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Setting the Deadline for Nuclear Weapon Destruction under the Treaty on the Prohibition of Nuclear Weapons

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ABSTRACT
The Treaty on the Prohibition of Nuclear Weapons requires nuclear-armed states that join the treaty while still possessing "nuclear weapons or other nuclear explosive devices" to "destroy them as soon as possible but not later than a deadline to be determined by the first meeting of States Parties." This article examines technical issues that can inform this deadline decision. It outlines the processes and issues involved in the dismantlement and destruction of a nuclear weapon relevant to the purposes of meeting this treaty obligation. It uses publicly available information on the size and evolution of nuclear weapon stockpiles and declared and estimated rates of warhead dismantlement to assess the time it may take to dismantle and destroy current weapon stockpiles, including weapons already scheduled for dismantlement. It focuses on the United States and Russia which possess the largest arsenals, but includes discussions of other weapon states as well. The findings suggest that a TPNW deadline of 10 years for nuclear weapon destruction, with a possible 10 year extension.

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Introduction

The Treaty on the Prohibition of Nuclear Weapons (TPNW) permits two paths for a nuclear-armed state to become a member. Such a state either can join the treaty after having eliminated its nuclear weapon programme and then verify that this elimination indeed has taken place (Article 4.1), or the state can join the treaty while still possessing its weapons and verifiably eliminate them in an agreed irreversible and time-bound process (Article 4.2 and 4.3). The latter option requires, under Article 4.2:

> […] each State Party that owns, possesses or controls nuclear weapons or other nuclear explosive devices shall immediately remove them from operational status, and destroy them as soon as possible but not later than a deadline to be determined by the first meeting of States Parties, in accordance with a legally binding, time-bound plan for the verified and irreversible elimination of that State Party's nuclear-weapon programme, including the elimination or irreversible conversion of all nuclear-weapons-related facilities. (United Nations 2017)

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In addition to the destruction of its weapons, the state also is required to eliminate its nuclear weapon programme in a verified manner according to a specific plan negotiated between the joining state and a treaty-designated "competent international authority." While this plan will be specific for each nuclear-armed state, a common deadline for the destruction of nuclear weapons will apply to all such states which join the treaty while still possessing their weapons.

According to the TPNW, the decision on the deadline for nuclear weapon destruction will be taken during the first meeting of States Parties (MSP), which is supposed to take place no later than 1 year after the treaty enters into force. The decision will be made by all members of the treaty at the time of the MSP. By the time of this first meeting, it is possible none of the current nine nuclear-armed states will have joined the treaty. It will be left to non-weapon states to set the required deadline for the destruction of nuclear weapons by any nuclear-armed state that in the future may join the treaty without having already eliminated its weapons.

The TPNW, like the nuclear Non-Proliferation Treaty (NPT), does not define what is a nuclear weapon. Sections 2 and 3 below offer a brief discussion of nuclear weapons and some existing definitions in other treaties. The article adopts the view that TPNW members states will have to define the "destruction" of a nuclear weapon so as to make clear what actions are required by a nuclear-armed state to meet this treaty obligation. One simple and robust definition was offered by former United States nuclear weapon designer and arms control expert Theodore B. Taylor in an early study of the verified elimination nuclear weapons: "All major components of the warheads or other payload items are destroyed, in the sense that they would require refabrication to be used in other warheads" (Taylor 1989). This definition recognizes the importance of preventing reconstitution of nuclear weapons from components of previously dismantled weapons. This article builds on his definition and a more extended discussion is presented in Section 3.

A simple first-order estimate for the average time which may be required by a nuclear-armed state to eliminate all its nuclear weapons can be determined by looking at the size of the global nuclear stockpile and how this has changed. As of May 2019, there are an estimated 13,890 nuclear weapons worldwide, including warheads already pending dismantlement (Kristensen and Korda 2019a). This global stockpile is a fraction of its peak size, which is estimated to have been in excess of 65,000 weapons (reached in 1986); a total of over 125,000 warheads are estimated to have been built between 1945 and 2013, when the stockpile stood at 17,200 (Kristensen and Norris 2013). Some of the weapons that were built were destroyed in the more than 2,050 reported nuclear tests that have been carried out (Comprehensive Test Ban Treaty Organization n.d.). This suggests that roughly speaking over 100,000 weapons were dismantled in the 70-year period from the construction, test and use of the first nuclear weapons in 1945 up to 2013. Thus, to first order, the historically average global dismantlement rate has been over 1400 nuclear weapons a year. At this average historical dismantlement rate, the almost 14,000 nuclear weapons in the world as of 2019 could be dismantled in about a decade, i.e., by about 2030 if dismantlement were to start now.

This rough estimate of about 10 years as the time required to dismantle all current nuclear weapons is consistent with a 2008 assessment of prospects for "transparent and irreversible dismantlement of nuclear weapons," which assumed that there were "more than 25,000 assembled nuclear weapons in the world" concluded that "it appears that it would be technically possible to dismantle all the world's nuclear weapons over a period of 10–20 years" (Bunn 2008). A similar estimate was offered in 2017 in response to the draft text of what became the TPNW, and included the possibility of a treaty obligation to eliminate dedicated nuclear weapon delivery systems (Mian 2017). The 1996 Model Nuclear Weapons Convention set a deadline of 15 years after entry into force for nuclear-armed states to have destroyed all nuclear weapons (United Nations 1997a, 2008a).

A more detailed technical and country-specific set of estimates is offered in this article, including factors that may slow down the actual dismantlement rate below the global long-term historical 70-year average. Another issue that could possibly extend the deadline is that under the TPNW not only dismantlement, but nuclear weapon destruction is required as part of the broader verifiable and irreversible elimination of nuclear weapon programmes. This may not be as much of factor as it appear at first sight, however.

It is possible that a nuclear-armed state, despite good faith efforts to destroy its weapons "as soon as possible" may not be able to meet the deadline set at the first meeting of TPNW state parties. This would not be the first time that a state failed to meet a treaty deadline and such an exceptional circumstance should be anticipated as part of setting the TPNW deadline. The TPNW is not the first disarmament treaty to require the establishment of a deadline for the destruction of treaty-prohibited weapons and as such can draw on the experience of setting such deadlines and possible extensions in other relevant recent treaty processes.

The Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and on their Destruction (Chemical Weapons Convention) sets a deadline of 10 years in the treaty (Organization for the Prohibition of Chemical Weapons 1997). A state is permitted an extension to this deadline, if approved by the Executive Council of the Convention, but the extension is not allowed to go beyond 15 years after the entry into force of the Convention; i.e., the extension at most can be for up to 5 years. However, further exceptional measures were required when it became clear that the extended chemical weapon destruction deadline of April 2012 would not be met by some states (Organization for the Prohibition of Chemical Weapons 2011).

Under the 1997 Convention on the Prohibition of the Use, Stockpiling, Production and Transfer of Anti-Personnel Mines and on their Destruction a deadline of 4 years is set for destruction of stockpiled mines, and of 10 years for any mines in mined areas under a member state's jurisdiction (United Nations 1997b). Similarly, the 2008 Convention on Cluster Munitions includes a specific deadline for destruction of 8 years. The Convention on Cluster Munitions permits extensions to this deadline. If a State Party "believes that it will be unable to destroy or ensure the destruction of all cluster munitions" within this 8-year period, it may request two extensions of 4 years each (United Nations 2008b).

These examples suggest the TPNW parties may need to set a deadline for nuclear weapon destruction that allows for exceptional circumstances and require a possible extension of this deadline. This perspective recognizes that a planned time-bound nuclear weapon destruction process which is verifiable and irreversible may face challenges to stay on schedule, a common problem for nuclear weapon complexes and other similar large complex socio-technical systems.

This article offers a general description of the nuclear weapon dismantlement process, detailing key steps and listing the key components that are separated during dismantlement process and would need to be disposed of as part of the destruction process, noting some of the risk factors. It assesses possible criteria for determining when a nuclear weapon has been destroyed for the purposes of meeting the TPNW obligation. Finally, it analyses some historical nuclear weapon dismantlement experiences of the United States, Russia, Britain, France and China to suggest a possible TPNW deadline of 10 years for nuclear warhead destruction, with a possible extension of an additional 10 years if there are exceptional circumstances that prevent a state from meeting this deadline.

Dismantling Nuclear Weapons

Most modern nuclear weapons have two stages with some components that undergo nuclear fission and others that undergo nuclear fusion. Figure 1 shows a schematic of a modern two-stage warhead, where a primary fission explosion is used to trigger a secondary thermonuclear explosion (Feiveson et al. 2014). The fission primary consists of a fissile material core or pit (typically plutonium), a neutron-reflecting tamper, conventional explosives to compress the pit, a neutron generator to provide an intense burst of neutrons to start the fission chain reaction and commonly a deuterium-tritium gas to boost the fission explosion. The thermonuclear secondary consists of lithium-deuteride as fusion fuel, and additional plutonium or uranium both as a tamper and a so-called "spark-plug" to start the fusion reaction that is driven by energy release from the fission primary. Both primary and secondary are enclosed in a casing, often made out of uranium, that also undergoes fission and can add significantly to the overall weapon yield at the final stage of the explosion (Feiveson et al. 2014). The fission and fusion components together make up what is often termed the physics package.

Besides the physics package, nuclear weapons include various other key components. The tritium used to boost the initial primary fission explosion is stored in a separate reservoir because it needs to be replaced regularly while the warhead is in service due to

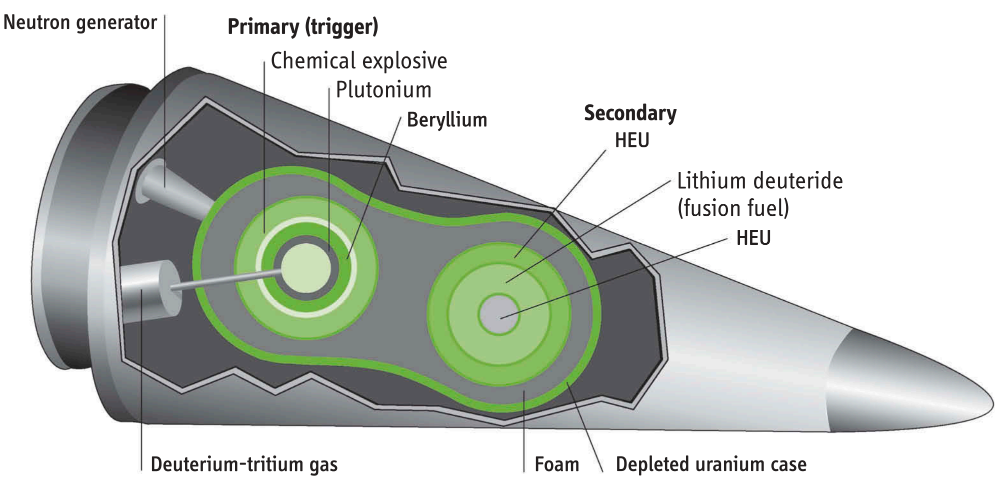

Figure 1. Schematic of a modern thermonuclear warhead. (Source: International Panel on Fissile Materials).

the 12.3-year half-life radioactive decay of tritium. Weapons have arming, fusing and firing mechanisms to ensure the weapon explodes as intended. They include a detonation system for the chemical explosive that compresses the fissile material pit into a super-critical mass able to sustain a nuclear fission chain reaction. Weapons also typically include safety mechanisms that prevent inadvertent weapon explosions due to accidents as well as due to intentional, but unauthorized weapon access. Other components relate to the delivery of the weapon: A re-entry vehicle shields the warhead assembly from the heat produced by the high-speed flight through the atmosphere towards the target in the final phase of the flight of a warhead launched on an intercontinental ballistic missile. For some nuclear bombs dropped from aircraft, parachute assemblies are used to slow-down the final stage of descent. Nuclear bombs can use guidance systems and adjustable fins as well as small rockets to spin the bomb body to improve accuracy during their fall.

A 1993 report *Dismantling the Bomb and Managing the Nuclear Materials* by the United States Congress Office of Technology Assessment provides a simple summary of what might be a fairly typical warhead dismantlement process and some key issues (Office of Technology Assessment 1993). A first step of the dismantlement process is an inspection of the weapon itself. Gamma spectrometry and neutron detection can be used to identify and confirm the specific weapon type. Since weapon components can degrade during the time of deployment, some checks also serve as part of safety assessments to determine if the weapon is in the expected physical state and is safe to dismantle. These checks can use x-ray or neutron radiography to generate images of the weapon interior. The results of such authentication and safety checks could also be used by inspectors as part of the treaty verification process. This may be needed since an exercise focused on verified warhead destruction conducted by the United States in the 1960s (Field Test 34) demonstrated that inspectors had an increased likelihood to confirm the authenticity of weapons when using methods beyond simple visual inspections (United States Arms Control and Disarmament Agency 1969).

Early in the process of dismantlement, the firing mechanism of a nuclear weapon has to be disabled. In some weapons, special disabling systems exist that serve as safety features during weapon transport. For example, some weapons owned by the United States can be disabled using the “Command Disable Systems” which “destroys a weapon’s ability to achieve a significant nuclear yield” (United States Department of Defense 1998). In addition, some, perhaps all, nuclear-armed states use permissive action links (PALs) as command and control assurance features in their nuclear weapons, and at least in the case of the United States, such PALs also include the capability to disable the warhead. Such warhead control systems include options of “disablement of critical warhead components or other violent or nonviolent methods for destroying the warhead and making it irreparably non-functional” (Cotter 1987, 50). Activating such systems where available could be the first step in rendering a nuclear weapon safe and non-functional before it leaves its deployment or storage site for dismantlement and destruction, and should be done if the systems would not increase the hazards involved in or the time required for weapon destruction.

Table 1 shows a summary of the components of a warhead that will be separated during the dismantlement process. The order of steps can vary depending on weapon type and design, but includes the removal of the non-nuclear components, the arming, fusing and firing components and the tritium containers.

Table 1. Materials generated from dismantling a typical nuclear warhead (Office of Technology Assessment 1993, 37).

Physics Package	Electronic Packages	Other Components
Detonators	Lead solder and other metals	Electromechanical devices
High explosives	Thermal batteries	Functional mechanical devices
Beryllium	Encapsulating material	Electronic components
Depleted uranium	Electrical components (PCBs)	Electric cables
Highly enriched uranium	Asbestos	Parachutes and explosives
Plutonium	Cables	Nonfunctional mechanical parts
Lithium deuteride		Residuals: O-rings, seals, fasteners
Plastic foam		
Neutron generators		
Tritium/deuterium gas canisters		

Commonly, components resulting from the dismantlement process, especially the fissile material components in the primary and secondary, are kept in storage pending reuse in other nuclear weapons or final disposal. Other components are disposed of after they have been demilitarized and sanitized. Demilitarized components have been rendered unusable for military use. Sanitized components are stripped of any properties that could reveal classified or sensitive data. Afterwards, components can be disposed (or recycled) in civilian facilities.

Nuclear-armed states typically carry out warhead dismantlement at a dedicated facility, which in most cases is also used for weapon assembly, warhead maintenance and modernization. The reliance on a small number of these facilities, often a single one, combined with the limited availability of special safe bays and cells for the various stages of weapon dismantlement may be a technical bottleneck for a speedy dismantling and destruction of all nuclear weapons. Since joining the TPNW would require an end to all warhead assembly and modernization activities, however, the facilities currently used for these programs could be used for weapon disassembly allowing for an increased capacity and faster rate of dismantlement and destruction than might be expected by simply extrapolating from current warhead dismantlement capacity and rates. Further, since the TPNW requires warheads be irreversibly dismantled and destroyed, it is possible that some current dismantlement and destruction processes could be redesigned so as to safely speed up these processes.

Special health and safety precautions have to be taken during warhead transportation between dismantlement steps, and during the dismantlement itself to prevent inadvertent explosions and to prevent exposure of workers to radioactive and toxic materials such as the fissile materials and beryllium and organic materials. Accidents and worker exposure during dismantlement are known to have occurred (Office of Technology Assessment 1993, 47). Some nuclear-armed states have shared their experiences regarding the challenges of warhead dismantlement – for instance, Russia and the United States in 2000 held a joint workshop on the safety of nuclear weapons dismantlement (Ruminer 2016).

Russia, the United States and the other weapon states could be much more transparent about their warhead dismantlement histories and problems that they have encountered so as to inform the global dialogue on advancing nuclear disarmament. This information also could help in setting the TPNW deadline for weapon destruction and clarify possible circumstances where a possible extension to such a deadline might be warranted.

When Has a Nuclear Weapon Been Destroyed?

Nuclear Weapon Definitions

The TPNW, like the Nuclear Non-Proliferation Treaty, does not contain a definition of a nuclear weapon. The TPNW also does not specify what it means to destroy a nuclear weapon. TPNW member states will need to decide together with the treaty-designated "competent international authority" what to use as a working definition for a nuclear weapon and for nuclear weapon destruction for assessing plans, practices and outcomes aiming at achieving the verified elimination of weapons the treaty seeks to bring about.

Although it seems straightforward to describe a nuclear weapon, experts and diplomats have struggled to come up with a universally shared legal definition of nuclear weapons (Glaser 2017). One of the first attempts to define nuclear weapons, in the Brussels Treaty from 1954, which prohibited West Germany from manufacturing atomic weapons, takes a very broad view, declaring in Article 1 of Annex II of Protocol III that:

> [a] An atomic weapon is defined as any weapon which contains, or is designed to contain or utilise, nuclear fuel or radioactive isotopes and which, by explosion or other uncontrolled nuclear transformation of the nuclear fuel, or by radioactivity of the nuclear fuel or radioactive isotopes, is capable of mass destruction, mass injury or mass poisoning … [b] Furthermore, any part, device, assembly or material especially designed for, or primarily useful in, any weapon as set forth paragraph (a), shall be deemed to be an atomic weapon. (Brussels Treaty 1954)

The treaties establishing Nuclear-Weapon-Free Zones include definitions of nuclear weapons that vary with regard to the salient characteristics of such weapons, the role of purpose, and of the level of assembly or disassembly. The 1977 Treaty of Tlatelolco, which created the first such zone, states (Article 5) that

> a nuclear weapon is any device which is capable of releasing nuclear energy in an uncontrolled manner and which has a group of characteristics that are appropriate for use for warlike purposes. An instrument that may be used for the transport or propulsion of the device is not included in this definition if it is separable from the device and not an indivisible part thereof. (United Nations 1967)

The most recent zone was created under the Central Asia Nuclear-Weapon-Free-Zone treaty, which entered into force in 2009 and defines a nuclear weapon or other nuclear explosive device as

> any weapon or other explosive device capable of releasing nuclear energy, irrespective of the military or civilian purpose for which the weapon or device could be used. The term includes such a weapon or device in unassembled or partly assembled forms, but does not include the means of transport or delivery of such a weapon or device if separable from and not an indivisible part of it. (United Nations 2006)

Some nuclear-armed states also have sought to find a common definition of a nuclear weapon. The five permanent members of the UN Security Council (the P5: the United States, Russia, Britain, France and China) who are also the only five states meeting the criteria designating a nuclear-weapon state under the NPT, in a 2015 common glossary agreed on a definition of a nuclear weapon as a "weapon assembly that is capable of producing an explosion and massive damage and destruction by the sudden release of energy instantaneously released from self-sustaining nuclear fission and/or fusion" (P5

2015). The focus in this definition on the fact and consequences of a nuclear explosion is particularly noteworthy.

All these definitions have one problem in common: nuclear weapons are defined by their functionality – how they explode and what they do when they explode – which cannot be reliably confirmed without carrying out a nuclear weapon test. Much of the information on nuclear weapon design, composition and characteristics that would be required to independently verify that any given object is in fact such a weapon is currently considered classified by these states. As a result, even the definition provided by the P5 is inadequate for the purposes of a verified process of nuclear disarmament.

For the TPNW, the nuclear-armed states could be required to carry the burden of proof on what is a nuclear weapon. To enable swift and quick destruction of nuclear weapons according to Article 4.2, it might be sufficient to solely rely on nuclear-armed states declarations of what they treat as a nuclear weapon. In its simplest form, whatever is declared as a nuclear weapon by a weapon state could be considered a weapon for the purpose of the article, since eventually the entire weapon programme must be verifiably eliminated. Declarations could additionally include historical records, legal documents or military planning. An early example of such a comprehensive declaration aimed at laying the basis for verified disarmament was proposed by the U.S. National Academy of Sciences Committee on International Security and Arms Control in 1997, which included declaring:

> the current location, type, and status of all nuclear explosive devices and the history of every nuclear explosive device manufactured, including the dates of assembly and dismantling or destruction in explosive tests;
>
> a description of facilities at which nuclear explosives have been designed, assembled, tested, stored, deployed, maintained, and dismantled, and which produced or fabricated key weapon components and nuclear materials; and
>
> the relevant operating records of these facilities (Committee on International Security and Arms Control 1997, 61)

Having provided such records, a state would then need to be verify that all previous and current nuclear weapons were accounted for and had either already been eliminated or would be subject to verifiable elimination. Any warhead or nuclear explosive device later discovered as unaccounted for would constitute a treaty violation. This approach would not necessarily be consistent across nuclear-armed states who might join the TPNW and as such could in principle cause problems over states having different standards about what was or was not a nuclear weapon, with implications for the possible respective speeds of reconstitution of weapons. Some of these potential problems would be mitigated by the TPNW obligation to not just destroy nuclear weapons but also to irreversibly eliminate nuclear weapon programmes or convert them to peaceful purposes.

There are criteria beyond inherent warhead properties which could be taken into account for the purpose of a definition to be used for a weapon's destruction. A simple criteria could for example specify that every warhead in a storage site with radiological safety measures, or assigned to or installed on a delivery system certified by a state as nuclear-capable would have to be destroyed. While it is possible that such a definition could include non-nuclear weapons, it would be up to the state concerned to prove weapons claimed as conventional were not in fact nuclear weapons.

Destruction of Weapon Components

After weapons have been identified and authenticated, it is important to determine when weapons are considered "destroyed" according to Article 4.2. For example, the United States considers that nuclear weapons "cease to exist" as soon as the fissile material pit is separated from the high explosive (United States Department of Energy 1997). As ceasing to exist is the common definition of destruction, that means a weapon would be considered destroyed at this stage. It can be argued that after a weapon's pit is separated from all other components, no single object exists anymore that would represent this particular nuclear weapon, and all components can be accounted for separately. As a result of a policy choice to not destroy warhead components, U.S. dismantlement efforts have lead to large stocks. As of 2012, the American Pantex plant reported producing about 50,000 components per year from its warhead dismantlement activities and having about 3.7 million weapon components in storage (United States Department of Energy 2013). In 2014, the U.S. had more than 14,000 pits in storage and the number has grown since (Alvarez 2014).

The U.S. definition of weapon destruction does not meet any meaningful requirement of being irreversible and as such is not appropriate as the definition of destruction to be adopted for the TPNW. Additional steps will be needed after the separation of the pit from the explosives to assure the destruction is irreversible and that pits and non-nuclear components that have been separated and put in storage are not used to quickly rebuild nuclear weapons.

To address the problem of stored weapon components, and recognizing that nuclear-armed states already have criteria and practices for demilitarization and sanitization of weapon components and materials, a nuclear weapon could be considered destroyed according to the following definition:

> A nuclear weapon is destroyed when all of the following steps have been carried out: Non-nuclear components are separated from the physics package, conventional explosives are separated from the fissile material, and all components of the physics package as well as electronics have been irreversibly mechanically or chemically altered such that they cannot be used in a weapons assembly without substantive additional processing steps.

The steps of mechanical or chemical alteration of components following weapon dismantlement are meant to prevent easy weapon reassembly. To comply with the TPNW's obligation to destroy weapons as soon as possible, processes should be selected that could be carried out without adding significant time to the dismantlement process, and preferably without the need to construct additional facilities.

Pits, which typically are hollow shells of fissile material, could be quickly deformed or otherwise altered mechanically. Changing the mechanical form extends the time to reverse the dismantlement process, as the material has to be recast into weapon form. It has been suggested that pits could for instance be flattened after enclosing them in a protective envelope at the dismantlement site – a 1994 study by the United States National Academy of Sciences claimed that "[C]onceptually, deformation operations using such envelopes appear relatively simple, and it would seem possible to carry them out even at locations such as Pantex that lack a genuine plutonium handling capability" (Committee on International Security and Arms Control 1994, 119). Richard Garwin in 2002 proposed that the "pit might be enclosed in a ductile aluminum or copper bag, which could be crimped and sealed airtight and enclosed for added assurance in another ductile metal bag; the packaged pit could then be squashed in a press so that it would need to be remelted and refabricated for use in a weapon" (Garwin 2002). The protective envelope is necessary to prevent facility and environmental contamination from the fissile material.

An alternative to changing the shape of the pit to render it unusable without remanufacture is to fill it with some other material – for example by inserting wire into the pit to prevent the pit from being compressed in a way that will lead to a nuclear explosion ("pit stuffing") (Bunn 1998). Modern pits commonly have a tube which is used to transfer the tritium gas into the pit cavity just prior to the explosion. If measures are taken to make it impossible to remove the wire without destroying the pit, such a pit would be effectively unusable without remanufacture. Pit stuffing reduces the risk of heavy metal contamination but cannot be carried out for weapons without boosting, which would not have the necessary tube to the inside.

The uranium components, which could include a highly enriched uranium pit, the highly enriched uranium components in the thermonuclear secondary and the uranium casing, can be shredded. As part of the 1993 agreement to sell 500 tons of highly enriched uranium recovered from nuclear warheads to the United States, Russian highly enriched uranium warhead components were "shredded into chips and shavings," the material "sampled and analysed" to confirm it was weapon-material and the shavings were then "oxidized in special furnaces, and the oxide … milled and sieved to produce a uniform powder" (Bukharin 1998). This uranium oxide was then sent for fluorination to make uranium hexafluoride and down-blended into low-enriched uranium to be shipped to the United States for use as power reactor fuel.

Disposition options for plutonium exist, too, but have so far not been put into place on a large scale. Separated plutonium could be used to make mixed uranium-plutonium oxide fuel for nuclear power reactors. There are, however, technical and economical disadvantages to such use (von Hippel and MacKerron 2013). In 2019, the United States abandoned its more than 10-year long effort to build a MOX Fuel Fabrication Facility to process 34 tons of weapon-grade plutonium declared excess and is now pursuing a dilute and dispose process involving blending this plutonium with an inert material for disposal as waste in an underground repository (IPFM Blog 2019). Other options include mixing the plutonium into a glass or ceramic, or adding radioactive waste to create a radiation barrier to impede proliferation and bury the mixture afterwards in a repository (von Hippel and MacKerron 2013). So far, no country has disposed of significant amounts of plutonium recovered from weapons dismantlement.[1] (IPFM Blog 2016; Podvig and Snyder 2019, 42). While final disposal of weapon-origin and weapon-grade fissile materials is advisable as part of meeting the TPNW requirement for the elimination of a

[1]The United States has disposed of 5.7 tons of plutonium in various forms of scrap between 1999 and 2014 in the Waste Isolation Pilot Plant (WIPP), after which it was closed until 2017 because of an accident (IPFM IPFM Blog 2016). This is part of a planned 6 tons of non-pit plutonium to be disposed there (Clements 2016). Russia planned to dispose weapon-origin plutonium using power reactors, but did not yet start producing fuel from military weapon-grade plutonium (Podvig and Snyder 2019, 42).

nuclear weapon programme, it may not be necessary as part of the specific obligation on the destruction of nuclear weapons.

Tritium gas bottles or reservoirs from nuclear weapons also need to be disposed of with care. Tritium is a form of hydrogen and can form water through oxidation, but is radioactive and as such cannot be released into the environment in large quantities. These reservoirs, typically made of stainless steel, could be emptied of tritium as is done during standard warhead tritium recycling operations and then shredded or burst by over-pressurization with water as happens for instance during regular burst-testing of tritium reservoirs at the U.S. Savannah River Site where warhead tritium operations are carried out (Savannah River Site 2013). The recovered tritium could be used for peaceful purposes, diluted and disposed of, or left to decay naturally through its 12.3-year half-life.

Lithium deuteride components from the secondary could be separated and lithium and deuterium could be used in various civilian industrial applications or treated as waste for disposal. Current U.S. recycling of lithium deuterium components from disassembled warheads at the Y-12 site in Tennessee includes them being "broken, crushed, and ground to produce powder" and then recast and fabricated into new warhead components – all these operations are carried out inside inert-atmosphere gloveboxes to prevent exposure to moisture (United States Department of Energy 2011, A4-A5). Instead of recasting, the powder could be dissolved in a solvent and treated as waste. Alternatively, recovered lithium can be used for modern batteries in which it is key element.

Tritium is also used in the neutron generators, the limited lifetime devices used to initiate the chain reaction in the fissile material pit of the primary as it is being compressed. In the United States, used neutron generators and their components are packaged and sent for disposal as low-level radioactive waste (United States Department of Energy 1996a, 2-1 – 3-1).

Eliminating the conventional high explosive used to compress the fissile material pit can be as straightforward as burning it (United States Department of Energy 1997). The U.S. Pantex warhead assembly/disassembly plant has a 23.5-ha (58 acre) area, "the Burning Ground," for incinerating high explosive recovered from nuclear weapons as part of the sanitization of former weapon components (United States Department of Energy 1996b, B-5). As part of this process (sometimes described as thermal treatment of explosives) "the hemisphere [of high explosive] was placed on a tray in an enclosed wire cage located in an open field. Diesel fuel was electrically ignited from a bunker ~100 ft [30.5 m] away from the pad. [...] Upon ignition, the material melted and became a component of the sand" (Robertson-DeMers 2011). The ash was put into a disposal trench at the site. Such activities released toxic chemicals into the environment, as is evident from the high explosive and degradation products found in the Burning Ground and within and around the larger Pantex site. The practice was halted in the early 1990s, and the area is now undergoing remediation (United States Department of Energy 2018a). The open-air burn cages were replaced by covered burn trays and incineration continues to be the preferred process at Pantex for sanitization and destruction of high explosives from dismantled weapons.

All other electronics and mechanical components recovered from warhead dismantlement activities could be modified as part of disposal. The quickest way would be to shred or crush these components. It is known that weapon states already apply shredding as part of sanitization processes to remove sensitive information from parts that need to be disposed (United States Department of Energy 2019). Some components may contain material that could be recovered and recycled for peaceful purposes. For dismantlement and destruction processes under the TPNW, either sanitization or recycling would seem possible as long they do not create hurdles that slow down the dismantlement and destruction process.

Warhead Dismantlement Rates

Past warhead dismantlement rates can serve as a plausible proxy future for warhead destruction rates since many destruction processes can begin immediately after a warhead has been dismantled and do not require the same tools, workers or facilities. Detailed information on nuclear warhead dismantlement facilities, capacities and practices and on historical and current rates of nuclear warhead dismantlement is sparse for almost all the nine nuclear-armed states, however. The United States has been the most transparent in making available information about historical and planned warhead dismantlement and the specific rates at which different warheads have been and can be dismantled. This is reflected in the following discussion.

In the U.S., the Pantex plant is responsible for weapon dismantlement, assembly, maintenance and modernization and also hosts a large pit storage facility. The plant has 13 cells (gravel gerties) and 60 bays which can be used for warhead dismantlement steps (United States Department of Energy 1997, 33). Gravel gerties are specially build bunkers that provide measures to contain possible radioactive contamination from inadvertent detonations of the high explosive in a nuclear weapon. A second more modern facility that could potentially be used for weapon dismantlement is the Device Assembly Facility (DAF) in Nevada which is equipped with five gravel gertie cells and has additional bays for warhead work (United States Department of Energy 1997, 34–35). The facility was built to assemble weapons for testing at the Nevada Test site but was never used for this purpose (Bunn 2008). To accelerate weapon dismantlement above current rates, along with ending assembly and disassembly for warhead life extension and maintenance at Pantex, the United States could task DAF with dismantlement operations. Components recovered from dismantlement activities at DAF may have to be sent elsewhere for destruction, however, since DAF lacks many of the facilities found at Pantex.

The United States has declassified some past nuclear weapon dismantlement data (Figure 2). It is estimated that by 2004 the United States had dismantled about 60,000 warheads (Norris and Kristensen 2004). In the early 1990s, dismantlement rates of more than 1500 warheads per year were achieved. Between 1999 and 2017, dismantlement rates were reduced to on average almost 300 warheads dismantled per year. Including assembly and maintenance activities, average throughput in this period was nearly 750 warheads per year. The complete dismantlement within 10 years of the U.S. stockpile as of early 2019 – estimated as 6,185 warheads – requires an average dismantlement rate of 620 warheads per year. Given the historical evidence, it seems reasonable to assume that such rates could be sustained for the decade that would be required. The actual time to dismantle all the warheads could be significantly less since facilities and labour currently used for warhead modernization, maintenance and reliability testing would be freed for dismantlement work as part of joining the TPNW.

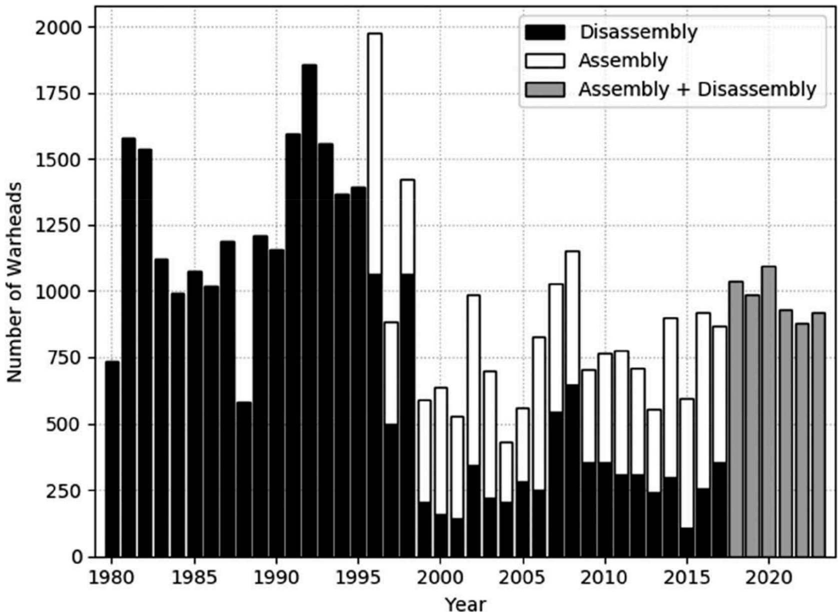

Figure 2. Warhead dismantlement rates in the United States since 1980. Black bars are explicit disassembly figures. For 1996 to 2017, the numbers depicted in white were calculated by subtracting the respective disassembly numbers from figures that include the total number of assemblies and disassemblies. Gray bars are those combined figures (no separate information on disassembly available). The data from 1980 to 1994 are from United States Department of Energy (2002); 1995 to 2017 from United States Department of Defense (2017); 1996–2023 from United States Department of Energy (2018b, 21). This includes projections as of 2016 until 2023 for numbers of warheads to undergo dismantlement, evaluation, maintenance, rebuild, limited life components or repair work.

A different approach to estimate the time needed to dismantle the U.S. nuclear arsenal is offered by data on the reported dismantlement time ("cycle times") for different weapon types as shown in Table 2 (United States Department of Energy 1997). The cycle time is the number of 8-hour work shifts needed to dismantle a single warhead and varies across warhead types. The monthly dismantlement rate is for one work-shift per 5-day work week and assumes dismantling of one weapon at a time. Table 2 also shows the number of warheads in the United States arsenal and the aggregate number of warheads (of different types) already in the dismantlement queue as of 2019.

Based on this information, two candidate United States nuclear weapon dismantlement cases are calculated to determine the time required to dismantle all existing United States nuclear weapons. It is assumed that the weapons already in the dismantlement queue will each on average require a cycle time of 3.5 shifts (i.e. neither the shortest nor the longest dismantlement time).

In a fast case, all weapons could be dismantled in a little under 9 years operating at one shift per day, 5 days a week, if there were nine parallel dismantlement operations, taking place in separate bays and cells. This case does not require using the full capacity at Pantex. In the slow case, where only four weapons are dismantled at a time in parallel, which might be possible to achieve at DAF alone, dismantlement of all the weapons would take 20 years. The rate could be much faster in both cases if multiple weapons were

Table 2. Estimated number and dismantlement times for current nuclear warheads in the United States.

Type of nuclear weapon	Number of nuclear weapons[a]	Cycle time (dismantlement work-days per weapon)[b]	Throughput (number of weapons dismantled per month)[b]
W78	600	3.5	6–7
W87	200	5	4–5
W76-0	46	3	7–8
W76-1	1490	3	7–8
W88	384	4.5	4–5
W80	528	3	7–8
B61-7/-11	322[c]	1.5	14–15
B83		5	4–5
B61-3/-4	230	1.5	14–15
Multiple types awaiting disassembly	2385		

Cycle time is the number of 8-hour work shifts required for dismantlement of a single weapon of a given type. Throughput is the estimated monthly disassembly number based on one 8-hour shift per day, and no parallel operation.

[a] (Kristensen and Korda 2019c).

[b] (United States Department of Energy 1997, 41).

[c] Only the total for both weapon types is given in (Kristensen and Korda 2019c). It is assumed here that the total number of 322 B61-7/-11 and B83 weapons is made up of 161 weapons of each type.

dismantled within a single bay or cell as happened in the 1990s, when, it is reported, "some weapon systems were dismantled three- or four-at-a-time within a bay or cell" (United States Government Accountability Office 2014). This raised safety concerns, however. Dismantlement also could be sped up significantly by moving from one 8-hour work-shift per day to multiple shifts a day. It is known that Pantex worked up to three shifts per day in the 1990s (Norris and Kristensen 2004). Increasing the number of shifts would need a larger workforce, but significantly reduce the time required for dismantlement and could be seen as a reasonable interpretation of the TPNW obligation to achieve warhead destruction "as soon as possible."

It appears that there is no technical reason why a nuclear weapon destruction deadline of 10 years could not be achieved by the United States, with a possibility for an extension of 10 years required by exceptional circumstances. There are possibilities for setbacks such as dismantlement accidents in which radioactive contaminations could make individual cells or even full dismantlement sites unusable for extended time periods – although no such accident has occurred to date, there have been reported near misses revealed in complaints by plant workers (Project on Government Oversight 2006; Pantex Employees for Safe & Sustainable Operations 2006). There might also be warheads that require special, longer treatment because they are not in a state that is according to the initial specifications because of wear and tear during deployment.

There is less public information about historical and current nuclear warhead dismantlement facilities, practices, and dismantlement rates in Russia (Podvig 2001, 115). At the "Third International Workshop on Verified Storage and Destruction of Nuclear Warheads", held in 1991, a senior arms control adviser to Russian President Boris Yeltsin suggested that about 1,500 warheads per year were being dismantled (Office of Technology Assessment 1993). Russian Atomic Energy Minister Victor Mikhailov in the early 1990s indicates that in the time between 1986 and mid-1992 the Soviet stockpile was reduced by about 20 percent from its 1986 peak of 45,000. This would be equivalent to an average of about 1,500 warheads per year for the time period (Bulletin of the

Atomic Scientists 1993). Another source quotes Victor Mikhailov as suggesting a dismantlement rate of 3,000 weapons for 1992, and a total 13,000 warheads dismantled warheads from 1987 to 1992, which would be equivalent to about 2,500 warheads per year (Mikhailov 1993).

United States experts estimated that the dismantlement rates in Russia were lower, possibly around 2,000 warheads per year, and perhaps between 1,000 and 1,500 warheads per year (Handler 1999, 13). A decade later, in 2007, the average dismantlement rate was estimated to have fallen to 400–500 warheads/year, including the dismantlement for remanufacturing of up to 200 warheads per year (International Panel on Fissile Materials 2007). One reason for the decline is that Russia closed down its warhead assembly/disassembly facilities at Sarov and Zarechny in the early 2000s (Bukharin 2001). It is believed, however, that if necessary Russia's remaining dismantlement plants at Lesnoy and Trekhgorny could be sufficient to dismantle perhaps 1,000 warheads per year (Bunn 2008).

Russia as of 2019 is estimated to have a stockpile of 6,490 warheads (Kristensen and Korda 2019b). A dismantlement rate of 650 warheads per year (similar to that for the United States) would be required to achieve complete elimination within a deadline of 10 years. It seems feasible that Russia could achieve such rates after joining the TPNW by using its two existing dismantlement plants. An extension of an additional 10 years for a total time of 20 years would be equivalent to a dismantlement rate of about 325 warheads/year, which should be achievable under present business as usual circumstances.

Britain is believed to have manufactured a total of 1250 weapons from 1953 to 2013. At its peak, from 1973 to 1981, the stockpile contained 500 weapons and this was reduced to 225 weapons as of 2013 (Norris and Kristensen 2013). Assuming that Britain does not have many nuclear weapons in a dismantlement queue, this suggests 1000 weapons were dismantled in the six decades from 1953 and 2013, a rate of over 160 weapons per decade, along with existing warheads being serviced and new warheads being built. As of 2019, the British stockpile is estimated to be 215 weapons with a plan to reduce by the mid-2020s to "not more than 180" weapons (Kristensen and Korda 2019a). Hence, it seems feasible to assume that in the absence of modernization and new nuclear weapon production, Britain should be capable of dismantling all of its current 215 nuclear weapons in about 10 years, and clearly during an extended deadline of 20 years. An independent study has suggested that it would be possible to dismantle all British nuclear weapons in 4 years (Campaign for Nuclear Disarmament 2012). One possible constraint, however, is that Britain's nuclear weapon assembly and disassembly takes place at the Atomic Weapons Establishment site at Burghfield, which has seen safety issues that could slow weapon dismantlement activities (Edwards 2007). Recent problems have been discovered that threatened to shut down the plant (Doward 2018).

France is believed to have produced 1260 nuclear weapons between 1960 and 2012 (Norris and Kristensen 2012). The nuclear arsenal has been reduced from a Cold War peak reported to be about 500 weapons around the mid-1990s to about 300 weapon since 2008 (Commissariat de Energie Atomique 2016, 95). In 2015 President Francois Hollande stated France "has been exemplary in terms of the volume of its weapons stockpile: 300" after "reducing by half the total number of its weapons" (Hollande 2015). France previously has announced: "All decommissioned weapons have been dismantled," and that "it possesses no non-deployed weapons. All its weapons are operational and deployed" (France 2010). This suggests France has dismantled 960 warheads between 1960 and 2008, an approximate rate of 200 warheads per decade, while at the same time undertaking warhead production. At such a rate, France could dismantle its current stockpile within 15 years. The 300 warhead dismantlements in a decade necessary to achieve elimination in a deadline of 10 years could probably be achieved by dismantlement capacity gains from ending warhead production, modernization and maintenance.

China's nuclear arsenal is the least transparent among the five nuclear-armed states of the NPT. This stockpile is believed to have remained constant in size over most of the last four decades, but started to increase recently reaching about 290 weapons as of 2019 (Kristensen and Korda 2019a). In 2018, it was presumed that 20 Chinese weapons are bombs for use by aircraft and the others are missile warheads (Kristensen and Norris 2018). The uncertainties in the history of the stockpile and facility capabilities make it difficult to assess a plausible destruction timeline for China's weapons. One option is to assume that China's nuclear weapons take as long to dismantle as the United States weapons needing the most dismantlement work (9 work shifts of 8 hours for the B53 nuclear bomb which was retired at the end of the Cold War) (United States Department of Energy 1997). At this rate, all of China's nuclear weapons could be dismantled in a decade.

In the following, it is assumed that India, Pakistan and Israel could achieve a dismantlement rate comparable to the time required for the United States to dismantle the B53 warhead. Working at this rate, it would take India and Pakistan within 5 years to dismantle their current stockpiles, estimated to be 140–150 weapons, while Israel would need a little more than 2.5 years to dismantle the 80 weapons it is believed to hold (Kristensen and Norris 2013; Kristensen and Korda 2018; Kristensen, Norris, and Diamond 2018). The Democratic People's Republic of Korea has an even smaller arsenal (perhaps 25–30 weapons), for which dismantlement should be possible in a similar timescale (Kristensen and Korda 2019a).

Conclusion

The TPNW requires any nuclear-armed state that joins the treaty while owning nuclear weapons to destroy these weapons "as soon as possible" but not later than a specified deadline set by TPNW member states. TPNW states will have to determine what constitutes effective destruction of a nuclear weapon for the purposes of this treaty.

An analysis of weapon characteristics and current practices suggests a simple definition of nuclear weapon destruction might be that a nuclear weapon is destroyed when all of the following steps have been carried out: Non-nuclear components are separated from the physics package, conventional explosives are separated from the fissile material, and all components of the physics package as well as electronics have been irreversibly mechanically or chemically altered such that they cannot be used in a weapons assembly without substantive additional processing steps. The key point is that all major components of the warhead are assumed destroyed if they would require remanufacture to be used in a weapon.

Weapon dismantlement is the first and key part of weapon destruction. The processes of nuclear weapon component destruction can take place in parallel with dismantlement and so need not add significantly to a destruction deadline derived from the time required for weapon dismantlement. Based on the past experience of weapon dismantlement in the states holding the largest arsenals, most notably the United States, it seems plausible that all nine current nuclear-armed states could dismantle their weapon inventories in less than 10 years if they gave this task priority. Moreover, nuclear-armed states currently have extensive programs for warhead assembly for modernization and maintenance. These activities would need to end upon the state joining the TPNW, freeing up facilities and workers to focus on weapon dismantlement and destruction.

In conclusion, the first Meeting of State parties to the TPNW could adopt 10 years as the deadline required in Article 4.2 for weapon destruction. As in other disarmament treaties with weapon destruction deadlines, an extension of 10 years could be granted upon request to allow for unexpected difficulties in the weapon dismantlement process.

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