to ensure the best possible management of the public funds being spent. A central element of this scrutiny should be annual inquiries and reports by the Defence Select Committee, as was the case during construction of the first generation of Trident submarines and warheads through the 1980s and early 1990s.

Introduction

On 25th February 2020 the Secretary of State for Defence announced the UK Government's programme to build a new nuclear warhead.[1] The announcement was largely a formality, as the existence of the programme had been revealed 12 days earlier by Admiral Charles Richard, commander of U.S. Strategic Command, attracting substantial media interest.[2] The revelation was included in written testimony submitted by Admiral Richard to the US Senate Committee on Armed Services about the proposed new US warhead known as the W93, which will be a 'parallel' programme to the UK's new warhead.[3]

This report investigates the current status of the UK's Replacement Warhead Programme and attempts to understand why it is going ahead, what strategic thinking underlies the decision and what can be inferred about its likely characteristics from all available sources. Given the relationship between the two warheads, a thorough treatment of these questions requires that they first be answered in relation to the W93. An analysis of the changes made to UK nuclear policy under the 2021 Integrated Review (IR) and the history of the lower-yield capability in the UK's Trident warhead are also essential for understanding the Replacement Warhead.

The UK Replacement Warhead Programme is the latest stage in the Ministry of Defence (MOD) plan, originating in the mid-2000s, to replace all three parts of the UK's nuclear weapons system: the submarine, missile and warhead.[4] The current Vanguard-class submarines are being replaced with a new Dreadnought class. Work on these submarines began in March 2007,[5] and the programme moved into its delivery phase in July 2016 following a parliamentary vote.[6] The Trident D5 missile was designed and built by the US for its nuclear-armed submarine (SSBN) fleet and UK missiles are leased from a common pool. The missile is undergoing a life extension programme in the US, with the upgraded missiles coming into service in 2017,[7] most likely beginning to be loaded onto the UK's submarines the same year.[8]

The UK's Trident warhead has also been upgraded using components designed and built by US nuclear weapons laboratories. The upgrade, called the Mk4A, is thought to have begun in late 2014 or 2015[9] and is still ongoing. While the Mk4A involved the replacement of key warhead components, the overall design and layout of the weapon remains largely unchanged. In contrast, the UK's Replacement Warhead will be a new design, built with new components. This does not mean it will necessarily be radically different from previous designs fielded by the US or UK, for reasons explored in this report. Instead it is likely to be a development of previous designs, possibly incorporating elements from more than one.

The UK is unique amongst the nine nuclear-armed states in fielding a single nuclear weapon platform and warhead,[10] and has the smallest nuclear weapon stockpile amongst the five nuclear-weapon states recognised by the 1968 Nuclear Non-Proliferation Treaty (NPT).[11] The UK and the other four recognised nuclear-weapon states have committed to eliminating their nuclear weapons and to reducing both the number of weapons they hold and the role they play in their security policies as interim steps towards disarmament.

In March 2021 the government announced an increase in the UK's warhead stockpile limit to 260, in a reversal of trends established towards the end of the Cold War. Combined with the overwhelming level of concerns expressed by non-nuclear states about nuclear modernisation programmes,[12] that announcement will likely exacerbate diplomatic tensions within the NPT about the failure of nuclear-weapon states to disarm. In 2017 these tensions led 122 states to agree the Treaty on the Prohibition of Nuclear Weapons (TPNW), which came into force in 2021 and seeks to conclusively establish the illegality of nuclear weapons in international law.

Given the importance of the W93 programme and the relative commitment to government transparency and accountability in the US, much of the key source material for this report is comprised of US public documents about the W93 and related programmes. Public policy documents from both states are another important source of evidence. The design specifics and 'missions' of nuclear weapons are amongst the most closely guarded security secrets. However, by incorporating what information is in the public domain in the context of wider US and UK policy decisions, it has been possible to draw together a picture.

Some sections of the report may not initially appear to be directly relevant to the UK Replacement Warhead, but have been included as they inform analysis and conclusions in the later sections. It should be noted that while the contents of the report are based on the best available public information, some of it is necessarily speculative.

This report makes the case that the W93 and the UK Replacement Warhead should be seen as being driven by political considerations, rather than technical factors. The evidence suggests they are motivated primarily by an internal desire to sustain capabilities within the UK and US nuclear enterprises, rather than by external developments. The policy environment of the 2018 Nuclear Posture Review (NPR) provided scope for this longstanding goal to be pursued within the US, but the decision was taken jointly with the UK, with both warhead programmes being used as internal justification for the other in their respective countries.

The reasons given in the US for the W93, publicly and within government, strongly suggest it will be designed with a higher explosive yield than the current UK warhead and the W76-1, which are widely understood to both have a yield of around 100kt. Technical pressures mean that the UK Replacement Warhead is very likely to follow the W93 design in most ways, including yield.

From being the NPT nuclear-weapon state that could claim to be the closest towards achieving disarmament, the UK is developing a new weapon that will likely have a larger explosive yield, and is now increasing warhead numbers and broadening the circumstances in which it would countenance a role for nuclear weapons in its security doctrine. While the internal processes that lead to these decision will have involved detailed deliberation on the merits of different options, this does not mean that the final decision by the Prime Minister would have been characterised by careful deliberation. Instead the overriding philosophy appears to be a desire for the UK to be less 'apologetic' about its continued possession of nuclear weapons.

In a democracy such as the UK, decisions such as these should be subject to meaningful public debate and informed popular consent. The degree of secrecy surrounding the UK's nuclear weapons remains an obstacle to democratic oversight and public debate. By placing this information about the Replacement Warhead into the public domain this report seeks to encourage a level of oversight and debate that has so far been lacking.

The report is divided into five parts. The first part provides background information that may be useful to readers who are less familiar with the subject matter. More knowledgeable readers may wish to skip parts of this section and refer back to them as necessary. The second part gives an overview of current developments in the UK and US and up-to-date information about the warhead programmes and related projects. The third part outlines the nuclear policy environment within which the programmes have been initiated. The fourth part sets out the argument in detail, drawing information from the previous sections into an analysis of the UK and US warhead programmes, the factors that lie behind their inception and the possible characteristics of the warheads. The fifth part provides concluding remarks and recommendations. To aid the reader key points are provided at the beginning of the most significant sections of the report, and further technical detail has been provided in annexes.

CREDIT: MOD/OGL.

HMS Vanguard test-firing a Trident missile in 2005.

1. Background and historical context

This part of the report contains contextual and historical information that is relevant to the following sections and may be necessary for full understanding of the report contents.

The first section gives a brief history of nuclear cooperation between the UK and US before giving an overview of the UK's Trident warhead and the techniques used for nuclear weapon design since the end of explosive nuclear testing. It also includes the Mark 4A warhead upgrade and the changes to the UK's warhead stockpile between 1998 and 2015.

The following sections deal with the nature of the UK's low-yield warhead capability, its relationship to the US W76-2 warhead and its role in the UK's security doctrine in the early years of the UK's Trident system. The final section in this part of the report introduces the US 3+2 warhead plan and the Integrated Warheads that were due to be produced under it.

US-UK nuclear cooperation

Although the UK participated in the Manhattan Project, which produced the first nuclear weapons in 1945, the 1946 McMahon Act put an end to US cooperation with the UK on these weapons. When the UK subsequently started its own nuclear weapons programme, re-establishing the cooperative relationship with the US was a major objective.

Following the UK's successful test of a hydrogen bomb in 1957 the two countries signed the 1958 Mutual Defence Agreement (MDA), which allows for the transfer of information and materials relating to nuclear weapon systems and military nuclear reactors.[13] This treaty was supplemented by the 1963 Polaris Sales Agreement, which provided the UK with its first submarine-launched nuclear missile system.

While the transfer of assembled nuclear weapons does not take place under the MDA, the two countries transfer components, fissile materials and knowledge. This distinction is in place to prevent the agreement from breaching the NPT prohibition on the transfer of nuclear weapons. Although both countries probably benefit from the exchange, the UK is the chief beneficiary due to the much greater scale and budget of the US nuclear weapons programme.

UK Trident warhead

While technical details about the UK's Trident warhead, sometimes known as Holbrook,[14] have never been made public, it is widely believed to be close in design to the W76. At a 1992 Defence Select Committee hearing an MOD official said it was 'not necessarily a direct copy or based solely on the W76'.[15] The two warheads are known to use different types of the high explosive that is used to compress the fissile material in the primary stage of the warhead to initiate a nuclear fission detonation.[16]

The UK appears to have begun receiving technical information about the W76 in 1980,[17] around the time that the US first agreed to provide the UK with Trident missiles.[18] At the time the UK's submarine-launched nuclear weapons were mounted on Polaris missiles that were deployed on Resolution-class submarines.

Due to concerns about Soviet missile defences, and the vulnerability of the original UK Polaris warhead to x-rays, the UK had secretly begun work on a new Polaris warhead, known as Chevaline, in the early 1970s. Chevaline, which deployed a novel system of decoys and penetration aids, became notorious for its huge cost overruns and was only in service for 12 years.

A firm decision to adopt the Trident system was taken in 1980,[19] and design work on the Holbrook warhead was completed in 1987, with production beginning in 1988.[20] The warhead came into service when the current Vanguard submarines began to replace the Polaris fleet in 1994.[21] In March 1998 the UK phased out its last WE-177 air-delivered tactical nuclear warheads, leaving Trident as the sole UK nuclear weapon system in service.[22]

It is widely presumed that the warhead's full yield is similar to the W76 yield of 100 kilotons.[23] A kiloton (kt) refers to an explosive power equivalent to 1,000 tons of TNT. The bomb dropped on Hiroshima had a yield of 15kt, so a 100kt blast would be around seven times more powerful.

Holbrook likely follows a typical modern thermonuclear design, where a boosted plutonium fission primary is compressed through implosion and the energy from the primary triggers a secondary component which produces most of the yield through a fusion reaction. These two yield-producing components are also referred to as the 'stages' of the warhead, and are collectively known as the 'physics package' of the warhead. The plutonium primary is also known as a 'pit'. The specifics of the warhead, such as the layout of the stages and the other components, have not been made public.

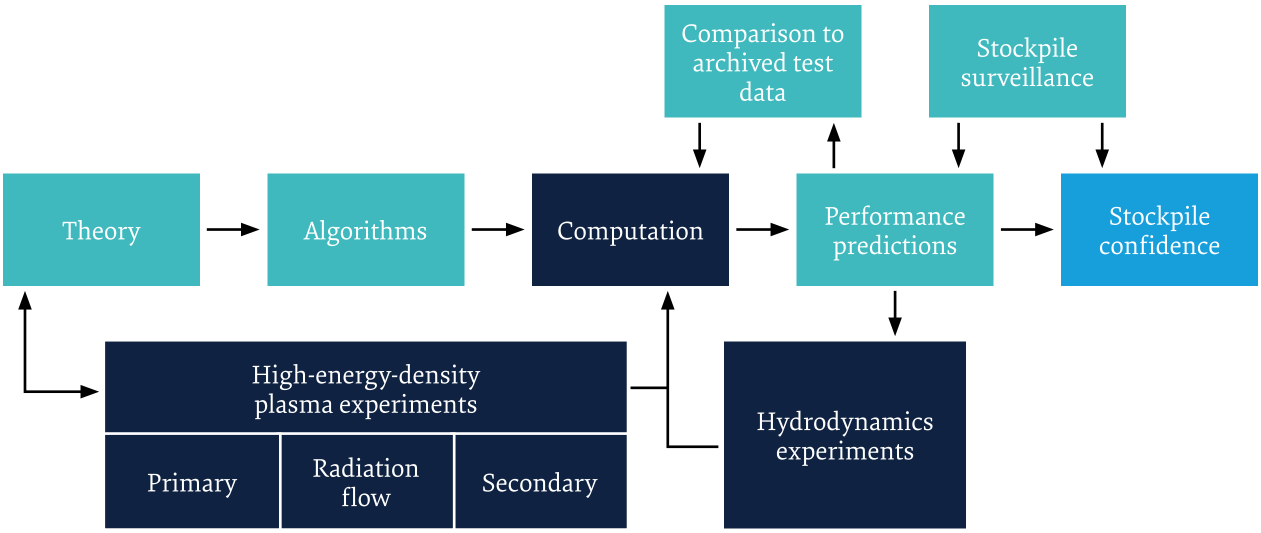
The warhead is mounted on a submarine-launched Trident II ballistic missile. Each missile contains several warheads, each within its own Multiple Independently Targetable Re-entry Vehicle (MIRV). Each MIRV[24] can be assigned to a different target within a large area and is manoeuvred into place so that it will re-enter the earth's atmosphere on a trajectory to hit the target. The shielding which protects the MIRV during re-entry is known as an 'aeroshell', and this term is also used to refer to the whole re-entry body, as distinct from the warhead.

Warhead development without live nuclear testing

After signing the 1958 Mutual Defence Agreement the UK had access to US nuclear test data and carried out its own nuclear tests at the US Nevada Test Site. However, in 1993 the US signed a moratorium on nuclear testing,[25] and since then neither the UK nor the US has carried out live nuclear tests. Instead, both countries have invested heavily in technologies that allow them to continue developing warhead designs through other experiments and simulation. The key techniques used are hydrodynamics, high energy laser experimentation, and computer modelling.

Hydrodynamics experiments involve capturing high-speed x-ray images of warhead components as they are subjected to high explosive force. When these experiments involve quantities of fissile material below the critical mass threshold for a self-sustaining

Figure 1. Data sources and modeling in nuclear weapon design without live testing[26]



nuclear reaction, they are also known as subcritical experiments. High-energy lasers are used to simulate the heat and energy experienced during warhead detonation. Data from these experiments and historical data from the live testing era are integrated into computer models which then help to design further experiments, with all three elements being interdependent.[27] The relationship between the different sources of data is illustrated in Figure 1.

While the UK and US run separate experimental programmes, there is frequent exchange of experimental results between them. Both countries also share information bilaterally with France, though this is more limited than UK-US information sharing.[28] Cooperation between the UK and France increased following the 2010 Lancaster House agreement.[29]

Mark 4A upgrade

The Mk4A upgrade to the UK warhead is part of a wider government project called the Nuclear Warhead Capability Sustainment Programme (NWCSP). Alongside the upgrade, the NWCSP has put in place infrastructure deemed necessary for the Replacement Warhead Programme. The wider NWCSP is discussed in more detail in a following section.[30]

The Mk4A upgrade extends the life of the Holbrook warhead by around 30 years,[31] meaning that it will remain in service until the late 2030s or early 2040s.[32] The Mark4A upgrade does not change the part of the weapon known as the 'physics package' – the fusion and fission components that comprise the primary and secondary, although some refurbishment of these components may take place. New components include the Mk4A arming, fusing and firing system, the gas transfer system and new high explosives.[33] The updated fuse allows more precision over the altitude of detonation and the accuracy of the weapon overall has been increased, meaning that the upgrade does increase the weapon's capability as it is more able to damage hardened targets, such as bunkers.[34]

The Mk4A upgrade mirrors an upgrade to the US W76 warhead, the W76-1. The name of the upgrade is taken from the Mk4A re-entry body which is common to both weapons. Documents from US nuclear weapon laboratories describe the UK Mk4A warhead as being a British implementation of the W76-1.[35]

Although it is distinct in bureaucratic and budgetary terms from the UK Dreadnought programme, the Trident life extension programmes and the UK Replacement Warhead, the Mk4A is best understood as part of the UK's long-term plan to replace all three elements of its nuclear weapon capability. As demonstrated by its inclusion within the NWCSP, the Mk4A was intended as a staging post on the way to a full replacement warhead, extending the life of Holbrook until the new warhead is ready to come into service.[36]

UK warhead stockpile figures 1998–2015

Due to surveillance and maintenance work on the stockpile the actual number of nuclear warheads the UK has assembled regularly fluctuates. This variance is likely to be higher during an upgrade programme such as the Mk4A. Official figures are expressed as a cap or ceiling which the stockpile numbers are supposed to remain below, rather than the actual number at a specific time.

In the past the UK has published figures[37] for the overall size of its warhead stockpile and the number of warheads which are operationally available. The difference between the two was explained as a 'margin… required to allow for routine processing, maintenance and logistic management so as to maintain the number of operationally available warheads at the required level.'[38] This margin appears to have been set at 40% of the operational stockpile for most of the period where reliable figures exist for both totals, but it would have risen to 50% of the overall stockpile, or 60 warheads, if the MOD had delivered the reductions promised by the mid-2020s.

Figure 2. UK warhead numbers 1998 to 2021[39]

Year	pre-1998 (actual)	2006 (actual)	2010 (actual)	2010 (planned)	2015 (actual)	2021 (planned)
Operational	300	200	160	120	120	–
Overall stockpile	–	281	225	180	–	260

The 1998 Strategic Defence Review (SDR) said that the increased accuracy of Trident missiles compared to Polaris meant that the number of operationally available warheads could be reduced to below 200, compared to the previous announced maximum of 300.[40] While the figure of 300 warheads was a substantial reduction compared to the peak of around 500 in the 1970s and early 1980s,[41] the total number of Trident warheads produced may have been lower than originally planned due to production difficulties during the warhead's initial run.[42]

The 1998 SDR also committed the UK to keeping only one submarine on patrol at a time and reducing the number of warheads per submarine to 48.[43] No figure was given for the overall stockpile at this time.

In the 2006 White Paper the government announced that the number of operationally available warheads would be cut by 20% from below 200 to below 160. A corresponding 20% cut to the overall warhead stockpile was also announced at this time, although no figure was given for the full stockpile either before or after the cut.[44] Using the 2010 figure we can infer that the cap for the full stockpile was 281 prior to the cut. This may be a nominal figure as the production problems could have prevented the stockpile from increasing to this size.

The 2010 Strategic Defence and Security Review (SDSR) for the first time gave an official figure for the stockpile cap of 225 and said it would be reduced to 180 'by the mid 2020s'. This timeline would have meant the reduction being completed as the stockpile was upgraded to the Mk4A warhead. The SDSR also said that each Vanguard submarine would carry no more than 40 warheads and eight operational Trident missiles, and the number of operationally available warheads would be cut from below 160 to less than 120.[45]

In January 2015 the MOD said that the reductions in operationally available warheads, missiles per submarine and warheads per missile had been completed.[46] Later that year the 2015 SDSR reaffirmed the cap of 120 operationally available warheads and that the cap on the overall stockpile would reduce to 180 by the mid 2020s. The maximum of 8 Trident missiles per submarine was restated, and the figure of 40 warheads per submarine was also confirmed, however on this occasion it was presented as a simple total, rather than a maximum. The decision in the 2021 IR to reverse these reductions is discussed in a following section.[47]

Low-yield capability

- The current UK warhead was designed with the capability to be detonated with a lower-yield explosion than a full detonation, probably using a variant of the warhead with a dud secondary.
- The US W76-2 warhead probably uses the same mechanism and is very close in design to the UK's lower-yield variant.
- The original intent was for UK Trident submarines to be able to deliver a range of nuclear strikes, using missiles carrying different numbers of warheads, some of which could detonate with a lower-yield. This practice may have stopped by the 2010s.

Existence and mechanism

As originally conceived, the UK Trident warhead was not restricted to the full 100kt detonation. In 1996 the government confirmed that the Trident system included what it called a 'sub-strategic capability'.[48] While the existence of this capability was not treated as secret at the time, it is a seldom-discussed aspect of the warhead, and government documents have not mentioned it since the mid-2000s. However, an understanding of its role is important for interpreting recent changes to UK nuclear doctrine and making predictions about future plans.

In 2006 the White Paper that laid the groundwork for the replacement of the Vanguard submarine fleet elaborated that the warhead provided a lower-yield capability.[49] The following year a government response to the Defence Select Committee described this as 'an ability to employ a reduced yield' from the warhead.[50] Earlier, in evidence to the committee, Retired Commodore Tim Hare, who was the MOD's director of nuclear policy from 1999 to 2002, said that the lower yield option didn't involve 'a great deal' in terms of configuration.[51]

The mechanism for the lower-yield option has not been made public, but the two most likely possibilities are detonating without using tritium to boost the primary, or replacing the secondary with an inert, or 'dud', component. If the primary was not boosted, that would have a knock-on reduction of the yield from the secondary and the fissioning of the radiation case. A dud secondary would need to have an identical weight distribution as the component it replaced. A warhead with the option to detonate without boosting the primary could be designed so that the chosen yield was selected prior to use, in a similar manner to the US B61 family of gravity bombs.[52]

Delivering the lower-yield using a dud secondary would mean that part of the stockpile would need to be adapted for this purpose and carried on each submarine in addition to its complement of full-yield warheads. However, it might be a more reliable approach and would represent a more efficient use of the available nuclear materials. In theory, any thermonuclear warhead could be adapted in this way, but there may have been particular aspects of the UK Trident warhead design that facilitated this, or allowed for easy replacement of the secondary with a dud.

In November 1991 the last British nuclear test at the Nevada Test Site, known as Julin Bristol, involved the warhead being tested at a lower yield.[53] The yield of the explosion is said to have been below 20kt.[54]

While the government have not publicly confirmed the retention of a low-yield option on the Mk4A warhead, in a 2007 response to the Defence Select committee the MOD stated that they would retain the 'flexibility' of having a low-yield option on the warhead.[55] As the NWCSP (which includes work on the Mk4A upgrade) was in the planning stages at this time,[56] it is likely that the upgraded warhead retains the capacity to be detonated at a lower yield.

US W76-2
The development of a US low-yield submarine warhead was announced in the Trump administration's 2018 Nuclear Posture Review (NPR). Within a year of the NPR being published, the first W76-2 units were being produced,[57] and full production was completed in June 2020,[58] less than 18 months after publication. The short production run affirms official statements that a small number of W76-1 warheads were converted to the W76-2 variant.[59] The short turnaround from concept to deployment suggests that the W76-2 did not require any significant design and development time and that the warhead components did not require any additional qualification or certification activities for the changed configuration.

The fact that the W76-2 went through a production line, and that the US elected to deliver its low-yield W76 through a separate warhead variant, suggests that converting the warheads to W76-2 involved the removal or alteration of existing components. The lack of a protracted development phase suggests that the US used a warhead configuration that was already certified and considered reliable. Taken together, the evidence suggests that UK's low-yield version of the Holbrook warhead shares a mechanism with the W76-2, most likely involving a dud secondary, and confidence in the design is derived from it having been successfully detonated in the Julin Bristol test. Sources briefing on the W76-2 back up the supposition that the warhead has a dud secondary and suggest the yield is around 5kt.[60] Other sources suggest the yield is 8kt.[61]

Role of the low-yield capability in UK nuclear doctrine
The 1998 Strategic Defence Review claimed that the 'credibility of deterrence' requires the UK to retain the capability of a limited nuclear strike 'that would not automatically lead to a full scale nuclear exchange', and that as the country's sole nuclear system Trident had to fulfil this role.[62]

The Government's 2006 White Paper again claimed that the existence of a low-yield option makes the UK's nuclear forces more 'credible' as a deterrent.[63] In his Defence Select Committee evidence Tim Hare said that the sub-strategic doctrine envisages it being used as 'an extra option in the escalatory process' prior to ordering a full nuclear strike.[64]

The Defence Secretary in 2006, Des Browne, told the select committee that a decision had been taken to cease using the term 'sub-strategic', but said it had previously referred to 'a limited use' of the UK's nuclear weapons.[65] The MOD's response to the Select Committee said that retaining a low yield capability made the UK 'more credible against the range of nuclear threats' the UK might face.[66]

Both Browne[67] and Hare emphasised that a low-yield Trident strike would not be used to achieve military objectives, with Hare differentiating this from a 'tactical' usage and elaborating that the purpose was to demonstrate the willingness to employ a full nuclear strike against adversaries. The 2006 White Paper stated that it was specifically intended to deter smaller nuclear threats.[68]

From the language at the time it would appear that UK nuclear strike options covered a range of attack sizes from a single low-yield warhead, through a small number of warheads at their full yield, to a full strike. Some of the options in between these extremes would have involved missiles carrying different numbers of warheads. This interpretation has been indirectly confirmed by Michael Quinlan, Permanent Secretary at the MOD from 1988 to 1992,[69] and government answers to questions in the House of Lords in 1996 confirm that at the time lower-yield and full-yield warheads were carried on separate missiles.[70]

The repeated references to 'credibility' invoke a hypothetical situation where an adversary might doubt the UK's willingness to order a full nuclear strike in response to a non-nuclear attack or a low-yield nuclear use. To prevent this, it was deemed necessary

CREDIT:MOD/OGL.

HMS Victorious near Faslane.

for ‘credibility’ that the UK be able to mount a range of nuclear responses using different numbers of warheads and/or the low yield option on the warhead to carry out a demonstrative nuclear strike on a scale that would be deemed appropriate.

Recently archival research has confirmed both the practice of missiles carrying different warhead loads and that the lower-yield capability was delivered by a separate warhead variant. The revelation that the lower-yield warheads required less highly enriched uranium supports the interpretation that they incorporated a dud secondary.[71]

The official limit of eight operational missiles and 40 warheads per submarine, published in the 2010 and 2015 SDSRs, would have allowed little margin for submarines to patrol with missiles carrying a range of warhead loads. The official silence on the lower-yield capability may indicate the practice had been discontinued by the 2010s, or it may be a consequence of the decision under Browne to cease using the term sub-strategic.

The apparent speed at which part of the US W76 stockpile was converted to the W76-2 variant suggests that the UK could similarly convert part of its warhead stockpile between lower-yield and full-yield configurations with relative ease. A recent statement that none of the UK’s weapons ‘are designed for tactical use during conflict’[72] does not rule out some of the stockpile being converted for use with a lower yield or the capability having been retained, given the previous insistence that the capability was not intended for tactical use. The current status of the low-yield capability is discussed in the ‘Reason for the warhead stockpile increase’ section below.[73]

US Interoperable Warheads and the 3+2 plan

- Between 2010 and 2018 the long term plan of the NNSA was to rationalise its stockpile from 12 warhead designs to just 5.
- Components from the 3 planned interoperable ballistic missile warheads would have been designed to be used in various other warhead designs.

The W93 programme arose directly from the previous US 3+2 plan, which aimed to rationalise the US nuclear weapon stockpile from 12 different types of weapon to five.[74] In US Navy budget requests the project for designing the W93 warhead and its Mk7 aeroshell was previously known as the Interoperable Warhead project,[75] which was to be the first warhead built under the National Nuclear Security Administration's (NNSA) 3+2 strategy.

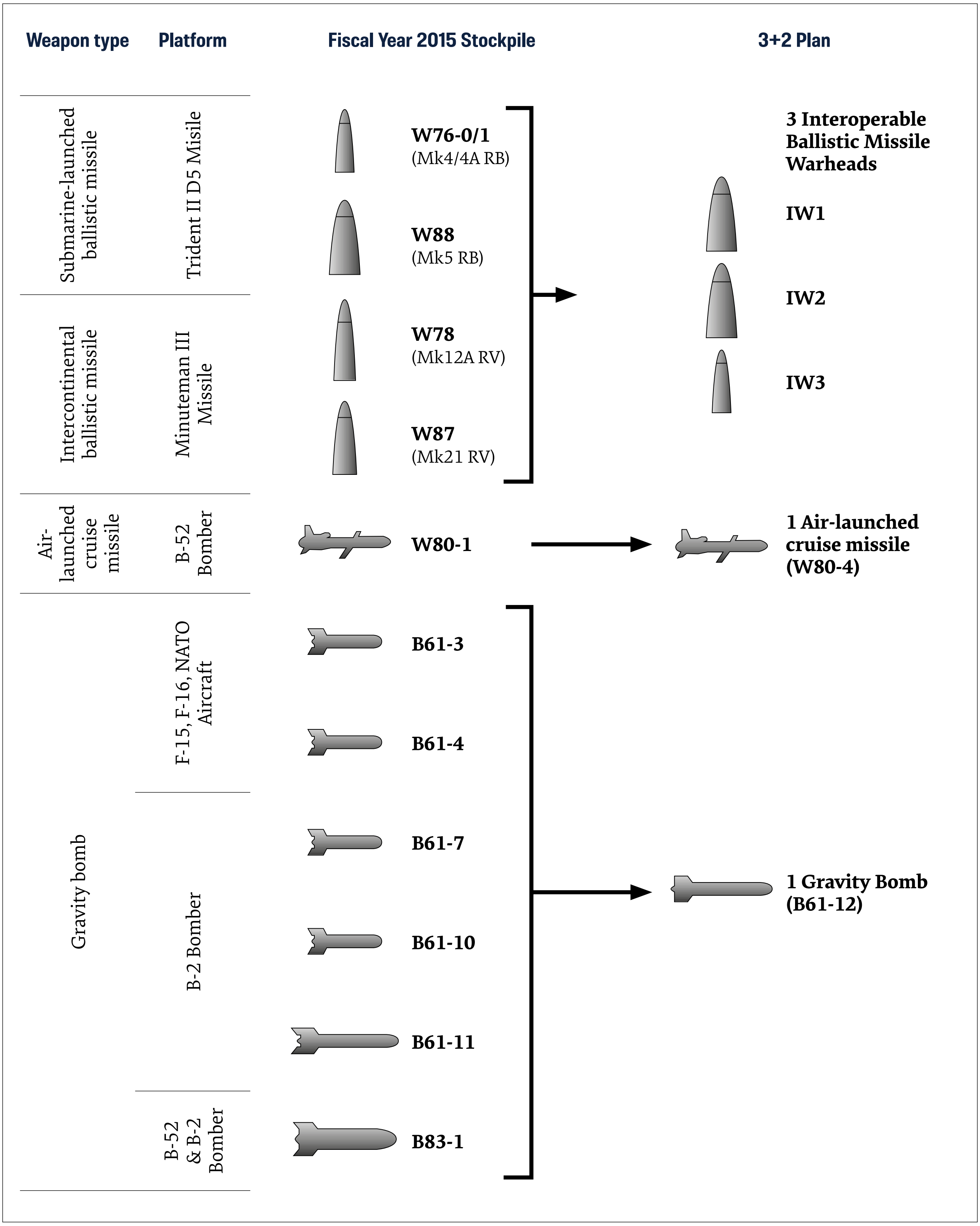
The 3+2 strategy arose from the Obama Administration's 2010 Nuclear Posture Review and National Security Strategy. Under it, warhead programmes that were already well advanced, such as the W76-1 and W88-Alt 370 upgrades, would continue as originally conceived.[76] However, when other warheads or nuclear bombs in the stockpile came towards the end of their service lives, instead of a new life-extension programme, they would have been replaced by one of the five designs.[77]

The intention was to produce three interoperable ballistic missile warhead designs that could all be fielded both on Trident missiles and silo-based Minuteman II missiles, as well as one air-delivered nuclear gravity bomb and one air-launched nuclear cruise missile.[78] Figure 3 shows the intended changes. The B61-12 life extension programme (LEP), while pre-dating the strategy, was intended to be the gravity bomb warhead, and the next priority for the strategy was to build the first interoperable ballistic missile warhead, the IW1. While the 3+2 strategy did not intend the three ballistic missile warheads to be direct replacements of the five existing designs, IW1 was intended to replace both the W88 Trident warhead and the W78 Minuteman warhead.[79]

The IW1 warhead would have consisted of a nuclear explosives package (NEP) that could be carried in both the Mk5 re-entry body currently used by the W88 warhead and the Mk21 re-entry vehicle currently used by the W87 ICBM warhead.[80] Many of the IW1 components would have been designed to be easily incorporated into other 3+2 warhead designs,[81] in order to minimise costs and simplify future manufacturing and maintenance work.

The IW1 was authorised by the US Nuclear Weapons Council in June 2012 and progress was accelerated in Fiscal Year(FY)[82] 2013 so that the programme could focus on a preferred design concept from an early stage. It was decided to use a primary core, or 'pit', similar to the one used in the W87, but the programme timetable was then delayed for budgetary reasons and to allow the NNSA to focus on the W80-4 cruise missile warhead. Under the revised timetable the IW1 First Production Unit would have been produced in FY 2030.[83] The steps which led instead to the W93 programme are discussed in detail below.[84]

Figure 3. US nuclear weapon stockpile plans: Fiscal Year 2015 vs 3+2 plan[85]



2. Current developments

This part of the report discusses current and recent developments related to the US W93 and the UK Replacement Warhead project. The early sections relate to programmes in the US that provide important context for the UK's Replacement Warhead: the W93 and Mk7 aeroshell programmes and the justifications for them. The following sections relate directly to the UK. The NWCSP has put in place the infrastructure that will be used to build the UK Replacement Warhead. The Replacement Warhead Programme section draws on the previous sections and sets out what is currently known about the programme.

W93 Warhead and other US developments

- The W93 will be a new warhead design, but will be based on components that were previously live tested
- The UK is a participant in the US W93 and Mk7. programmes and probably has input into the design but no decision-making power.
- After a period identifying possible design concepts, in FY 2022 the two programmes progressed towards reviewing and refining these concepts in order to select a single chosen design.

W93 and Mk7 Programmes

The proposed W93 programme was revealed in the Trump administration's NNSA budget request for FY 2021. After the budget was published the Pentagon briefed that W93 will be a new warhead design. It will include new conventional components and additional safety features, but will be based on existing designs and components that are already in the stockpile. As an example of the kind of changes that might take place, it was suggested that the position of the secondary and primary within the warhead might be swapped.[86]

The W93 NNSA budget request for FY 2021, which was approved by Congress,[87] asked for funds to begin Phase 1 of the NNSA-DOD Phase 1-7 weapons acquisition process, the Concept and Assessment Refinement Stage. During this initial phase a range of potential warhead designs are evaluated against various desired attributes, characteristics and constraints.[88] During FY2021 the respective design spaces for the nuclear and non-nuclear parts of the warhead were identified.[89]

The FY 2022 NNSA budget request anticipated the W93 transitioning into Phase 2 during FY 2022, following approval from the Nuclear Weapons Council.[90] During Phase 2 the warhead concepts identified during Phase 1 will be reviewed and developed into a series of design options that will eventually be winnowed down to a single proposed design. Phase 2 is planned to continue during FY 2023,[91] during which work will take place to down-select the nuclear explosive package. Part of this work will involve a system level assessment of possible primary designs.[92]

Once a single design has been selected the programme will proceed to Phase 2A: Design Definition and Cost Study,[93] possibly in FY 2025 or 2026.[94] Coordination with the UK Replacement Warhead Programme is an integral part of the project,[95] and the UK will likely have some input into the W93 project but no decision-making authority. The remaining stages of the weapons acquisition process can be seen in Figure 4. A similar 6.x process is used in life extension projects such as the W76-1 LEP.[96]

The Mk 7 re-entry body which will house the W93 has a separate budget, which falls under the US Navy's budget request. The Mk7 and W93 programmes are run as separate, but closely related, projects with synchronised timetables. The W93 Phase 1 concepts will inform the design requirements for the Mk7 re-entry body[97] and the two will be designed in parallel, as each will need to take into account aspects of the other. The Mk7 design will be predicated on a specific warhead mass and weight distribution, but its dimensions and shape will also circumscribe those of the warhead.

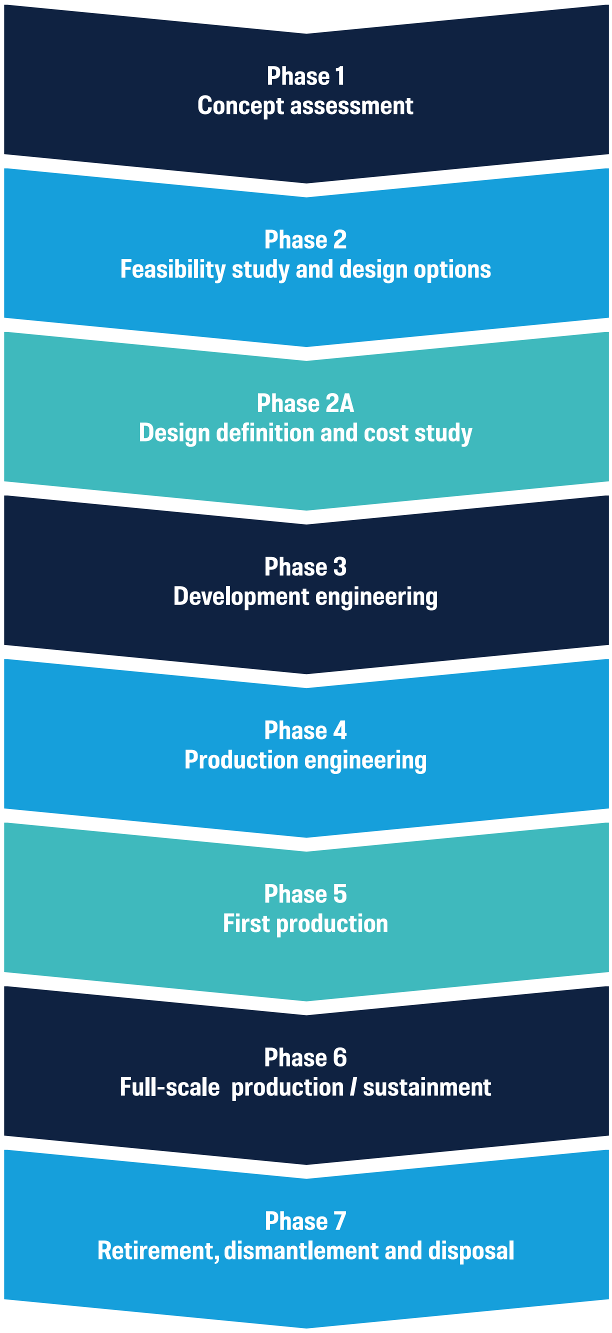
Navy budget requests for the Mk7/W93 programme in FY 2021 include the commencement of a trade study for aeroshell design options and development of material for the aeroshell thermal protection system, including analysis and modelling potential materials for vulnerabilities, accuracy, reliability and performance in flight. FY 2022 plans include initial data analysis for fire control software support for the W93 and the early stages of developing material for the aeroshell, including ground testing. It is anticipated that aeroshell development will include a mock flight experiment once the programme moves into Phase 3.[98] The Mk7 design will involve a new Arming, Fusing, and Firing (AF&F) subsystem and Release Assembly.[99] Annexe A includes further detail on the planned outputs from the two programmes during these years.

The 2022 NNSA Stockpile Stewardship and Management Plan provides a 'planning estimate' cost of between $13.4bn and $15.5bn for the W93. This was said to be 'based on preliminary assumptions for the... design, with increased uncertainty', and is expected to be revised in the future.[100]

Since 2016 the US and UK have been working together on new warhead technology as part of the Joint Technology Demonstrator (JTD) project. Although the JTD works on technology that is not tied to a specific new warhead design its short-term focus means that many of the technologies it develops will be utilised in the W93 and UK Replacement Warhead.

Workstream 2 of the JTD is focussed on a reference warhead design based on the Mk21 aeroshell, which houses the W87 warhead. Workstream 1 was until recently focussed on a reference design based on the Mk5 aeroshell that houses the W88 warhead, but has recently transitioned away from that and its current reference design is probably based on the expected characteristics of the Mk7 aeroshell.

Figure 4. NNSA-DOD weapons acquisition process[101]



The JTD has investigated advanced manufacturing technologies and worked on enhanced surety. Surety in nuclear weapons design refers to measures that are intended to prevent the weapon being used without authorisation, while ensuring it is as reliable as possible at the time of authorised use and maximising safety at all other times. Surety technologies can be an internal design feature of the warhead, something outside the warhead itself, or a mix of the two.[102] Outside the JTD the UK and US have carried out research on system survivability. More detail on the JTD and other joint research can be found in Annexe B.

Instead of replacing the Trident D5 missile the US now plans a second life-extension programme for the missile, known as the D5LE2. The programme is intended to at least match the current missile accuracy and range while being more able to counter and survive missile defence systems. More detail on the D5LE2 can be found in Annexe C.

Justification

In December 2020 an unpublished section of a joint Pentagon and Department of Energy (DOE) memo, listing justifications for the W93 programme, was leaked to the Guardian newspaper.[103] The memo listed three overall factors and five more specific reasons for the decision, many of which also appear in public statements by US officials.[104]

The three overall factors were:

- Changes in the 'threat environment', particularly improvements to defences in countries the US considers as adversaries.
- The age and makeup of the US submarine-launched warhead stockpile.
- The move to a smaller nuclear-armed submarine fleet with fewer missile tubes when the planned new Columbia-class SSBN comes into service.

The five reasons given were:

1. To better meet the operational requirements of US Strategic Command. This was said to have two elements:
    - According to the memo the stock of W88 warheads will be reduced by the W88 Alt 370 programme and surveillance activities and the resulting warhead mix will not give sufficient confidence that the warheads could destroy all the targets in US war plans.
    - The W93's lighter weight would allow a Trident missile strike from a greater distance, and over a greater spread of targets, increasing submarine patrol areas at a time when submarine detection capabilities are improving.
2. To support the UK's Replacement Warhead Programme.
3. To mitigate the risk from delays to life extension or replacement programmes for either the W76 or W88, which are said to be reaching the end of their service lives 'at nearly the same time' during the '2030s–2040s'.
4. For the W93 to act as a technical hedge for the sea-leg of the US nuclear triad, an additional design that would be unaffected if a serious technical issue were discovered in one of the other two designs, particularly the W76.
5. To revitalise the US nuclear industrial base, particularly in aeroshell development.[105]

While the purpose of the memo is evidently to make the case for the decision, and it should not be taken entirely at face value, its contents do give some insight into the possible reasoning behind the decision. The approach of the 2018 Nuclear Posture Review is clearly evident in several of its reasons. An analysis of these justifications and, the rationale behind the W93 project and its role in the US warhead stockpile can be found below.[106] Alongside the available information about the W93 and related programmes, this then informs an analysis of the likely characteristics of the W93.

Nuclear Warhead Capability Sustainment Programme

- The NWCSP put in place the infrastructure necessary for delivering the Replacement Warhead Programme and included the Replacement Mk4A upgrade to the UK Trident warhead.
- Several projects within the NWCSP related directly to the technologies used to develop nuclear warheads without nuclear explosive testing.
- Delays and cost overruns have affected some of these projects and at least one is likely to have part of its cost included in the Replacement Warhead Programme.

The Mk4A warhead programme, as discussed above,[107] was part of the larger NWCSP. Announced in 2005,[108] the NWCSP was intended to sustain the UK's ability to produce nuclear weapons in the long term. Aside from delivering the Mk4A warhead upgrade, the NWCSP's main objectives have been to build the facilities needed for the Replacement Warhead Programme, and to develop and retain the skills and capability necessary for the continued production of nuclear weapons.[109]

The official start date of the NWCSP was in April 2008 and it was due to run until April 2025. As well as the full running costs for the Atomic Weapons Establishment (AWE) over that time, the programme included numerous infrastructure projects including new facilities for manufacturing high explosives, conventional manufacturing and chemical processing.[110] The total cost of the NWCSP was projected to be just below £20bn.[111]

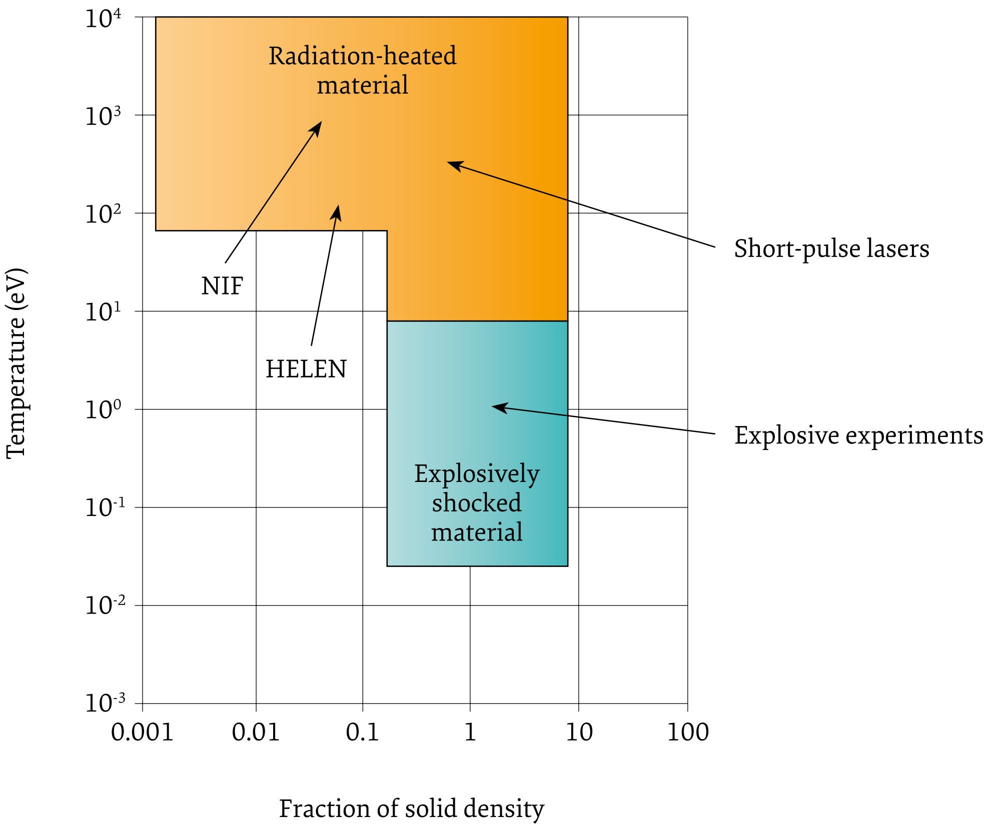
Several of the infrastructure projects relate directly to hydrodynamics, high energy laser experimentation, and computer modelling, the three techniques that have been used for nuclear weapon development in place of live nuclear explosive testing and will be used to design the Replacement Warhead.

AWE's Orion laser facility became operational in April 2013. The facility combines 10 long-pulse laser beams and two petawatt short-pulse beams, creating conditions of up to 10 million degrees centigrade. Orion was designed to complement the research programme at the US National Ignition Facility.[112] Figure 5 shows a diagram published in 2002 illustrating the range of conditions that different experiments and facilities can simulate.

The 'Orchard' computing facility at AWE, constructed under the NWCSP, will likely house the latest supercomputer purchase: a seven petaflop[113] Cray Shasta supercomputer, which will be named 'Vulcan'. The acquisition of Vulcan was announced in December 2019, and it was planned to go into general production by the end of 2020.[114] At present it has not appeared on the most recent rankings of the most powerful computers in the world, but with theoretical peak performance of 7.42 Petaflops it will be nearly twice as fast as AWE's Damson supercomputer, which was built in 2017, and is currently considered to be the 156th most powerful computer in the world.[115]

In November 2010 the hydrodynamic facility planned under the NWCSP was cancelled in favour of a joint French-UK facility at Valduc in France, known as Epure. The joint project, known as Teutates, is late and over budget, although the MOD claims it is still able to be completed on time.[116] The UK Government will not release information on the cost of the programme and its final in-service date, saying that to do so would harm relations with France.[117] The facility appears to currently be operational, but only able to capture data in two dimensions until the third axis for the facility is built.[118] It is not clear whether this reduced capability will have any implications for the UK's Replacement Warhead timetable.

Figure 5. Conditions created in a nuclear warhead[119]



Teutates is not the only project under the NWCSP to have run into problems. The Mensa warhead assembly and disassembly facility at AWE Burghfield was until recently seven years behind schedule and expected to cost £1.8bn, nearly 2.5 times its original budget.[120] However in February 2022 the Government admitted that the completion date for Mensa had moved from 2023 to 2024 and the project is now expected to cost just under £2bn.[121]

Work on the Pegasus enriched uranium facility, also considerably delayed and over budget, was paused for several years. The official rationale for this was to re-evaluate options for the project, but it is likely that a desire to limit short-term costs was a major factor. The government announced in March 2021 that work on the project was re-starting, with work on the store part of the project to commence immediately with the aim of having the manufacturing facility able to begin production in 2030.[122]

The total cost of the project is expected to be higher than the approved £634m budget. No official estimate of the full cost of the project has been made public. The government plan to spend part of the remaining budget on building the store and assessing the cost of completing the manufacturing facility. The cost of this second stage of the Pegasus project is likely to be included in the budget of the Replacement Warhead Programme, which will probably also include additional infrastructure projects.[123]

As this report was being prepared for publication, the Government published its annual release of data on its major projects portfolio. The NWCSP does not appear on the list, but Mensa, Pegasus and Teutates were included as separate projects, with all project details redacted. [124] This suggests that the NWCSP, if it still exists as a distinct government project, is not large enough to meet the threshold for being included in the Major Projects Portfolio. Whatever the current status of the NWCSP and its subsidiary projects, the cost overruns and delays that have dogged it raise questions about the ability of the UK's nuclear enterprise to deliver the Replacement Warhead Programme on time and to budget, particularly any infrastructure projects that might be included.

UK Replacement Warhead Programme

- The UK Replacement Warhead Programme is at a similar stage of development to the W93 and will currently be refining warhead design options.

- There is no official budget and timetable for the warhead, but it is likely to come into service in the late 2030s or early 2040s. Using the US planning estimate for the W93 we can estimate a ballpark cost for the warhead of between £10.9bn and £12.6bn.

Preparatory work

The government has made few details public since the February 2020 announcement of the Replacement Warhead Programme. In response to parliamentary questions the decision was presented as having been taken by the government as a collective under the leadership of the Prime Minister.[125] The government was said to have spent £116m on planning the warhead replacement to the end of financial year 2018-19, and £98m in financial years 2019-20 and 2020-21, which was referred to as the 'Replacement Warhead readiness phase'.[126]

This 'readiness phase' was not publicly announced in the government's annual 'Future Nuclear Deterrent' updates to parliament, but during that time the language about warhead replacement activities was changed from the previous references to 'developing replacement options'[127] to 'refin[ing] options and technical solutions' in December 2018[128] and 'develop[ing] the evidence to support a government decision' in December 2019.[129] Project data released in July 2018 listed one of the aims of the NWCSP as providing evidence for the warhead decision.[130] This work will have built on earlier studies that were carried out from 2008 onwards.[131] Annexe A, which details the outputs of the W93 and related programmes, gives an idea of the types of documents which will be being produced internally since the decision to go ahead with the warhead.

The timing of the announcement fits within the timescale that had been long predicted by the government,[132] although in 2018 the update alluded to the timetable being dependent on US plans following the NPR earlier that year.[133] The most likely chain of events is that part way through 2019 US plans arising from the NPR and the Navy Feasibility Study[134] were sufficiently certain for the UK to bring the warhead replacement project to the readiness phase, and the formal decision to go ahead was scheduled to be taken after the announcement of the December 2019 election.

Cost and timescale

Although the Replacement Warhead Project will likely use a separate programme management system from NNSA-DOD Phase 1-7 weapons acquisition process,[135] the development stages it will pass through will be broadly similar.[136] As discussed below,[137] the warhead is likely to closely follow the design of the W93, but as a bare minimum it will need to fit within the Mk7 aeroshell and have an identical weight distribution to the W93. Due to its dependencies on both aeroshell and weapon design choices,[138] and in order to feed into the US design processes, the Replacement Warhead Programme will need to follow the Mk7/W93 timetable until the design and specifications for the aeroshell are agreed.

In June 2021 the MoDs' Director General Nuclear commented that the project had to do a lot of work to 'get through those designs'.[139] This confirms that the project was in a stage analogous to the US Concept Assessment phase and had yet to move into something akin to the Feasibility Study and Design Options phase.

The government says it is too early to provide cost estimates for the project,[140] but the Strategic Outline Case was approved by the Cabinet Office's Major Projects Review Group in September 2021.[141] It was not included into the Government's Major Projects data release in July 2022.[142] This suggests that funding has only been released for the early stages of the project and the currently approved budget for the project is not large enough to meet the threshold for including in the Major Projects Portfolio. If so, an official budget estimate is unlikely to be made public until after a warhead design is selected. The current $13.4bn to $15.5bn planning estimate for the W93 is equivalent to between £10.9bn and £12.6bn. Given the uncertainties in the original US figures and the potential for costs differing between the two countries this should be regarded as a ballpark figure, rather than an accurate estimate. If infrastructure work is included within the UK warhead project, the final cost could be higher.

The government refused to give information about the timeline of the project in response to a parliamentary question, citing national security.[143] However, the likely timescale of the project can be inferred from information already in the public domain. The US W76-1 was said to extend the service life of the W76 to 60 years,[144] meaning that the earliest manufactured units will expire in the late 2030s. The UK's warheads were manufactured later, but may have a shorter service life than the W76 due to the ageing of US-made components.[145] The 2016 update to parliament said that the replacement warhead would not be needed 'until at least the late 2030s, possibly later'[146] Given that the decision to proceed with the replacement programme was broadly in line with the timetable envisaged in 2016, it would seem that the Replacement Warhead is intended to come into service some time in the late 2030s or early 2040s. This also aligns with the estimate in the 2011 Trident Alternatives Review of a 17 year turnaround for a new warhead.[147]

The production of the warhead is likely to be spread out over a relatively long period of time. Conversion of the stockpile to Mk4A started before 2016[148] and may last nearly a decade.[149] Given the issues caused by long fallow periods in the nuclear enterprise,[150] it seems likely this practice of extending production runs in order to minimise the downtime between warhead production and upgrade cycles will continue.

Renationalisation of AWE

In September 2020 the government announced that AWE, previously operated as a government owned, commercially operated enterprise, was being brought back into public ownership. This was achieved by making the MOD the sole shareholder of AWE Plc, the company that owns the AWE sites.

NIS understands that the change was in part a consequence of the poor regulatory and programme delivery performance of the Lockheed Martin-Serco-Jacobs Engineering consortium who previously held the contract, and the poor value for money that the contract represented for the government. However, the desire to exercise greater control over AWE as the warhead project commenced was clearly also a major factor.[151] AWE will be run as an arms-length body of the MOD. There have been some changes at board level, but much of the senior leadership team, including the chief executive Alison Atkinson who was appointed in May 2020, remain in post.[152] This suggests that the decision to renationalise was motivated by concerns about accountability and cost rather than dissatisfaction with management at the sites.

3. US and UK nuclear policy changes

This part of the report deals with the policy environment surrounding the decisions to develop the W93 and the UK Replacement Warhead. The first section looks at the US 2018 Nuclear Posture Review (NPR), which provided the policy environment that led to the W93 decision and informed much of the thinking that underlies its justification. The second section looks at the UK's 2021 IR. Although the IR came out a year after the announcement of the Replacement Warhead Programme, the two appear to be part of a single process of policy development. Due to the limited information we have about the two warhead programmes, the policy documents of the two states provide important contextual information that enable greater understanding of the reasoning and purpose behind the decision. This information will be drawn out in part 4 of the report.

The 2018 US Nuclear Posture Review

- The 2018 NPR increased the role of nuclear weapons to deal with a greater range of threats than had been the case previously.
- The concept of hedging in the NPR is used to justify additional layers of redundancy in the US nuclear stockpile.

The Trump administration's 2018 Nuclear Posture Review (NPR) enlarged the role of nuclear weapons in US doctrine to include the deterrence of non-nuclear threats, including 'chemical, biological, cyber, and large-scale conventional aggression'.[153] It stated there was 'no 'one size fits all' for deterrence', meaning 'a tailored and flexible approach' was needed to 'effectively deter across a spectrum of adversaries, threats and contexts.'[154] In practice this was said to require an increasing 'diversity and flexibility of platforms, weapons and modes of operations'.[155]

The review claimed that in order to counteract a supposed Russian 'escalate to de-escalate' strategy it was necessary to increase the 'flexibility and range' of 'credible' US nuclear strike options. To this end it announced a new low-yield submarine-launched nuclear warhead, later revealed to be the W76-2. Over the longer-term the NPR also pledged to develop a new nuclear-armed sea-launched cruise missile.[156]

Claims about a Russian 'escalate to de-escalate' strategy are a long-standing feature of debate in US nuclear policy circles. The Russian government has publicly rejected the claim and analysts are divided about whether such a strategy exists in Russian nuclear doctrine.[157]

Hedging is a major concept in the NPR. Nuclear weapons are said to provide a hedge against four categories of risk: geopolitical (the emergence of new adversaries, or of new capabilities or behaviour from existing adversaries), technological (both technological failure in US nuclear capabilities, or the technological developments of adversaries), operational (ranging from mistakes made by US forces to US intelligence failures), and programmatic (meaning issues within the US nuclear weapons programme, such as delays, ageing warheads or an inability to produce components).[158] The NPR envisages nuclear weapons both reducing the risk of these issues occurring and minimising the impact if they do occur, and says that decisions about US nuclear forces and infrastructure will be guided by this hedging strategy.[159]

This expansive conception of hedging found in the 2018 NPR goes beyond how the term has been used in the past. Introduced in the 1994 NPR under the Clinton administration, the application of the term changed in both the 2002 Bush administration and the 2010 Obama administration NPRs, but of the four categories of risk in the 2018 NPR it was applied only to some aspects of geopolitical and technological risk.[160] As can be seen from the joint Pentagon and DOE memo, this concept of hedging is used to justify additional layers of redundancy within the US nuclear stockpile. The memo justifies the W93 as an additional hedge within the submarine leg of the triad, should a problem arise in one of the SLBM warheads, whereas in the 1994 conception, the three legs of the triad are considered hedges against failures in one of the other legs.

The Biden administration's 2022 NPR
At the time of writing the Biden administration's NPR has been released to the US Congress but an unclassified version has not yet been published. Initial expectations that the NPR would make significant changes to US nuclear posture were dampened after the abrupt removal, two months into its work, of Deputy Assistant Secretary of Defense for Nuclear and Missile Defense Leonor Tomero, who had initially been in charge of the review.[161] A fact sheet released by the US Department of Defense confirms that the NPR does not follow through with Biden's campaign promise to define US nuclear weapons as having a sole purpose of deterring a nuclear attack on the US or its allies; the phrase used instead is 'fundamental purpose', leaving open the possibility of them serving other purposes.[162]

Budget documents for FY 2023 show that the Biden administration had decided to scrap the sea-launched cruise missile promised in the 2018 NPR. Press reports confirmed that this decision was mandated by the forthcoming NPR.[163] It appears that neither the W76-2 nor the W93 will be cancelled by the Biden administration. It remains to be seen whether any policy changes in the NPR will impact upon the design choices for the W93.

The UK's 2021 Integrated Review

- The IR increased the UK's stockpile cap to 260 warheads and withheld other information about the UK's nuclear posture that had previously been disclosed.

- The IR also enlarged the qualification to the UK's negative security assurance.

In March 2021 the UK released its Integrated Review of Security, Defence, Development and Foreign Policy, entitled 'Global Britain in a competitive age'. The IR was an attempt to avoid the problems of earlier similar reviews, which set out the UK's military priorities without reference to the Treasury's willingness to fund the required spending. The IR was intended to incorporate the work of the Foreign, Commonwealth and Development Office and to be conducted with sufficient Treasury input to ensure that its plans would be fully funded.

The most significant change to the UK's nuclear posture in the IR was a reversal of a decades-long trend of reductions in the UK nuclear stockpile. The planned reduction of the stockpile ceiling to 180 by the mid 2020s[164] was said to be no longer possible due to the 'evolving security environment, including the developing range of technological and doctrinal threats'. Instead the stockpile ceiling was increased to 260.

The size of the UK's nuclear arsenal is said to be determined by 'maintaining the minimum destructive power needed to guarantee that the UK's nuclear deterrent remains credible and effective against the full range of state nuclear threats from any direction' and 'the capability required to impose costs on an adversary that would far outweigh the benefits they could hope to achieve should they threaten our, or our Allies', security.'[165]

Alongside the increase to the overall stockpile, the review reversed the policy of providing information about numbers of operational warheads and the number of deployed warheads and submarines. This was presented as an extension of a 'long-standing policy of deliberate ambiguity', maintaining that this ambiguity 'complicates the calculations of potential aggressors, reduces the risk of deliberate nuclear use by those seeking a first-strike advantage, and contributes to strategic stability.'[166]

Figure 6. Changing threat characterisation and negative security assurances from strategic reviews 2010–2021

2010	2015	2021
No state currently has both the intent and the capability to threaten the independence or integrity of the UK.	Other states continue to have nuclear arsenals and there is a continuing risk of further proliferation of nuclear weapons.	We have previously identified risks to the UK from major nuclear armed states, emerging nuclear states, and state-sponsored nuclear terrorism.
But we cannot dismiss the possibility that a major direct nuclear threat to the UK might re-emerge…	There is a risk that states might use their nuclear capability to threaten us, try to constrain our decision making in a crisis or sponsor nuclear terrorism. Recent changes in the international security context remind us that we cannot relax our guard. We cannot rule out further shifts which would put us, or our NATO Allies, under grave threat…	Those risks have not gone away. Some states are now significantly increasing and diversifying their nuclear arsenals. They are investing in novel nuclear technologies and developing new 'warfighting' nuclear systems which they are integrating into their military strategies and doctrines and into their political rhetoric to seek to coerce others…
… the UK will not use or threaten to use nuclear weapons against non-nuclear weapon states parties to the NPT. In giving this assurance, we emphasise the need for universal adherence to and compliance with the NPT, and note that this assurance would not apply to any state in material breach of those non-proliferation obligations.	The UK will not use, or threaten to use, nuclear weapons against any Non-Nuclear Weapons State party to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). This assurance does not apply to any state in material breach of those non-proliferation obligations.	The UK will not use, or threaten to use, nuclear weapons against any non-nuclear weapon state party to the Treaty on the Non-Proliferation of Nuclear Weapons 1968 (NPT). This assurance does not apply to any state in material breach of those non-proliferation obligations.
We also note that while there is currently no direct threat to the UK or its vital interests from states developing capabilities in other weapons of mass destruction, for example chemical and biological, we reserve the right to review this assurance if the future threat, development and proliferation of these weapons make it necessary.	While there is currently no direct threat to the UK or its vital interests from states developing weapons of mass destruction, such as chemical and biological capabilities, we reserve the right to review this assurance if the future threat, development or proliferation of these weapons make it necessary.	However, we reserve the right to review this assurance if the future threat of weapons of mass destruction, such as chemical and biological capabilities, or emerging technologies that could have a comparable impact, makes it necessary.

CREDIT: NIS

Citadel Gate and part of the Waste Management Complex at AWE Aldermaston.

The IR says that other nuclear-armed states are developing new capabilities in order to coerce other states. The review also enlarged the qualification to the UK's long-standing negative security assurance that it would not use or threaten to use nuclear weapons against a non-nuclear NPT state that was fulfilling its obligations, broadening the reservation to also cover 'emerging technologies that could have a comparable impact' to WMDs.[167] An assertion from the wording in previous reviews that 'there is currently no direct threat to the UK or its vital interests' from states developing WMDs[168] has also been removed. The changing language in the characterisation of geopolitical risk and the UK's negative security assurance from the 2010 and 2015 SDSRs to the IR can be seen in Figure 6.

The other element of the UK's declaratory policy, the statement that the UK would only use nuclear weapons in 'extreme circumstances of self-defence' was retained in the IR.[169] This language is a reference to the 1996 International Court of Justice's (ICJ) advisory opinion. The opinion was not able to definitively conclude whether threatening or using nuclear weapons would be legal or illegal 'in an extreme circumstance of self-defence, in which the very survival of a State would be at stake'.[170] Despite a statement by the President of the Court that this part of the ruling 'cannot in any manner be interpreted as having opened the door to the recognition of the legality of the threat and use of nuclear weapons',[171] nuclear-armed states have incorporated this wording into their security doctrines, suggesting that they believe it legitimises their continued possession of nuclear weapons.

The IR confirms that the UK's nuclear weapons continue to be assigned to NATO, as they have been since the 1962 Nassau agreement,[172] but the precise role they play in NATO's joint nuclear war plan remains unknown.[173]

An assessment of the UK's nuclear policy under the IR and the implications for the Replacement Warhead can be found in the following section.

4. Analysis

This part of the report uses information from the previous parts of the report to analyse the policy environment that produced the decisions to go ahead with the W93 and the UK Replacement Warhead, the reasons for those decisions and the inferences that can be drawn about the warheads themselves, based on the available evidence.

The first sections deal with two key elements of the analysis: the tensions on nuclear-armed states that are members of the NPT and the factors behind the push for recapitalising the nuclear enterprises of the UK and US. The following sections deal with policy and the IR, its contradictions, the stockpile increase and warhead numbers.

The focus then moves to the warheads themselves, looking at the purpose, lineage and characteristics of the W93, before addressing the likely characteristics of the UK Replacement Warhead, and the reasons it is likely to be very close in design to the W93. As with the previous sections, much of the available technical information relates to the US programme, but has been leveraged to draw inferences about the UK.

The level of secrecy surrounding nuclear weapons in general, and the UK programme in particular, means that some of the points made in this part are necessarily conjectural, based on the best available information, rather than confirmed.

Janus-faced: nuclear-armed states under the NPT

- The NPT-recognised nuclear-weapon states face a fundamental tension between their treaty obligations and their desire to retain nuclear weapons for the foreseeable future.
- Solutions do exist to address the technical issues underlying this tension through other means than producing new warheads.
- The significance of the W93 and Replacement Warhead Programme is as a statement of intent, signalling a move away from realising disarmament commitments.

To understand the decisions to go ahead with the W93 and the UK Replacement Warhead, it is necessary to first understand the fundamental tension in the avowed nuclear policies of the five NPT-recognised nuclear-weapon states. All are committed both to the abandonment of their nuclear weapons in the long-term, and to their retention for the foreseeable future. Practical and technical considerations mean it becomes increasingly difficult to reconcile these twin contradictory goals over time. Retaining nuclear weapons with a limited service life requires a certain amount of remanufacture and refurbishment, with some aspects of those processes becoming increasingly difficult as the weapons age and components wear and become obsolete.

A notable example of these kind of issues in the US is the loss of the institutional knowledge of how to manufacture a material called Fogbank, which was used in several warhead designs including the W76. Re-establishing the capacity to produce Fogbank cost around $82m[174] and delayed the W76-1 programme by around two years.[175] The US Government Accountability Office identified similar issues in the production of explosive materials used in around 100 nuclear weapon components. A further example was the Thatcher government's decision, at the time when a life extension of the Polaris missile was being considered, to pay Dupont around £100,000 a month in order to retain the capability to manufacture a key material. These examples are covered in more detail in Annexe D.

This physical infrastructure necessary for manufacturing components itself requires periodic maintenance. Externally produced parts will become unavailable without a constant demand driving production. Changing standards around safety and other factors may require certain components or processes to be changed or replaced. Staff skills that go unused for long periods of time will tend to atrophy, and staff members themselves may seek alternative employment where they can be challenged and break new ground. It may also be harder to attract new staff. Consequently, and because it is politically easier to fund through new initiatives than as a stand-alone budget line, the institutional preference within the nuclear enterprises in both the US and UK has been for these issues to be addressed through the production of new nuclear weapons.

The tension between this preference and disarmament commitments has doubtless played out within the bureaucracies of these states, with the priorities of the institutions and agencies tasked with sustaining nuclear weapon capabilities running counter to the agendas of those who wish to make progress towards disarmament commitments. In the US, the most transparent of the nuclear-armed states, ongoing pressure from within the nuclear weapons programme for the manufacture of new weapon designs was demonstrated by the emergence of the Reliable Replacement Warheads[176] and the 3+2 plan.[177]

With these programmes not progressing beyond the design stage, capabilities within the US nuclear programme have been sustained through life-extension and stockpile stewardship work. This appears to have been successful. The W76-1 involved the NNSA undertaking 'full-scale design activities' for a weapon system for first time since 1982.[178] The W87-1 replacement is planned to have all new manufactured components and a nuclear material manufacturing modernisation plan, requiring large multi-year investments in component and material capabilities,[179] and was recently described as the 'pathfinder' programme for ballistic missile upgrades that will develop the infrastructure and technological processes needed for future programmes.[180]

If the goal of sustaining capabilities within the US and UK nuclear weapons programme is considered an absolute necessity, despite the disarmament commitments of the two states, there do not appear to be any fundamental technical barriers to fulfilling that goal through projects such as the JTD, and life extension programmes. The same goes for the particular requirement cited in the joint Pentagon and DOE memo for the W93 programme to sustain aeroshell capabilities.[181] Given the internal preference for sustaining nuclear capabilities through the production of new weapon types, sustaining these capabilities through other means would require substantial political will and determination. Nonetheless, the decision to pursue new warheads should be seen as primarily political decision, rather than a technical one.

In the UK there was a continuity of policy through the Blair, Brown, Cameron and May governments of reducing the UK's warhead stockpile as a demonstrable act of compliance with disarmament commitments, while at the same time substantially funding the nuclear enterprise, replacing the submarines, missiles and warhead, and building up its capacity to sustain its nuclear weapons system into the future.

The contradictions in this position may not have been politically sustainable in the long term, but the UK Replacement Warhead and the associated policy changes in the IR represent a decisive break with it. Instead of maintaining capabilities, the UK is developing a new weapon, increasing its warhead numbers and broadening the circumstances in which it would countenance a role for nuclear weapons in its security doctrine.

These changes are in part presentational. In design terms, the W93 and UK Replacement Warhead may not be any more novel than the previously planned IW1 would have been, being based on known and tested warhead designs. Similarly, the UK's decision on going ahead with a new warhead builds upon groundwork laid over 12 years under the NWCSP. However, while the 3+2 warheads would have been novel designs, they were presented as a consolidation of the existing stockpile, enabling further force reductions, and tied into the life extension plans of existing warheads, replacing them over a 40-year time period.[182]

What is most significant about the W93 and the UK Replacement Warhead is the implicit statement of intent. Their presentation as wholesale redesigns signals a move away from realising disarmament commitments under the NPT, resolving the tensions in the UK's previous policy under Blair, Brown, Cameron and May in favour of retrenching and renewing its status as a nuclear weapon possessor. In the US the W93 is envisaged as the first in a series of new warheads.[183]

At a time when these two related warheads are proceeding through the design refinement process, this shift and the accompanying policy will have a determining effect on the concept of operations for the warheads and on the final chosen designs. Decisions taken now will have consequences that last for as long as the two warhead designs remain in service.

Previous assurances to NPT partners show that the UK was well aware that upgrading its nuclear capabilities was a provocative move.[184] The consequent damage to the global arms-control regime may be compounded by other nuclear-armed states interpreting the move as providing diplomatic license for them to also develop new nuclear weapon designs.

UK nuclear policy under the Integrated Review

- The warhead cap increase will allow for an increase in the number of deployed nuclear weapons without any public scrutiny. This could allow an increase of the size of a full nuclear strike or of the range of strike options, or both.
- Several of the positions and claims within the IR appear inconsistent or poorly justified, including the citing of strategic ambiguity as a justification for withholding information about the UK's nuclear posture.
- Suggestions that the changes in the IR are a consequence of the desire to assert British power appear to be more credible than the justifications provided.
- The reversal of transparency measures and reductions in warhead numbers are breaches of commitments made under the NPT, as is the IR's willingness to countenance an increased role for nuclear weapons.

The IR was originally planned to be released in 2020 but had to be delayed due to the Coronavirus pandemic. Although the government has not made the links explicit, it appears that the Replacement Warhead Programme and the changes to nuclear policy in the IR were the product of a single decision-making process.[185] As such, the changes made in the IR are an important piece of evidence for the government's intentions in beginning the Replacement Warhead programme. The changes to the UK nuclear stockpile, to transparency and declaratory posture are also significant in their own right.

While the changes to the UK's declaratory posture in the IR do not go as far as those in the NPR, parallels have been noted by several observers.[186] The IR does technically preserve the UK's negative security assurance that nuclear weapons would not be used against a non-nuclear armed NPT member state in compliance with their treaty obligations. However, the threat from chemical or biological weapons, or emerging technologies, that are listed as potentially warranting a change to that policy, could materialise quickly. As such, the retention of the assurance provides only a minimal bulwark against an increased role for nuclear weapons in the UK's security policies.[187]

IR inconsistencies

There are a number of apparent inconsistencies and poorly justified claims in the IR's declaratory policy. Chemical or biological weapons, despite being inhumane and prohibited under international law,[188] would not necessarily cause harm on the same scale as nuclear weapons. The IR does not attempt to explain how their threat or use could meet the threshold of threatening the survival of a state. Neither is it explained how emerging technologies, strikes at the lower end of the 'full range' of nuclear threats, or threats to the security of the UK or its allies could meet that threshold, despite the IR suggesting that any of these factors might result in it abandoning its negative security assurance. The impression given is that the IR is paying lip service to the threshold in the 1996 ICJ ruling,[189] but is willing to countenance nuclear weapons use in a wider range of scenarios.

Similarly, no explanation is given as to why ambiguity and complicating the decision-making of other states is believed to contribute more towards strategic stability than the alternatives of transparency and clarity in order to reduce the possibilities of strategic miscalculation. Ambiguity is said to 'complicate the calculations of potential aggressors' and make it less likely that an adversary would employ a nuclear first strike,[190] as they cannot be certain whether this would engender a nuclear response. No attempt is made to explain why this is considered more likely than a hypothetical adversary instead interpreting the lack of clarity as a bluff and following through with their planned aggression.

One definite consequence of ambiguity, particularly when it is extended to withholding information about the UK's nuclear posture, is that it prevents meaningful public debate about that posture and nuclear policy more generally and blocks democratic accountability and scrutiny. In extending this policy of ambiguity to no longer publishing its numbers of deployed nuclear weapons, the UK is also breaching it's NPT commitments to transparency about its nuclear capabilities.[191] This is unacceptable in both diplomatic and democratic terms, and the failure to justify the change with substantive argument suggests it is motivated more by a desire to escape scrutiny than by strategic calculation.

Reason for the warhead stockpile increase

A further inconsistency in the IR is the attempt to justify the increase in the warhead stockpile in terms of the offensive capabilities and intent of other states: the 'developing range of technological and doctrinal threats'. The size of the UK's nuclear arsenal has long been dictated by an assessment of the scale of damage necessary to deter another state. Historically known as the 'Moscow criterion', the assessment was based on the ability to cause damage on a scale deemed unacceptable to the leadership of the then USSR. While the precise way this was determined and the targets appear to have varied over the years, the basic principle seems to have remained fairly consistent.[192] The language in the IR about 'impos[ing] costs on an adversary' confirms that a similar assessment is still central to British nuclear weapons planning.

The scale of another state's offensive capabilities has no bearing on the scale of damage from a nuclear strike that it would deem unacceptable. After publication of the IR the Secretary of State for Defence, Ben Wallace, claimed in an interview that Russian defensive capabilities were a motivating factor for the increase. An increase in the number of warheads deployed on each submarine would give greater confidence that a nuclear strike could overwhelm missile defence systems, but Wallace gave no justification for the omission of this explanation from the IR.[193]

While the new warhead will not come into service for over a decade, changes in the IR have an immediate effect. However, as the cap increase replaced a plan to reduce the stockpile over a period of around 15 years, the fact it has not been presented as a temporary measure suggests it is intended to last beyond the service life of the current warhead. Therefore, we can be relatively certain that the reduction in transparency and the increase of the warhead stockpile cap were devised with the current nuclear arsenal in mind, but are expected to remain in place when the Replacement Warhead comes into service. Observed activity within the programme[194] indicates that warhead numbers have already begun to rise.

The increase in the warhead stockpile will allow the number of deployed warheads to increase without reducing the proportion of the stockpile held in reserve. The decision to no longer release information about deployed warheads, missiles and the size of the operational warhead stockpile means that these increases will not be disclosed to the public or parliament and could be implemented with no accountability or democratic challenge.

Assuming the operational stockpile is set at 60% of the total stockpile size, as was the case between 2006 and 2010, the increase to 260 warheads would give an operational stockpile of 156. If these warheads were equally distributed between the three submarines that are not undergoing deep maintenance, this would result in a warhead load of 52 warheads per submarine, four more than the maximum announced in the 1998 SDR.

There appear to be two broad goals that an increase could be intended to achieve. A rise in the deployed warhead numbers could increase the overall number of warheads that would be used in a full strike, in order to hold more targets at risk, to target more than one country at the same time, to overwhelm missile defence systems or to offset some decrease in effectiveness of the system.[195] Alternatively the rise could increase the range of different strike options available by fielding missiles carrying different numbers of warheads, with some missiles potentially carrying a lower-yield variant of the warheads.[196] The increase could also be intended to achieve both of these goals, or be primarily intended as a statement of intent[197] while fulfilling one or several of the above operational objectives.

The statement in the IR that the warhead stockpile is still set at the 'minimum, credible'[198] level suggests that a substantial increase in the number of targets or a desire to target more than one country at a time are unlikely to have played a significant role in the change. A more likely explanation is that decision-makers have taken a different view on what is determined to be 'credible'. This could refer to either increasing the numbers of warheads used in a full strike or, as was the case with the references to 'credibility' in the early years of the UK Trident programme and the US 2018 NPR, a desire to increase the range of strike options. The reference in the IR to remaining 'credible and effective against the full range of state nuclear threats,'[199] and 'doctrinal threats' may indicate the fielding of missiles carrying a lower-yield warhead variant in order to counter the claimed Russian 'escalate to de-escalate' strategy,[200] but the two possibilities are not mutually exclusive.

Vanessa Nichols, Director General of the Defence Nuclear Organisation, confirmed in June 2021 that determinations of 'credibility' rely substantially on an assessment of the perceptions of actors that the UK wishes to deter, and that decisions of this nature are ultimately taken by the Prime Minister, at that time Boris Johnson. While substantial written assessments play a role in decision-making in this area, different governments will make different judgements about 'how close do they want to be to that line', and '[in] 20, 30 years, where do we pitch our tent?' Nichols said the IR can be seen as the Johnson Government's statement on these questions and that the increase in the stockpile ceiling was driven by a desire to 'create a little bit more room'.[201] Nichols' comments appear to be referring both to decisions around the Replacement Warhead Programme and to the warhead stockpile decision.

While the process of devising the IR will doubtless have involved setting out a number of options through detailed and careful analysis in the written assessments Nichols mentions, it should be borne in mind that this does not mean the final ministerial decision would have been characterised by careful deliberation. The Guardian's Defence Editor quoted sources saying that the warhead stockpile increase was driven by a desire to be more assertive and 'not apologise' for the UK's position as a nuclear state.[202] Rear Admiral John Gower, a former Assistant Chief of Defence Staff with responsibilities for nuclear policy, described the decision as being driven by the 'nationalist exceptionalism' characteristic of the Johnson Government.[203]

Given the contradictions within the IR, these assessments are more convincing than its own self-justifications. The IR appears to be the product of a contested political process. A willingness amongst some decision-makers to countenance an enlarged role for nuclear weapons in the UK's security doctrines and the increase to the warhead stockpile were tempered by the retention of the negative security assurance and the reference to the threshold in the ICJ 1996 ruling, providing a veneer of legality and adherence to treaty obligations that is inconsistent with the overall disposition of the review.

Warhead numbers and deployment after the IR

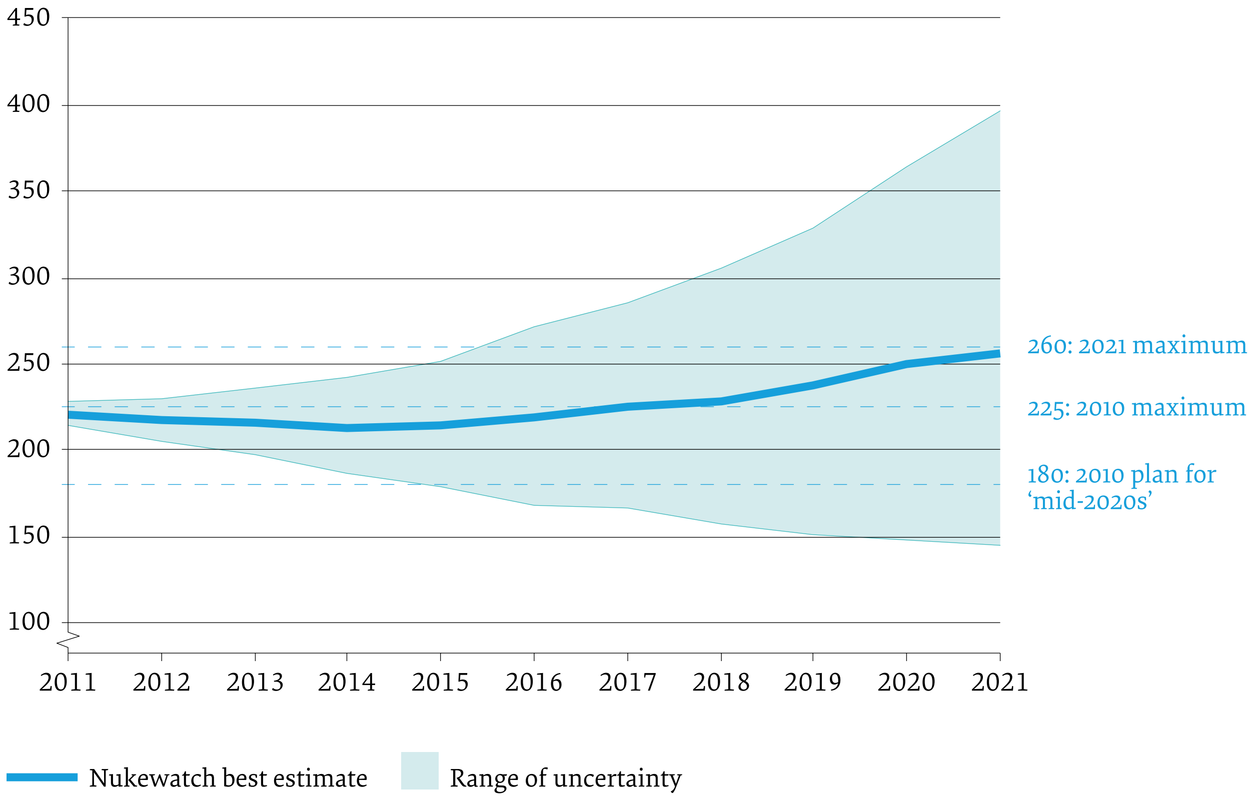
Despite the pledge to reduce the stockpile to 180 by the mid 2020s in the 2010 and 2015 SDSRs, warhead numbers do not appear to have been decreasing prior to the policy process that led to the IR. While there are uncertainties in estimating the numbers of warheads, an analysis of nuclear convoy movements by the Nukewatch network suggests that the warhead numbers were reduced by around 12 between 2010 and 2015, a trajectory that was consistent with the planned reductions, before increasing again as the Mk4A programme began production. This is broadly consistent with sources briefing the Federation of American Scientists that warhead numbers did not fall substantially from the 2010 level of 225.[204] Nukewatch analysis suggests that the stockpile level returned to its 2010 level around 2017 or 2018, with substantial increases in warhead numbers in 2019 and 2020.[205] Despite the uncertainties in estimating warhead numbers based on convoy movements, it seems that a ramp up of warhead production may have been planned to coincide with the original release date for the IR and the possibility that the stockpile rose above 225 in 2020 cannot be ruled out. In any case, it seems almost certain that the policy of increasing the stockpile cap presaged an imminent increase in actual warhead numbers.

While the practice of submarines patrolling with missiles carrying a range of warhead loads may have been discontinued by the 2010s,[206] the decision to withhold information about the number of warheads per missile and missiles per submarine, as well as the number of operationally available warheads, provides scope for it to be recommenced while preventing informed speculation about the exact configuration of warheads and missiles on the submarines.

Production of Mk4A warheads is thought to have begun in 2014 or 2015, with the first units being slated for loading onto HMS Vengeance, which completed its Long Overhaul Period (Refuelling) refit in February 2016.[207] Although Nukewatch convoy figures suggest overall warhead numbers are fast approaching the new cap of 260, it is not possible to be certain. Until recently the Mensa warhead assembly and disassembly facility at AWE was expected to become operational in 2023, and given the programmatic risks of long fallow periods where staff and facilities are not engaged in the production process, it seemed likely that a proportion of the work was intended to be deferred to be completed in Mensa. Given the recent announcement of a delay into 2024,[208] it remains to be seen whether this will now happen and whether production of the Mk4A upgrade will be completed by the longstanding predicted end date for the NWCSP in April 2025.

The decision to increase the stockpile, coming before the completion of the Mk4A upgrade, will have set the baseline size of the Mk4A arsenal for the service life

Figure 7. UK warhead stockpile estimates using Nukewatch convoy data 2011–2021[209]



of the upgraded warhead. Although AWE would retain the capacity to manufacture more in the future and will maintain an ongoing programme of surveillance, maintenance and upkeep, it would be much easier for the MOD to maintain the arsenal at the level envisaged at the time of initial production than it would have been to source additional components from the US to increase numbers if a decision had been taken to increase numbers after the initial production run.

It seems likely that the recent observed increases in the stockpile included warheads assembled using components from previous stockpile reductions.[210] This apparent reversal of these reductions calls into question assurances given in 2013 that these reductions were irreversible. In response to an FOI request the MOD said that components from disassembled warheads were 'processed… in such a way that prevents the warhead from being reassembled' and that some warheads had been 'modified to render them unusable'[211] It would seem that these claims were either misleading in terms of the numbers of warheads processed in this way or the processes used were in fact reversible.

Treaty commitments under the NPT
As recently as March 2019, the UK's report to the NPT Preparatory Committee reaffirmed its commitment to the goal of reducing its warhead stockpile below 180, and presented this goal and previous stockpile reductions as a 'step-by-step approach to nuclear disarmament consistent with the NPT and… other treaty commitments'.[212] By that measure, the decision to increase the stockpile cap to 260, reversing the trend of reductions that has been ongoing since the 1990s, is inconsistent with the UK's disarmament commitments.

The consensus documents agreed after the NPT review conferences of 2000 and 2010 committed the nuclear-armed members of that treaty to 'general and complete disarmament'. As part of those agreements the UK and the US have committed to a number of steps, including the following:

- To take further steps to unilaterally reduce their nuclear arsenals.
- Increased transparency about their nuclear weapons capabilities.
- Unilateral initiatives to reduce numbers of non-strategic nuclear weapons.
- A diminishing role for nuclear weapons in their security policies.
- That the principle of irreversibility should apply to nuclear disarmament measures.[213]

The 2010 agreement also recognised that non-nuclear parties to the treaty had a legitimate interest in 'constraining… the development and qualitative improvement of nuclear weapons and ending the development of advanced new types of nuclear weapons.'[214]

By reversing the reductions in the UK's nuclear stockpile, which the UK had presented as steps towards disarmament, instead of further unilateral reductions, by reversing transparency around its numbers of deployed warheads, and by countenancing an increased role for nuclear weapons under the IR, the UK is in breach of these commitments. If the Mk4A warhead does indeed retain a low-yield capability, and the warheads are again being deployed and produced in greater numbers under the changes made in the IR, the UK is also breaching its commitments to reduce non-strategic weapons. The decision to proceed with the Replacement Warhead Programme is directly contrary to the legitimate interest of its treaty partners recognised in the 2010 agreement.

More broadly, the IR shows that the Replacement Warhead is being designed in a context where it is considered possible that the UK might decide to use nuclear weapons to respond to chemical, biological and other non-nuclear attacks, and where a desire to be more assertive about the UK's possession of nuclear weapons appears to be driving the decision to field a larger nuclear force. The stated desire to remain 'credible' against a range of nuclear threats may indicate a renewed desire to field warheads capable of detonating at a lower-yield.

W93: purpose, genesis and characteristics

- The two factors that appear to have played a major role in the decision to go ahead with the W93 are the desire for a hedge within the sea-launched leg of the US nuclear triad and a desire to revitalise the nuclear industrial base.

- The longstanding desire for a new warhead programme combined with a more amenable policy environment under the 2018 NPR led to the W93's approval.

- The limitations of modelling and experimental development without live testing mean that the W93 will be closely based on tested warhead designs, but may mix elements from several.

This section of the report draws together the available evidence about the W93, assessing the reasons given for going ahead with the programme, the constraints on its design and its likely characteristics.

Rationale

Many of the reasons given for the W93 programme in the joint Pentagon and DOE memo appear tenuous, or simply do not stand up to scrutiny.

The W88 stockpile is planned to undergo the Alt 370 Upgrade between FY 2021 and FY 2026. As the W93 is not expected to enter production until the mid-2030s it will not be available to supplement the stock of W88s during the Alt 370 upgrade as the memo claims.[215]

While achieving a lighter warhead weight, and therefore the potential of an increased range with a Trident missile strike and a wider target footprint, is likely to be a design goal for the W93, this is probably not a deciding factor in the decision to go ahead with the programme. The W93 appears to be intended to supplement the two current warhead designs, rather than fully replace them, and it is not clear that it will be lighter than both models. There also does not seem to be a pressing operational need for the benefits that a lighter warhead would provide.

The memo states the W93 is necessary to support the UK's Replacement Warhead Programme. It says that the UK programme is particularly dependent on the Mk 7 aeroshell development, and highlights the UK's role in the joint NATO war plan in order to justify the support that is being rendered. As discussed below,[216] the replacement UK warhead is certainly dependent on the US pursuing a similar programme. The need to wait for US plans was cited in the 2018 Update to Parliament, and in Summer 2020 the British Defence Secretary took the highly unusual step of lobbying the US Congress to approve funding for the W93.[217]

However, due to this dependency, the UK would not be pursuing a new warhead programme if the US were not doing so. Although long-term UK plans have been based around the expectation of this decision, had the US decided instead to proceed with a further life extension of the W76, it is a near certainty that the UK would have followed suit. It does not seem plausible that a desire to support the UK's Replacement Warhead provided the main impetus for the W93 programme, particularly given the cavalier attitude towards UK sensibilities revealed by the US unilaterally announcing the Replacement Warhead in a congressional hearing. The situation appears to be more a case of the nuclear bureaucracies of both countries using each others' warhead plans to justify their own institutional preferences, than of UK needs driving US decision-making.

The claim in the memo that the W93 is necessary to limit the risk from delays to the life extension or replacement programmes for the W76 and W88 does not seem credible. If the DOE has concerns about the NNSA's ability to manage these activities on time and to budget over the two decade period that they are scheduled, this would mean that its ability to deliver its core activities is in doubt. Diverting resources, capacity and attention towards an entirely new warhead design is likely to increase, rather than decrease, the likelihood of problems arising. If this reason was genuine, the NNSA should have received new management and an amended mission, rather than the budget for a new warhead programme.

While it is not listed as one of the five reasons, improvements to adversary defences is listed as one of the factors influencing the W93 decision. Advances in Russian and Chinese missile defence capabilities are likely to be factored into the W93 design process, but are unlikely to be the key reason for approval of the warhead programme. The recently deployed Russian S-500 system was publicly announced in 2009,[218] and if there had been a specific assessment that it might significantly affect the impact of a US nuclear strike, the memo would likely have said so and included this argument in the list of reasons. It is also difficult to know to what extent the design of the warhead itself will counteract missile defence capabilities. While the specific measures used in the Trident system are classified, many of the known methods for beating missile defence systems, such as decoys and penetration aids, are deployed by missiles and do not form part of the warhead itself.[219] It appears the D5LE2 programme is already planning to incorporate survivability measures,[220] so future missile defence improvements may have little to no impact on the warhead design.

If the US, and by extension the UK, are concerned about the strategic instability caused by missile defence, the most effective remedy would be a diplomatic initiative to resurrect the Anti-Ballistic Missile (ABM) Treaty, and bring other nuclear-armed states besides Russia into an updated version of the treaty. The US left the ABM treaty in 2002 in order to build a missile defence system, and the novel Russian and Chinese nuclear delivery systems that are currently being developed can be traced directly back to this decision.

By a process of elimination it would seem the two factors that have played a significant role in the decision are the desire for technical hedge within the sea leg of the US nuclear triad, in keeping with the concept of hedging in the 2018 NPR, and the ambition to revitalise the US nuclear industrial base.

Options exist to address these issues by means other than designing and building a new warhead. Pursuing interoperability with the Mk5 aeroshell more vigorously in the IW1 project that became the W87-1[221] could have addressed concerns about the ratio of warheads between the W76 and W88, and also provided a potential hedge against the impact of an unforeseen technical issue in the W76. As noted above,[222] there are several potential approaches to revitalising the industrial base that do not require a new warhead design. However, this would require enlightened and engaged political leadership willing to prioritise disarmament treaty commitments to a greater degree than has been the case to date.

The desire for a technical hedge within the sea-leg of the US nuclear triad is a new development following the 2018 NPR. The memo claims this is necessary because nuclear bombers are less responsive than ballistic missiles and hedging with ground launched ballistic missiles would increase reliance on a launch-under-attack posture. This reasoning raises the question of whether these two legs of the triad should be retained at all. Similarly, if additional warhead designs are required to guard against the possibility of an unforeseen technical problem in one of the currently fielded designs, it calls into question the efficacy of the substantial cost and effort spent by the US on testing these warheads and qualifying their components through the original production run and their life extension programme.

Although unforeseen problems in complex technical systems are not unheard of, particularly where there is a limited circle of knowledge, decisions about whether to mitigate theoretically possible problems should be taken on the basis of the full spectrum of costs and benefits. While the hedging strategy of the memo and the 2018 NPR is justified in terms of the threat environment, the philosophy behind the NPR stems from a desire for the US nuclear weapons posture to include layers of reassurance and redundancy way beyond what was deemed necessary in the past, and to design a nuclear response for a broader range of scenarios than was previously the case.[223]

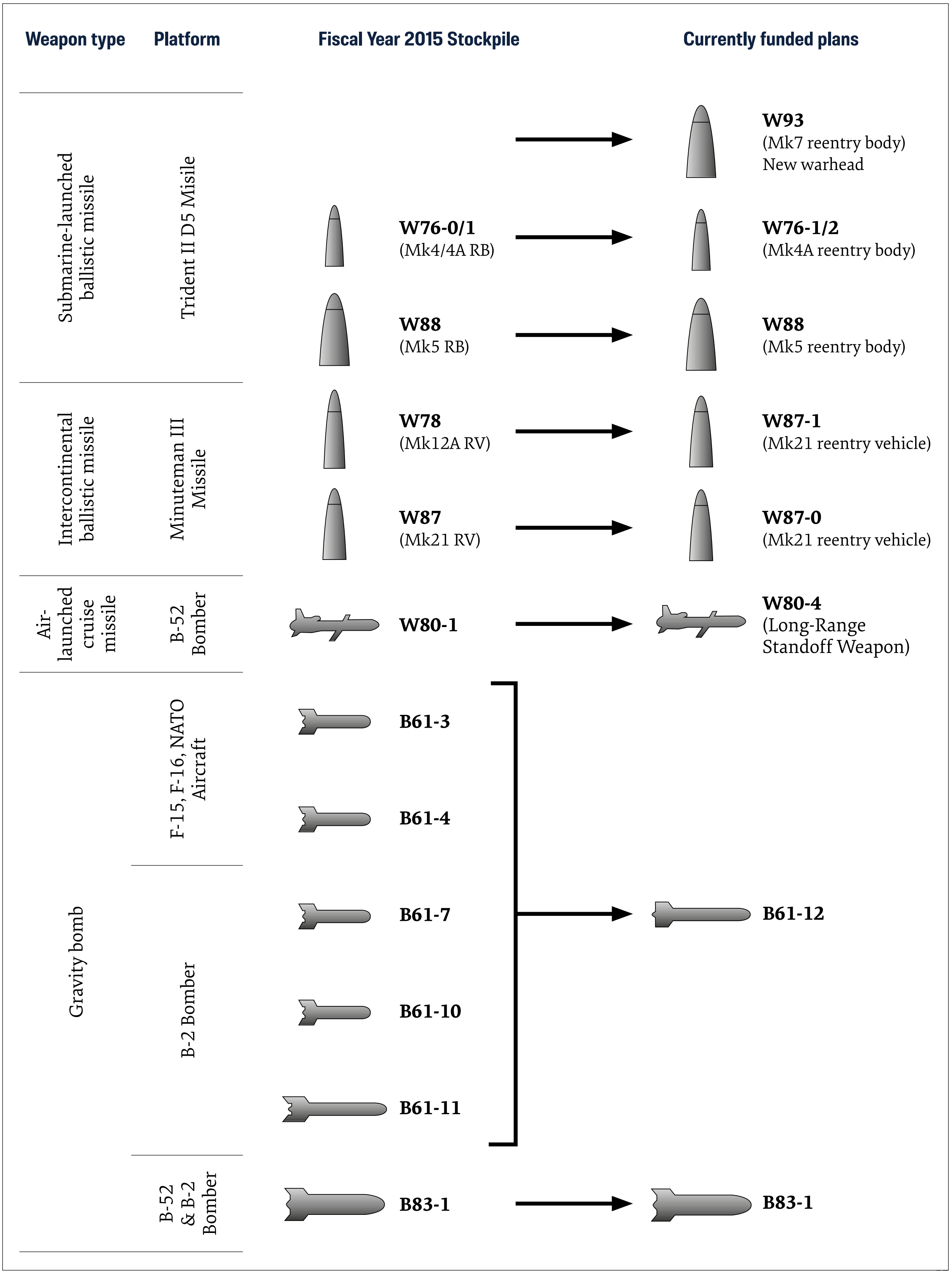
W93 antecedents

The history of the programmatic antecedents to the W93 support the theory that building up the US nuclear industrial base was a major factor in the decision to go ahead with the new warhead. As previously mentioned,[224] in Navy budget requests the Mk7/W93 project was previously known as the Interoperable Warhead,[225] This does not mean that the W93 warhead is the same as the IW1 warhead would have been, but it strongly suggests that it fulfils much the same role in the internal bureaucracy of the US nuclear enterprise.

While the programmatic lineage is less direct in NNSA budget documents, it does appear that the W93 is a direct outgrowth of the earlier programme. The details of the transition are covered in Annexe E. Figure 8 shows the changes from the US stockpile at the time of the 2015 Stockpile Stewardship Management Plan to currently funded plans.

The interoperability of the IW1 was being de-emphasised from the time the project was re-started. A FY 2019 Feasibility Study,[226] which determined that the IW1/W87-1 would not be interoperable with the Trident missile, appears to have confirmed a change that was already in motion. It is probable that the study did not identify an insurmountable obstacle to interoperability, but that the policy environment created by the 2018 NPR's concept of hedging was

Figure 8. US nuclear weapon stockpile plans: Fiscal Year 2015 vs currently funded plans[227]



CREDIT: PANTEX PLANT.

Handling a warhead during the W76 Life Extension Programme.

less amenable to it. The W93 does appear to be a direct outcome of the feasibility study however, being announced soon after the study's conclusion with its design timetable being closely-aligned with what had earlier been proposed for the IW1, and the Navy simply changing the name of the project within their budget. The FY 2023 DOE and Navy budgets confirmed that the Feasibility Study actually formed the basis for the W93/Mk7 Phase 1 Concept Assessment studies.[228]

In summary, the W93 is the consequence of a long-standing desire within the US nuclear programme to revitalise its industrial production capacity through the design and manufacture of a new warhead and aeroshell. The desire to adjust the current ratio of SLBM warheads (in which there are four times as many lower-yield W76 warheads as there are higher yield W88s) and to field a lighter submarine launched warhead may also have played a secondary role. The policy environment of the 2018 NPR provided scope for these objectives to be pursued in a way that had not been possible previously. The decision was taken in tandem with the UK decision to develop a Replacement Warhead, and both programmes are being used as internal justification for each other in their respective countries.

The continuities with the 3+2 plan should be noted. When the W93 comes into service the goal of fielding three different ballistic missile warheads will have been achieved within the sea-leg of the US nuclear triad. The successor warheads that would have followed the IW1 have also not been abandoned. As well as the W93, the FY 2022 Stockpile Stewardship Plan anticipates a Future Strategic Land-Based ICBM warhead to replace the W87, a Future Strategic Sea-Based SLBM warhead to replace the W88, and a Future Air-Delivered warhead being delivered in the 2030s. A submarine-launched warhead to replace the W76-1/2 would follow these, probably in the 2040s. These warheads are currently described as 'notional',[229] but it is clear that the abandonment of the 3+2 strategy does not mean that there is no longer an ambition within the NNSA to develop and produce a range of new warheads over the coming decades, and to shift the focus of the US nuclear enterprise from sustainment and life extension to the production of new warhead models.

Design constraints

While the nuclear enterprises in both the UK and US have put in place highly sophisticated computer modelling programmes to allow nuclear weapon development in the absence of live nuclear testing, the models do not completely eliminate uncertainty. US modelling is based on Integrated Design Codes

(IDCs), mathematical descriptions of the physical processes involved in nuclear weapons systems.[230] The operation of a warhead is broken down into separate steps, with the models for each step being refined by experiments,[231] such as subcritical tests and high-energy laser experimentation. IDCs are used to reintegrate these separate models and are combined with the specific data for particular weapon designs to create extremely detailed physical models that are used for the design, maintenance and dismantling of weapons.[232]

Predicting the full behaviour of a weapon based on its subsystems is an extremely complex endeavour. The models need to account for material damage, fluid mixing, and the behaviour of high explosives on detonation. A full simulation needs to integrate models for 'material equations of state, material motion, interaction of neutrons with materials, radiation flow' and more. Experiments used to refine the models can replicate some of the conditions experienced by warhead components, but not all.[233] The FY 2021 NNSA budget says that current models are not sufficiently accurate to account for ageing warheads, new threats or new manufacturing techniques, and suffer from limitations in modelling complex physics and integrating multi-scale and multi-dimensional models.[234]

These uncertainties mean that the W93 design is very unlikely to radically diverge from warhead designs that were tested before the US moratorium on nuclear testing came into effect in 1992. While it will be based on live tested weapon designs, it may incorporate stages from different weapons and is likely to involve iterative changes to the designs of its stages. When this approach was proposed for the Interoperable Warhead family, it was still considered controversial,[235] as deviating from a known and trusted weapon design involves inherent uncertainties compared to replicating a design that has previously been live tested. So we can be fairly certain that this approach represents the furthest extent of design innovation planned for the W93.

W93 design and characteristics
The approach of basing a warhead design on previously tested designs and components, but using them in combinations that have not been tested in full nuclear explosions was planned for the IWs[236] and also for the Reliable Replacement Warheads (RRW), a putative series of new warheads planned under the Bush administration. The first of these proceeded as far as selecting a design before having its funding cut by Congress and then cancelled by the Obama Administration in 2008.[237] The W93 could be based on one of these previous design, on elements of it, or on one of many other fielded or non-fielded warhead designs that were detonated during the era of live nuclear testing. Pentagon briefing at the time the W93 was approved confirms this will be the approach taken.[238]

Systems to increase the surety of the warheads were a long-term priority for the IWs, with options being worked up for the planned FY 2020 start date.[239] The focus on surety in the JTD[240] indicates that surety technologies developed in that programme will be incorporated into the W93.

Another long-standing priority for the NNSA[241] is to migrate the entire nuclear weapon stockpile to designs utilising Insensitive High Explosive (IHE), rather than conventional high explosive. IHE is much less sensitive to physical shocks than conventional explosive, meaning it is much less likely to explode if the warhead is damaged in a missile explosion. Its introduction has been called the 'single greatest improvement that can be made to nuclear weapon safety, and part of the rationale for selecting a variant of the W87 to replace the W78 warhead was that there is more room within the Mk21A aeroshell to accommodate IHE, which takes up more space than conventional explosives. There are also production efficiencies to be gained from manufacturing IHE, as safety measures during handling do not need to be as stringent.[242]

Other technical developments being planned for the W87-1 include replacing a 'hazardous, inefficient and obsolete' manufacturing process for a 'strategic material', with a greater potential for recovery and recycling of the material and allowing it to be produced with cheaper and less hazardous ingredients, and an aspiration to use additive manufacturing of polymers and metals in the manufacturing process.[243] It seems likely that these innovations will also be utilised in the W93 programme, particularly given the W87-1's status as a 'pathfinder' programme.[244]

The focus in the joint Pentagon and DOE memo warhead on building a lighter warhead and countering defensive measures suggest that these factors may play a role in the W93 design. However, it is not clear to what extent missile defence countermeasures will be incorporated into the warhead design, or whether the W93 design will be lighter than both current US SLBM warheads or just the W88.[245]

While statements from the US administration and the memo suggest no firm decision has been taken about which warheads the W93 will replace in the SLBM stockpile,[246] several pieces of evidence suggest that it is primarily intended to replace and/or supplement the W88 rather than the W76. The W93 programme appears to have been temporarily known as the Mk5/W88 LEP.[247] The reasoning in the joint Pentagon and DOE memo around the yield difference between the W88 and W76, and a Pentagon briefing that the W93 is 'in size' (i.e. yield) intended to be somewhere in between W76 and W88,[248] both imply that the W93 will be tasked with covering targets currently assigned to the W88 in US war plans. As such, while the eventual yield of the W93 may not be as high as the 455kt of the W88, due to increased accuracy,[249] it should be expected to be higher than the 100kt of the W76-1.

The focus in the 2018 NPR on 'flexibility' and being able to meet a range of scenarios with a nuclear response suggests that the W93 design could incorporate the capability to detonate at different yields.

CREDIT: US DEPARTMENT OF ENERGY.

W88 warhead undergoing a drop test as part of the Alt-370 Life Extension.

UK Replacement Warhead

- Meaningful divergence from the W93 design is very unlikely. It would be more expensive and probably result in a warhead that was less certain to work as planned.
- The warhead will almost certainly follow the W93 in having a larger yield than the current UK warhead, and it may be designed to also detonate with a lower-yield.

Likelihood of diverging from W93 design

The design of the UK Replacement Warhead is unlikely to significantly diverge from the design of the W93. Technically speaking, the two warheads only need to be similar in a few key areas. They need to fit within the same re-entry body, so that will act as a limit to both in terms of size and shape. They will use a common interface with the missile and will need to be identical in terms of weight and weight distribution so that the re-entry body behaves identically during flight, regardless of which warhead it is carrying.

However, even within this limited scope for divergence, other constraints and pressures mean that meaningful divergence from the design of the W93 is unlikely. The UK will depend on the US not just for the supply of certain warhead components, but also for the process of certification and qualification of those components.[250] This process involves rigorous testing in order to provide reassurance that warhead components will behave as intended over the service life of the warhead, and to ascertain the physical limits within which the behaviour of the component can be relied upon.

As mentioned above,[251] the components in the W93 will be based on components already in use in the US stockpile. While the UK could theoretically decide to develop separate components for its Replacement Warhead, the cost would likely be prohibitively expensive. Much of the equipment and facilities, such as the centrifuges and vibration table used by the JTD programme are highly specialised and are unlikely to be available in the UK. Producing alternative parts would likely require either a substantial infrastructure investment or securing the use of US facilities.

W93 components that are derived from components in existing warheads will come with the added assurance of data from years of stockpile surveillance work on their predecessors. They will also be produced in larger numbers than unique UK components would, due to the larger size of the US arsenal and the fact that they will likely be used in multiple warhead designs. Producing components at a larger scale not only has implications for the overall cost of each unit, it most likely improves quality control and the overall reliability of the components.[252] For these reasons the UK has routinely purchased US components for use in its warheads, dating back to the late 1950s. This practice extends to the wholesale incorporation of

CREDIT: TIM MENZIES/FLICKR.

Model of warheads on top of a Trident C4 missile at the National Museum of Nuclear Science and History, New Mexico.

certain systems. Only a handful of UK warheads have not incorporated a US-designed fusing and firing system, for example.[253]

Significant design divergence is even unlikely for the nuclear material components of the weapon's physics package, which will not be imported from the US and will be manufactured domestically. The reliance on US components has implications for overall design of the weapon, in that the components in the W93 will be designed and certified for use in that weapon design. The level of certainty that components will function as desired may drop substantially if the UK's weapon design diverges, particularly for components that need to work after the initial detonation of the primary, due to the extreme physical conditions within the warhead.

The factors above which explain why the W93 will be based on existing US weapon designs, and why any changes are likely to be incremental rather than revolutionary, also mean that the UK Replacement Warhead is very likely to be close to the W93 in design terms. While the UK's computing capabilities are comparable to those in the US[254] and both countries benefit from sharing research data, the drawbacks from deviating substantially from the W93 far outweigh the benefits. The UK could incur substantial additional costs to the Replacement Warhead Programme to produce a warhead that was considered less reliable.

The experience of the Chevaline programme illustrates the issues the UK could face, and will doubtless feature in the minds of planners when considering design options for the warhead. As the endeavour to sustain production of the Polaris rocket motor material shows,[255] the risks of compatibility divergence last far beyond the design and production stage.

Chevaline was the last occasion where the UK pursued a nuclear weapon system with no corollary in the US arsenal. The project was subject to cost overruns so substantial it became untenable for it to remain secret. The system was eventually brought into service by the Thatcher government because the project was too far advanced for cancellation to save any money, but was replaced with the Trident system after only 12 years. In order to maintain the secrecy of its decoy measures, no flight test of the system was ever carried out. The episode remains a salutary lesson for the UK nuclear enterprise of the dangers of diverging from fielded US weapon designs.

Characteristics
Based on the available evidence we can make the following predictions. The UK Replacement Warhead is highly likely to be close in design to the W93. For the reasons above, particularly the experience of the Chevaline system, it is extremely unlikely that the UK will field a different design. As such, the warhead will probably follow the W93 in having a yield somewhere in between the W76-1 and the W88. The increased accuracy of the Trident system[256] means that the yield is unlikely to be as high as the W88, but it would still be a significant step up from the yield of the current UK warhead.

The government is doubtless aware that many of its NPT treaty partners would consider an increase in its nuclear capabilities to be contrary to its treaty commitments.[257] However, the disregard for these commitments as displayed in the IR, particularly the decision to increase the warhead stockpile cap, strongly suggest that the programme will go ahead despite this.

The emphasis in the IR on being credible against a range of nuclear threats suggests a lower-yield capability may be designed into the warhead. Part of the initial production run could even be adapted to explode with this lower yield. For the same reason it is likely the design process will anticipate that the warhead could be hosted on missiles carrying different numbers of warheads, allowing for a range of strike sizes.

As with the W93, the warhead will be based on existing US warhead designs, but may incorporate different elements from multiple designs. Its components will also be based on components in the US arsenal, but many will be newly manufactured as updated versions. Novel or additive manufacturing is likely to be incorporated in the production process, and in engineering terms many of the major innovations in the warhead may be in production techniques, rather than the characteristics of the warhead itself.

The warhead will be housed in the Mk7 re-entry body with its new thermal protection system and release assembly. The Mk7's new arming, fusing and firing system will probably be one of the outputs of the US Joint Warhead Fuze Sustainment Program.[258]

If the Biden administration's Nuclear Posture Review rejects its predecessor's requirement for multiple warhead designs as a hedge against unforeseen technical problems in the stockpile, the W93 could be designed so that the US can deploy the nuclear explosives package in the aeroshell for a ground-based missile. Whether or not this happens the W93/ Replacement Warhead's components are likely to be planned for use in future US warhead designs.

It is a near certainty that the warhead design will incorporate some of the enhanced surety technologies being developed in the JTD, and that the design will use Insensitive High Explosives.

The warhead will be designed to work with the current life-extended version of the Trident missile, but the planned capabilities of the D5LE2 are almost certain to be taken into account during the design process.

Work in the JTD on certifying pit-reuse[259] suggests that the warhead design could use an identical primary to an existing US weapon. If so, unless the design uses the W76 pit, the UK will need to manufacture new pits according to the chosen design.[260]

The warhead is likely to have a lighter mass than the current US W88 warhead, but it may not be lighter than the W76 and the current UK warhead.

Measures that increase survivability are likely to be factored into the design. The warhead components will be built so as to be resistant to radiation and electromagnetic interference, possibly including cold x-rays. Features intended to defeat future missile defence systems are more likely to be built into the aeroshell and missile than the warhead itself.

5. Conclusions and recommendations

Conclusions

The nuclear-weapon state members of the NPT face a fundamental tension between their treaty obligations and their desire to retain nuclear weapons for the foreseeable future. Practical and technical pressures make it increasingly difficult to reconcile these goals over time. Options do exist to sustain nuclear weapon production capabilities without taking the provocative step of developing new generations of weapons. States could continue to life-extend existing weapons, or to build updated versions with no increase in capabilities if that was not technically feasible. However, to do this would require political leadership and a willingness to face up to the fundamental incompatibility of new nuclear weapons with disarmament commitments.

In the US the W93 programme is the consequence of a longstanding desire for a new warhead programme to sustain capabilities within that country's nuclear enterprise, combined with the more receptive policy environment for such a venture under the Trump administration. Although the W93 and UK Replacement Warhead may not be significantly different in design terms from previously planned US warheads, such as the IW1, the presentation of them as new is significant as a statement of intent. In the US the W93 is envisaged as the first in a series of new nuclear warheads. In the UK the Replacement Warhead's probable increased capabilities, and the IR's increase in the warhead stockpile mark a decisive break from the policy under the Blair, Brown, Cameron and May governments to retain existing capabilities while reducing warhead numbers.

Although both the W93 and UK Replacement Warhead are yet to reach the stage of selecting a final design, key decisions are happening now. Design decisions taken today will have consequences that will last for the service life of these weapons and may have implications for the UK's nuclear posture throughout that time. While there is no public information about the design options being considered, policy documents from both states demonstrate the strategic thinking that justified their development and allow us to draw inferences about the likely designs in this report.

The decision to proceed with the W93 is a direct consequence of the 2018 US Nuclear Posture Review, which sought to increase the range of nuclear responses available to planners, to have nuclear weapons fulfil multiple missions and for them act as a hedge against a wider variety of risks. The UK appears to have decided to go ahead with its Replacement Warhead as part of a decision-making process which also produced the 2021 IR, which increased the size of the nuclear stockpile and considers it possible that the UK might broaden the situations in which it would use nuclear weapons.

The increase in the UK's nuclear stockpile size allows for a greater number of nuclear weapons to be deployed. This means more warheads could be used in a full nuclear strike, planners could have a greater variety of strike options, or both. These changes would be made without any public or parliamentary discussion or oversight. The decision to withhold previously released information about the number of deployed nuclear weapons and the numbers carried on each submarine and missile is justified in terms of 'strategic ambiguity', but this claim is not well substantiated. Suggestions that the stockpile cap increase has more to do with a desire to assert British power than an objective assessment of risk are more persuasive than the reasons given in the IR.

The language of 'credibility' used in the IR, and echoed in the 2018 US NPR, suggests that the concerns which were used to justify the lower-yield capability in the UK's Trident warhead are once again ascendant in nuclear planning circles in the US and UK. This capability, which probably took the form of a variant of the warhead with a dud secondary, was publicly acknowledged on multiple occasions when the current warhead first came into service. During this time British submarines probably went to sea fielding missiles with different strike options, including some with warheads configured for a lower-yield strike. This practice may have been discontinued by the 2010s, but the stated desire in the IR for the UK to remain 'credible' against a range of nuclear threats and the changes to warhead numbers may indicate that it has been reintroduced, or a desire to retain the option to do so in the future.

The limitations of the experimental and modelling techniques used to develop nuclear weapons without live testing mean that the W93 is unlikely to radically depart from previous US weapon designs that have been live tested. However, it may be based on elements from several previous weapons. The original justification for the W93 suggest it will be designed with a yield that is able to destroy targets allotted to W88 warheads in current US strike plans. While the increased accuracy of the Trident system probably means this can be accomplished with a lower yield than the 455kt W88, it is likely to have a higher yield than the 100kt W76. It may also incorporate a lower yield-capability.

The technological dependency of the UK nuclear weapons programme on the US means the UK Replacement Warhead is likely to have a similar design to the W93, and may therefore produce a significantly higher yield than the current UK warhead. Doing otherwise would expose the Replacement Warhead Programme to additional costs and programmatic risk throughout the life of the warhead, resulting in a design that was more expensive but less certain to function as intended. A lower-yield capability is a strong possibility if one is designed into the W93.

The UK IR's reversal of stockpile reductions, reductions in transparency and its countenancing of an increased role for nuclear weapons in security doctrine are all breaches of commitments made within the NPT. The reversal of cuts to the UK's warhead stockpile call into question public assurances that components from dismantled warheads were being rendered unusable. The Replacement Warhead project runs contrary to the recognised interest of non-nuclear NPT members in constraining the development of new and improved nuclear weapons, and together these changes are likely to further weaken a treaty regime which is already struggling with a loss of credibility and accusations of bad faith on the part of nuclear weapon states.

This is a clear demonstration of the limitations of a model of disarmament whereby nuclear-armed states make incremental reductions in their arsenals at a pace determined by their political convenience. Instead of reorganising the UK nuclear enterprise with the aim of delivering on the UK's disarmament commitments, the Blair, Brown, Cameron and May governments carried out warhead stockpile reductions alongside a renewal of the physical infrastructure of the programme. Even if it was not intended by policymakers at the time, this approach laid the groundwork for the current government to begin building a new nuclear warhead that may well field an increased yield, whist increasing the size of its warhead stockpile. Internationally, non-nuclear states that have historically supported a 'progressive' incremental approach to nuclear disarmament[261] should consider the shortcomings of this approach, as revealed by this turn of events.

The need for negotiated disarmament agreements to reduce international tensions is greater than at any time since the end of the Cold War. The nuclear threats issued in relation to the Russian invasion of Ukraine are a stark illustration of the instability and mutual insecurity that characterises a nuclear-armed world, the political obstacles to progress in disarmament and the unthinkable alternative if progress is not made. Whatever the outcome of that conflict, still ongoing at the time of writing, the nuclear-armed states will still need to find the political will to advance towards their shared objective of a world without nuclear weapons. That goal is as relevant and urgent as it ever has been, and the January 2022 joint statement from the five NPT-recognised nuclear-weapon states,[262] while falling far short of their Article 6 commitments, shows that common ground could still be found on this issue at a time of rising tensions.

In the UK, where the government's nuclear policy has been described by a former insider as being driven by 'nationalist exceptionalism', the political will to make progress on disarmament is unlikely to emerge without external scrutiny and pressure. In the first instance that scrutiny and pressure should aim to ensure that nuclear weapon upgrades such as the Replacement Warhead Programme do the minimum possible harm to the international arms control regime. While the relative size of the UK's nuclear forces means it is unlikely to play a significant role in a renewed nuclear arms race, a reversal of reductions from the NPT nuclear-weapon state that had reduced its stockpile to the lowest level will still damage the credibility of the treaty. Fielding a new warhead with an increased yield would doubtless have a similar effect.

However, the way the UK nuclear enterprise currently operates provides little scope for oversight, scrutiny or democratic accountability. The move away from transparency in the IR is a retrograde step that limits the scope of public discussion and debate about the merits of the UK's nuclear posture at a critical time. While preparation for the Replacement Warhead decision had clearly been taking place at the time of the 2019 election, no public disclosure was made during the campaign that it was imminent.

This aversion to accountability echoes the December 2006 White Paper on replacing the UK's submarine fleet, which was published less than seven months after an election where the government downplayed its importance as an election issue and did not disclose that there were any concrete plans in place.[263] However, the Dreadnought submarine programme was then subject to a parliamentary vote. The warhead programme was not, despite a public undertaking by the then Foreign Secretary in 2007 that it would be.[264] The substantial government majority in parliament after the 2019 election confirms that this decision was not taken through any uncertainty about the result, but from a decision not to consult parliament on principle

There are further reasons that the UK Replacement Warhead Programme should be subject to greater scrutiny. While no official estimate of the budget for the programme has been published, the current US estimate for the W93 is between $13.4bn and $15.5bn, equivalent to between £10.6bn and £12.3bn. Even in the US context this is a provisional figure and the budget may be revised upwards. In order to ensure that public money is as well spent as possible, there should be considerably more scrutiny of the Replacement Warhead Programme and the government's nuclear weapon upgrades more generally. The annual reports carried out by the Defence Select Committee while the Trident system was being built provide a good model for this.

As the Replacement Warhead Programme is at an early stage in development, the potential harms to the international arms control regime can be avoided with sufficient political will and leadership. The most appropriate course of action would be for the UK to forgo a new warhead design and instead transition to extending the life of the current warhead until such time as the UK is ready to disarm. If this does not happen, for example if there are technical reasons which make this untenable, the Replacement Warhead Programme should involve no increase in the offensive capabilities of the warhead. Aside from the safety and surety measures that appear to be currently planned for the warhead, the UK should draw upon its longstanding disarmament verification work[265] to ensure that the new warhead can easily be disarmed and dismantled, with a team of international observers from non-nuclear states able to verify that its components have been put permanently beyond use. It should also be designed for indefinite life extension, in order to eliminate any future technical pressures to develop subsequent warheads. These objectives should be clearly communicated to the public and the UK's NPT treaty partners.

The UK dependency on the US nuclear weapons programme means it would not be able to deliver a warhead that fitted these criteria on its own. The UK's warhead plans were so reliant on the US that they appear to have been put on hold until a decision was taken to go ahead with the W93. The risks of fielding a separate weapons platform are so substantial that the UK's nuclear weapons programme as currently constituted is bound to follow the US programme.

In order to deliver a warhead programme that is more commensurate with its disarmament commitments, the UK would need to use both its diplomatic influence and its input into the W93 programme to lobby for both warheads to be designed such that they didn't involve an increase to the UK's nuclear capabilities. Although the chances of this course of action proving successful may be considered slight, this does not absolve the UK of its disarmament obligations.

Recommendations

Nuclear Information Service advocates for the swift realisation of the UK's disarmament commitments in order to achieve the UK government's professed goal of a world without nuclear weapons. The decision to go ahead with the Replacement Warhead Programme runs contrary to this goal and to the interests of non-nuclear states. If the programme goes ahead as planned despite this, the following steps are suggested to help mitigate the harm.

1. the Government should make a public statement to the effect that the programme will not result in any change to the UK's nuclear capabilities, and any changes to the warhead design will be solely focussed on:
    a) Improvements to safety and surety
    b) Ease of verifiable dismantlement, using lessons learned in the UK's disarmament verification research
    c) Easy replacement and life-extension of components, in order to eliminate any technical pressures for new future warhead designs while the UK remains a nuclear weapons state.
2. The UK government should release a detailed justification for the recent increase to it's warhead stockpile cap, in order to allow public debate about the merits of the change.
3. This justification should include a statement about the status of any lower-yield capability on the UK's current warhead and a timetable for the permanent phase-out of this capability, in keeping with its commitments to the 2000 and 2010 NPT Review Conferences.
4. The UK should abandon its doctrine of strategic ambiguity. It has the potential to confuse decision-making in a crisis and any strategic benefit it might provide is outweighed by the harms done to democratic scrutiny, accountability and strategic stability.
5. The UK government should immediately make public the size of its operational warhead stockpile, as well as the maximum number of missiles and warheads carried on each submarine. It should commit to updating parliament on any changes to these numbers.
6. The UK's nuclear weapons programme, particularly the Dreadnought programme and the Replacement Warhead Programme, should be subject to detailed parliamentary scrutiny to ensure the best possible management of the public funds being spent. A central element of this scrutiny should be annual inquiries and reports by the Defence Select Committee, as was the case during construction of the first generation of Trident submarines and warheads.

Annexes

Annexe A. Planned outputs from the W93 and Mk7 programmes Fiscal Years 2021–2022

A key output of the first phase of the Concept Assessment and Refinement Stage is the Phase 1 study report, which was produced in FY 2021, and included recommendations for Phase 2, the Feasibility Study and Design Options phase.[266]

Work to be done before the transition to Phase 2 included documenting the results of the Concept Assessment Study, assessing whether the technologies envisaged in different designs are mature enough to be included,[267] and considering how to mitigate potential vulnerabilities.[268]

Work in FY 2020 included defining a working group charter and drafting a programme plan and cross-agency plans,[269] and FY 2021 plans include producing an integrated master plan and master schedule for both the W93 and Mk7. Cross-agency coordination appears to be an ongoing focus of the programme.[270]

According to Navy budget requests, documents to be produced for the Mk7/W93 programme in FY 2021 included a systems engineering plan, a stockpile concept of operations, and a preliminary reliability and safety assessment.[271]

FY 2022 plans include initial data analysis for fire control software support for the W93 and the early stages of developing material for the aeroshell, including ground testing.[272]

Annexe B. Joint Technology Demonstrator and other UK-US cooperation

UK-US cooperation on warhead design has been ongoing since the two countries signed the 1958 MDA. However, their active cooperation on this generation of warheads pre-dates the announcement of the W93 and UK Replacement Warhead Programmes.

Since 2016 the two countries have been working together on the JTD project. The stated purpose of the JTD is to develop demonstration warhead systems that are not tied to a particular warhead design but could potentially be deployed in a number of future warheads. Reference warhead designs are used so that multiple elements of the design can be assessed from a 'system-level perspective' rather than in isolation.[273]

When the JTD was announced the UK MOD implied that the project's outputs could be used in a future warhead, and said that, as well as working to increase safety and security, the project was investigating advanced manufacturing technologies.[274] The areas of focus are: 'nuclear weapon science, component and subsystem technologies, cost and time-efficient production methods, and systems integration.' Compared to other US stockpile development work, the focus of the JTD is relatively short-term,[275] so it can be assumed that many of the technologies it develops will be utilised in the W93 and UK Replacement Warhead.

The choice of technologies in the JTD is a balance between integrating those that are already deemed sufficiently mature and developing others based on the expected requirements of future warhead designs. The project works with full system architectures, subsystems and components, integrating them into the reference system design[276] and developing through the stages of manufacture, ground testing and assembly until they are deemed 'flight ready'.[277]

One purpose of the JTD is sustaining and developing capabilities[278] and developing the expertise of people working in both countries' programmes. The project also hopes to reduce the risks involved in producing and certifying components so they can be integrated into fully-fledged weapon designs as easily as possible.[279]

The JTD is comprised of 3 workstreams. Workstream 1 involves the NNSA, US Navy and MOD, focussed on a reference design using the Mk5 aeroshell, which currently houses the W88 warhead. Workstream 2 involves the NNSA and US Air Force and focusses on the Mk21 aeroshell, which currently houses the W87 warhead. Workstream 3 is a collaboration between the MOD and NNSA and works on technology maturation in general.[280] Although the documentation around the JTD stresses that the aeroshells chosen for each workstream are reference designs, it is notable that the two designs are those that the IW1 would have been carried in.

Several hydrodynamics tests have been carried out under the JTD. FY 2017 saw two relating to certification exercises for pit reuse and the use of insensitive high explosive (IHE) for primary detonation in the future. Another in FY 2019 related to certification and qualification work.[281] Others were carried out in FYs 2018, 2020, and 2021.[282]

Other work has included a 'hubcap experiment' in FY 2017, which examined the fracturing of advanced manufactured components under explosive stress[283] In FY 2018 Two Ground Test Units were also tested at the Little Mountain test facility,[284] which tests components' resilience against physical shocks and vibration as well as radiation and electromagnetic interference.[285] The tests used hardware created under the enhanced surety programme,[286] but were also listed under the heading of weapons technology development in the FY 2021 budget, suggesting a broader application.[287]

In FY 2017 the JTD completed its planning phase and moved into the execution phase, which consisted of validating a reference system design and ground testing.[288] during that year JTD surety work also resulted in prototype hardware being produced.[289]

In FY 2020 Workstream 2 completed its final round of testing with a flight simulation using centrifuges and vibration equipment,[290] and JTD Workstream 1 transitioned away from using a Mk5 reference system. The workstream is currently using a different ballistic missile design, but is officially described as 'system agnostic' and is intended to change over the course of the project to retain its relevance to all future systems.[291] The change presumably reflects the decision to go ahead with the W93, and the current reference system is likely to be based on the expected characteristics of the Mk7 Aeroshell.

The scope of the JTD goes beyond joint experiments. The JTD has also seen DOE contractors being integrated into UK nuclear weapons work during FYs 2019 and 2020.[292] The two countries also have an integrated computer network system called JODE, for direct data exchange and communications between the weapons programmes of the two nations.[293] JODE may be linked to the Kansas City National Security Campus (KCNSC) hybrid cloud platform, a secure enterprise network enabling the sharing of classified data, secure communications and hosting specialist classified applications to 'allow design, development and prototyping of weapon hardware, software, systems, and applications'.[294] This platform was planned to be used for the JTD in FY 2021,[295] and the involvement of KCNSC suggests that this part of the programme focusses on non-nuclear hardware.

The FY 2020 Budget envisaged future milestones for the JTD between FYs 2021 and 2024. Workstream 1 was to complete ground testing of the Mk5 design, carry out two hydrodynamic experiments, a 'tri-lab photon radiography experiment' and US/UK systems demonstrations and studies'. However, the move away from the Mk5 reference design may have changed priorities. Over the same time period Workstream 2 was to 'conduct system mechanical and electrical ground testing demonstrations' of the Mk21.[296]

Outside the scope of the JTD the US and UK also investigated 'non-nuclear survivability options and capabilities'[297] and worked on fissile material air transport containers in FY 2017.[298] In FYs 2020 and 2021 the two nations were working on ways to assess system survivability 'under a non-ideal blast'. The research seems to have involved testing the cold x-ray response of materials at the National Ignition Facility (the US high-energy laser facility) using both three-dimensional and two-dimensional test objects.[299] The UK is also listed as a partner in a programme of work which began in FY 2021 trying to address digital risks to the US nuclear enterprise.[300]

Annexe C. Trident D5 Life Extension 2

It was originally intended that, after completion of the initial D5LE life extension to the Trident D5 missile which extended its service life until the end of the 2030s,[301] the US would develop a replacement missile. However, a decision has since been taken to instead put the missile through a second, more extensive, life extension programme.

The D5 Life Extension 2 (D5LE2) programme will extend the life of the missile into the 2080s. The programme is justified in terms of the obsolescence of 'safety critical' components, including flight electronics and critical components, that pass out of their qualification period by FY 2039, and are no longer supported or produced by the industry. Stocks of other components are expected to be used up in flight tests or for spares.

While the first Trident missile life extension (known as D5LE) just extended the life of some missile components, the D5LE2 will be more substantial, involving shipboard systems too. The approach will be a mix of incorporating some cost-effective replacement technology, such as solid rocket motors and igniters, and redesigning other systems, such as the avionics, guidance and the system architecture.[302]

It will use some components that are still in production, but will restart the industrial base for other components. The programme intends to increase the capabilities of the missile, although cost is also said to be a key driver.[303] Budget documents say the D5LE2 will deliver the 'range and accuracy' of the current system, but will also address the improved defensive capabilities of 'near peer adversaries'[304] and will need 'additional attributes' to make it more survivable.[305]

The immediate focus of the programme is on developing technologies that will need to be included regardless of the final missile architecture: a post-boost control system, guidance instruments, radiation-hardened electronics, battery technologies and cyber-security frameworks.[306] The timescale of the project will be similar to the D5LE which began concept studies in the late 1990s, began design in 2004, completed design in 2011 and was deployed in 2017.[307] A system requirements review for the D5LE2 is expected in FY 2025, followed by ground testing and a first test flight in FY 2032, followed by early production. The missiles will be loaded onto submarines in FY 2039.[308]

Annexe D. Known problems in the US and UK nuclear enterprises caused by lost production capabilities

One notable example of a problem caused by a lost capability in the US nuclear weapons programme, is the loss of the institutional knowledge of how to manufacture a material called Fogbank. Fogbank is thought to be an aerogel that channels radiation between the primary and secondary stages, and was used in several warhead designs including the W76.[309] Few records were kept at the time of manufacture in the 1980s, and production was dormant for 25 years, during which time almost all staff with expertise retired or left.[310] Re-establishing the capacity to produce Fogbank cost around $82m[311] and delayed the W76-1 programme by around two years.[312]

A 2019 US Government Accountability Office (GAO) report identified similar challenges to Fogbank in the production of specialised explosive materials needed for around 100 different nuclear weapon components. These were created decades ago and the knowledge base is gone. Some have a very limited supply, including one that has only one container left. Even if the 'lost recipes' can be recovered, suppliers would need to be found for small quantities of specialist materials that meet the relevant standards.[313] Additionally, a 2021 GAO report identified similar challenges to Fogbank in producing high quality depleted uranium (DU) and components using a DU-niobium alloy.[314] The second Trident missile life extension programme is being justified on similar grounds.[315]

An example from the UK programme occurred when the Thatcher government was considering extending the life of its Polaris missiles so that Chevaline could remain in service. They encountered significant problems trying to acquire fibreglass material that would have been needed for the casing of the first stage rocket motor. No equivalent could be obtained on the open market, and numerous live firing tests would have been needed for certification if one were available. While the life-extension option was being considered, the UK paid Dupont around £100,000 a month to retain key personnel and keep the production plant certified, so that the capacity to manufacture additional batches of the material remained available.[316]

Annexe E. From the Integrated Warhead to the W93

Work on IW1 had been planned to re-start in FY 2020,[317] but funds to re-start Phase 6.2 of the project, the feasibility study and design options phase, were requested in the FY 2019 budget.[318] This work was to include a system requirements definition, early design work, and planning for the programme, including flight and ground tests.[319] It was intended that the warhead would come into service by 2030 to replace the W78, but the earlier intention that it could also replace the W88[320] was no longer certain, and part of the work plan in FY 2019 was to investigate the feasibility of deploying the NEP of the warhead on a Trident missile.[321]

Seven months later, in October 2018, the project had been renamed the W78 Replacement Warhead and was to use the Mk21 re-entry vehicle used in the W87, but the study to use it on a Trident missile was still planned. Two further interoperable warheads were also still planned although they were now known as the BM-Y and BM-Z respectively.[322]

According to the NNSA FY 2021 budget, the study to investigate the interoperability of the now W87-1 was completed in FY 2019[323] The same budget, five months after the end of FY 2019, included the initial request for the W93 and Mk7. The start date for the W93 was closer to that proposed for the IW1, despite it more closely resembling the BM-Y and being much closer to that warhead in its production cycle.[324] The implication of this is that the W93 project is filling an internal demand for warhead design activities to be carried out in this time period.

The interoperability of the IW1/W87-1 was being de-emphasised from the time the project was re-started. The 2019 feasibility study formalised a move away from interoperability that was already in effect, and therefore may have been driven by factors beyond warhead design considerations. Although the IW1 project was accelerated in FY 2013 and therefore may not have spent as long as possible considering the potential vulnerabilities of its chosen design, it is striking that the project got to the stage of identifying a pit design without there being any question over its potential interoperability, despite that being the major overall strategic focus of the NNSA. It seems unlikely that an insurmountable obstacle was then discovered in the 2019 feasibility study. A more probable scenario is that the policy environment created by the 2018 NPR's concept of hedging meant that there was no political appetite for overcoming technical obstacles in pursuit of interoperability.

While a replacement for the W78 seems to have been considered the highest priority due to age and service life considerations, and the W87-1 does serve as a justification for some reinvestment in the US nuclear industrial base, such as the targets for pit production, it apparently does not offer the same benefits as a new warhead project would. The rebuilding of the industrial base for building re-entry bodies as mentioned in the DOD-DOE memo, would appear to be a prime example. As a consequence, a little over a year after the FY 2019 feasibility study completed, the W93 was announced with a design period closely fitting what had previously been planned for the IW1, and it inherited the Navy programme that was previously slated for that warhead. The FY 2023 DOE and Navy budgets confirmed that the relationship was so direct that the Feasibility Study actually formed the basis for the W93/Mk7 Phase 1 Concept Assessment studies.[325] Navy plans for FY2023 include investment relevant to both aeroshell development and recapitalisation of the industrial base.[326]

Endnotes

1. GOV.UK. 'Defence Secretary Announces Programme to Replace the UK's Nuclear Warhead', 25 February 2020. https://www.gov.uk/government/news/defence-secretary-announces-programme-to-replace-the-uks-nuclear-warhead.
2. Dan Leone. 'Planned W93 Warhead Will Contribute to New U.K. Nuke, DOD Officials Say'. Defense Daily, 13 February 2020. https://www.defensedaily.com/planned-w93-warhead-will-contribute-new-u-k-nuke-dod-officials-say/nuclear-modernization/;Jamie Doward. 'Pentagon Reveals Deal with Britain to Replace Trident'. The Observer, 22 February 2020, https://www.theguardian.com/uk-news/2020/feb/22/pentagon-gaffe-reveals-uk-deal-replace-trident-nuclear-weapon.
3. Charles A Richard. 'Statement of Charles A. Richard, Commander United States Strategic Command, before the Senate Committee on Armed Services', 13 February 2020. https://www.armed-services.senate.gov/imo/media/doc/Richard_02-13-20.pdf. p13.
4. See Matthew Taylor. 'Britain Plans to Spend £3bn on New Nuclear Warheads'. The Guardian, 24 July 2008, sec. Science. https://www.theguardian.com/world/2008/jul/25/nuclear.weaponstechnology. Building new infrastructure, often regarded as the fourth element in the system, is an intrinsic part of the upgrade projects.
5. 'The United Kingdom's Future Nuclear Deterrent: The Submarine Initial Gate Parliamentary Report'. Ministry of Defence, May 2011. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/27399/submarine_initial_gate.pdf. p4.
6. Comptroller and Auditor General. The Defence Nuclear Enterprise: A Landscape Review. London: National Audit Office, 2018. https://www.nao.org.uk/wp-content/uploads/2018/05/The-Defence-Nuclear-Enterprise-a-landscape-review.pdf. p46.
7. Lockheed Martin. 'Modernized Lockheed Martin Trident II D5 Missile Test Certifies Submarine for Patrol', 28 March 2018. https://news.lockheedmartin.com/2018-03-28-Modernized-Lockheed-Martin-Trident-II-D5-Missile-Test-Certifies-Submarine-for-Patrol.
8. US budget documents suggest that conversion of the Trident missile stockpile is ongoing and may last until the D5LE2 programme begins in 2023 (see 'Fiscal Year (FY) 2022 Budget Estimates – Justification Book Volume 1 of 1 – Weapons Procurement, Navy'. Department of Defense, May 2021. https://www.secnav.navy.mil/fmc/fmb/Documents/22pres/WPN_Book.pdf. p2,4). Media reports that the September 2017 visit of HMS Vigilant to the Kings Bay submarine base in Georgia, which attracted media attention due to the behaviour of the crew, was to pick up nuclear warheads are likely a misunderstanding of the real purpose of the trip, which was probably to swap the submarine's load of missiles with life-extended versions.
9. See Peter Burt. 'AWE: Britain's Nuclear Weapons Factory; Past, Present, and Possibilities for the Future'. Nuclear Information Service, 2016. https://www.nuclearinfo.org/wp-content/uploads/2022/04/NIS_AWE_Executive_Summary.pdf. p26–27. and 'Warhead Convoy Movements Summary 2016'. Nukewatch, 2016. http://www.nukewatch.org.uk/wp-content/uploads/2014/04/Convoy-log-2016.pdf.
10. See Hans M. Kristensen and Matt Korda. 'World Nuclear Forces'. In SIPRI Yearbook 2021: Armaments, Disarmament and International Security. Oxford University Press, 2021. https://www.sipri.org/sites/default/files/2021-06/yb21_10_wnf_210613.pdf. p333–404.
11. Federation Of American Scientists. 'Status of World Nuclear Forces'. Accessed 9 November 2021. https://fas.org/issues/nuclear-weapons/status-world-nuclear-forces/.
12. Sanem Topal. 'Nuclear Weapon Modernisation: Attitudes of Non-Nuclear Weapon States'. Nuclear Information Service, August 2021. https://www.nuclearinfo.org/wp-content/uploads/2021/08/Attitudes-to-Nuclear-Weapons-Modernisation.pdf.
13. See Claire Mills. 'UK-US Mutual Defence Agreement'. Standard Note SN/IA/3147. House of Commons, 20 October 2014. https://researchbriefings.files.parliament.uk/documents/SN03147/SN03147.pdf.

14. DST Secretariat Strategy Secretariat. 'Copy of the Trident Holbrook Warhead Programme Project Definition Document or Equivalent', 13 October 2015. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/470321/20151013-FOI_2015_07375.pdf.
15. Peter Burt. 'AWE'. p10.
16. *Ibid*. p25.
17. Nicola Butler and Mark Bromley. 'Secrecy and Dependence: The UK Trident System in the 21st Century'. BASIC: British American Security Information Council, November 2001. p16
18. See Suzanne Doyle. 'The United States Sale of Trident to Britain, 1977–1982: Deal Making in the Anglo-American Nuclear Relationship'. Diplomacy & Statecraft 28, no. 3 (3 July 2017): 477–93. https://doi.org/10.1080/09592296.2017.1347447. The 1980 agreement was for purchase of the C4 Trident missile, but sale of the newer D5 Trident missile was later agreed by the Reagan administration.
19. Michael Clarke. 'Does My Bomb Look Big in This? Britain's Nuclear Choices after Trident'. International Affairs 80, no. 1 (January 2004). p55.
20. Peter Burt. 'AWE'. p10.
21. The first Vanguard patrol began in December 1994. See 'The Future of the United Kingdom's Nuclear Deterrent – Fact Sheet 4: The Current System'. Ministry of Defence and Foreign & Commonwealth Office, 1 December 2006. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/27382/Cm6994_Factsheet4.pdf.
22. 'Strategic Defence Review: Modern Forces for the Modern World'. Ministry of Defence, July 1998. https://webarchive.nationalarchives.gov.uk/ukgwa/20121018172816/http:/www.mod.uk/NR/rdonlyres/65F3D7AC-4340-4119-93A2-20825848E50E/0/sdr1998_complete.pdf. p24.
23. Kristensen and Korda. 'World Nuclear Forces'. p360, 336
24. US budget documents (see 'FY 2019 Congressional Budget Request – National Nuclear Security Administration – Volume 1: Federal Salaries and Expenses, Weapons Activities, Defense Nuclear Nonproliferation, Naval Reactors'. Department of Energy, March 2018. https://www.energy.gov/sites/default/files/2018/03/f49/FY-2019-Volume-1.pdf. p94.) make the distinction between a re-entry body warhead and a re-entry vehicle warhead, with the Trident Warheads being the latter. It is not clear whether there is any significant distinction between the two, but both conform to this description of an MIRV.
25. See 'The Decision to End U.S. Nuclear Testing'. Arms Control Association. Accessed 31 December 2021. https://www.armscontrol.org/act/2019-12/features/decision-end-us-nuclear-testing.
26. Reprinted by permission from Nature. Taken from 'Science of nuclear warheads', O'Nions et al. © 2002. 415, pages 853–857 (2002). The figure is presented in reference to understanding the performance of an existing weapon stockpile, but the process for new warhead development is the same.
27. Mark Welland. 'Hydrodynamics – Cooperation with France', 7 July 2010. D/CSA/13/1/2 (359/10). http://nuclearinfo.org/sites/default/files/04%20Mark%20Welland%20Hydrodynamics%20paper%20070710.pdf
28. See 'Anglo-French Nuclear Co-Operation and the "Teutates" Programme'. Nuclear Information Service, November 2010. https://www.nuclearinfo.org/wp-content/uploads/2020/09/NIS-Anglo-French-co-operation-briefing-November-2010-1.pdf.
29. Nuclear Information Service. 'UK and France Extend Warhead Research Collaboration into New Areas', 5 February 2014. http://nuclearinfo.org/article/government-development-awe-aldermaston/uk-and-france-extend-warhead-research-collaboration.
30. See page 23
31. Peter Burt. 'AWE'. p26.
32. See the 'Costs and timescale' section on page 25 for more detail.
33. 'Assuring Destruction Forever: 2015 Edition'. Reaching Critical Will, 2015. https://reachingcriticalwill.org/images/documents/Publications/modernization/assuring-destruction-forever-2015.pdf. p72–73; Peter Burt. 'AWE'. p26–27.
34. Hans M. Kristensen, Matthew McKinzie, and Theodore A. Postol. 'How US Nuclear Force Modernization Is Undermining Strategic Stability: The Burst-Height Compensating Super-Fuze'. Bulletin of the Atomic Scientists, 1 March 2017. http://thebulletin.org/how-us-nuclear-force-modernization-undermining-strategic-stability-burst-height-compensating-super10578.
35. Hans M. Kristensen. 'British Submarines to Receive Upgraded US Nuclear Warhead'. Federation Of American Scientists, 1 April 2011. https://fas.org/blogs/security/2011/04/britishw76-1/.

36. See, for example, the government's 2012 description of the NWCSP's purpose: "… to maintain and where necessary to develop … capabilities to ensure that the UK has the ability to underpin any decision on a future UK nuclear warhead". 'MOD Government Major Projects Portfolio Data'. Ministry of Defence, 23 April 2013. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/203310/20130524_mod_gmpp_data.xls.
37. The caps announced between 1998 and 2006 were formulated in terms of a figure that warhead numbers would remain below. From 2010 onwards the caps have been announced as a maximum, meaning that warhead numbers could be equal to the cap figure.
38. GOV.UK. 'UK Minister Attends Review Conference Following UK Disclosure of Nuclear Stockpile', 26 May 2010. https://www.gov.uk/government/news/uk-minister-attends-review-conference-following-uk-disclosure-of-nuclear-stockpile.
39. These figures were presented as a threshold that warhead numbers would remain below. All other figures were presented as a maximum that numbers would not rise above. The overall stockpile figure for 2006 was not made public but can be inferred from other public information.
40. Ministry of Defence. 'Modern Forces for the Modern World'. p25.
41. Robert S. Norris and Hans M. Kristensen. 'The British Nuclear Stockpile, 1953–2013'. Bulletin of the Atomic Scientists 69, no. 4 (July 2013): 69–75. https://doi.org/10.1177/0096340213493260.
42. Peter Burt. 'AWE'. p10.
43. Ministry of Defence. 'Modern Forces for the Modern World'. p26.
44. 'The Future of the United Kingdom's Nuclear Deterrent'. HM Stationery Office, December 2006. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/27378/DefenceWhitePaper2006_Cm6994.pdf. p12.
45. 'Securing Britain in an Age of Uncertainty: The Strategic Defence and Security Review'. London: HM Government, 2010. http://www.direct.gov.uk/prod_consum_dg/groups/dg_digitalassets/@dg/@en/documents/digitalasset/dg_191634.pdf. p39
46. 'Nuclear Deterrent: Written Statement'. Hansard UIN HCWS210', 20 January 2015. https://www.parliament.uk/business/publications/written-questions-answers-statements/written-statement/Commons/2015-01-20/HCWS210/.
47. See pages 34–37
48. See 'Trident'. Hansard Volume 569, 1996. https://hansard.parliament.uk/Lords/1996-02-22/debates/0b85ad1e-c0b7-4f36-be2a-b64f4ed2625a/Trident.
49. HM Stationery Office. 'The Future of the United Kingdom's Nuclear Deterrent'. p23.
50. The Future of the UK's Strategic Nuclear Deterrent: The White Paper – Government Response to the Committee's Ninth Report of Session 2006–07'. House of Commons Defence Select Committee, 24 May 2007. HC 551. https://media.nti.org/pdfs/15_11.pdf. p44.
51. Mr Peter Whitehouse and Commodore (Rtd) Tim Hare. Minutes of Evidence – Whitehouse and Hare (Questions 142–159), House of Commons Defence Select Committee (2006). https://publications.parliament.uk/pa/cm200506/cmselect/cmdfence/986/6032802.htm. Q149–152.
52. See Carey Sublette. 'The B61 Bomb'. The Nuclear Weapon Archive. Accessed 18 July 2022. https://nuclearweaponarchive.org/Usa/Weapons/B61.html.
53. '26 November 1991 – Last UK Nuclear Test'. Comprehensive Test Ban Treaty Organization. Accessed 18 July 2022. https://www.ctbto.org/specials/testing-times/26-november-1991-last-uk-nuclear-test.
54. Wm. Robert Johnston. 'Database of Nuclear Tests, United Kingdom'. Nuclear Tests – Databases and Other Material, 11 June 2009. http://www.johnstonsarchive.net/nuclear/tests/UK-ntests1.html.; The Nuclear Weapon Archive. 'Sandia National Laboratory Official List of UNEs in Nevada', July 1994. http://nuclearweaponarchive.org/Usa/Tests/Nevada.html.
55. House of Commons Defence Select Committee. 'Government Response'. p7.
56. The NWCSP was announced to Parliament in July 2005 and the project officially began in April 2008, see 'Written Ministerial Statements (part 3)'. Hansard Column 59WS, 19 July 2005. https://publications.parliament.uk/pa/cm200506/cmhansrd/vo050719/wmstext/50719m03.htm#50719m03.html_sbhd0; 'MoD Government Major Projects Portfolio data, 2021'. Ministry of Defence, 15 July 2021. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1002095/MOD_Government_Major_Projects_Portofolio_Data_March_2021.xls
57. Hans M. Kristensen. 'US Deploys New Low-Yield Nuclear Submarine Warhead'. Federation Of American Scientists. Accessed 25 February 2020. https://fas.org/blogs/security/2020/01/w76-2deployed/.

58. 'FY 2022 Congressional Budget Request – National Nuclear Security Administration – Volume 1: Federal Salaries and Expenses, Weapons Activities, Defense Nuclear Nonproliferation, Naval Reactors'. Department of Energy, May 2021. https://www.energy.gov/sites/default/files/2021-06/doe-fy2022-budget-volume-1-v4.pdf. p86.
59. See Charles Richard. 'Statement, February 2020'. It is thought that around 25 warheads were converted. See Kristensen and Korda. 'World Nuclear Forces'. p333–404.
60. Stephen Young. 'The Case of the "Low-Yield" Trident Warhead'. Union of Concerned Scientists: All Things Nuclear, 19 March 2018. https://allthingsnuclear.org/syoung/low-yield-trident/.
61. Kristensen and Korda. 'World Nuclear Forces'. p336.
62. Ministry of Defence. 'Modern Forces for the Modern World'. p25.
63. HM Stationery Office. 'The Future of the United Kingdom's Nuclear Deterrent'. p23.
64. Whitehouse and Hare. 'Minutes of Evidence' 2006. Q149–152.
65. Des Browne, Desmond Bowen, Tom McKane, Andrew Mathews, Nick Bennett, and Mariot Leslie. House of Commons – Defence – Minutes of Evidence – Session 2006–07, House of Commons Defence Select Committee (2007). https://publications.parliament.uk/pa/cm200607/cmselect/cmdfence/225/7020601.htm. Q358.
66. House of Commons Defence Select Committee. 'Government Response'. p7.
67. Browne *et al*. 'Minutes of Evidence'. Q358.
68. HM Stationery Office. 'The Future of the United Kingdom's Nuclear Deterrent'. p23.
69. See Michael Quinlan, 'The British Experience' in Henry D. Sokolski, ed. Getting MAD: Nuclear Mutual Assured Destruction, Its Origins and Practice. Carlisle/Pa: Strategic Studies Institute, 2004. p272. Quinlan uses the formulation '[t]his has been conjectured to mean that some missiles might have only a single warhead, and that warhead might have reduced explosive yield' when he was doubtless in a position to know for certain. Presumably this form of words allowed him to confirm conjecture that is in the public domain without breaching the Official Secrets Act.
70. Hansard. 'Trident'.
71. Geoffrey Chapman. ''Sub-Strategic' Trident'. In Workshop on UK Nuclear Weapons Politics, Student and Young Pugwash Conference. University of Leicester, 2022. https://youtube.com/V1UvjYN6K0k.
72. 'Nuclear Weapons'. Hansard UIN 170597, 17 March 2021. https://questions-statements.parliament.uk/written-questions/detail/2021-03-17/170597.
73. See page 34.
74. 'Fiscal Year 2015 Stockpile Stewardship and Management Plan'. National Nuclear Security Administration (NNSA), April 2014. https://www.energy.gov/sites/default/files/2017/08/f36/2014-04-11%2520FY15SSMP_FINAL_4-10-2014%5B1%5D.pdf. ch1 p2–3.
75. Department of Defense Fiscal Year (FY) 2021 Budget Estimates – Research, Development, Test & Evaluation, Navy – Justification Book Volume 5 of 5', February 2020. https://www.secnav.navy.mil/fmc/fmb/Documents/22pres/RDTEN_BA7_Book.pdf. p88. See also Annexe E.
76. NNSA.'Fiscal Year 2015 Stockpile Stewardship and Management Plan'. ch1 2–3.
77. Fiscal Year 2018 Stockpile Stewardship and Management Plan'. National Nuclear Security Administration (NNSA), November 2017. https://www.energy.gov/sites/default/files/2017/11/f46/fy18ssmp_final_november_2017%5B1%5D_0.pdf. ch2 p23.
78. NNSA. 'Fiscal Year 2015 Stockpile Stewardship and Management Plan'
79. *Ibid*.
80. *Ibid*.
81. NNSA. 'Fiscal Year 2018 Stockpile Stewardship and Management Plan'. ch2 p28.
82. Federal fiscal years in the US run from October 1st to September 30th and each is numbered according to the later of the two calendar years it spans, so Fiscal Year 2021 ran from October 1st 2020 until September 30th 2021.
83. 'Fiscal Year 2016 Stockpile Stewardship and Management Plan'. National Nuclear Security Administration (NNSA), March 2015. https://www.energy.gov/sites/default/files/2017/08/f36/FY16SSMP_FINAL%25203_16_2015_reducedsize%5B1%5D.pdf. ch2 p25–26.
84. See the 'W83 Antecedents' section on page 40 and Annexe E.
85. Adapted from Fiscal Year 2015 Stockpile Stewardship and Management Plan. See note 74.
86. Aaron Mehta. 'Inside America's Newly Revealed Nuclear Ballistic Missile Warhead of the Future'. Defense News, 24 February 2020. https://www.defensenews.com/smr/nuclear-arsenal/2020/02/24/inside-americas-newly-revealed-nuclear-ballistic-missile-warhead-of-the-future/.
87. Department of Energy. 'FY 2022 Congressional Budget Request'. p74.
88. 'FY 2021 Congressional Budget Request – National Nuclear Security Administration – Federal Salaries and Expenses, Volume 1: Weapons Activities, Defense Nuclear Nonproliferation, Naval Reactors.'. Department of Energy, February 2020. https://www.energy.gov/sites/prod/files/2020/03/f72/doe-fy2021-budget-volume-1_2.pdf. p119.

89. FY 2023 Congressional Budget Request – National Nuclear Security Administration – Volume 1: Federal Salaries and Expenses Weapons Activities Defense Nuclear Nonproliferation Naval Reactors'. Department of Energy, April 2022. https://www.energy.gov/sites/default/files/2022-05/doe-fy2023-budget-volume-1.pdf. p115.
90. Department of Energy. 'FY 2022 Congressional Budget Request'. p85.
91. Department of Energy. 'FY 2023 Congressional Budget Request'. p114.
92. *Ibid.* p118.
93. Department of Energy. 'FY 2022 Congressional Budget Request'. p5,67.
94. Department of Energy. 'FY 2023 Congressional Budget Request'. p91.
95. Department of Energy. 'FY 2022 Congressional Budget Request'. p89.
96. *Ibid.* p67.
97. *Ibid.* p84.
98. Department of Defense 'FY 2022 Budget Estimates'. p290.
99. Department of Defense. 'FY 2021 Budget Estimates'. p114.
100. 'Fiscal Year 2022 Stockpile Stewardship and Management Plan'. National Nuclear Security Administration (NNSA), March 2022. https://www.energy.gov/sites/default/files/2022-03/FY%202022%20SSMP%20March%202022.pdf. ch8 p32–33. This estimate is based on the cost of the spending at the time it is incurred: 'then-year dollars'. In 2022 dollars the cost estimate is between $8.9bn to $10.1bn.
101. Adapted from Fiscal Year 2022 Stockpile Stewardship and Management Plan. p2–11. See note 100.
102. Department of Energy 'FY 2021 Congressional Budget Request'. p295.
103. See Dan Sabbagh. 'US Nuclear Warhead Standoff "Has Significant Implications for UK"'. the Guardian, 8 December 2020. http://www.theguardian.com/uk-news/2020/dec/08/us-nuclear-warhead-standoff-has-significant-implications-for-uk.
104. See, for example, Charles Richard. 'Statement, February 2020'; and 'Department of Defense Background Briefing on Nuclear Deterrence and Modernization'. US Department of Defense, 21 February 2020. https://www.defense.gov/Newsroom/Transcripts/Transcript/Article/2090986/department-of-defense-background-briefing-on-nuclear-deterrence-and-modernizati/.
105. This summary is taken from a copy of the memo seen by the Nuclear Information Service, entitled 'W93/Mk7 Navy Warhead – Developing Modern Capabilities to Address Current and Future Threats'.
106. See page 38.
107. See page 13.
108. 'Atomic Weapons Establishment'. Hansard, 19 Jul 2005: Column 59WS https://publications.parliament.uk/pa/cm200506/cmhansrd/vo050719/wmstext/50719m03.htm#50719m03.html_sbhd0
109. See Peter Burt. 'AWE'. p15. for more details
110. *Ibid.* p16
111. Ministry of Defence. 'MoD Major Projects Portfolio data 2021'.
112. 'ORION-Fact Sheet – Shaping the Future of Plasma Physics'. AWE, 2013. https://www.awe.co.uk/app/uploads/2014/07/ORION-Fact_Sheet.pdf.
113. A petaflop is a unit used to measure computing power, derived from the contraction FLOPS, meaning 'floating point operations per second'. One petaflop is equal to one thousand million million floating point operations (10^{15}) per second.
114. AWE. 'AWE Names Its New Supercomputer "Vulcan" in Honour of the RAF Aircraft', 12 November 2019. https://www.awe.co.uk/2019/11/awe-names-its-new-supercomputer-vulcan-in-honour-of-the-raf-aircraft/.
115. TOP500. 'AWE'. Accessed 4 July 2022. https://www.top500.org/system/179409/.
116. Stephen Lovegrove. 'Accounting Officer Assessment for UK/France TEUTATES Programme', 4 February 2019. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/778596/20190212_Accounting_Officer_Assessment_for_the_TEUTATES_programme_MSU_4.2.4.6-Min_DP-Penny_Young.pdf.
117. 'France: Nuclear Weapons'. Hansard UIN 20361, 22 June 2021. https://questions-statements.parliament.uk/written-questions/detail/2021-06-22/20361.
118. Lovegrove. 'TEUTATES Accounting Officer Assessment'; CEA. 'UK/French Joint Technological Developments EPURE'. Accessed 29 November 2021. http://www-teutates.cea.fr/uk/joint-technological-developments.html.
119. Reprinted by permission from Nature. Taken from 'Science of nuclear warheads', O'Nions et al. © 2002. 415, pages 853–857 (2002). Since the original publication the Orion laser has come online with a short-pulse capability.
120. Managing Infrastructure Projects on Nuclear-Regulated Sites'. National Audit Office, 10 January 2020. p55.
121. https://questions-statements.parliament.uk/written-questions/detail/2022-02-21/126551/
122. Stephen Lovegrove. 'Project Pegasus Accounting Officer Assessment', 10 March 2021. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/973246/20210310_-_NWCSP__Pegasus__AOA_-_2-_OS_1__Redacted.pdf.

123. Vanessa Nichols. 'Day One Keynote Speech and Q&A'. Presented at the UK Project on Nuclear Issues Annual Conference 2021, 8 June 2021. https://www.youtube.com/watch?v=V1gbHl82oRw&list=PLFAgO2TZWpwBXydLuAfAWO016_GbG2QxM&index=2.
124. 'MOD Government Major Projects Portfolio Data March 2022'. Ministry of Defence, 20 July 2022. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1092315/MOD_Government_Major_Projects_Portfolio_Data_March_2022.xls.
125. 'Nuclear Weapons'. Hansard UIN 21807, 24 June 2021. https://questions-statements.parliament.uk/written-questions/detail/2021-06-24/21807
126. 'Nuclear Weapons: Expenditure'. Hansard UIN 21809, 24 June 2021. https://questions-statements.parliament.uk/written-questions/detail/2021-06-24/21809
127. 'The United Kingdom's Future Nuclear Deterrent: The Dreadnought Programme 2017 Update to Parliament'. Ministry of Defence, 20 December 2017. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/669771/20171220-2017_Annual_Update_to_Parliament-The_United_Kingdoms_Future_Nu_____002_.pdf.
128. 'The United Kingdom's Future Nuclear Deterrent: The 2018 Update to Parliament'. Ministry of Defence, December 2018. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/767326/2018_Nuclear_Deterrent_Update_to_Parliament.pdf.
129. Ministry of Defence. 'The United Kingdom's Future Nuclear Deterrent: The 2019 Update to Parliament', 2019. http://data.parliament.uk/DepositedPapers/Files/DEP2019-1091/nuclear_Deterrent_2019Update_to_Parliament.pdf.
130. 'MoD Government Major Projects Portfolio data, 2018'. Ministry of Defence, 4 July 2018. https://www.gov.uk/government/publications/mod-government-major-projects-portfolio-data-2018
131. Peter Burt AWE p29.
132. 'The United Kingdom's Future Nuclear Deterrent: 2016 Update to Parliament'. Ministry of Defence, 20 December 2016. https://www.gov.uk/government/publications/the-united-kingdoms-future-nuclear-deterrent-2016-update-to-parliament predicted a decision "in this Parliament or early in the next", which at the time would have scheduled the decision either before or soon after an election in May 2020.
133. Ministry of Defence. 'The 2018 Update to Parliament'. p4.
134. See the 'W93 Antecedents' section on page 40.
135. See the 'W93 and Mk7 Programmes' section on page 20 and Figure 4.
136. The MOD's Smart Acquisition process follows a very similar path, for example, see Claire Taylor. 'UK Defence Procurement Policy'. House of Commons Library, 20 October 2003. Research paper 03/78 https://researchbriefings.files.parliament.uk/documents/RP03-78/RP03-78.pdf. p16–18
137. See the 'Likelihood of diverging from the W93 design' section on page 44.
138. See the 'W93 and Mk7 Programmes' section on page 20.
139. Vanessa Nichols. 'Day One Keynote Speech and Q&A'.
140. Nuclear Weapons: Costs'. Hansard UIN 21808, 24 June 2021. https://questions-statements.parliament.uk/written-questions/detail/2021-06-24/21808.
141. 'Nuclear Weapons: Procurement'. Hansard UIN 20362, 22 June 2021. https://questions-statements.parliament.uk/written-questions/detail/2021-06-22/20362.
142. Ministry of Defence. 'Major Projects Portfolio Data March 2022'. The government's censoring of data about the NWCSP and its subsidiary projects suggest that it will also withhold information about the Replacement Warhead Project from its releases.
143. 'Hansard. 'Nuclear Weapons: Procurement'.
144. 'W76-1 Life Extension Program'. National Nuclear Security Administration, January 2019. https://www.energy.gov/sites/default/files/2019/02/f59/02-13-2019-Factsheet-W76-1%20LEP.pdf.
145. If the service life of a component is dated from the time of manufacture and both UK and US components are part of a single production run, then its service life will end at a particular calendar date, irrespective of when it was incorporated into a warhead.
146. Ministry of Defence. 'The 2016 Update to Parliament'. p5.
147. 'Trident Alternatives Review'. Cabinet Office, 16 July 2013. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/212745/20130716_Trident_Alternatives_Study.pdf.
148. See note 9.
149. See the 'Warhead numbers under the IR' section on page 36.
150. See the 'Janus Faced: nuclear armed states under the NPT' section on page 31.
151. Vanessa Nichols. 'Day One Keynote Speech and Q&A'. spoke of "simplification" and ministers wanting a "within government" relationship with AWE.
152. See Nuclear Information Service. 'AWE Becomes a Non-Departmental Public Body', 29 September 2021. https://www.nuclearinfo.org/article/awe-becomes-public-body/.
153. 'Nuclear Posture Review 2018'. Office of the Secretary of Defense, February 2018. https://media.defense.gov/2018/Feb/02/2001872886/-1/-1/1/2018-NUCLEAR-POSTURE-REVIEW-FINAL-REPORT.PDF. p38.
154. *Ibid.* pVII.

155. 'Fiscal Year 2019 Stockpile Stewardship and Management Plan'. National Nuclear Security Administration (NNSA), October 2018. https://www.energy.gov/sites/prod/files/2018/10/f57/FY2019%20SSMP.pdf. ch1 p8.
156. Office of the Secretary of Defense. 'Nuclear Posture Review 2018'. p30, 53–55.
157. See Russia Matters. 'Is "Escalate to Deescalate" Part of Russia's Nuclear Toolbox?', 8 January 2020. https://www.russiamatters.org/analysis/escalate-deescalate-part-russias-nuclear-toolbox; Olga Oliker and Andrey Baklitskiy. 'The Nuclear Posture Review and Russian "De-Escalation:" A Dangerous Solution to a Nonexistent Problem'. War on the Rocks, 20 February 2018. https://warontherocks.com/2018/02/nuclear-posture-review-russian-de-escalation-dangerous-solution-nonexistent-problem/.
158. Office of the Secretary of Defense. 'Nuclear Posture Review 2018'. p37.
159. *Ibid.*
160. See 'DOD Review Recommends Reduction in Nuclear Force'. Office of Assistant Secretary of Defense, 22 September 1994. http://missilethreat.csis.org/wp-content/uploads/2022/01/1994-NPR-News-Release-Slides-Clinton.pdf; 'Nuclear Posture Review [Excerpts]'. Secretary of Defense, 8 January 2002. https://uploads.fas.org/media/Excerpts-of-Classified-Nuclear-Posture-Review.pdf; and 'Nuclear Posture Review Report'. United States Department of Defense, April 2010. https://dod.defense.gov/Portals/1/features/defenseReviews/NPR/2010_Nuclear_Posture_Review_Report.pdf. The interoperability aspect of the 3+2 programme was intended to reduce the numbers of non-deployed warheads needed for hedging, as they could be assigned to multiple platforms.
161. See Stephen Schwartz. 'Ready, Aim, Fired: Can Biden Rescue the Nuclear Posture Review?' Bulletin of the Atomic Scientists, 30 September 2021. https://thebulletin.org/2021/09/ready-aim-fired-can-biden-rescue-the-nuclear-posture-review/.
162. See Daryl G. Kimball. 'Biden Policy Allows First Use of Nuclear Weapons'. Arms Control Association. Accessed 12 April 2022. https://www.armscontrol.org/act/2022-04/news/biden-policy-allows-first-use-nuclear-weapons.
163. See https://crsreports.congress.gov/product/pdf/IF/IF12084; https://breakingdefense.com/2022/03/biden-administration-kills-trump-era-nuclear-cruise-missile-program/
164. See the 'UK warhead stockpile figures 1998–2015' section on page 13.
165. 'Global Britain in a Competitive Age: The Integrated Review of Security, Defence, Development and Foreign Policy'. HM Government, March 2021. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/975077/Global_Britain_in_a_Competitive_Age-_the_Integrated_Review_of_Security__Defence__Development_and_Foreign_Policy.pdf. p76.
166. *Ibid*. p76–77.
167. *Ibid*. p77.
168. HM Government. 'Strategic Defence and Security Review 2015'. p35.
169. HM Government. 'Global Britain in a Competitive Age'. p76–77. The policy encompasses threats to both the UK and its allies.
170. International Court of Justice. Legality of the Threat or Use of Nuclear Weapons: Advisory Opinion of 8 July 1996. The Hague: International Court of Justice, 1996.
171. Nicholas Grief. 'Legality of the Threat or Use of Nuclear Weapons'. International and Comparative Law Quarterly 46, no. 3 (July 1997): 681–88. https://doi.org/10.1017/S0020589300060863.
172. Ian Davis. 'The British Bomb and Nato: Six Decades of Contributing to Nato's Strategic Nuclear Deterrent'. Stockholm International Peace Research Institute and Nuclear Education Trust, November 2015. http://nucleareducationtrust.org/sites/default/files/NATO%20Trident%20Report%2015_11.pdf.
173. The UK's role in NATO is cited in the joint US Pentagon and DOE memo as a reason the W93 and Mk7 programmes are needed, due to the support they will give to the UK Replacement Warhead Programme. See the 'Rationale' section on page 38.
174. Jonathan V. Last. 'The Fog of War'. Washington Examiner, 18 May 2009. https://www.washingtonexaminer.com/weekly-standard/the-fog-of-war.
175. Ralph Vartabedian. 'Nuclear Weapon Retrofit Falters'. Los Angeles Times, 29 May 2009. https://www.latimes.com/archives/la-xpm-2009-may-29-na-broken-warheads29-story.html.
176. Jonathan Medalia. 'Nuclear Warheads: The Reliable Replacement Warhead Program and the Life Extension Program'. Congressional Research Service, 3 December 2007. https://sgp.fas.org/crs/nuke/RL33748.pdf. p29–33.
177. For an overview of the plan see Department of Energy. 'Fiscal Year 2015 Stockpile Stewardship and Management Plan'. ch2 p13.
178. 'Nuclear Triad: DOD and DOE Face Challenges Mitigating Risks to U.S. Deterrence Efforts'. United States Government Accountability Office, May 2021. https://www.gao.gov/assets/gao-21-210.pdf. p33.

179. NNSA. 'Fiscal Year 2019 Stockpile Stewardship and Management Plan'. p47.
180. Charles A Richard. 'Statement of Charles A. Richard Commander United States Strategic Command'. Senate Armed Services Committee, 8 March 2022. https://www.armed-services.senate.gov/imo/media/doc/2022%20USSTRATCOM%20Posture%20Statement%20-%20SASC%20Hrg%20FINAL.pdf. p22.
181. See the 'Justifaction' section on page 22.
182. NNSA. 'Fiscal Year 2018 Stockpile Stewardship and Management Plan'. ch2 p23.
183. NNSA. 'Fiscal Year 2022 Stockpile Stewardship and Management Plan'. ch2 p15
184. United Kingdom of Great Britain and Northern Ireland. 'National Report Pursuant to Actions 5, 20, and 21 of the Nuclear Non-Proliferation Treaty (NPT) 2010 Review Conference Final Document'. United Nations, 25 April 2019. NPT/CONF.2020/PC.III/7. https://undocs.org/en/NPT/CONF.2020/PC.III/7. p4.
185. Vanessa Nichols. 'Day One Keynote Speech and Q&A'.
186. See Nuclear Threat Initiative. 'Q&A: Des Browne on the UK's Decision to Increase the Cap on Nuclear Warheads', 14 April 2021. https://www.nti.org/analysis/atomic-pulse/qa-des-browne-on-the-uks-decision-to-increase-the-cap-on-nuclear-warheads/; John Gower. 'Hubris, Hypocrisy or Hedge?' BASIC, 6 April 2021. https://basicint.org/hubris-hypocrisy-or-hedge/.
187. John Gower. 'Hubris, Hypocrisy or Hedge?'.
188. ICRC. 'Customary IHL – Rule 74. Chemical Weapons'. Accessed 23 November 2021. https://ihl-databases.icrc.org/customary-ihl/eng/docs/v1_rul_rule74; ICRC. 'Customary IHL – Rule 73. Biological Weapons'. Accessed 23 November 2021. https://ihl-databases.icrc.org/customary-ihl/eng/docs/v1_rul_rule73.
189. See 'The UK's 2021 Integrated Review' section on page 30.
190. HM Government. 'Global Britain in a Competitive Age'. p76–77.
191. See the 'Treaty commitments under the NPT' section on page 37.
192. John Ainslie. 'Unacceptable Damage: Damage Criteria in British Nuclear Planning', February 2013. http://picat.online/wp-content/uploads/2016/09/Exhibit-JA02.pdf.
193. 'The Andrew Marr Show', 21 March 2021. https://www.bbc.co.uk/iplayer/episode/m000tjc6/the-andrew-marr-show-21032021. Quotes from the interview are excerpted in Helen Warrell and Sylvia Pfeifer. 'UK Nuclear Warhead Increase Prompted by Russia's Missile Defence Capability'. Financial Times, 21 March 2021. https://www.ft.com/content/a86e8ca8-365e-4774-b22c-fbdf12237935.
194. See the following section.
195. See Tom Plant and Matthew Harries. 'Going Ballistic: The UK's Proposed Nuclear Build-Up'. Royal United Services Institute, 16 March 2021. https://www.rusi.org/explore-our-research/publications/commentary/going-ballistic-uks-proposed-nuclear-build; Heather Wiliams. 'U.K. Nuclear Weapons: Beyond the Numbers'. War on the Rocks, 6 April 2021. http://warontherocks.com/2021/04/u-k-nuclear-weapons-beyond-the-numbers/.
196. Plant and Harries. 'Going Ballistic'.
197. If so, Plant and Harries (*Ibid*.) suggest this could either be aimed at decision-makers in the US or potential adversaries.
198. HM Government. 'Global Britain in a Competitive Age'. p76.
199. *Ibid*
200. See 'The 2018 US Nuclear Posture Review' section on page 27.
201. Vanessa Nichols. 'Day One Keynote Speech and Q&A'.
202. Dan Sabbagh. Twitter, 16 March 2021. http://web.archive.org/web/20210316123443/https://twitter.com/dansabbagh/status/1371802016465453063. NIS has heard almost identical language used to describe the decision from a government source under Chatham House rules, suggesting that 'not apologise' might be a direct quote from Boris Johnson.
203. John Gower. 'Hubris, Hypocrisy or Hedge?'.
204. Hans M Kristensen. 'Virtual Program – The UK's new nuclear posture: What it means for the global nuclear order' Bulletin of the Atomic Scientists:YouTube, 28 May 2021. https://www.youtube.com/watch?v=lyjlvM7ezkY&t=947s.
205. Warhead Convoy Movements Summary 2017'. Nukewatch. Accessed 21 April 2022. https://www.nukewatch.org.uk/wp-content/uploads/2020/04/Convoy-log-2017.pd; 'Warhead Convoy Movements Summary 2018'. Nukewatch. Accessed 21 April 2022. https://www.nukewatch.org.uk/wp-content/uploads/2020/04/Convoy-log-2018.pdf; 'Warhead Convoy Movements Summary 2019'. Nukewatch. Accessed 22 July 2022. https://www.nukewatch.org.uk/wp-content/uploads/2020/04/Convoy-log-2019.pdf; 'Warhead Convoy Movements Summary 2020'. Nukewatch. Accessed 22 July 2022. https://www.nukewatch.org.uk/wp-content/uploads/2021/01/Convoy-log-2020.pdf.
206. See the 'Role of the low-yield capability in nuclear doctrine' section on page 16.

207. 'Warhead Convoy Movements Summary 2016'. Nukewatch. Accessed 8 December 2018. http://www.nukewatch.org.uk/wp-content/uploads/2014/04/Convoy-log-2016.pdf; Nuclear Information Service. 'Doubling of Nuclear Transports May Indicate Delivery of Upgraded Warheads'. Accessed 12 January 2019. https://www.nuclearinfo.org/article/transport/doubling-nuclear-transports-may-indicate-delivery-upgraded-warheads.
208. See the 'Nuclear Warhead Capability Sustainment Programme' on page 23.
209. Taken from Nukewatch annual convoy movement logs, available at https://www.nukewatch.org.uk/convoys/annual-convoy-movements/. The range of uncertainty combines Nukewatch's annual minimum estimate for warheads taken from Coulport to AWE Burghfield and its maximum estimate for warheads taken in the opposite direction for its upper bound, and vice versa. In practice neither extreme would be sustainable for the programme beyond the short term and the true stockpile size will be substantially closer to Nukewatch's best estimate.
210. The speed of the apparent observed increases do not appear to allow for a long period of manufacturing components after the probable decision point in late 2019 or early 2020. It is not possible to be certain, but the rise to 260 may involve a returning of the entire stock of dismantled warheads to service with the stockpile rising to the total number of Trident warheads in the initial production run. See the 'UK warhead stockpile figures 1998–2015' section on page 13.
211. Ministry of Defence. 'Request for Information under the Freedom of Information (FOI) Act – 25-03-2013-173601-014', 25 July 2013. https://robedwards.typepad.com/files/mod-foi-response-on-dismantling-nuclear-weapons.pdf.
212. United Kingdom of Great Britain and Northern Ireland. 'National Report'.
213. 2000 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, Final Document – Volume I (Parts I and II)'. United Nations, 10 May 2001. NPT/CONF.2000/28NPT/CONF.2000/28(PartsIandII). https://undocs.org/NPT/CONF.2000/28(PartsIandII). p15. Commitment to these measures was reaffirmed in the 2010 Review Conference, see '2010 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons. Final Document . Volume I'. United Nations, 2010. https://undocs.org/NPT/CONF.2010/50(Vol.I). p21.
214. *Ibid*. p20.
215. NNSA. 'Fiscal Year 2022 Stockpile Stewardship and Management Plan'. ch2 p10.
216. See the 'Likelihood of diverging from the W93 design' section on page 44.
217. The Guardian. 'UK Lobbies US to Support Controversial New Nuclear Warheads', 1 August 2020. http://www.theguardian.com/world/2020/aug/01/uk-trident-missile-warhead-w93-us-lobby.
218. RIA Novosti. 'Russia to Revamp Air-Space Defenses by 2020 – Air Force Chief', 14 August 2009. https://web.archive.org/web/20090814211437/http://en.rian.ru/mlitary_news/20090811/155782307.html.
219. A particularly high level of secrecy is applied to such measures, but Russia's use of conventionally-armed Iskander-M missiles in the Ukraine conflict provided some rare images of the types of countermeasures used: John Ismay. 'Russia Deploys a Mystery Munition in Ukraine'. The New York Times, 15 March 2022, sec. U.S. https://www.nytimes.com/2022/03/14/us/russia-ukraine-weapons-decoy.html.
220. 'Fiscal Year (FY) 2019 Budget Estimates – Research, Development, Test & Evaluation, Navy – Justification Book Volume 5 of 5'. Department of Defense, February 2018. https://www.secnav.navy.mil/fmc/fmb/Documents/19pres/RDTEN_BA7_book.pdf. p101.
221. See the 'W93 Antecedents' section on page 40.
222. See the 'Janus Faced: nuclear armed states under the NPT' section on page 31.
223. See the '2018 US Nuclear Posture Review' section on page 27.
224. See the '2018 US Interoperable Warheads and the 3+2 plan' section on page 18 for this detail and for further background to this section.
225. Department of Defense. 'FY 2021 Budget Estimates'. p114. gives the name as the 'Interoperative Warhead', but this appears to be a malapropism, as the correct name can be found in earlier budget documents. The previous years' budget makes it clear that this project (3097 RDTEN) was for the first Interoperable Warhead IW1, which would have replaced the W88 and W78 (see 'Fiscal Year (FY) 2020 Budget Estimates – Research, Development, Test & Evaluation, Navy – Justification Book Volume 5 of 5'. Department of Defense, March 2019. https://www.secnav.navy.mil/fmc/fmb/Documents/22pres/RDTEN_BA7_Book.pdf. p117).
226. The study appears to have been carried out between October 2018 and March 2019 (see NNSA. 'Fiscal Year 2019 Stockpile Stewardship and Management Plan'. ch2 p13; 'FY 2020 Congressional Budget Request – National Nuclear Security Administration – Federal Salaries and Expenses, Weapons Activities, Defense Nuclear Nonproliferation, Naval Reactors. Volume 1'. Department of Energy, March 2019. https://www.energy.gov/sites/default/files/2019/04/f62/doe-fy2020-budget-volume-1.pdf. p86).

227. Derived from Fiscal Year 2015 Stockpile Stewardship and Management Plan and Fiscal Year 2022 Stockpile Stewardship and Management Plan. See notes 74 and 100.
228. 'FY 2023 Congressional Budget Request'. p430; 'Fiscal Year (FY) 2023 Budget Estimates – Research, Development, Test & Evaluation, Navy – Justification Book Volume 5 of 5'. Department of Defense, April 2022. https://www.secnav.navy.mil/fmc/fmb/Documents/23pres/RDTEN_BA7_Book.pdf. p286.
229. NNSA. 'Fiscal Year 2022 Stockpile Stewardship and Management Plan'. p2–10,2–15. The latest Department of Energy budget anticipates Concept Assessment for the first of these warheads beginning in FY 2027. See Department of Energy. 'FY 2023 Congressional Budget Request'. p115.
230. *Ibid*. p279.
231. 'Fiscal Year 2019 Stockpile Stewardship and Management Plan'. ch2 p3.
232. Department of Energy. 'FY 2021 Congressional Budget Request'. p279.
233. NNSA. 'Fiscal Year 2019 Stockpile Stewardship and Management Plan'. ch2 p3.
234. 'FY 2021 Congressional Budget Request – National Nuclear Security Administration'. p279.
235. Tom Z. Collina. 'Future of '3+2' Warhead Plan in Doubt'. Arms Control Association, May 2014. https://www.armscontrol.org/act/2014_05/Future-of-3-2-Warhead-Plan-in-Doubt.
236. *Ibid.*
237. One option for the first RRW design was apparently the W89: a warhead design that was explosively tested before being cancelled after the end of the Cold war and had been suggested as a possible replacement for the W88 (see: Ian Hoffman. 'Lab Officials Excited by New H-Bomb Project'. Alameda Times-Star, 6 February 2006. http://web.archive.org/web/20060209021533/http://www.insidebayarea.com:80/oaklandtribune/localnews/ci_3480733), but the final design was said to have included the SKUA9, a primary only previously used to test various secondary designs (see David Biello. 'Special Report: New Nukes Are Good Nukes?' Scientific American. Accessed 2 November 2021. https://www.scientificamerican.com/article/new-nukes-are-good-nukes/.)
238. See the 'W93 and Mk7 Programmes' section on page 20.
239. Department of Energy. 'FY 2019 Congressional Budget Request'. p163.
240. See the 'W93 and Mk7 Programmes' section on page 21.
241. See R.E. Kidder. 'Assessment of the Safety of US Nuclear Weapons and Related Nuclear Test Requirements: A Post-Bush Initiative Update', 10 December 1991. https://doi.org/10.2172/10130593.
242. 'W78 Replacement Program (W87-1): Cost Estimates and Use of Insensitive High Explosives'. National Nuclear Security Administration, December 2018. https://nukewatch.org/newsite/wp-content/uploads/2019/02/W78-Replacement-Program-Cost-Estimates-IHE.pdf. p9.
243. Department of Energy. 'FY 2020 Congressional Budget Request'. p231,235. Additive manufacturing is the term used for a more advanced and larger-scale process of 3D printing.
244. See Charles Richard. 'Statement, March 2022'. p22.
245. See the 'Rationale' section on page 39.
246. Aaron Mehta. 'Inside America's Newly Revealed Nuclear Ballistic Missile Warhead of the Future'. Defense News, 24 February 2020. https://www.defensenews.com/smr/nuclear-arsenal/2020/02/24/inside-americas-newly-revealed-nuclear-ballistic-missile-warhead-of-the-future/.
247. Department of Defense 'FY 2021 Budget Estimates'. p174.
248. Aaron Mehta. 'Inside America's Newly Revealed Warhead'.
249. A typical process of nuclear targeting will look to provide a high certainty of inflicting enough blast damage to destroy a desired list of targets. Greater accuracy allows for warheads with a lower yield to be employed, while retaining the same level of certainty. The accuracy of the Trident system has increased as part of the D5LE life extension programme and there are projects underway to further increase its accuracy using multiple stars for error correction during flight and submarine navigational data prior to launch. The Mk 4A arming, fusing and firing system also includes an air-burst fuse that increases accuracy. The accuracy of the trident system as a whole has therefore increased since the current warheads were originally produced.
250. Author's interview with Brian Burnell, July 2021. See also Whitehouse and Hare. 'Minutes of Evidence'. Q152, where design case substantiation is mentioned as one of three key areas where the UK is reliant on the US.
251. See the 'W93 design and characteristics' section on page 43.
252. Brian Burnell. Interview with the author, July 2021.
253. *Ibid.*
254. The Summit and Sierra computers, housed at the Oak Ridge National Laboratory and the Lawrence Livermore National Laboratory respectively, are the second and third most powerful computers in the world. They are around 20 and 12 times more powerful than Vulcan. See https://www.top500.org/lists/top500/2021/11/

255. See Annexe D. This experience will have doubtless contributed to the government's alarm when they learned, after negotiating the purchase of the C4 Trident missile, that they still faced the prospect of compatibility divergence as the US was planning to upgrade Trident from the C4 to the current D5 model. See Suzanne Doyle 'The United States Sale of Trident to Britain, 1977–1982: Deal Making in the Anglo-American Nuclear Relationship'. Diplomacy & Statecraft 28, no. 3 (3 July 2017): 477–93. https://doi.org/10.1080/09592296.2017.1347447.
256. See note 249.
257. See, for example, the assurance in the UK's report to the 2019 NPT Preparatory Committee that the Dreadnought submarine programme was not an upgrade to the UK's capabilities: United Kingdom of Great Britain and Northern Ireland. 'National Report'. p3.
258. Department of Defense. 'FY 2022 Budget Estimates' p261.
259. See Annexe B.
260. A new plutonium facility to replace the existing A90 complex was originally part of the NWCSP, and was scheduled for construction in the late 2020s. If there is a requirement to manufacture new pits for the replacement warhead, the project to construct building is likely included as part of the larger warhead programme.
261. See, for example, 'A Progressive Approach to a World Free of Nuclear Weapons: Revisiting the Building Blocks Paradigm'. United Nations, 30 March 2016. undocs.org/A/CN.10/2016/WG.I/WP.3.
262. P5. 'Joint Communiqué – P5 Conference, Paris', 3 December 2021. https://www.diplomatie.gouv.fr/IMG/pdf/p5_statement_2_3-12-21_cle04ad34.pdf.; P5. 'Joint Statement of the Leaders of the Five Nuclear-Weapon States on Preventing Nuclear War and Avoiding Arms Races', 3 January 2022. https://www.whitehouse.gov/briefing-room/statements-releases/2022/01/03/p5-statement-on-preventing-nuclear-war-and-avoiding-arms-races/.
263. BBC News. 'Fears over "Replace Trident Plan"', 3 May 2005. http://news.bbc.co.uk/1/hi/uk_politics/vote_2005/frontpage/4508151.stm.
264. Trident'. Hansard 14 Mar 2007: Column 299. https://publications.parliament.uk/pa/cm200607/cmhansrd/cm070314/debtext/70314-0005.htm.
265. For an overview of this work see: Henrietta Wilson. 'Disarmament Verification Research at AWE: What It Is, Why It's There, and What Next'. Nuclear Information Service. Accessed 4 December 2020. http://nis.netuxosandbox.co.uk/blog/henrietta-wilson/2020/07/disarmament-verification-research-awe-what-it-why-it's-there-and-what/.
266. Department of Energy. 'FY 2022 Congressional Budget Request'. p89.
267. Department of Energy. 'FY 2022 Congressional Budget Request'. p84–85.
268. Department of Energy. 'FY 2021 Congressional Budget Request'. p122.
269. Department of Defense. 'FY 2021 Budget Estimates'. p114.
270. Department of Defense. 'FY 2022 Budget Estimates'. p290.
271. *Ibid*
272. *Ibid*. p291.
273. NNSA. 'Fiscal Year 2018 Stockpile Stewardship and Management Plan'. ch2 p17.
274. Ministry of Defence. 'The 2016 Update to Parliament'.
275. 'FY 2018 Congressional Budget Request – National Nuclear Security Administration – Federal Salaries and Expenses, Weapons Activities, Defense Nuclear Nonproliferation, Naval Reactors. Volume 1'. Department of Energy, May 2017. https://www.energy.gov/sites/default/files/2017/05/f34/FY2018BudgetVolume1_1.pdf. p98.
276. NNSA. 'Fiscal Year 2018 Stockpile Stewardship and Management Plan'. ch2 p17–18.
277. Department of Energy. 'FY 2018 Congressional Budget Request'. p98.
278. Ministry of Defence. 'The 2016 Update to Parliament'.
279. NNSA. 'Fiscal Year 2018 Stockpile Stewardship and Management Plan'. ch2 p18.
280. Department of Energy. 'FY 2019 Congressional Budget Request'. p107.
281. Department of Energy. 'FY 2021 Congressional Budget Request'. p264.
282. Department of Energy. 'FY 2020 Congressional Budget Request'. p110; Department of Energy. 'FY 2022 Congressional Budget Request'. p215; Department of Energy. 'FY 2023 Congressional Budget Request'. p442.
283. Department of Energy. 'FY 2019 Congressional Budget Request'. p134.
284. Department of Energy. 'FY 2021 Congressional Budget Request'. p299.
285. King, D.B., R.M. Fleming, E.S. Bielejec, J.K. McDonald, and G. Vizkelethy. 'Test Simulation of Neutron Damage to Electronic Components Using Accelerator Facilities'. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 365 (December 2015): 294–99. https://doi.org/10.1016/j.nimb.2015.08.026; 'Boeing: Every Minute Counts'. Accessed 14 October 2021. https://www.boeing.com/features/2017/03/minuteman-03-17.page.
286. Department of Energy. 'FY 2020 Congressional Budget Request'. p167.

287. Department of Energy. 'FY 2021 Congressional Budget Request'. p299.
288. Department of Energy. 'FY 2019 Congressional Budget Request'. p81.
289. *Ibid*. p158.
290. Department of Energy. 'FY 2022 Congressional Budget Request'. p245.; Sandia National Laboratories. 'Centrifuge/Superfuge – Validation and Qualification Sciences Experimental Complex'. Accessed 22 October 2021. https://www.sandia.gov/vqsec/facilities/centrifuge/.
291. Department of Energy. 'FY 2022 Congressional Budget Request'. p245.
292. Department of Energy. 'FY 2020 Congressional Budget Request'. p115.
293. Department of Energy. 'FY 2021 Congressional Budget Request'. p556; 'Fiscal Year 2020 Stockpile Stewardship and Management Plan'. National Nuclear Security Administration (NNSA), July 2019. https://www.energy.gov/sites/default/files/2019/08/f65/FY2020__SSMP.pdf. ch4 p29.
294. Mark Rockwell. 'Nuclear Weapons Security Agency Moving Apps to Cloud'. FCW, 1 August 2019. https://fcw.com/articles/2019/08/01/nnsa-cloud-rockwell.aspx.
295. Department of Energy. 'FY 2021 Congressional Budget Request'. p549.
296. Department of Energy. 'FY 2020 Congressional Budget Request'. p110.
297. Department of Energy. 'FY 2019 Congressional Budget Request'. p158.
298. *Ibid*. p86. See also Philpott, W.J., and R. Jones. 'AWG-711, a Type C Transport Package'. France, 2019; and Douglas James Ammerman, David C. Harding, and Daniel Villa. 'AWG 711 Package Development Program at Sandia.' Sandia National Lab. (SNL-NM), Albuquerque, NM (United States); Sandia National Laboratories., 1 June 2009. https://www.osti.gov/biblio/1141566.
299. Department of Energy. 'FY 2022 Congressional Budget Request'. p225; Department of Energy. 'FY 2023 Congressional Budget Request'. p454.
300. Department of Energy. 'FY 2023 Congressional Budget Request'. p138.
301. Department of Defense. 'FY 2022 Budget Estimates'. p262.
302. *Ibid*. p262, 275.
303. See Charles Richard. 'Statement, February 2020'. p11.
304. Department of Defense. 'FY 2022 Budget Estimates'. p275.
305. Department of Defense. 'FY 2021 Budget Estimates' p101.
306. Department of Defense. 'FY 2022 Budget Estimates'. p276.
307. *Ibid*. p275.
308. *Ibid*. p277.
309. Jeffrey Lewis. 'FOGBANK'. Arms Control Wonk, 7 March 2008. http://www.armscontrolwonk.com/archive/201814/fogbank/.
310. 'Nuclear Triad: DOD and DOE Face Challenges Mitigating Risks to U.S. Deterrence Efforts'. Government Accountability Office, May 2021. https://www.gao.gov/assets/gao-21-210.pdf. p34–35.
311. Jonathan V. Last. 'The Fog of War'. Washington Examiner, 18 May 2009. https://www.washingtonexaminer.com/weekly-standard/the-fog-of-war.
312. Ralph Vartabedian. 'Nuclear Weapon Retrofit Falters'. Los Angeles Times, 29 May 2009. https://www.latimes.com/archives/la-xpm-2009-may-29-na-broken-warheads29-story.html.
313. Government Accountability Office. 'Nuclear Triad: DOD and DOE Face Challenges'. p43.
314. *Ibid*. p35.
315. See Annexe C.
316. Brian Burnell. Interview with the author.
317. 'Fiscal Year 2018 Stockpile Stewardship and Management Plan'. US Department of Energy, November 2017. https://www.energy.gov/sites/default/files/2017/11/f46/fy18ssmp_final_november_2017%5B1%5D_0.pdf. p2–10,2–13.
318. *Ibid*. p59;'Department of Energy FY 2019 Congressional Budget Request'. p74.
319. 'Department of Defense Fiscal Year (FY) 2020 Budget Estimates – Research, Development, Test & Evaluation, Navy – Justification Book Volume 5 of 5', March 2019. https://www.secnav.navy.mil/fmc/fmb/Documents/22pres/RDTEN_BA7_Book.pdf. p118.
320. See NNSA.'Fiscal Year 2015 Stockpile Stewardship and Management Plan'. ch1 p4, where it is also known as the 'W78/88-1 warhead'. The W88 was already planned to undergo the Alt 370, so it may have been the intention that some or all of the W88 stockpile would remain in service alongside the IW1 until subsequent Interoperable Warheads were built.
321. 'Department of Energy FY 2019 Congressional Budget Request'. p93.
322. NNSA. 'Fiscal Year 2019 Stockpile Stewardship and Management Plan'. p44.
323. Department of Defense. 'FY 2022 Budget Estimates' lists the feasibility study as having run throughout the calendar year 2020, but this is almost certainly an error as it doesn't fit with other known dates. See note 226 and Department of Energy. 'FY 2021 Congressional Budget Request'. p123.

324. In November 2017 the IW1 was due to begin Studies and Engineering in FY 2020, with baseline costs being calculated in FY 2024 and warhead production running from FY 2030 to FY 2041 (see NNSA. 'Fiscal Year 2018 Stockpile Stewardship and Management Plan'). In July 2019, when the IW1 has become the W87-1, the IW2/BM-Y is known as the "Next Navy Warhead", but Studies and Engineering were not due to start until FY 2024. However, the production dates from that time of 2034 to 2041 (see NNSA. 'Fiscal Year 2020 Stockpile Stewardship and Management Plan') are similar to current plans for the W93, which anticipates production beginning between 2034 and 2036 (see NNSA. 'Fiscal Year 2022 Stockpile Stewardship and Management Plan'.).
325. Department of Energy. 'FY 2023 Congressional Budget Request'. p430; Department of Defense. 'FY 2023 Budget Estimates'. p286.
326. *Ibid*. p288; 317.

Glossary

3+2 Plan – Initiative under the Obama administration to consolidate the US nuclear weapon stockpile to five designs.
Aeroshell – Heat-proof shield that prevents damage during re-entry into earth's atmosphere. The term is also used to refer to an entire re-entry body or vehicle.
AWE – UK Atomic Weapons Establishment, where the UK's nuclear weapons are designed, built and serviced.
Chevaline – Historical UK-designed warhead, mounted on Polaris missiles.
D5LE2 – Planned second life-extension programme for the Trident D5 missile
DOD – US Department of Defence.
DOE – US Department of Energy
Holbrook – Name sometimes used for the original UK Trident warhead.
Hydrodynamics – The study of the behaviour of materials which display fluid properties. Used to refer to explosive experiments used in warhead design.
ICJ – International Court of Justice.
IR – The 2021 Integrated Review of Security, Defence, Development and Foreign Policy followed the previous SDR/SDSRs in updating the UK's nuclear posture.
IW1 – Interoperable Warhead 1. Putative US warhead, intended to be the first new warhead under the 3+2 plan.
JTD – Joint Technology Demonstrator, a US-UK warhead development project.
kt – kiloton. A unit of explosive power used to measure the yield of nuclear weapons. Equivalent to 1,000 tons of TNT.
LEP – Life Extension Programme.
MDA – 1958 Mutual Defence Agreement. US-UK treaty for the sharing of nuclear information and materials. Later supplemented by the 1963 Polaris Sales Agreement.
MIRV – Multiple Independent Re-entry Vehicle(s). System for mounting several warheads, which are assigned different targets, on a single missile.
Mk4A – Re-entry body fitted to the W76 as part of the W76-1 life-extension. Also used to refer to the UK version of this life extension programme and warhead variant.
MOD – UK Ministry of Defence.
NEP – Nuclear Explosives Package.
NNSA – Nuclear National Security Administration
NPR – US Nuclear Posture Review. A series of reviews setting US nuclear posture under different presidential administrations.
NPT – Treaty on the Non-Proliferation of Nuclear Weapons, commonly referred to as the Non-Proliferation Treaty.
NWCSP – Nuclear Warhead Capability Sustainment Programme.
Polaris – Historical US SLBM, also operated by the UK.
Primary – Part of a thermonuclear warhead that provides the initial explosive yield through a fission reaction.
Re-entry body/vehicle – Heat-shielded craft designed to carry a warhead during its re-entry and descent onto its target.
Replacement Warhead Programme – Programme to build a new UK nuclear warhead. While not officially confirmed, there are indications this is the programme name used within government.
RRW – Reliable Replacement Warheads. A putative series of new warheads planned under the George W. Bush administration.
Secondary – Part of a thermonuclear warhead providing an explosive yield through fusion, after the primary explosion. Generally responsible for the majority of the yield.
SDR – 1998 Strategic Review, set out the UK's nuclear posture under the Blair government.
SDSR – The 2010 Strategic Defence and Security Review and the 2015 joint SDSR and National Security Strategy updated the UK's nuclear posture.
SLBM – Submarine Launched Ballistic Missile.
SSBN – Ship Submersible Ballistic Nuclear. NATO designation for a nuclear-armed and nuclear-powered submarine.
Surety – Measures to prevent unauthorised detonation of a warhead and maximise the reliability of authorised use.
Trident D5 – US SLBM. Currently undergoing a life-extension programme, with the further D5LE2 planned.

For US warhead and aeroshell designations, please refer to Figure 3 on p19 and Figure 8 on p41.

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