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Research article

Disposal, Destruction and Disarmament: Comparative Analysis of US Chemical Weapon and Weapons Plutonium Stockpile Reductions

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Abstract

The elimination of stockpiled weaponry constitutes a key step in arms control and disarmament processes, lending permanence and irreversibility to arms reductions. Yet it has proven challenging in practice. The destruction of advanced weapon components, like lethal chemical agents and the fissile materials from which nuclear weapons are constructed, is often technically complex and costly. To elucidate the dynamics of this back-end of arms control and disarmament processes, this article compares two representative cases involving analogous challenges but divergent outcomes: the nearly complete elimination of the US chemical weapon stockpile and stalled efforts to shrink the US weapons plutonium stockpile. Drawing from both engineering and organisation theory, technical and social distinctions between these efforts are assessed to identify key factors governing their outcomes. This analysis shows that the technical bases for stockpile reductions were broadly analogous between the two cases, and thus fail to explain their divergence. Rather, differing organisational characteristics among the responsible institutions proved decisive. These fostered either adaptive (in the chemical weapon case) or path-dependent (in the weapons plutonium case) organisational planning, influencing the ability of the *responsible entities to pivot from stockpile maintenance to an unfamiliar reductions mission.*

Keywords: *arms control, stockpile reductions, chemical weapons, nuclear weapons, organization theory*

Introduction

Arms control commonly entails cooperation between states to constrain the development, production, proliferation, use or stockpiling of weapons (Bull 1961: vii). Limitation of the first four activities is easily envisioned, requiring only that a state refrain from actively creating, distributing or wielding arms. Addressing preexisting weapon stockpiles is more challenging, requiring not merely abstention, but the active disposal or destruction of these weapons—the reversion of what is typically a demanding weapons acquisition process. While challenging, this elimination of stockpiled weaponry constitutes a key aspect of arms reductions and disarmament processes, lending permanence and irreversibility to these efforts (Cliff, Elbahtimy & Persbo 2018).

Despite its difficulty, history is replete with examples of successful weapon stockpile reductions. In perhaps the earliest instance, Carthage slaughtered its war elephants following a 201 BCE treaty with Rome (Burstein 1992). More recently, major powers have destroyed warships, missiles, tanks and other tools of war under the terms of the 1922 Washington Naval Treaty, the 1987 Intermediate-Range Nuclear Forces Treaty and the 1990 Treaty on Conventional Armed Forces in Europe. While these reductions targeted diverse weapons systems, they were achieved by similar, facile means: disassembly.[1]

The synthesis and weaponisation of advanced materials—the fissile materials used in nuclear weapons, lethal chemical agents and biological warfare agents, for example—has introduced new complications to this endeavor.[2] While conventional arms can often be effectively neutralised by disassembly, these advanced materials cannot; their weaponisability is primarily embodied not in the assembly of armaments, but in the initial synthesis of the exotic materials that serve as the central ingredients of nuclear, chemical and biological arms. For example, the dismantlement of a nuclear warhead does little to diminish the military utility of the fissile plutonium contained therein, and that plutonium represents the majority of the labour and expense of nuclear weapon production (Tylor 1989: 4-5).

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[1] I adopt here a broad definition of 'disassembly' in the case of war elephants.

[2] Fissile materials are those which can sustain a nuclear fission chain reaction. Two specific fissile materials, weapons-plutonium and highly-enriched uranium, comprise the basis for modern nuclear explosives.

Unlike simple disassembly, methods for the disposal or destruction of advanced weapon materials are often costly and technically complex.

While a large body of work in the security studies literature addresses the factors that might prompt arms reductions efforts—norm development, the negotiation of legal instruments and public support for weapons bans, for example—the ensuing logistics of stockpile management and elimination have been largely neglected.[3] A better understanding of these latter stages of arms limitations and disarmament processes as they relate to advanced weapons systems is needed, since prior programmes have met with mixed success. For example, even the world's sole case of complete renunciation of nuclear weaponry—South Africa's dismantlement of their small arsenal starting in 1990—has not led to elimination of the corresponding fissile material. South Africa still retains a portion of this inventory.[4] Global inventories of weapons plutonium have grown monotonically for decades, even as many states have ceased production and declared large portions of their stockpiles excess to military needs (International Panel on Fissile Materials 2015: 23-28). Furthermore, reducing stockpiles of advanced weaponry will likely be a central concern of security policy in the near future. For instance, addressing stockpiles of fissile materials is a key issue for advocates of the recent Treaty on the Prohibition of Nuclear Weapons, which bans the possession of nuclear arms (Shea 2018). And while many nations' arsenals of chemical weapons have been eliminated, North Korea possesses several thousand tonnes of lethal chemical agents that must be dealt with if risks are to be reduced on the Korean Peninsula (Varriale 2018).

To better elucidate the dynamics of advanced weapon stockpile reductions and the determinants of their success, this article problematises the act of stockpile reductions in the wake of an arms control agreement, asking how a state proceeds once it has chosen to pursue reductions and what factors—material or social—play central roles in the completion or failure of that mission. Given the paucity of available data on reduction efforts and of prior analysis, this work constitutes an initial, exploratory investigation, making use of a comparative case study approach to identify key bifurcations in cases with broad similarities yet divergent outcomes (Weatherbee 2012). By identifying critical junctures in

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[3] Much of this literature deals with nuclear weapons, chemical weapons, biological weapons, landmines and cluster munitions, all of which have been the focus of concerted international disarmament activity (Egeland 2022; Gibbons 2018; Lodgaard 2017; Hynek & Smetana 2016; Petrova 2016; Kelleher & Reppy 2011; Borrie 2009; Koblenz 2009; Perkovich & Acton 2009; Anderson 2000; Price 1997). The limited prior work that specifically investigates stockpile reductions focuses mainly on cases wherein one state compels and oversees the elimination of another state's arsenal (Tal-shir & Mitz 2018; Bleek, Kane & Pollack 2016).

[4] A portion of the inventory, estimated initially at several hundred kilograms of highly-enriched uranium, has been converted for use in civilian applications (Feiveson et al. 2014: 65-67).

the histories of these cases, the relative explanatory power of potential explanations for their outcomes can be assessed.

In selecting cases with broad similarities but disparate outcomes, US efforts to eliminate chemical weapons and excess weapons plutonium stand out. US chemical disarmament is nearing completion, with more than 95% of the inventory eliminated (Quinn 2022). Meanwhile, the plutonium stockpile remains undiminished, with analysts characterising reduction efforts as a 'failure' (Hyatt 2018; Kenausis 2018; Lubkin 2018; Maloney 2019). These cases are particularly interesting from an analytical perspective because, while many facile explanations for their divergent outcomes might be imagined—differences in cost, complexity or political interest, for example—these fail to adequately explain the divergence. Both programmes, which targeted legacies of rampant Cold War production, were plagued by near-identical cost growth, with eventual projected costs of roughly $40 billion dollars (Walker 2010; Aerospace Corporation 2015).[5] They presented analogous technical challenges involving the use of well-established chemical and nuclear engineering processes, but at a much larger scale than the US had dealt with previously. And in neither case did the US appear disinterested in the outcome; it actively negotiated and signed binding international legal instruments requiring stockpile reductions in both cases, and subsequently spent billions of dollars in the pursuit of those reductions.[6]

It is this surprising similarity between the two programmes, as well as the availability of extensive documentation of both, that makes them attractive targets for exploratory investigation of the sociotechnical dynamics of weapons stockpile reductions. Why, despite facing similar obstacles, was reduction of the chemical weapon stockpile successful, while attempts to reduce the weapons plutonium stockpile have stalled? What factors—technical or social—shaped the outcomes of these efforts?

This article examines the histories of US chemical weapon and weapons plutonium stockpile reduction efforts in order to elucidate the causes of their divergent outcomes. Because reductions are an inherently technical activity carried out by large, bureaucratic organisations, both technical and organisational aspects of each case are considered. This analysis ultimately demonstrates that technical factors and material characteristics of these weapon systems were not the primary determinants of stockpile reductions outcomes. The technical challenges faced in each case and the associated costs were comparable, such that neither stockpile was intrinsically more amenable to elimination. Rather, organisational path-dependence—a tendency to favour repetition over innova-

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[5] Dollar amounts are given in 2022 dollars throughout the text.

[6] Approximately $6 billion was spent on the plutonium effort before it unraveled (US Department of Energy 2014a: 22; Holt & Nikitin 2017). Expenditure to date on the chemical weapon destruction effort is much higher, given its greater progress.

tion—proved decisive. It hindered the adoption of novel elimination techniques in the plutonium case, while circumstances favouring organisational adaptation facilitated a successful pivot from stockpile maintenance to elimination in the chemical agent case.

The remainder of this article proceeds as follows. The first section provide brief historical surveys of US chemical weapon and weapons plutonium stockpile reductions efforts. The second section examines the technical bases for elimination, proposing a simple typology of reductions techniques and comparing the associated technical challenges. The third section assesses the social contexts of reductions and the influence of organisational heuristics on stockpile management practices. The article concludes with discussion of the policy implications of these findings and of their potential for generalisation to the analysis of other stockpile reductions efforts.

A brief history of US chemical weapon and weapons plutonium reductions

Chemical weapons

Following the widespread use of chemical weapons in World War I, the US acted as a primary champion of chemical arms control. Concerns about the indiscriminate nature of these arms and their potential use against noncombatants, their association with the unpopular German government and a moral repugnance regarding their effects on soldiers combined to generate opposition amongst both the public and political elites (Price 1997: 46-47). In 1925 the United States signed the Geneva Protocol, which banned the first use of these weapons.[7] Nevertheless, it readied itself for widespread chemical warfare in World War II, then continued development and stockpiling of chemical agents and munitions as part of the US-Soviet arms race (Moon 1984; Tucker 2006: 122-189). Only in 1968 was production halted.[8]

This left the United States with a vast chemical stockpile, consisting primarily of the nerve agents GA (tabun), GB (sarin) and VX, alongside the vesicants lewisite and the sulfur mustards (US National Research Council 1984: 1; US Office of Technology Assessment 1992: 13-14).[9] These liquid agents were contained in both artillery shells and one-ton containers, distributed among nine depots in the continental United States and Johnston Atoll.[10]

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[7] While failing to ratify for half a century, the United States upheld the treaty's stipulations as a matter of policy.

[8] The United States took steps to produce binary chemical munitions—containing non-lethal chemicals that are mixed upon firing to produce a lethal agent—in the 1980s.

[9] Nerve agents disrupt the working of the human nervous system, while vesicants attack the skin, eyes and mucous membranes.

[10] Designation of chemical weapons as 'poison gases' is a misnomer. On the battlefield,

While no large-scale or systematic elimination programme existed at the time, aging of the stockpile necessitated periodic disposal of small quantities of agents and munitions, constituting the earliest US chemical weapon stockpile reductions. Absent a legal obligation for elimination or strict political oversight, the Army Chemical Corps opted for cheap, rudimentary methods of disposal. Prior to 1970, these agents were treated much the same as any other form of refuse; burning in open pits, release to the atmosphere, burial and ocean dumping were typical. The latter method culminated in Operation CHASE (Cut Holes And Sink 'Em) in which, from 1964 to 1970, hundreds of tonnes of agents and munitions were loaded onto ships that were subsequently scuttled in the Atlantic Ocean (Flamm, Kwan & McNulty 1987). Public outcry eventually halted the programme after details of this dumping were leaked to the US Congress and the media (Wagner 2004: 311-312).

Finding its preferred approach demonised on environmental grounds, in 1969 the Department of Defense (DOD) commissioned the US National Academy of Sciences (NAS) to review Operation CHASE. The NAS recommended substitution of ocean dumping with two technologically advanced methods of agent destruction: incineration and chemical neutralisation (US National Academy of Sciences 1969). Incineration entails extraction of agents from the containers in which they are stored, followed by heating in large furnaces (US National Research Council 1984: 73-80). Combustion of the agents renders them less toxic, such that the products can be vented to the atmosphere or disposed of as hazardous waste. Neutralisation involves mixing of agents with other chemicals that react with the agent to yield less toxic products, which can then be disposed of. For example, GB and VX can by neutralised by mixing with large volumes of water and sodium hydroxide, a common industrial chemical (US National Research Council 1984: 26-33). Adopting these NAS recommendations, the Army tested both incineration and neutralisation throughout the 1970s. The latter method fared poorly and was abandoned by the 1980s due to 'the sheer complexity of the process', while incineration became the preferred means of elimination (Flamm, Kwan & McNulty 1987: 8).

In parallel to this evolution of the means of chemical weapon elimination the United States developed a legal context for stockpile reductions. In 1982, the NAS outlined a plan for incineration of the entire stockpile (US National Research Council 1984: 68). In 1985, Congress tasked the DOD with this mission, marking the official start of the systematic chemical stockpile reductions programme (US Congress 1986). The process was bilateralised under the 1990 US-Soviet Chemical Weapons Accord, which limited each state to 5000 tonnes of agents. It was multilateralised three years later when the United States signed

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these liquids are dispersed as a fine mist. The chlorine-based gases (e.g., chlorine and phosgene) are an exception.

the Chemical Weapons Convention (CWC), obliging it to destroy the entirety of its chemical arsenal and to refrain from further production.

However, this flourishing of the international context for reductions was accompanied by recurrent delays and financial failings in the US programme. In its 1984 report, the NAS predicted a total cost of $3.8 billion (all figures are given in 2022 dollars) for elimination of the stockpile, while the Army estimated $4.5 billion and completion by 1997 (US National Research Council 1984: 4-5, 92-94; US General Accounting Office 1985). By 1991, these projections had increased to $12.6 billion and completion by 1999 (US General Accounting Office 1991: 3). Six years later this was again revised to $22 billion (US General Accounting Office 1997: 7). And the Army's woes were not merely financial. Opponents in local and state governments, as well as environmental groups, argued that the Army had inadequately studied both the risks to nearby communities from gases released during incineration and the relative environmental risks of alternative disposal methods (US Office of Technology Assessment 1992: 3-4, 18-20).

Responding to these concerns, in 1996 the Army launched the Assembled Chemical Weapons Alternatives (ACWA) programme to assess and implement new means of elimination. Its adoption of the challenging neutralisation approach has further increased costs and delayed the programme. Current projections anticipate completion no sooner than 2023, a dramatic overrun of the 2007 CWC deadline (Lewis 2013). Estimates peg final programme costs at roughly $40 billion, a more than twenty-fold increase from initial projections (Walker 2010).

Despite suffering from seemingly interminable delays and exorbitant costs, the chemical disarmament programme appears poised to meet its goal. The DOD has thus far acquired sustained congressional funding. Inventories at seven of the nine US depots have been fully incinerated, while ACWA-run neutralisation programmes are underway at the final two sites (Quinn 2022). There remain several obstacles to the complete elimination of the US chemical arsenal—many of the remaining munitions are severely degraded, complicating agent extraction, and local communities are often opposed to this work—yet the destruction processes in use have been extensively and successfully demonstrated. This outcome stands in stark contrast to the US experience with weapons plutonium wherein, despite analogous challenges, it has failed to eliminate even a small fraction of this stockpile.

Weapons plutonium

The United States first sought to limit the stockpiling of weapons plutonium—an artificial, radioactive metal and a central ingredient of nuclear weaponry—in 1946, just three years after the first synthesis of this material (Barnard et al. 1946). Its proposal to place existing stocks under international control was rejected by the Soviet Union, which was then pursuing its own plutonium production capability (Wheeler 2002: 23). Soviet acquisition of plutonium in 1949 positioned fissile materials as a centrepiece of the bipolar, US-Soviet deterrence relationship. In this context the United States pursued rampant production throughout the Cold War, continuing to enlarge its stockpile until 1988. By this point it was left with nearly 100 metric tonnes of weapons plutonium, enough for tens of thousands of nuclear weapons (International Panel on Fissile Materials 2015: 23-25).

The dissolution of the Soviet Union in 1991 prompted a dramatic shift in the nuclear security landscape. Previously, most bilateral arms limitations had focused on warhead delivery systems (e.g., missiles and bomber aircraft) rather than fissile materials, due in part to the difficulty of monitoring and accounting for the latter (von Hippel, Albright & Levi 1986: 1). But concerns regarding the security of the Russian stockpile amidst political and economic upheaval brought nuclear material management to the forefront (Perkovich 1993). In this environment, US policymakers came to perceive the very existence of plutonium stockpiles, and the accompanying risk of theft by non-state actors, as an inherent security threat. International negotiation began on a Fissile Material Cutoff Treaty (FMCT) that would ban further plutonium production. In tandem, the United States and Russia, possessing the vast majority of the global weapons plutonium inventory, began to explore bilateral approaches to reducing the sizes of their stockpiles.

The two sides quickly reached agreement on plans to reduce stockpiles of one of the two most commonly-used fissile materials: highly enriched uranium. The enrichment process that renders this fissile material useful for weapons purposes can be undone by simple blending with unenriched uranium extracted from natural ores.[11] Plutonium stockpile reductions posed a greater challenge, as plutonium does not require the same enrichment prior to use in a weapon.

In 1992 the NAS convened discussions on plutonium stockpile reductions with its counterpart, the Russian Academy of Sciences. The Bush administration then tasked the NAS with a comprehensive technical study of reductions prospects, published in 1994 (US National Academy of Sciences 1994). This report shaped the contours of future reductions efforts. Crucially, it argued that the best approaches to elimination were those that rendered weapons plutonium as unattractive for use in a weapon as is the vast quantity of plutonium found in spent nuclear fuel from civilian reactors.[12] Given that the plutonium in spent

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[11] Several hundred tonnes of US and Russian highly enriched uranium have since been eliminated via downblending (Pavlov & Rybachenkov 2013).

[12] This inventory constitutes a few thousand tonnes of plutonium (International Atomic Energy Agency 2017: 10).

fuel is unlikely to be eliminated in the near future and will therefore remain a potential target for diversion or theft, this ‘spent fuel standard’ represents the maximum meaningful level of irreversibility that might be achieved in the near term.

The weaponisation of plutonium contained in spent nuclear fuel is hindered, to some extent, by both its dilution in a highly radioactive mixture of non-weaponizable material and its relatively high concentration of certain isotopes of plutonium (referring to varieties of plutonium with different numbers of subatomic particles, and thus different nuclear properties) produced by long-term exposure to radiation within a nuclear reactor.[13] Plutonium containing high concentrations of these isotopes, known as reactor-grade plutonium, is somewhat less attractive for weapons use. To mimic these conditions with weapons plutonium, the NAS recommended two potential methods: conversion of weapons plutonium to nuclear fuel followed by irradiation in a nuclear reactor, or immobilisation in a highly-radioactive mixture of materials (US National Academy of Sciences 1994: 220-230).

The first method involves mixing of plutonium with uranium dioxide—the most common commercial nuclear fuel—and irradiation of the resulting uranium-plutonium fuel. This yields highly radioactive spent fuel with unfavourable plutonium isotopic composition. While uncommon in commercial nuclear energy programmes, this technique relies on well-established technologies. It has been practiced routinely, cost-efficiently and at industrial scale in France since the 1970s (Paviet-Hartmann, Benedict & Lineberry 2009: 332).[14] The second method, immobilisation, entails mixing of the plutonium with preexisting radioactive nuclear waste so as to mimic the dilution of plutonium in spent nuclear fuel, but without altering its isotopic composition.

Armed with this vision of cooperative stockpile reductions, bilateral consultation soon reached the highest levels of the US and Russian governments. Discussion between Presidents Clinton and Yeltsin at the 1996 Moscow Nuclear Safety and Security Summit was followed by a declaration emphasising the pressing need for excess plutonium to be ‘transformed into spent fuel or other forms equally unusable for nuclear weapons’ (International Atomic Energy Agency 1996). The US Department of Energy (DOE), responsible for managing the US fissile material stockpile, soon began preparations for carrying out this reductions mission (US Department of Energy 1996).

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[13] Weapons using reactor-grade plutonium are less reliable and produce lower explosive yields than those using similar quantities of weapons plutonium. The precise influence of isotopic composition on weaponisability is controversial (Mark, von Hippel & Lyman 2009; Pellaud 2002).

[14] While costs may be somewhat higher than direct disposal of nuclear fuel without plutonium reprocessing, the French government maintains that reprocessing increases energy costs by only a few percent (Charpin, Dessus & Pellat 2000).

By 2000, the United States and Russia had negotiated and signed the Plutonium Management and Disposition Agreement (PMDA), requiring each to eliminate 34 metric tonnes of weapons plutonium and to refrain from the production of new material until finished.[15] The technical means of elimination proved a point of contention. Russia showed little enthusiasm for immobilisation, deriding it as 'just another form of storage' that, because it did not change the isotopic composition of the plutonium, would leave plutonium vulnerable to retrieval and reuse were the United States to renege on its commitments (Bunn 2007). Thus, the PMDA mandated conversion to nuclear fuel and irradiation for the bulk of the plutonium it addressed (Clements, Lymann & von Hippel 2013).[16] With this technical stumbling block overcome, there emerged a clear path forward for international cooperation on stockpile reduction.

As in the chemical weapon case, this progress was soon marred by delays and rapidly escalating cost projections, which came to overshadow concerns of reduction irreversibility in the US discourse. In 2002 the DOE projected a cost of $6 billion (all figures are given in 2022 dollars) for conversion of the plutonium to nuclear fuel by approximately 2020 (US National Nuclear Security Administration 2002). By 2015, forecasts had ballooned to at least $37 billion for completion in 2059, as the DOE found construction of the necessary conversion infrastructure to be more complex than anticipated (Aerospace Corporation 2015; Lubkin 2018). The US commitment to its PMDA obligations floundered in the face of these cost overruns. The DOE convened a series of working groups to unilaterally assess cheaper, alternative elimination methods (US Department of Energy 2014b; Aerospace Corporation 2015; Oak Ridge National Laboratory 2015). They recommended an approach distinct from those identified in the earlier NAS report: dilution of plutonium in a non-radioactive material and burial deep underground in a geologic repository. The DOE formally adopted this method in 2016 (US Department of Energy 2016: 6).

This pivot to dilution and burial ran afoul of the long-held Russian opposition to such techniques and, without Russian assent, contravened the terms of the PMDA. President Putin swiftly voiced concern that buried plutonium could 'be retrieved, reprocessed, and converted into weapons-grade plutonium again' (President of the Russian Federation 2016a). In 2016 he suspended Russia's commitment to the PMDA citing, among other grievances, 'the inability of the United States of America to ensure the fulfillment of its obligations on the disposition of surplus weapons-grade plutonium' (President of the Russian Fed-

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[15] This moratorium on production built on a bilateral 1994 agreement mandating the shutdown of certain plutonium production reactors.

[16] The agreement allowed for a small portion of US plutonium to be disposed of by immobilisation, a strategy later abandoned on budgetary grounds. A 2010 renegotiation of the PMDA allowed Russia to irradiate plutonium in newly developed fast reactors, rather than the light water reactors specified in the initial agreement.

eration 2016b). This ended what the US Congress had earlier described as 'one of the most important nonproliferation initiatives undertaken between the United States and Russia' (US House of Representatives 2001: 131).

Much of this history mirrors that of the chemical weapon stockpile: the accumulation of vast inventories for deterrence purposes, vacillation between multiple elimination techniques, and financial challenges that threaten the reductions endeavor. Yet while the United States has nearly met its obligations under the CWC, the international context for plutonium stockpile reductions has unraveled. While the PMDA mandated US reduction of its weapons plutonium stockpile fifteen years after the US Congress mandated the elimination of the chemical weapons stockpile, the plutonium programme is far less developed than the chemical disarmament effort was fifteen years ago. No weapons plutonium has been eliminated from the US inventory to date and prospects for further bilateral progress are meagre. The United States is poised to carry out any future unilateral reductions via a highly contentious, allegedly reversible means.[17] In seeking to identify the sources of this divergence in outcome, this article looks first to the weapon materials and the technical bases for their elimination.

The technical basis for stockpile reductions

The most obvious distinction between chemical weapon and weapons plutonium stockpile reductions is the nature of the material being eliminated. Thus, the immediate question is this: did fundamental characteristics of these weapon materials and the means by which they can be eliminated determine the divergent outcomes of reductions efforts? Did some property of weapons plutonium, absent from chemical agents and munitions, preclude its successful elimination?

Chemical agents and weapons plutonium are physically and chemically dissimilar. Chemical agents are predominantly liquids composed of complex organic molecules (specific combinations of atoms bound to one another in a unique arrangement) (Stockholm International Peace Research Institute 1971b: 22-59). Their constituent chemical elements are relatively common and harmless in isolation (for example, carbon, oxygen, fluorine, phosphorus, sulfur and nitrogen); it is the bonding of these atoms to one another in a particular molecular structure (e.g., $C_5H_{11}N_2O_2P$ for the nerve agent tabun) that lends them lethality and efficacy as tools of war.

In contrast, weapons plutonium is a solid metal composed of only a single, artificial chemical element: plutonium (Clark, Gleeson & Hanrahan 2019). Plutonium weapon components consist of a large number of plutonium atoms bound

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[17] The reversibility of burial is a topic of controversy (Lyman & Feiveson 1998; Peterson 1999).

to one another.[18] It is not any particular arrangement of atoms that lends this material its military efficacy, but rather the initial synthesis of this chemical element within a nuclear reactor.

These essential distinctions between molecular chemical agents and single-element weapons plutonium govern the manner in which these materials can be eliminated. Chemical agents can be effectively destroyed by chemical means: breaking of their constituent chemical bonds such that the individual atoms making up the lethal molecule remain intact, but the molecule itself is destroyed. Incineration and neutralisation accomplish this by driving chemical reactions with hot air or with other chemicals that decompose agents into less-lethal—yet often still highly toxic—reaction products, such as hydrofluoric acid or methylphosphonic acid (US National Research Council 1984: 68-83).

Plutonium cannot be chemically decomposed, as it consists of only a single chemical element. Instead nuclear alteration (the decomposition or modification of the atoms themselves) is required to fully eliminate this material. Conversion of weapons plutonium to nuclear fuel and irradiation in a nuclear reactor—the means of stockpile reductions dictated by the PMDA—accomplishes this (US National Academy of Sciences 1994: 154-159). When placed in an operating nuclear reactor, this material is bombarded with neutrons, a type of subatomic particle. If impacted by a neutron of sufficient energy, a plutonium atom can split into two fragments, each of which is a different chemical element. Alternatively, it can absorb the neutron and transition into a different isotope of plutonium (US National Academy of Sciences 1995: 27-43). In the former case, plutonium is converted or decomposed into non-weaponizable elements like ruthenium and iodine (Katcoff 1958). In the latter, neutron absorption by the isotope plutonium-239 produces plutonium-240, an isotope that is somewhat less amenable to weaponisation (US National Academy of Sciences 1994: 32-33).[19]

Both chemical weapon and weapons plutonium stockpile reductions efforts have also made use of other, non-destructive reductions techniques. Chemical weapon reductions began with the dumping of munitions and agent tanks into the Atlantic Ocean, an approach which relies on the difficulty of recovery from the sea floor to prevent reuse. Similarly, the recently proposed dilution and burial of plutonium would leave this material largely intact, relying on chemical dilution and subterranean isolation to prevent reuse.

This analysis reveals a correspondence between the means of chemical weapon and weapons plutonium elimination. The various techniques utilised in both cases can be grouped into two broad categories: destruction and disposal. De-

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[18] Small quantities of other elements, such as gallium, are added to enhance plutonium's physical properties.

[19] Irradiation will simultaneously breed new plutonium, rich in plutonium-240, from uranium present in the fuel.

struction entails alteration of the material via some form of decomposition so as to render it intrinsically less attractive for weapon use. The incineration or neutralisation of chemical agents and the irradiation of weapons plutonium are thus both means of material destruction that represent, to some extent, reversion of the synthesis processes that initially produced these materials.[20] These methods are analogous to the disassembly techniques used for elimination of conventional weapon systems; like deconstructing a tank, heating of a chemical agent 'disassembles' weaponised molecules and irradiation of plutonium 'disassembles' weaponised atoms. Given its technical complexity, destruction tends to be relatively expensive, but highly irreversible.

Disposal involves no substantial alteration of the material itself, but rather the establishment of extrinsic barriers to its recovery and reuse. Ocean dumping and burial are thus means of disposal, as they rely on hundreds of meters of overlying seawater or rock to render recovery expensive, slow and observable. Disposal tends to be cheap relative to destruction, since it entails widely practiced activities such as ocean transport and geologic excavation. For example, the switch from ocean dumping of chemical munitions to incineration increased costs severalfold (Ripley 1971). Likewise, cost projections for irradiation of weapons plutonium are substantially higher than those of burial (Aerospace Corporation 2015). Yet this cost advantage is counterbalanced by the potential for material recovery. Because disposal does not alter the intrinsic characteristics of weapon materials, reversion of this process remains possible, assuming the costs of recovery are low relative to the material's value.

In light of this tension between recovery cost and use-value, it is instructive to quantitatively assess both. Recovery of chemical weapons disposed of on the sea floor would require a deep ocean salvage operation, typically costing up to tens of millions of dollars (Bartholomew & Milwee 2009).[21] This is a high price for the recovery of agents that can be synthesised for a few dollars per kilogram (Stockholm International Peace Research Institute 1971b: 53). It is also high relative to the military utility of these weapons on a per unit mass basis. The US chemical weapons stockpile consists mainly of mortar projectiles containing a few kilograms of chemical agent each (US Department of the Army 1977). Under ideal weather and delivery conditions, a single munition can disperse agent over a roughly 10,000 square meter area (US Departments of the Army, the Navy and the Air Force 1966). Assuming dense packing of enemy combatants and the absence of chemical defenses such as gas masks, a few kilograms of agent might yield up to several hundred casualties.

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[20] In both cases, the products of destruction could be weaponised, but would be intrinsically less effective than the initial materials.

[21] Surveys of dumped chemical munitions indicate that they remain largely intact, and therefore recoverable (Silva & Chock 2016).

The costs of recovering buried weapons plutonium are similar. Mining of a geologic repository would cost up to approximately ten million dollars (Peterson 1999). For a repository containing tens of metric tonnes of weapons plutonium, this would yield recovery costs of perhaps a few thousand dollars per kilogram of plutonium, even assuming a conservative recovered fraction on the order of 10%. This cost is quite low compared to that of producing new plutonium from the irradiation of nuclear fuel in a nuclear reactor and subsequent separation of the plutonium produced. One estimate predicts costs to separate plutonium from spent nuclear fuel in excess of one hundred thousand dollars per kilogram of plutonium (Berkhaut et al. 1993: 200).

In contrast to the chemical weapon case, the low cost associated with recovery of buried plutonium is dwarfed by this material's tremendous destructive power. Less than ten kilograms of plutonium—a sphere slightly larger than a baseball—is sufficient to produce a nuclear explosive device (International Atomic Energy Agency 2002: 23). The bomb dropped on Nagasaki in 1945, for example, contained 6.4 kilograms of plutonium and produced a blast yield equivalent to approximately 22 kilotons of TNT (Penney, Samuels & Scorgie 1970). Detonation of such a device in a major city would yield hundreds of thousands of casualties.

This clear nonequivalence in the cost/value relations for chemical weapons and weapons plutonium reveals a corresponding nonequivalence in the efficacy of disposal as a means of elimination. While disposal strongly disincentivises the reuse of chemical agents, since the costs of recovery are high relative to both the costs of producing new agents and to their military use-value, its efficacy in the plutonium case is questionable.

This simple typology of the technical bases for stockpile reductions yields two key findings. First, comparable means of destruction and disposal exist for both chemical weapons and weapons plutonium. No intrinsic property of weapons plutonium precluded successful implementation by the United States of its PMDA obligations at costs comparable to those deemed acceptable for chemical stockpile reduction. Thus, the characteristics of these weapon materials and the technical bases for their elimination fail to explain the divergent outcomes of the associated reductions efforts. Second, these two cases evolved along opposing paths. Chemical disarmament proceeded from effective disposal (e.g., ocean dumping) to more costly destruction (incineration and chemical neutralisation). Conversely, plutonium stockpile reduction efforts shifted from destruction (conversion to nuclear fuel and irradiation in nuclear reactors) to cheaper and potentially less effective disposal (dilution and burial)—a shift which prompted the eventual downfall of the PMDA. This distinction raises new questions regarding strategic decision-making by the organisations responsible for reductions. The roles these organisations played through selection and implementation of the means of stockpile reductions are addressed next.

Organisational factors in stockpile reductions

Organisational heuristics and path-dependence

With technical factors failing to fully explain the divergent outcomes of these stockpile reductions efforts, their broader social contexts must be considered. Highlighting the role that organisational interests can play, Wyn Jones characterises the stockpiling of these weapons as 'the result of a rather fragile interplay of professional, technical, economic, and political factors and the product of a coalition of interests and alliances that will disintegrate if not constantly reproduced' (Wyn Jones 1999: 143). The central question is this: did differing organisational interests govern the outcomes of these stockpile reductions efforts?

These efforts were carried out by organisations with distinct institutional histories, capabilities and preferences: the DOD's Department of the Army, Chemical Demilitarization Program managed the chemical stockpile, while weapons plutonium was the purview of the DOE's National Nuclear Security Administration (NNSA), Office of Material Management and Minimization.[22] Both were tasked with costly, technically complex reductions missions that ran directly counter to the prior work of their parent organisations producing and maintaining these stockpiles. This necessitated broad organisational change and adaptation—a challenge for any large bureaucracy (Van De Ven & Poole 1995).

Organisational characteristics shape the heuristics decision-makers employ when confronted with the need to solve newly encountered problems. Organisation theory identifies common heuristics that bureaucratic organisations typically follow in these instances. In their seminal work, March and Simon found that organisations tend to approach new problems by 'recognizing a situation as being of a familiar, frequently encountered, type, and matching the recognized situation to a set of rules' established in prior problem-solving (March & Simon 1993: 8). This gives rise to path-dependence, wherein strategy is characterised by the reproduction and synthesis of past actions; 'adaptation takes place through a recombination of lower-level programs that are already in existence' (March & Simon 1993: 171). Thus, the programmes or routines that an organisation has previously engaged in—developing relevant experience and capabilities—comprise a semi-exclusive range of options available to decision-makers when confronted with a new problem. Courses of action that align with prior experience tend to appear 'sensible or even inevitable', while alternatives appear radical or infeasible (Eden 2004: 50).

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[22] Organisational nomenclature changed throughout both programmes.

This reliance on reproduction confers several benefits to bureaucratic organisations. Routinisation of problem-solving and strategic planning allows for the efficient dispersal of institutional knowledge and ensures that the resources necessary to develop new capabilities are mustered only when necessary (March & Simon 1993: 163-190). Yet it can also 'constrain optimal choice in order to achieve the efficiencies of established routines' (Allison & Zelikow 1999: 156). Routines become self-reinforcing as investment in corresponding capabilities and infrastructure ensures that, from the perspective of those in an organisation, 'the relative benefits of the current activity compared with other possible options increase over time' (Pierson 2000: 254). Thus, characteristics of the organisation itself, rather than those of the problem to be solved, can dominate the strategy selection process. In extreme cases, this tendency to gravitate towards familiar strategies can yield technological monocultures in which specific technologies are favored despite glaring shortcomings (Walker 2000). This can detrimentally influence organisational performance in activities that involve complex technologies and unfamiliar objectives, such as stockpile reduction. In the words of Allison and Zelikow, 'projects that demand that existing organizational units depart from their established programs to perform unprogrammed tasks are rarely accomplished in their designed form' (Allison & Zelikow 1999: 179).

Adding to this challenge, the governmental organisations responsible for management of weapon stockpiles act within a complex web of political interests, both domestic and international. The institutionalist school of organisation theory identifies this broader sociopolitical environment as a key factor shaping the development of organisational routines since, to some extent, 'the rules' that an organisation follows in problem-solving 'are formed in the state or even world system, external and hierarchically superior to the organization' (Zucker 1987: 450). This institutional context—in this case the contemporary security environment and dominant discourses in state security culture—can further 'explain departures from technical rationality' (Eleanor Westney 1993: 54). Along these lines, prior work has demonstrated the key role of ideational forces and social network effects in the persistence of nuclear weapon systems in several states (Ritchie 2010; Bourne 2016; Adamsky 2019). In a recent, comprehensive study of disarmament processes Egeland summarises the often decisive role of these normative factors when observing that disarmament is, in nearly all instances, 'precipitated by the . . . emergence of new conceptions of appropriate action' (Egeland 2022: 122).

Organisational sclerosis in the plutonium stockpile reductions effort

Tensions between organisational routinisation and mission novelty are evident in the weapons plutonium case. Prior to the PMDA, the DOE had little experience with the production and use of plutonium-bearing nuclear fuel, the elimination method mandated by the agreement. Limited US testing of this technology in the 1970s was halted by a 1977 federal moratorium, based on fears that normalisation of plutonium use in civilian applications would hasten the proliferation of nuclear weaponry (von Hippel 2001). This ban was lifted in 1981, but commercial and research interest proved minimal given the low cost of conventional, uranium-based nuclear fuel (Bunn et al. 2005). Unlike in other nations, most prominently France, plutonium was not adopted as a fuel for US nuclear reactors. So unfamiliar was the DOE with plutonium fuel technology that, when tasked with the conversion of weapons plutonium to fuel under the PMDA, it had to rely heavily on a subsidiary of Areva, the French state-owned nuclear firm, for design and construction services (Lubkin 2018).

In contrast, the DOE possessed extensive experience with nuclear waste dilution and burial. Since the earliest days of nuclear energy there has existed a consensus in the United States that disposal in stable geologic formations is the best means of dealing with unwanted nuclear materials (US National Research Council 1957). The 1982 Nuclear Waste Policy Act codified in law the government's commitment to geologic disposal. But perhaps the most meaningful expression of the DOE's adherence to burial is found in its infrastructure. Since 1999 the DOE has operated WIPP, the world's only deep geologic repository for nuclear waste, into which it plans to invest upwards of $20 billion (Feder 1999).

Under these conditions, typical organisational heuristics would strongly favour abandonment of the irradiation approach, an unfamiliar technique imposed by external political forces, and its substitution with dilution and burial, an approach that aligns with existing capabilities and capitalises on prior investments. The DOE's swift reversion to its preexisting waste management routine aligns with an organisational preference for more familiar alternatives to irradiation. Just one year after the PMDA's signing, the US Congress chided the department for 'consideration of alternative plutonium disposition and management scenarios', mainly dilution and burial, alongside a 'much lower than expected budget request' (US House of Representatives 2001: 131).

The DOE's apathetic approach to plutonium irradiation bordered on self-sabotage. After failing to request from Congress the requisite appropriations, the department commissioned a succession of reports claiming inadequate funding for the irradiation technique and suggesting its replacement with burial (US Department of Energy 2014b; Aerospace Corporation 2015; Oak Ridge National Laboratory 2015). According to Congress these DOE assessments had 'not accurately represented the comparative life cycle costs of these alternatives', suggesting ancillary motives for the DOE's preference (US House of Representatives 2014: 143). The DOE's ardent pursuit of more familiar alternatives to irradiation—the adoption of which scuttled the PMDA—corresponds to the predictions of organisation theory that 'damaging interactions can occur . . . when new, unfamiliar tasks are superimposed onto old routines' (Allison & Zelikow 1999: 158).[23]

These internal factors hindering organisational change within the DOE were accompanied by an evolving institutional environment that grew increasingly unconducive to stockpile reductions. Unsurprisingly, negotiation of the PMDA coincided with a reassessment of the role of nuclear weapons in global security policy. The fall of the Soviet Union did away with a primary justification for US reliance on nuclear weapons, prompting a revival of nuclear reductionist, delegitimationist and abolitionist thought (Nitze 1994; Canberra Commission on the Elimination of Nuclear Weapons 1996; US National Academy of Sciences 1997).

But support for the arsenal rebounded in subsequent decades, buoyed by a renewed focus on great power conflict and familiar deterrence relationships (Freedman & Michaels 2019: 631-648). As the PMDA unraveled, dominant US discourses reflected a belief that 'the conditions that might make possible the global elimination of nuclear weapons . . . would require a fundamental transformation of the world political order' (Congressional Commission on the Strategic Posture of the United States 2009: xvi). Perceptions of the immutability of existing nuclear postures extended to the plutonium stockpile. The 2018 US Nuclear Posture Review called for a 'sustained plutonium pit manufacturing capability needed to . . . prepare for future uncertainty' (US Department of Defense 2018: 62). This conception of stockpiled plutonium as a safeguard against unknown dangers stood in stark contrast to the stockpile reductions mission. It instead signified preoccupation with a possible 'loss of influence over what happens to be the means of supreme political potency' identified by von Meier, Miller, and Keller in their sociological study of plutonium stockpile management (von Meier, Miller & Keller 1998: 25).

In line with the institutionalist account of organisational decision-making, DOE strategy mirrored this evolution in the social framing of weapons plutonium. Documents spanning the reductions programme exhibit a corresponding shift in rhetorical focus. Early planning identified two motivations for reduc-

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[23] Management issues at the NNSA may have further hindered its performance. The agency is regularly featured in the US GAO's list of federal programmes vulnerable to waste and mismanagement (US Government Accountability Office 2019: 217-221). The presence of seemingly 'built-in' resistance to execution of the plutonium stockpile reduction effort raises questions about why the US pursued reductions. Analysis by Lubkin suggests a role of principal-agent problems, wherein the interests of key actors—such as those within the US Department of State responsible for negotiating the PMDA and those within the Department of Energy responsible for implementing it—are imperfectly aligned (Lubkin 2017).

tion: 'the risk that either weapons or fissile materials could be obtained by unauthorized parties' (i.e. nonproliferation) and 'the risk that weapons or fissile materials could be reintroduced into the arsenals from which they came' (i.e. arms control) (US National Academy of Sciences 1994: 3). The former frames plutonium as an intrinsically valuable material to be protected from theft, the latter as an undesirable threat to global security that must be made inaccessible to everyone, including its current possessors. It is the arms control motivation alone that mandates permanent, irreversible elimination; nonproliferation aims could be achieved more cheaply by secure storage of plutonium to protect it from non-US actors.

In the ensuing decades, this arms control impetus faded and was eclipsed by the nonproliferation justification. A 2014 DOE report arguing for substitution of the means of disposal mandated by the PMDA spoke only of 'danger to national and international security due to proliferation concerns and potential use by non-state actors for nuclear terrorism purposes' (US Department of Energy 2014b: 7). The arms control justification, previously a central pillar of the reductions mission, was conspicuously absent.

While technical factors alone fail to explain the trajectory of the US weapons plutonium reductions effort, organisational factors exhibit substantial explanatory power. Evolution of the institutional context in which reductions were sought acted in tandem with the DOE's path-dependent tendencies to promote abandonment of the initial goal of permanent elimination by irradiation, and its substitution with a more familiar—and thus more organisationally tenable—means of disposal.

Organisational adaptation in chemical weapon stockpile reduction

In its execution of the chemical weapon stockpile reductions mission, the DOD has managed transitions between multiple unfamiliar, costly, complex elimination methods. In switching from the maintenance of chemical weapon inventories to their destruction, and from primitive forms of disposal to incineration and neutralisation, the DOD appeared remarkably unconstrained by its prior routines, willingly adopting new destruction techniques without major impairment of its chemical disarmament mission. If, according to organisation theory, reproduction of preexisting routines is the norm and the development of new capabilities is rare, what enabled the DOD to accomplish this remarkable feat of organisational adaptation?

Constant, drawing from his study of aircraft engine development, presents a facile model of institutional-technological change wherein members of an organisation are 'vectors for a specific replication code, carriers of a powerful set of programs that constitute the relevant tradition of practice' (Constant 2012: 221).

To successfully engage in new activities, some force must 'slice open an organization, insert the new vector and its programming, and presto! the organization starts replicating turbojets rather than piston engines' or, in this case, starts destroying chemical agents rather than stockpiling or dumping them (Constant 2012: 221-222). In this surgical metaphor, what driving force plays the role of the scalpel? Eden, in her analysis of nuclear war planning, posits several possibilities: the cycling of personnel, disruptive alteration of an organisation's operating environment, and the recognition of new opportunities for organisational gain (Eden 2004: 57-58, 221-226).

Assessing the chemical weapon case through this 'organisational change' lens reveals the confluence of several organisational forces that favored the department's successful adoption of a new reductions mission. There were three key factors. First, fifteen years passed between the cessation of ocean dumping and the 1985 congressional mandate for destruction of the chemical weapon stockpile. Systematic destruction did not begin until the late 1990s. The intervening decades provided sufficient time for turnover of personnel and fading of institutional experience, breaking the continuity of action on which organisational path-dependence rests (McNeil & Thompson 1971).

Second, the early stages of the destruction endeavour were punctuated by passage of the 1986 Goldwater-Nichols Act, which radically reshuffled the DOD's management structure and further cleared a path for organisational change (Lederman 1999: 33-50). The effects of this change on organisational agility are apparent in external evaluations of the Army's adaptation to the stockpile reductions mission. After the US General Accounting Office (GAO) attributed early problems with the Army's work on chemical demilitarisation to 'long-standing leadership, organizational, and strategic planning weaknesses', the Army rapidly revamped its programme management structures, garnering praise from the GAO for the alacrity with which these management failings were rectified (US General Accounting Office 2003: 12; US Government Accountability Office 2007). The Army's subsequent success in chemical weapon destruction has been broadly attributed to its ability to effectively exert centralised managerial control over the programme (Greenberg 2003).

Third, the unique nature of the DOD's financial structure incentivised the adoption of a costly stockpile reductions mission. As demonstrated by Allison's study of DOD decision-making processes, the department's behaviour is uniquely 'characterized by effective imperatives to avoid . . . a decrease in dollars budgeted' (Allison & Zelikow 1999: 169). From this perspective, the development of new technologies required for stockpile reductions represented an opportunity to capture additional dollars in the defense budget. That the DOD was motivated by its organisational propensity for budgetary expansion is evident in the tenacity with which it pursued this new mission. Congressional appropriators were at one point 'disturbed to learn that individuals employed by the Department of Defense have visited the Congress with paid consultants to "promote" the chemical agents and munitions destruction program' (US House of Representatives 1999: 281). Together, these organisational conditions fostered a recontextualisation of the DOD's framing of the chemical stockpile, from tools of war to be maintained for future use, to trash to be discarded, to the justification for costly, technologically-complex engineering programmes that would enable the capture of additional budgetary resources.

Alongside these factors, internal to the DOD, that facilitated its successful adoption of new routines, the international security environment within which this organisation acted evolved in a manner favourable to the reductions mission. During World War II, these weapons were perceived by the United States as a critical source of in-kind deterrence, preventing chemical weapon use by adversaries (Moon 1984: 17; Stockholm International Peace Research Institute 1971a: 147-152). Such thinking continued into the early decades of the Cold War.

Yet this belief in the deterrent benefits of chemical weapon stockpiling began to falter in the 1980s, contributing to the US transition from production and stockpiling of these weapons to their systematic destruction. In 1994 the Chairman of the Joint Chiefs of Staff told the Congress that 'Desert Storm proved that retaliation in kind is not necessarily required to deter the use of chemical weapons' (US Senate 1994: 39). Beyond this strategic reassessment, broader normative shifts drove stockpile reductions efforts. By the late 1990s, Price identified a contemporary conception of these arms as a 'weapon of the weak'. Chemical warfare was associated with discourses of 'barbarism', and nonuse with those of 'civilization' (Price 1997: 134-163). By the onset of systematic elimination in the 1990s, chemical weapons no longer occupied a privileged place in the US arsenal, as they had in the first half of the century.

Thus, stockpile reductions were prefaced by what Schelling termed a 'dominant negative preference' wherein 'not having the weapon is preferred irrespective of whether the other side has it' (Schelling 1984: 244). As predicted by the institutionalist account of organisational behavior, this evolution in the framing of the chemical stockpile created an environment particularly conducive to the DOD's adoption of a new stockpile reductions mission, and its acquisition of the necessary funding.

Unlike the technical bases for chemical weapon and weapons plutonium elimination, which were broadly analogous, dramatic differences are apparent in the organisational contexts in which these reductions missions were pursued. Organisational heuristics, path-dependence and evolution of the institutional framings of stockpiled armaments provide explanations for both the DOE's deleterious pivot to plutonium burial and the DOD's ability to reconfigure its relevant capabilities at great expense.

Conclusions

This analysis of technical and organisational characteristics of US chemical weapon and weapons plutonium stockpile reductions efforts yields two main findings. First, material and technical factors—process complexity, cost, etc.—did not unambiguously dictate their divergent outcomes. Effective, internationally accepted means of highly irreversible stockpile destruction were available in both cases, at similar costs. Second, organisational factors offer compelling explanations for both the relative success of the chemical weapon reductions effort and the failure of the weapons plutonium reductions effort. The destruction of weapons plutonium was stymied, in large part, by the DOE's path-dependent preference for alternative means of disposal, supported by the resilience of plutonium's dominant framing in US strategic discourses. Conversely, chemical disarmament has been facilitated by unique characteristics of the DOD and its operating environment, allowing for organisational change in accordance with a pervasive societal disinterest in the possession of these weapons.

Organisation theory proves a powerful tool for explaining the central puzzle of this disparity in outcomes. It also draws attention to two critical factors that facilitate successful stockpile reductions: liberation of the managing organisation from path-dependent organisational constraints and institutionalisation of the inherent undesirability of the stockpiled material (e.g., the formation of a dominant negative preference against stockpiling). While it may appear obvious that a state must be normatively committed to the elimination of weapons if it is expected to bear the potentially massive costs of eliminating them, the plutonium stockpile reduction case considered here suggests that the effects of these normative forces (or their absence) extend far beyond cases of complete renunciation of a weapons system. They may also, as in the plutonium case, influence the ability of a state to eliminate even a small fraction of a stockpile that has been declared excess to military needs.

These findings provide several lessons for future stockpile reductions efforts. First, the delegation of responsibility for managing these efforts constitutes a key determinant of their future progress. In the weapons plutonium case, the deleterious effects of staid organisational routines might be avoided by delegation of the reductions mission to a new organisation.[24] Alternatively, as recently proposed by the US Senate Armed Services Committee, the NNSA might be divorced from the DOE, insulating its management of the weapons stockpile from the 'flawed DOE organizational process' (Daly 2018). Second, reductions are un-

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[24] This mirrors recommendations for extrication of civilian nuclear waste management responsibilities from the DOE (Reset Steering Committee 2018: 27-41).

likely to find success unless paired with a broader security strategy and a political framing of the stockpile that are supportive of elimination. For example, integration into a broader arms control regime can help to stabilise individual agreements and programmes (Young 1986). Considering again the plutonium case, pursuit of a Fissile Material Cutoff Treaty alongside reductions could yield a more durable mandate for irreversible, multilateral stockpile reductions.

While this study focused on just two instances of US stockpile reductions, its approach and findings might be applied more broadly. As other states confront their aging stockpiles of chemical, nuclear and biological weapon materials, additional cases of relevance will arise. Many will involve the same technical and social challenges discussed here. For example, Russia's chemical weapon destruction programme, declared complete by the Organisation for the Prohibition of Chemical Weapons in 2017, was plagued by 'a lack of funding from domestic and international sources, political and bureaucratic instability, disagreements between federal authorities and regional leaders and public concerns about the environmental consequences of destruction' (Pikayev 2001: 31). These factors mirror those encountered in the US chemical and nuclear stockpile reductions programmes, and will likely arise in future reduction efforts.

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