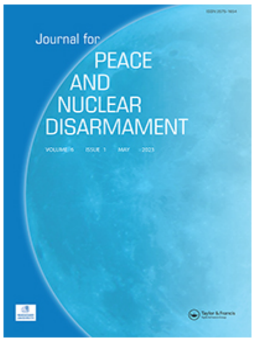
Article:

Ritchie, Nick orcid.org/0000-0002-6397-7498 (2023) Irreversibility and Nuclear Disarmament:Unmaking Nuclear Weapon Complexes. Journal for Peace and Nuclear Disarmament. pp. 218-243. ISSN 2575-1654

https://doi.org/10.1080/25751654.2023.2282737



Routledge
Taylor & Francis Group

Journal for Peace and Nuclear Disarmament

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rpnd20

Irreversibility and Nuclear Disarmament: Unmaking Nuclear Weapon Complexes

Nick Ritchie

JOURNAL FOR PEACE AND NUCLEAR DISARMAMENT
https://doi.org/10.1080/25751654.2023.2282737

Irreversibility and Nuclear Disarmament: Unmaking Nuclear Weapon Complexes

Nick Ritchie

Department of Politics, University of York, York, UK

ABSTRACT

This article develops a framework for examining "irreversible nuclear disarmament" by drawing on Science and Technology Studies (STS). It argues that maximising the irreversibility of nuclear disarmament is about the "unmaking" of a nuclear weapons complex understood as a large socio-technical system. This entails the discontinuation, or unravelling, of the system's network of materials, competencies, meanings and institutions, the erosion of tacit knowledge, the discursive reframing of nuclear weapons, and new governance processes to manage discontinuation. The article applies this framework to the experiences of the US nuclear weapons complex in the aftermath of the Cold War to illustrate the ways in which the weapons complex of an established nuclear-armed state could come apart.

ARTICLE HISTORY
Received 25 July 2023
Accepted 8 November 2023

KEYWORDS
Irreversible nuclear disarmament; large socio-technical systems; nuclear weapons complexes; United States nuclear weapons programme; science and technology studies

Introduction

The idea of "irreversibility" has long been a feature of nuclear disarmament discourse and tied into ideas about verification, transparency and universality. It formally entered disarmament diplomacy in the final document of the 2000 Review Conference of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) that set out 13 "practical steps for the systematic and progressive efforts to implement article VI of the Treaty", which commits states to work in good faith on measures to achieve nuclear disarmament. The fifth of the "13 steps" was "The principle of irreversibility to apply to nuclear disarmament, nuclear and other related arms control and reduction measures".

However, detailed thinking about irreversibility in relation to nuclear disarmament has been limited. There was some engagement with the concept in the 1990s, chiefly in relation to arms control agreements, specifically the Comprehensive Test Ban Treaty (CTBT), US-Russia strategic nuclear arms control reductions, and proposals for a Fissile Material (Cut-off) Treaty (FMCT) and its verification regime (for example, see White House 1995). In 2011 the Swiss government commissioned a study on irreversibility and nuclear disarmament by David Cliff, Hassan Elbahtimy and Andreas Persbo at the UK NGO VERTIC (Cliff, Elbahtimy, and Persbo 2011). More recently, in the early 2020s the UK and Norway funded research to unpack the concept of irreversibility in more detail and this article is a product of that work through a collaborative project on

CONTACT Nick Ritchie nick.ritchie@york.ac.uk Department of Politics, University of York, York YO10 5DD, UK

"Understanding irreversibility in global nuclear politics" led by King's College London (Wilton Park 2023).[1] The focus of this body of work is on how we can understand the irreversibility of a nuclear disarmament process in practice, rather than conditions for realising a disarmament process in the first place. Much of this work on irreversibility has focussed on questions of arms control, law and verification. The purpose of *this* article is to develop a framework for examining and understanding what "irreversibility" might mean in practice in a broader sense by drawing on Science and Technology Studies (STS). STS has rarely been used to examine nuclear weapons politics, but it is a rich body of conceptual and methodological ideas that has much to offer, as this article hopes to demonstrate.[2] Specifically, the article argues that: 1) nuclear weapons are social objects as much as they are a material technology; 2) a nuclear weapons complex is a large socio-technical system; 3) maximising the irreversibility of nuclear disarmament is about the "unmaking" of this socio-technical system within a society (MacKenzie 1999). A second purpose is to demonstrate the *possibility* (though not the inevitability) of practical irreversibility and therefore to challenge arguments that nuclear disarmament is to all intents and purposes impossible (for example Colby 2008).

In doing so, the article makes two original contributions. In the first section, it develops a conceptual framework for understanding irreversibility as unmaking nuclear weapons complexes. Here, it brings together STS analysis in nuclear studies with STS analysis of innovation, governance, disruption and discontinuation in large socio-technical systems. The second contribution is the application of this framework to the experiences of the US nuclear weapons complex in the aftermath of the Cold War in order to demonstrate the plausibility of the framework and point the way to further study. The United States was chosen because of the diversity of its nuclear experiences and the level of detailed information available on these experiences that is not available in other nuclear-armed states. The analysis is necessarily speculative because we have yet to experience the nuclear disarmament of an established nuclear-armed state.[3] Nevertheless, informed speculation serves an important purpose, because thinking through processes to maximise the irreversibility of nuclear disarmament will shape shared understandings of the very possibility of nuclear disarmament in the first place. First, though, the article unpacks what a "spectrum of irreversibility" might look like.

[1]Some readers will be sceptical that the UK government as a nuclear-armed state that seems committed to remaining so is serious about examining what nuclear disarmament could and should look like for two main reasons. First, an argument that this is a performative process to show that the United Kingdom is doing "something" on nuclear disarmament and that if the United Kingdom were really serious about it, it would get on with actually disarming. This is a valid criticism (see Harrington 2011). Second, an argument that this is a process to demonstrate a predetermined conclusion that nuclear disarmament is not assuredly irreversible and therefore nuclear disarmament is not possible. This is a less substantive criticism given the investment by the UK government in nuclear disarmament verification and statements that verification and irreversibility do not need to be perfect to enable disarmament processes. See IPNDV (IPNDV 2018) and Browne (2008). Moreover, the UK government is not a homogenous entity and there are those within its offices of state that take the disarmament commitment more seriously than others. But perhaps more importantly, discussions with officials from non-nuclear-armed states (for example at the Wilton Park conference cited above) suggest value in examining what the troika of "verification, transparency and irreversibility" mean in practice in order to lay some of the groundwork for nuclear disarmament and make the most of opportunities to achieve progress when they arise.

[2]There is a small body of work that applies STS to nuclear studies, including: Flank (1993), Spinardi and MacKenzie (1995), Spinardi (1994), Ritchie (2010), Harrington and Englert (2014) and Walker (2000).

[3]South Africa comes close and other scholars involved in the project have examined this case, e.g. Pretorius (2023).

A Spectrum of Irreversibility

The 2011 study by Cliff, Elbahtimy and Persbo developed the idea of irreversibility as a spectrum based on the cost and difficulty of rearmament. At the minimum end of their reversibility scale is the dismantlement of all nuclear explosive devices but with everything else in place, including warhead components. At the maximum end lies "the complete abandonment of all nuclear weapons as well as their means of production" (Cliff, Elbahtimy, and Persbo 2011, 47). This is reflected in diplomatic initiatives. For example, the Model Nuclear Weapons Convention submitted to the UN General Assembly by Malaysia and Costa Rica in 2007 is at the more minimal end of the spectrum with its definition of disarmament as, *inter alia*, to "dismantle and irreversibly disable the warhead and its components" (United Nations 2007, 16). Conversely, the 2017 Treaty on the Prohibition of Nuclear Weapons (TPNW) is towards the maximal end of the spectrum through its requirement for nuclear-armed states that join the treaty to "verify the irreversible elimination of their nuclear-weapons programme, including the elimination or irreversible conversion of all nuclear weapons-related facilities".

However, any state with a military nuclear reactor capability (for example to power submarines) and/or a mature civil nuclear infrastructure will be better placed to reverse a nuclear disarmament process than a state that does not. The maximum end of the irreversibility spectrum should therefore be extended to include constraints on or even elimination of nuclear fuel cycle facilities and nuclear power reactors. This is not to claim that a sustainable nuclear disarmament process *must* include such constraints, only to note that the irreversibility of such a process would be maximised by doing so (Perkovich and Acton 2008). Currently, however, this sits in tension with "the inalienable right" enshrined in the NPT "of all the Parties to the Treaty to develop research, production and use of nuclear energy for peaceful purposes", a right that was also embedded in the TPNW, and support for the role of nuclear energy in the shift away from fossil fuels.

One can go further still and extend the irreversibility spectrum to encompass restrictions on major weapon systems captured in proposals for "General and Complete Disarmament" (GCD) developed after the Second World War (White House 1962). A final step might include a dilution of militarism as a "cultural system" in disarmed states through a change in prevailing strategic cultures that value and legitimise nuclear weapons in particular and the maintenance of large military establishments and militarisation in general (Gusterson and Besteman 2019; Ritchie 2013). This speaks to the challenge of dislodging "nuclearism" as an ideology of security and undoing the "nuclearisation" of a society as a social-historical process (Ritchie 2022).

Extending the spectrum this far might appear unrealisable and therefore undermine the possibility of a nuclear disarmament process in the first place. Here, the distinction drawn between "adequate irreversibility" based on increasing the *level* of irreversibility and "total irreversibility" based on an unrealisable idea of permanent, guaranteed, absolute irreversibility is useful. This distinction was made in a paper on "Achieving Irreversibility in Nuclear Disarmament" for Working Group 1 of the International Partnership for Nuclear Disarmament Verification (IPNDV) chaired by the United Kingdom and the Netherlands (2018).

This means acknowledging that there is no process through which irreversibility can be guaranteed. Any disarmed state that is determined to redevelop nuclear weapons as a national priority irrespective of time, difficulty and cost will probably be able to do so. When we talk about irreversibility in nuclear disarmament, we are therefore talking about *maximising the extent to which* a disarmament process is irreversible in terms of a state's capacity and intent to reverse a set of decisions and processes to relinquish nuclear weapons and, to some degree, a nuclear weapons capability. Capacity refers to the resources, materials, expertise and infrastructure to reverse the process. Intent refers to a political intention to reverse a disarmament process based on shared understandings about what nuclear weapons and disarmament mean. In this sense, "irreversibility" is an example of what the German philosopher Immanuel Kant called a "regulative ideal": something that is not practically realisable but sets a direction and standards for a practice that can be approached though not attained (Elmet 1994).[4] The focus of this article is not on the full spectrum outlined here, but on the unmaking of a nuclear *weapons* complex as large socio-technical system.

Irreversibility as the 'Unmaking' of Nuclear Weapons Complexes

Actor-Networks and 'Large Technical Systems'

Science and Technology Studies (STS) and its scholarship on "Large Technical Systems" (LTS) Actor-Network Theory (ANT) and the social construction of technology (SCOT) provide the key conceptual tools for developing a framework for understanding irreversible nuclear disarmament. This scholarship is rooted in a social constructivist understanding of the relationship between technology and the social world. The core argument is that technology and society "constitute" each other, i.e. they shape and define each other. Therefore, the development of technologies and what they are understood to mean are dependent on social context, and at the same time social context is shaped by technologies and what they are understood to mean. The idea that technology is somehow autonomous and independent of the social world is rejected (Cressman 2009, 9). The notion of the "co-production" of technology and society through a network of relations has been developed by Sheila Jasanoff. She argues that STS concerns "the investigation of knowledge societies in all their complexity: their structures and practices, their ideas and material products, and their trajectories of change" (Jasanoff 2004, 2).

The framework developed here draws on the LTS scholarship that investigates the emergence and consolidation of large infrastructure and production systems in their social contexts, and actor-network theory that conceptualises actor-networks as a web of relationships or associations between a diverse set of actors encompassing people, texts, institutions, organisations, regulations, material objects, knowledge, practices, ideas, systems of meaning, and so on (Hughes 1983). Actor-networks have been studied in order to understand how a variety of social, economic, political and technical elements are shaped and assimilated together into a network, or socio-technical system, rather than taking the existence of the system for granted or assuming the processes and histories that produced it are obvious (Law 1987, 113). The social and technical aspects of these networks are always "intertwined and constitute each other" (Geels 2005, viii).

[4]Thanks to Benoit Pelopidas for this insight.

Studies of LTS tend to start with "system builders": those actors that unify and discipline diverse allies and orchestrate scientific, technological, political, economic and legislative processes to enable successful production of the system's technology (Spinardi 1994, 16). Successful technological systems are not politically or technologically inevitable, but contingent upon recruiting and sustaining a diverse set of allies in a large coalition whose interests have been successfully aligned with, or provide essential support for, the system's core technological output, for example safe, secure, deployed, and deliverable nuclear weapons.

Starting with system builders is helpful, because it enables us to see that being a nuclear-armed state means sustaining a national nuclear weapons complex over time because it won't endure by itself: decisions must be made, programmes must be funded, scientific and industrial sites must be modernised, organisations must work, manuals must be written, expertise must be sustained, new recruits must be trained, technologies must be developed, weapons must be refurbished, missiles and warheads must be tested, politicians must be enrolled, and so on. It takes organisational effort, knowledge, money, and political will to bring a nuclear weapons complex together and sustain it. If these dilute over time, then a nuclear weapons complex as a socio-technical system will start to come apart and become increasingly difficult to put back together. Steven Flank examined the assembly and then disassembly of the South African nuclear weapons actor-network. He shows that "a country's development of nuclear weapons *is* the evolution of a large technological system" that can be made and unmade (Flank 1993, 259). From this perspective, structurally embedding a nuclear disarmament process and therefore maximising its irreversibility means disassembling or unmaking the actor-network or socio-technical system that produces nuclear weapons (Ritchie 2010).

This scholarship also foregrounds the importance of shared systems of meaning that shape how technologies are understood through discourses (Bijker 1995). As STS scholar John Law, drawing on Foucault, put it: "discourses define conditions of possibility, making some ways of ordering webs of relations easier and others difficult or impossible" (Law 2007, 10). Moreover, "discursive stability" is one of the ways in which a LTS holds itself together over time. Jasanoff, also drawing on Foucault, explains that co-production is rooted in shared systems of meaning that make sense of social and material things and endow technologies with legitimacy (Hecht 2000; Jasanoff 2004, 6). This body of work also pays attention to the ways in which technologies shape the identities of social groups and "constructs the user every bit as much as the user constructs the technology" (Pinch 1998, 11). Nuclear weapons are therefore social objects insofar as there are no objective meanings innate to nuclear weapons as material things outside of their social context (Finnemore 1996, 6). Roscow, for example, argued that nuclear weapons are "cultural artefacts which derive meaning from the complex interaction of economic, cultural, and political forces" and that "nuclear weapons are not 'things', mere objects separable from the social, economic, and cultural systems which produce them" (Roscow 1989, 568).

Dismantling a Socio-Technical System

LTS studies have explored the phases LTS can go through, including stagnation and decline, but the *deliberate* dismantling of a LTS has not really been studied and we therefore know little about how technologies are purposely phased out and how incumbent socio-technical systems unravel and then cease to exist (Koretsky and van Lente 2020, 302; Stegmaier, Kuhlmann, and Visser 2014, 111). Nevertheless, the scholarship has approached the phase-out of a technology and the discontinuation of a socio-technical system in a variety of ways. Koretsky and van Lente define it as "a process of scaling down production, use and/or research and development of particular equipment, processes and associated practices to the point of their abandonment in wider society through a process of unravelling of the socio-technical configuration that makes up a technology" (Koretsky and van Lente 2020, 302). Turnheim defines it as "deliberate (governance) interventions seeking the partial or total discontinuation of a socio-technical form that is deemed undesirable" (Turnheim 2023, 45). Martin David uses the term "exnovation" as the opposite of innovation to describe the process whereby "a given technology is currently no longer used because its physical infrastructure has been deliberately removed" (David 2017, 139). He uses the example of the removal of fossil fuel technologies because "such technologies are societally framed as obsolete and undesirable" (David 2017, 138). Case study work shows that phase-out and discontinuation can be more or less complete, deliberate or organic, as a result of technology substitution or obsolescence, through policy termination via phase-out or an outright ban, or a gradual decline, labelled "decrementalism" (Turnheim 2023, 86, 89).

A number of scholars have looked in more detail at the destabilisation and discontinuation of socio-technical systems. Shove et al. develop a practice-based approach to explain how socio-technological systems and "complexes of practice" form and unravel. They argue that the process of phase-out/discontinuation is the process of disrupting, or unravelling, the linkages between three sets of elements that comprise a socio-technical system: 1) materials (objects, infrastructures, tools, hardware, the body); 2) competencies (know-how, background knowledge and understanding, shared understandings); and 3) meanings (mental activities, emotion, beliefs, and motivational knowledge) (Shove, Pantzar, and Watson 2012, 14, 23). To this I would add: 4) institutions (shared patterns of practice and formal organisations). When links are disrupted, these elements can disappear, become dormant to potentially be reactivated in the future, or become parts of other systems. The re-emergence of a socio-technological system is therefore possible if materials, competencies, meanings and institutions still exist even if they have been disconnected but remain dormant. The possibility of re-emergence is *enabled* by the precedent of these elements having been successfully connected before. It is only when the elements themselves start to disintegrate and be forgotten and unfamiliar that re-emergence, or reversibility, becomes much more difficult (Koretsky and van Lente 2020, 312).

In a similar vein, Koretsky explores decline as a series of "misalignments" between materials, competencies and knowledge. He introduces a distinction between "weak" and "strong" decline. Weak decline is where a technology is not used or produced anymore but all the other elements of the socio-technical system remain in place and therefore reversing the decline can be straight-forward (Koretsky 2023, 30). Strong decline refers to a more fundamental misalignment of the core relationships between materials, competencies and knowledge to the point where realignment is very hard: "associations are impossible because slippage, de-anchoring and/or un-learning are too profound (e.g. all materials are destroyed, carriers of competence or knowledge are gone, specific parts of technology are banned from use or manufacture) ... all that remains are dissociated materials, meanings, and competencies 'debris'" (Koretsky 2023, 32). Socio-technological systems can return from strong decline, but the process will be very difficult.

Studies also suggest that discontinuation will likely involve the restructuring, scaling down, and fracturing of parts of a larger set of LTS within which the target LTS is nested. Stegmaier, for example, describes the discontinuation of a LTS as an expansive process that affects "technology as well as the science, politics, economy, everyday practice, or law that supports it" (Stegmaier 2023, 79). For example, the deep entangling of civil and military nuclear complexes in the United Kingdom forces us to think about where we should draw the boundaries of a "nuclear weapons socio-technical system" whose range of activities, sites, materials, institutions, knowledges, discourses and so on should unravel *enough* to render the reversal of its unmaking extremely difficult (Stirling and Johnstone 2018). It is very likely that the boundaries of a nuclear weapons socio-technical system will scale in line with the degree of irreversibility deemed "adequate" on the spectrum of irreversibility outlined above (see Figure 1). In this example, the UK nuclear weapons complex is nested within a wider UK nuclear LTS and a military LTS that are themselves part of wider UK energy and industrial large socio-technical systems.

The loss of tacit knowledge is an important part of discontinuation. This type of knowledge is not explicated but acquired through experience and the practical craft of "doing" rather than "explicit knowledge" acquired through documents, technical manuals, simulations or instruction.[5] Spinardi and MacKenzie show that tacit knowledge is an essential part of sustaining a nuclear weapons complex and that the loss of tacit knowledge is very difficult to reacquire and would have to be reinvented and relearned

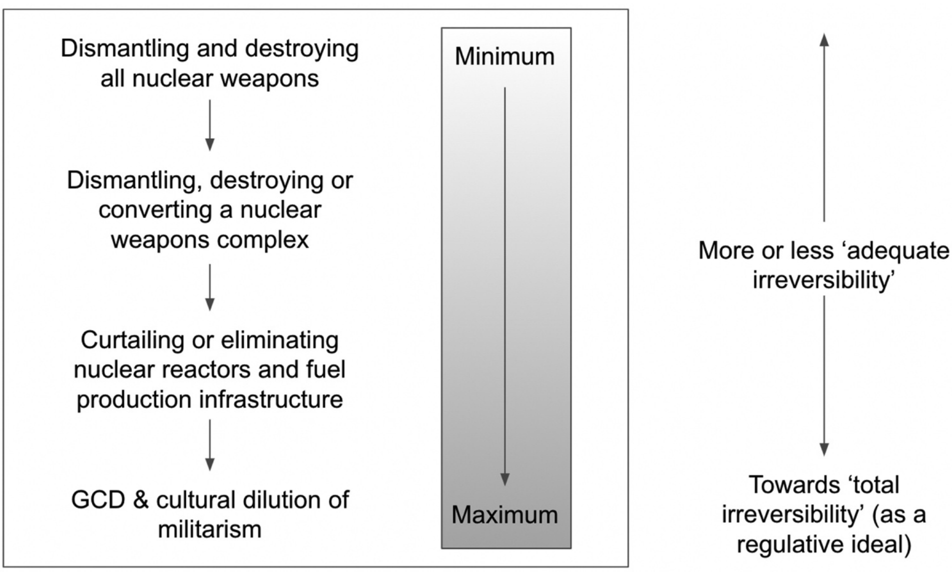


Figure 1. An irreversibility spectrum.

[5]For the best discussion, see Collins (2010). He breaks down tacit knowledge into relational, somatic and collective categories.

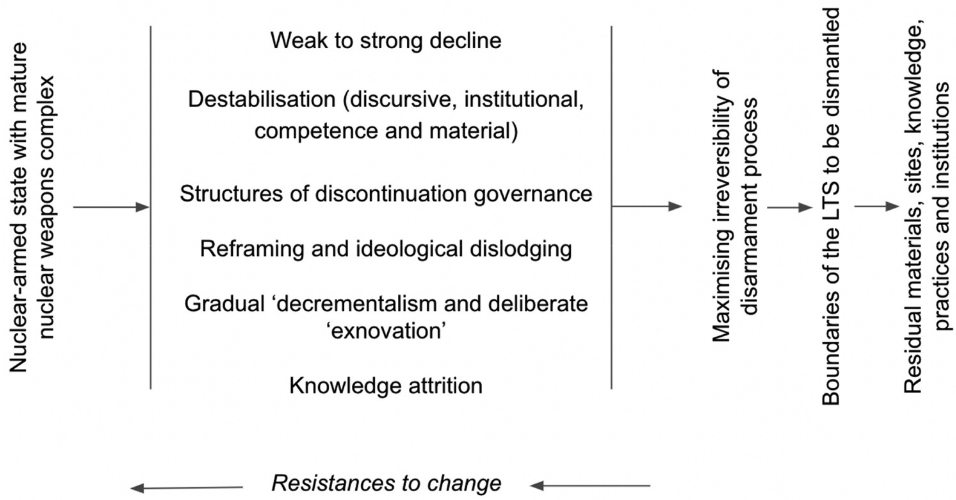


Figure 2. Factors in the 'unmaking' of a large nuclear socio-technical system.

through experience (Spinardi and MacKenzie 1995, 47, 62). Koretsky looks at processes that can lead to a "collective forgetting" or "unlearning" in an organisation, such as the degradation of methodological instructions in scientific organisations, retirements and career changes, loss of data, and loss of records when people die (Koretsky 2023, 28). Sturm highlights precisely these processes in the nuclear power industries in Eastern Europe after the collapse of the Soviet Union (Sturm 1993). The erosion of tacit knowledge due to the lack of continual performance gives a practice-based take on irreversibility as the *inability to perform core practices and thereby sustain competencies* (Koretsky 2023, 30). Overall, scholarship on processes of "unmaking" shows that elements of a LTS are unlikely to completely disappear for a long time. Instead, "What is left is often a remnant of usage and knowledge, infrastructure, and function, for a transitional period . . . In short, it seems as if almost nothing disappears completely at first" (Stegmaier 2023, 99). Time is therefore a key factor. For example, the capacity to transfer tacit knowledge, recruit a new generation and stem knowledge attrition within a LTS that is being discontinued is likely to reduce over time.[6]

Governance of Termination

This scholarship has more recently developed the idea of the "governance of termination" insofar as the termination, dismantling or discontinuation of complex socio-technological systems is a governance problem (Stegmaier, Kuhlmann, and Visser 2014, 115). What scholars like Stegmaier et al. mean by this, is that new governance processes are necessary to *unmake* the governance structures and processes underpinning the system to be discontinued and dismantled. For example, "the governance and policies that accompany the ending and the aftercare of what cannot be fully dismantled (like nuclear waste)" (Stegmaier, Kuhlmann, and Visser 2014, 115). They contend that

[6]Thanks to an external reviewer for this insight.

"The governance of the discontinuation of socio-technical systems appears on the political agenda whenever an actor or group of actors (a government, parliament, company or industry association, or group countries) make a sharp reversal of direction and actively disengage from on-going policy or governance commitment" (Stegmaier, Kuhlmann, and Visser 2014, 112). The focus of this work is on "ending phenomena: the processes and acts of destabilisation, deinstitutionalisation, deconstruction, dismantling, termination and related strategies and structures in socio-technological contexts" (Stegmaier, Kuhlmann, and Visser 2014, 116). David looks at how this can be done by "discontinuation entrepreneurs" promoting policy initiatives and change that can involve considerable effort "to invent and operate a governance of discontinuation" (David 2017, 87, 88). Governance in this sense refers to "a process of mutual shaping a political, market, technoscientific, or any other social order" at the national and international level. The purpose of "governance-making and governance structures" being "the stabilisation, maintenance/repair, and/or destabilisation of a given order" (Stegmaier 2023, 80).

From this perspective we can understand irreversible nuclear disarmament as both "the discontinuing of a governance (of a socio-technical system) *and* the governance of the discontinuing (of a socio-technical system)" (Stegmaier 2023, 116. Emphasis added). Doing so requires the mobilisation of existing governance instruments *and* the invention of new ones, insofar as "discontinuation is not mere retreat and downsizing, it is the construction of new forms of governance to support the discontinuation of existing orders" (Stegmaier 2023, 88). Hence there is an element of co-constitution here insofar as processes of undoing the governance structures of an established order and constructing the governance structures to *enable* that process are not parallel or sequential endeavours, but intertwined. The anti-nuclear testing regime, for example, has required the invention of a network of technologies (such as nuclear warhead stewardship programmes and the International Monitoring System), institutions (such as the Comprehensive Test Ban Treaty Organisation), norms, laws, and practices to normalise and operationalise the end of nuclear testing (Rosert et al. 2013, 122–27). Here, we can see how institutionalising the "unmaking" of a socio-technical system through governance processes helps embed the process and increase the challenge of reversing it.[7]

Reframing

Framing is an important part of producing and sustaining socio-technical systems, and studies show that "system builders" often purposefully frame systems and their core technologies through discourses that connect them to broader rhetorical or ideological agendas (Sovacool, Lovell, and Ting 2018, 1072). Framing is a social process that involves the construction of meanings because frames "help to render events or occurrences meaningful and thereby function to organize experience and guide action" (Benford and Snow 2000, 614). McAdam et al describe framing as "conscious strategic efforts by groups of people to fashion shared understandings of the world and of themselves that legitimate and motivate collective action" (McAdam, McCarthy, and Zald 1996, 6).

Unmaking socio-technical complexes involves discursive destabilisation through reframing. Social scientists describe this as the process of moving from one set of shared

[7]On the notion of "invention" in this context, see Ritchie (2018).

understandings that constitute a practice or technology such as nuclear weapons to another set of understandings that constitutes the practice or technology differently. Reframing is often based on active efforts to reassess the value, necessity and legitimacy of a practice. STS scholars like Stegmaier see reframing as an important part of "discontinuation governance" insofar as "[t]he discontinuation of governance practices . . . is seen as the discontinuing of a particular way of solving a policy or a governance problem as the result of a changed framing (formulation, perception) of a problem or solution" (Stegmaier 2023, 88). Moreover, delegitimisation can be central to reframing. In their study of coal phase-out, Markard et al. argue that "the struggle over phase-out policies is also very much a struggle over the legitimacy of the focal practice or technology . . . Only if the established technology loses its legitimacy can we expect widespread societal and political support to enact phase-out policies" (Markard, Isoaho, and Widdel 2023, 120).

Changes to established meanings can become embedded in organisations and social institutions over time and internalised to the extent they become conflated with an actor's sense of identity. This can lead to the redundancy and even stigmatisation of previously accepted practices that have been prohibited (Price 1995, 87). In fact, social stigmatisation is the acme of *ideational* irreversibility. For example, the social changes required for a state like the United Kingdom to re-legitimise stigmatised practices such as slavery, genocide, chemical warfare and so on, would be considerable and are difficult to imagine (though it is, of course, always possible).[8]

In sum, Science and Technology Studies provides a number of conceptual tools to develop a framework for thinking about irreversibility in relation to nuclear disarmament. Specifically, we can conceptualise nuclear disarmament as maximising irreversibility in terms of the destabilisation, discontinuation and "strong decline" of a nuclear weapons complex as a socio-technical system. This can be deliberate or organic and gradual through "decrementalism" or more complete through termination and phase-out ("exnovation"). This entails the coming apart of a system's materials, competencies, meanings and institutions and the erosion of tacit knowledge and the ability to perform the system's core practices. Moreover, by introducing examples of the "governance of termination", we can think about "irreversibility as invention" as well as unmaking, and the different forms disarmament governance could take through a process of "inventing" nuclear disarmament. Finally, unmaking a nuclear weapons complex will involve discursive destabilisation through a reframing process that changes the systems of meanings that currently make sense of these weapons in nuclear-armed societies.

Resistances to 'Unmaking' Large Socio-Technical Systems

The sections above have outlined processes from the STS scholarship involved in the unmaking of large socio-technical systems (see Figure 2). This scholarship also highlights ways in which processes of change and unmaking of LTS can be resisted even when political decisions have been taken to discontinue, repurpose, or dismantle a LTS. Sovacool, Lovell and Ting, for example, argue that an "attribute of LTS, which arises in

[8]Reframing and stigmatisation can also go beyond specific weapons or other materials, like coal, and target a wider cultural assemblage, such as colonialism or slavery. Extending the role of reframing in this way can encompass the process of diluting a culture of militarism within a society at the maximum end of the spectrum of irreversibility.

their maturity, is *obduracy*, or resistance to change through path-dependence, "lock in" and inertia agendas (Sovacool, Lovell, and Ting 2018, 1070). Jordan, Green-Pedersen and Turnpenny (2012) highlight the ways in which "policy dismantling" can be inhibited by the fracturing of coalitions for change, unequal distribution of the costs and benefits of change that prompt resistance, and the ability of party politics and interest groups to mobilise opposition. Bauer and Knill (2012) highlight the role of external events and crises that can increase the costs of discontinuation and generate resistance.

LTS scholarship also demonstrates the ways in which some technologies necessitate particular types of social relations that can become deeply embedded in a society. Langdon Winner's study of US nuclear reactors is the classic example, in which he argues that ensuring the safety of nuclear reactors *requires* authoritarian systems of management, extremely tight security and policing of the hazards and vulnerabilities that nuclear reactors produce (Winner 1986, 175). Similarly, he argues that "the atom bomb is an inherently political artifact. As long as it exists at all, its lethal properties demand that it be controlled by a centralized, rigidly hierarchical chain of command closed to all influences that might make its workings unpredictable. The internal social system of the bomb must be authoritarian; there is no other way. The state of affairs stands as a practical necessity independent of any larger political system in which the bomb embedded, independent of the type of regime or character of its rulers" (Winner 1980, 131).

William Walker (2020) examines in more detail the challenges of "dislodging" and "disembedding" nuclear weapons complexes from societies in terms of resistance to change and resistance to reversal if change occurs. He develops a framework that establishes six aspects of a nuclear weapons complex that can become deeply embedded in nuclear-armed states and would need to be *disembedded* in order to maximise the irreversibility of a nuclear disarmament process: 1) the formation of a "nuclear estate" (the infrastructure of nuclear weapons development, deployment, maintenance, intelligence and command and control); 2) the incorporation of nuclear strategy in political and military doctrines and practices; 3) the framing of threats and security dilemmas that are deemed to necessitate a nuclear arsenal; 4) the conflation of ideas of national identity with nuclear weapons; 5) the development of a dogmatic belief system that reifies nuclear deterrence; and 6) international acceptance of a nuclear programme and its association with status and prestige in international society.

Nuclear weapons as a material technology shape, and are shaped by, social relations that form a nuclear weapons complex as a large socio-technical system that would likely be highly resistant to change even in a situation in which a political decision to relinquish nuclear weapons has been taken. As van der Vleuten notes, "If mature large technical systems are characterized by a large momentum and resist change, only extreme external conditions like warfare, oil crises, environmentalism and government interference may change the development trajectory" (van der Vleuten 2009, 221).

The United States and 'Structural Nuclear disarmament' in the 1990s

The second part of the article applies aspects of this framework to the experience of the US nuclear weapons complex in the 1990s to illustrate the ways in which a nuclear weapons socio-technical complex could *potentially* come apart. The US experience is particularly useful because it encompasses a number of empirical cases for which detailed information is available and that illustrate key aspects of the framework.[9] Three cases are explored: 1) organic destabilisation of the US nuclear weapons complex at a macro level; 2) managed discontinuation of a core practice through the end of nuclear weapons testing; and 3) discontinuation governance through the Cooperative Threat Reduction (CTR) programme with the successor states to the Soviet Union.

Organic Destabilisation of the Nuclear Weapons Complex

The first case demonstrates a process of "decrementalism": a gradual, organic set of changes on a path towards the unmaking of the US nuclear weapons complex as a heterogeneous socio-technical system through four forms of destabilisation: discursive, institutional, competency and material. This decremental process unfolded in the 1990s under the Clinton administration and became a source of deep concern given that the United States was committed to sustaining a large nuclear arsenal. Critics interpreted these developments as "erosion by design" (Spence 1994; Kyl 1994, H3542; Thurmond 1991, 3) and "self-imposed structural disarmament" (Gaffney 1991, 818) to shrink the complex and reduce the role of nuclear weapons and warned that it would lead to unilateral disarmament if unchecked. It resulted in concerted action by the state to reverse the process and prevent "weak" decline becoming "strong" decline. The case is therefore illustrative of the *potential* for a decremental process to lead to the unmaking of a nuclear weapons complex *unless* active steps are taken to prevent it, notably by the "system builders".

The first form of destabilisation affecting the nuclear weapons complex was *discursive destabilisation*. The destabilisation of established discourses is one way in which the framing of policy choices and priorities can change (Milliken 1999). This began in the mid-1980s and accelerated when the termination of the Cold War conflict shifted the system of meaning that prioritised nuclear weapons in US national security culture (Mehan, Nathanson, and Kelly 1990). During the Cold War, US national security was defined by military competition with and containment of a Soviet Union that was portrayed as an aggressive, expansionist enemy capable of launching a devastating surprise nuclear attack and intent on political coercion through strategic military superiority. Nuclear weapons were central to this paradigm and the rationales and roles for US nuclear weapons were conceived almost exclusively through the lens of US-Soviet competition. The nuclear competition was linked to global political power such that an inferior US nuclear force would permit Soviet coercion and a loss of US influence in the world (Kull 1988, 114). The US was determined to retain the strategic superiority on which it perceived its security to rest, and this supported the growth of a sprawling nuclear-military-industrial complex and the development of a massive nuclear arsenal. This paradigm evaporated with the sudden and unexpected demise of the Soviet Union and was soon replaced by a much more expansive national security paradigm in the 1990s that encompassed human rights abuses, international crime, drug trafficking, WMD proliferation, terrorism, climate change, civil war, famine and genocide. Perceptions of nuclear threats shifted from the large nuclear arsenal of a peer-

[9]Other work has drawn on STS to examine the South African case of nuclear disarmament, e.g. Flank (1993).

competitor to regional WMD-armed "rogue" states with small or embryonic nuclear weapons programmes (Ritchie 2009). Moreover, the end of the Cold War was interpreted by many states and civil society organisations as a window of opportunity to devalue nuclear weapons and push them into the background of inter-state relations on a path towards their eventual elimination (Aspin 1992; Barkenbus 1989; Canberra Commission 1996).[10]

The nuclear weapons complex was subject to *institutional destabilisation* as the political executive (the core system builder) began to lose interest in nuclear weapons at senior political and military levels, chiefly because nuclear weapons now mattered far less to US national security than in the past and no major procurement decisions were required (Garrity 1991, 485). US nuclear weapons policy quickly became a second or third order priority in the Department of Defense (DOD) and garnered much less senior-level attention (Gray 1999, 41, 60). Incentives to pursue a nuclear career in the armed services diminished and fell out of the mainstream, with no single dedicated nuclear career track and dwindling nuclear policy and planning expertise in the services (Garrity 1991; Joseph and Lehman 1998a; Hamre 1998). Nuclear weapons were institutionally de-emphasised in DOD through the reorganisation of the Defense Nuclear Agency into a new Defense Threat Reduction Agency (DTRA) in which the nuclear weapons mission was only one of four core missions (Harahan and Bennett 2002, 10); changes to the position of Deputy Assistant Secretary of Defense for Nuclear Forces and Arms Control Policy to reflect the de-emphasis of nuclear weapons (Crouch 2001); and the erosion and elimination of the position of the principal advisor to the Secretary and Deputy Secretary of Defense for all matters concerning nuclear weapons policy and staff director of the Nuclear Weapons Council (the Assistant to the Secretary of Defense for Nuclear, Chemical and Biological Defense Programs (ATSD(NBC)) leaving no single point of contact in DOD on nuclear weapons issues (Cohen 1997; Harahan and Bennett 2002). By the end of the 1990s, critics argued that there was no focal point for US nuclear weapons policy, little senior-level involvement, no centre of expertise for nuclear policy issues, no planning to retain nuclear-related skills leading to critical expertise shortfalls, institutional fragmentation of nuclear weapons responsibilities, minimal activity at the Nuclear Weapons Council, causing an erosion of the US nuclear posture (DSB 1993, iii; DSB; DSB 1998, 22–23; DSB; DSB 2006, 33).

The complex was also subject to *competency destabilisation* through loss of expertise and tacit knowledge, especially at the nuclear weapons laboratories where the practical knowledge base had built up gradually over decades through hands-on development of nuclear weapons and explosive nuclear testing (Spinardi and MacKenzie 1995, 62). Congress expressed deep concern about the loss of nuclear weapons expertise and mandated a number of task forces to address it. These included the Commission on Maintaining United States Nuclear Weapons Expertise to develop a plan for recruiting and retaining nuclear weapons expertise in 1996 (DOE DOE 1999a); a study of DOE's management of the nuclear weapons programme in 1997 (Richanbach et al. 1997), and a "30-day review" in 1999 (DOE DOE 1999b). These reports criticised DOE, highlighting poor management, the importance of retaining nuclear weapons expertise, the significant difficulties in attracting and retaining staff for senior positions, the limited opportunities

[10]Aspin was at the time Chairman of the House Armed Services Committee.

to exercise the full range of weapon design and production skills, and a piecemeal approach to sustaining critical nuclear skills.[11]

Finally, the complex was subject to *material destabilisation* that left the ability to sustain a Cold War legacy nuclear stockpile over the long term in doubt. Under legal, budgetary and congressional pressure the nuclear weapons complex was forced to shift its focus from large scale nuclear weapons production to clean-up as safety, security and environmental problems caught up with the complex (Hecker 1992; Olshanksky and Williams 1990). This severely limited ongoing nuclear weapon production plans that still required thousands of new warheads as the Cold War ended (Albright, Zamora, and Lewis 1990; Herzfeld 1990, 53). The closure of the Rocky Flats Plant, for example, left the United States little choice but to end production of W-88 warheads for the Trident D5 SLBM and cease production of fissile materials for nuclear weapons (Claytor 1992, 19). It was estimated at the time that it would take at least 12 years to relocate these capabilities (Reis 1998). New tritium and plutonium pit production facilities to sustain a large nuclear arsenal were not forthcoming and processing operations at the Oak Ridge Y-12 plant for producing uranium components for nuclear warheads were shut down in 1994 due to violations of safety controls, eventually restarting in the late 1990s (Reis 1998). Overall, the nuclear weapons complex infrastructure was in poor shape after years of neglect and massive clean-up problems throughout the 1990s with a growing backlog of deferred maintenance of key facilities that affected production programmes.

These four interrelated forms of destabilisation unfolded together in the 1990s and constituted an organic process of "decremental" unmaking of the nuclear weapons complex that had to be addressed if the United States were to remain a nuclear weapon state with a large, diverse nuclear arsenal. Together, they provide a useful framework for examining a process of "unmaking".

Managed Discontinuation of Explosive Nuclear Testing

The second case is the end of explosive nuclear testing in the 1990s in the context of the negotiation of the Comprehensive Test Ban Treaty (CTBT) in 1996 and the consolidation of the US nuclear weapons complex. This is a case of the managed discontinuation of a core practice of the complex and the challenges of maintaining the infrastructure to resume that practice if required to do so. The case is illustrative insofar as it casts doubt on the ability of states to hold a nascent nuclear weapons complex in a permanent state of readiness to reverse a nuclear disarmament process, thereby reinforcing the possibility of irreversibility in the ways outlined above.

Widespread concern in the United States about the erosion of the nuclear weapons complex after the Cold War was fuelled by the end of explosive nuclear weapons testing following a testing moratorium in 1992 and negotiation of the CTBT that was signed by President Clinton. Managing the discontinuation of nuclear testing had two outcomes based on resistance to complete phase-out and deliberate "strong decline": first, plans to reverse the decision in the future if security conditions deteriorated or

[11]In 1996 the Senate Armed Services Committee Report on the National Defense Authorization Act for FY 1997 also expressed concern about the ability of the Department of Defense to maintain the necessary expertise to sustain the US nuclear arsenal without nuclear testing. See Cohen (1997).

a serious problem emerged with a warhead-type in the stockpile in order to reassure domestic political sceptics of the CTBT; and second, long-term investment in a science and technology-based Stockpile Stewardship Program (SSP) to ensure the safety and reliability of existing nuclear warheads and to potentially design new ones without nuclear testing through a suite of expensive new diagnostic facilities. The SSP was also designed to address concerns about atrophying of nuclear expertise, skills and tacit knowledge necessary to maintain a nuclear weapons programme without nuclear testing (DOE DOE 1999b; DSB; DSB 2006). The programme's primary rationale was to develop an understanding of the functioning of all aspects of nuclear weapons and the behaviour of the materials involved as they aged; maintain the capability to identify problems in nuclear warheads; repair any problems; and certify the repairs or replace warheads that could not be repaired – all without explosive testing (Collina and Kidder 1994; Hecker 1997, 207).

Clinton set this out in a series of "safeguards" in 1997 as he sought, unsuccessfully, to secure ratification of the CTBT by Congress (the Senate rejected the treaty in 1999). These were: 1) continuation of a robust Stockpile Stewardship Program; 2) maintenance of modern nuclear laboratory facilities and programmes to attract and retain nuclear weapons expertise; 3) maintenance of the basic capability to resume nuclear tests if needed; 4) a comprehensive programme to improve CTBT monitoring capabilities; 5) an annual stockpile certification process in domestic law that required the Secretaries of Defense and Energy to certify to a high degree of confidence that the stockpile is safe and reliable, and, if not, whether testing is necessary; and 6) acceptance that the President, in consultation with Congress, would be prepared to withdraw from the CTBT to conduct whatever testing might be required if a major problem arose with the safety or reliability of a nuclear weapon-type that the Secretaries of Defense and Energy considered critical to the US arsenal (Clinton 1997, 1998; Reis 1997).

The Clinton administration therefore required DOE to maintain the capability to conduct an underground test within 24–36 months of a decision to do so, set out in Presidential Decision Directive-15 (PDD-15) in 1993. This meant maintaining the required infrastructure, personnel, skills and knowledge to conduct nuclear tests through subcritical experiments, hydrodynamic tests, and exercises (PDD 1993). The US nuclear weapons laboratories maintained a permanent presence at the test site and assigned technical staff to the Test Readiness programme managed by the National Nuclear Security Administration (NNSA). Together with staff at the Nevada Test Site (since renamed the Nevada National Security Site), they were required to conduct annual assessments of test readiness and support NNSA in its biannual report to Congress on essential nuclear workforce skills, capabilities, and infrastructure requirements to support test readiness (Government Accountability Office 2007). The Nevada Test Site conducted training exercises to practice the skills and processes necessary to conduct a nuclear test and maintained a roster of retirees with experience of nuclear testing to be called upon should testing resume (Reis 1996). In 2001 the Bush administration announced it would reduce the time required to conduct a nuclear test to 18 months by September 2005 but it did not make this a legal requirement and Clinton's PDD-15 requirement to be able to test within 24–36 remained in force. Nevertheless, in 2017, DOE published a new interpretation of PDD-15 that planned for "6 to 10 months for a simple test, with waivers and simplified processes; 24 to 36 months for a fully instrumented test to address stockpile needs with the existing stockpile; 60 months for a test to develop a new capability" (DOE 2017).

However, despite this policy and planning, the US struggled to sustain a robust test readiness posture. A detailed report on the resumption of nuclear testing in 2021 by the Johns Hopkins Applied Physics Laboratory concluded that the United States would struggle to conduct a nuclear test in the time-frames currently required because nuclear test teams has long since dispersed since the last test in 1992, first-hand knowledge has atrophied, and most of the equipment, facilities, and supporting infrastructure has fallen into disuse and would have to be reconstituted (Frankel, Scouras, and Ullrich 2021, 38). They set out the scale of the task of conducting an underground nuclear test citing retired associate director of LANL, John C. Hopkins, who said "In sum, there is essentially no test readiness. The whole testing process – whether to conduct one test or many – would in essence have to be reinvented, not simply resumed" (Frankel, Scouras, and Ullrich 2021, 39 citing; Hopkins 2016). Geoffrey Steeves (US Air Force) also unpacked the costs, complexities and challenges of a resumption of nuclear testing based on the type of test required on spectrum from a hydronuclear diagnostic test to a full experimentation test for a new warhead design (Steeves 2020, 26). He argues that the United States lacks the organisational, technical, and logistical expertise needed to integrate "15 specialties as part of an entire system to conduct an underground nuclear test … containment, security, assembly, storage and transportation, insertion, emplacement and stemming, timing and control, arming and firing, diagnostics, test control centre activities, post-shot drilling, nuclear design, weapons engineering, test integration, and nuclear chemistry. All these specialized areas either complement or are in addition to the aforementioned challenges in that they represent a unique level of complexity" (Steeves 2020, 35–36).

This case of managed discontinuation foregrounds a number of issues. First, it shows how a commitment to an irreversible change through a prohibition and phase-out was conditioned on a plausible pathway to reversal. Second, it demonstrates the serious challenges of sustaining a plausible pathway over time and preventing planned "weak" decline from drifting to "strong" decline that becomes very difficult to reverse. In this case, despite continuous concerns over the post-Cold War period about the ability of DOE to resume nuclear testing within the 2–3 years mandated in PDD-15, major challenges remain to the extent that explosive nuclear testing cannot be re*started* but would have to be re*invented*. Third, it shows how discontinuation governance can encompass the invention of infrastructure, institutions, expertise, discourse and practices, in this case through the SSP.

On the latter, Benjamin Sims (from Los Alamos National Laboratory) and Christopher Henke draw on Science and Technology Studies to describe the SSP as a process of "sociotechnical repair" (Sims and Henke 2012, 325). Sociotechnical repair refers to a set of practices enacted to hold a socio-technical system together that is facing a systemic crisis. In this context, "the techniques actors use to maintain the practices, institutions, and technologies that form a system such as the nuclear weapons complex" (Sims and Henke 2012, 326). They identify three forms of repair. First, "discursive repair" to stabilise and sustain the discourses that make sense of the system and normalise and legitimise its continuation. In this context "stockpile stewardship" became the central "organizing concept of the US nuclear weapons complex" (Sims and Henke 2012, 325) despite initial resistance from critics who argued that the SSP was a high risk strategy that was unlikely to replace knowledge previously gained through nuclear testing and would undermine confidence in the reliability and safety of the nuclear stockpile (Bailey 1998; Joseph and Lehman 1998b; Robinson 1999). Second, "material repair" to fix, rebuild, manufacture or replace the material components of the socio-technical system through massive investment in the nuclear weapons laboratories. Third, "institutional repair" to revitalise the social structures and practices essential to the socio-technical system, in this case by transforming the institutions that produce weapons knowledge through modelling and simulation (Sims and Henke 2012, 326). Their study shows that "regimes of knowledge" are not static but must be continually "maintained through ongoing processes of repair and revision" to prevent erosion. They also demonstrate "the level of effort devoted to maintaining a set of technological artifacts [warheads] in an essentially static state" through massive investment (Sims and Henke 2012, 323). What they are talking about here is a deliberate process to hold a destabilised actor-network together over time and prevent organic processes of organic weak decline and managed discontinuation in specific areas like explosive testing from escalating to strong decline of the wider socio-technical system (Sims and Henke 2012, 343).

Cooperative Threat Reduction as Discontinuation Governance

The third case is the Cooperative Threat Reduction (CTR) programme pioneered in the early 1990s by Senators Richard Lugar and Sam Nunn. Lugar, Nunn and others feared that the Soviet nuclear weapons complex was "coming apart at the seams" as the country disintegrated, requiring an emergency response from the United States (Bernstein and Wood 2010). This led to an unprecedented effort to secure or eliminate Soviet nuclear weapons systems and related materials and capabilities, establish safe, secure and verifiable means of transport and storage for weapons and materials, and prevent the diversion of scientific expertise that could contribute to WMD programmes in other states. The programme came to involve the Departments of Defense, Energy and State and it is an excellent example of reactive "discontinuation governance" in nuclear politics, i.e. the invention of new forms of governance to manage the discontinuation of a nuclear practice, or set of nuclear practices.

CTR was enabled by a discursive reframing of Soviet nuclear weapons within the US nuclear enterprise from an overwhelming direct military threat in the hands of a peer-adversary, to a dangerous liability through a frame centred on reassurance, vulnerability, safety and coordinated and cooperative initiatives with partners in the former Soviet states, including a much-weakened Russia. This led to new discourses, institutions, practices and material capabilities to deal with the fractured Soviet nuclear weapons complex, resulting in a web of agreements, initiatives, partnerships and funding programmes. These included:

- The US Department of Energy's Initiatives for Proliferation Prevention (IPP) programme to provide alternative employment for Russian nuclear scientists.
- A Strategic Offensive Arms Elimination programme to facilitate the dismantlement and elimination of nuclear weapons and their launchers under the START I nuclear arms control agreement.

- A chain of custody programme to ensure continued security and custody of nuclear weapons and materials, including transportation security, fissile material storage and weapons storage security programmes, including helping Russia design and build a highly secure long-term fissile material storage facility at Mayak.
- Establishing an International Science and Technology Center (ISTC) in Moscow and a Science and Technology Center of Ukraine (STCU) in Kiev to facilitate science projects with former weapons scientists, technicians and engineers.
- A Government-to-Government Agreement in 1998 to establish the Nuclear Cities Initiative (NCI) managed jointly by the US DOE and Russian Minatom to assist Russia with the downsizing of its nuclear weapons complex and to promote alternative, commercial enterprises in the closed nuclear cities.
- A programme in 2002 to shut down old plutonium production reactors and replace them with fossil fuel power stations.
- A DOE Material Protection, Control and Accounting (MPC&A) programme to secure Soviet-era nuclear weapons and weapons-usable materials.
- A DOE Materials Consolidation and Conversion Programme to consolidate Russian nuclear materials at secure sites.
- A Defense Enterprise Fund to support the demilitarisation of industries and conversion of military technologies and capabilities into civilian activities.

Related agreements included the Plutonium Management and Disposition Agreement signed in 2000 and the United States-Russia Highly Enriched Uranium Purchase Agreement in 1993, also known as the "Megatons to Megawatts Program" through which Russia down-blended highly-enriched uranium from retired nuclear weapons and supplied the low-enriched uranium to the United States to convert into nuclear fuel for civil nuclear reactors. It also involved inventing new institutions such as the Demilitarization Enterprise Fund and the ISTC and STCU science centres (Weiner 2011). This enabled the irreversible elimination or decommissioning of a significant number of nuclear weapons, weapons materials and production sites and the managed discontinuation of parts of the Soviet weapons complex as a socio-technical system.

This required not only reframing and invention, but the forging and embedding of a CTR actor-network as an extension of the US nuclear weapons enterprise. This involved building domestic coalitions between US executive agencies, weapons laboratories and Congress and forging international agreements and partnerships with governments and agencies in the successor states of the Soviet Union (Walker 2016). It required the negotiation of agreements for provision of funds, contractor liabilities, rights and responsibilities assumed by each of the parties, specific project objectives with recipient countries and the passing of the 1993 Cooperative Threat Reduction Act by Congress along with other legislation to authorise these programmes. In doing so, the Clinton administration elevated CTR to a national security priority, a "core strategic concept" and a "central organising principle" for dealing with nuclear dangers with the National Security Council responsible for its oversight and coordination (Krepon 2003, 12). Some of these programmes fared better than others, notably those centred directly on the irreversible elimination of nuclear weapons and weapons materials (Weiner 2011, 294–97). But nonetheless, this constituted the invention of a system of direct discontinuation governance through reframing, institution-building, and major material changes to manage the undoing of the Soviet nuclear weapons programme and irreversibly eliminate parts of the system, whilst consolidating others.

Conclusion

The purpose of this article has been to unpack what maximising "irreversible nuclear disarmament" means using the conceptual tools developed in Science and Technology Studies, especially the scholarship on Large Technical Systems. The first part argued that irreversibility is a spectrum on which a state can be more or less "disarmed", and that nuclear weapons are social objects embedded in a nuclear weapons complex understood as a large socio-technical system. Maximising irreversibility therefore means the practical unmaking of a nuclear weapons complex as a socio-technical system through: 1) destabilising the connections between the system's materials, competencies, meanings and institutions; 2) discursive reframing to shift the system of meanings that constitute nuclear weapons, including in relation to shared ideas of national identity, and perhaps to the point of stigmatisation; 3) the discontinuation of core practices and the erosion of tacit knowledge; and 4) inventing a "governance of termination" through new actor-networks of discourses, practices, institutions and materials. These dynamics can structurally embed disarmament over time as strong decline kicks in through a combination of deliberate and organic processes, "decrementalism" and "exnovation", but they can also be subject to resistance.

The second part illustrates the utility of this framework by applying it to the US experience after the Cold War in lieu of an empirical case of the nuclear disarmament of an established nuclear-armed state (acknowledging that the cases of South Africa, Kazakhstan, Belarus and Ukraine have been studied in detail). Three aspects of the US experience are explored: organic destabilisation of the nuclear weapons complex; managed discontinuation of explosive nuclear testing; and CTR as discontinuation governance. These three cases are illustrative of the possibility of irreversible nuclear disarmament once a decision to relinquish nuclear weapons has been taken: they show how organic processes of destabilisation can take multiple forms and escalate to unmake a LTS unless resisted, how maintaining a nascent nuclear weapons complex is likely to be very difficult, and how new modes of governance can emerge to enable the discontinuation of a nuclear weapons complex.

There are many other cases for future research to examine the possibility of irreversible nuclear disarmament. These include the US and Soviet/Russian Presidential Nuclear Initiatives in 1991 and 1992, the processes of shutting down nuclear test sites (for example the dismantling by France of its nuclear test sites on the Moruroa and Fangataufa atolls in French Polynesia between 1996 and 1998), the phase-out of fissile material production plants (for example at the Marcoule site in France and the Capenhurst Gaseous Diffusion Plant in the United Kingdom), and the denuclearisation of branches of armed services (for example the UK Royal Air Force and the US Army).

Overall, the US experience shows that the continuation of a LTS is not inevitable but takes a lot of political, intellectual, organisational work and expense, especially when incentives to sustain it start to change and diminish. In a context in which a nuclear disarmament process has been agreed, the types of processes outlined here would very likely escalate, perhaps quickly, and make re-establishing a safe, secure and reliable nuclear arsenal and the complex to support it very difficult. Claims that a nuclear weapons complex could be sustained in a state of readiness to rapidly reproduce and redeploy nuclear weapons in a disarmed world should therefore be treated with caution. Not only will the LTS and its components degrade significantly over time, but the political will to retain people, facilities, materials, and expertise to be rapidly mobilised to redevelop nuclear weapons will very likely diminish, particularly since a disarmament process will almost by definition involve the significant devaluing and delegitimisation of nuclear weapons.

An ebbing away of the expertise and tacit knowledge necessary to sustain a nuclear weapons complex will be an important part of the process of maximising the irreversibility of nuclear disarmament to the point where nuclear weapons could be said to have been "uninvented" in the sense that reversing a disarmament process will not mean restarting but *reinventing*. MacKenzie uses the example of uninventing the car to make the case: "We cannot reverse the invention of the motor car, perhaps, but imagine a world in which there were no car factories, no gasoline, no roads, where no one alive had ever driven, and where there was satisfaction with whatever alternative form of transportation existed. The libraries might still contain pictures of automobiles and texts on motor mechanics, but there would be a sense in which that was a world in which the motor car had been uninvented" (MacKenzie 1993, 426).

This is not to suggest that if nuclear weapons are eliminated, the erosion of a nuclear weapons complex and its base of tacit knowledge will assuredly prevent their reconstitution. Knowledge of the practical possibility of nuclear weapons and explicit knowledge of their design and production would remain alongside tacit knowledge within a residual community of practitioners for a period of time. Some level of relevant knowledge, expertise, materials and infrastructure could also be sustained within a civilian nuclear power programme, especially if it involves a full nuclear fuel cycle. For example, a relatively simple fission nuclear bomb programme for delivery by bomber aircraft would be more straight-forward to reconstitute or reinvent compared to small but much more powerful warheads for delivery by ballistic missile (Spinardi and MacKenzie 1995, 82–83). But reconstituting the "paradigmatic strategic weapon" comprising a miniaturised two-stage thermonuclear warhead designed to maximise explosive yield/weight and yield/diameter ratios using a minimum of specialised materials such as tritium and delivered by intercontinental ballistic missile is a much more difficult task – one that assumes long-range land- or sea-based ballistic missiles are still available with which reconstituted warheads can be safely integrated (MacKenzie 1999, 436). A state in which the nuclear weapons socio-technical system has to all intents and purposes completely come apart and in which the unacceptability of nuclear weapons has been normalised within society will find it very difficult indeed to reverse the disarmament process.

Irreversible disarmament understood in this way is possible, perhaps even likely, once the process begins and we should therefore be sceptical about deterministic claims that irreversible nuclear disarmament through the unmaking of a nuclear weapons complex and *de facto* uninvention of nuclear weapons is not possible (Bourne 2016, 20).

Acknowledgments

The author thanks Hassan Elbahtimy and two anonymous reviewers for their feedback on previous drafts of this article.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the Foreign, Commonwealth and Development Office.

ORCID

Nick Ritchie http://orcid.org/0000-0002-6397-7498

References

Albright, H., T. Zamora, and D. Lewis. 1990. "Turn off Rocky Flats." *Bulletin of the Atomic Scientists* 46:5. pp. 11–19. https://doi.org/10.1080/00963402.1990.11459840.

Aspin, L. 1992. *From Deterrence to Denuking: A New Nuclear Policy for the 1990s*. Washington, D. C: U.S. House of Representatives, Committee on Armed Services.

Bailey, K. C. 1998. "Prepared Statement of Dr Kathleen C. Bailey. Senate Committee on Governmental Affairs Hearing on 'The Comprehensive Test Ban Treaty and Nuclear Nonproliferation'." Government Printing Office. 18 March.

Barkenbus, J. 1989. "Devaluing Nuclear Weapons." *Science, Technology, & Human Values* 14 (4): 425–440. https://doi.org/10.1177/016224398901400406.

Bauer, M., and C. Knill. 2012. "Understanding Policy Dismantling: An Analytical Framework." In *Dismantling Public Policy: Preferences, Strategies, and Effects*, edited by M. Bauer, 30–51. Oxford: Oxford University Press.

Benford, R., and D. Snow. 2000. "Framing Processes and Social Movements: An Overview and Assessment." *Annual Review of Sociology* 26 (1): 611–639. https://doi.org/10.1146/annurev.soc.26.1.611.

Bernstein, P., and J. Wood. 2010. *The Origins of Nunn-Lugar and Cooperative Threat Reduction. Center for the Study of Weapons of Mass Destruction. Case Study 3*.National Defense University.

Bijker, W. 1995. *Of Bicycles, Bakelites, and Bulbs: Toward a Theory of Sociotechnical Change*. Cambridge, MA: MIT Press.

Bourne, M. 2016. "Invention and Uninvention in Nuclear Weapons Politics." *Critical Studies on Security* 4 (1): 6–23. https://doi.org/10.1080/21624887.2015.1106427.

Browne, D. 2008. "Laying the Foundations for Multilateral Nuclear Disarmament. UK Ministry of Defence." Remarks to the Conference on Disarmament in Geneva, Palais des Nations, February 5.

Canberra Commission. 1996. *The Canberra Commission on the Elimination of Nuclear Weapons*. Government of Australia, Department of Foreign Affairs and Trade.

Claytor, R. 1992. "Prepared Statement of Richard Claytor. House of Representatives Committee on Armed Services Hearing on 'National Defense Authorization Act for Fiscal Years 1993-H.R.

5006'." *European Journal of Applied Physiology and Occupational Physiology* 65:295–301. https://doi.org/10.1007/BF00868131.

Cliff, D., H. Elbahtimy, and A. Persbo 2011. "Irreversibility in nuclear disarmament: Practical steps against nuclear rearmament." VERTIC, London. http://www.vertic.org/media/assets/Publications/Irreversibility_Report_Sept_2011.pdf .

Clinton, W. J. 1997. "Message to the Senate Transmitting the Comprehensive Nuclear Test-Ban Treaty and Documentation, September 22." *Weekly Compilation of Presidential Documents* 33 (39): 1371–1429.

Clinton, W. J. 1998. "Remarks at Los Alamos National Laboratory in Los Alamos, New Mexico February 3." *Weekly Compilation of Presidential Documents* 34 (6): 175–225.

Cohen, W. 1997. *Nuclear Weapon Systems Sustainment Programs*. Washington, D.C: Office of the Secretary of Defense.

Colby, E. 2008. "Nuclear Abolition: A Dangerous Illusion." *Orbis* 52 (3): 424–433. https://doi.org/10.1016/j.orbis.2008.05.008.

Collina, T., and R. Kidder. 1994. "Shopping Spree Softens Test-Ban Sorrows." *Bulletin of the Atomic Scientists* 50 (4): 23–29. https://doi.org/10.1080/00963402.1994.11456536.

Collins, H. 2010. *Tacit and Explicit Knowledge*. Chicago: University of Chicago Press.

Cressman, D. 2009. "A Brief Overview of Actor-Network Theory: Punctualization, Heterogeneous Engineering & Translation." Working paper. Centre for Policy Research on Science & Technology (CPROST) School of Communication, Simon Fraser University.

Crouch, J. 2001. *Media Roundtable with ASD (ISP) Crouch*. Washington, D.C: U.S. Department of Defense.

David, M. 2017. "Moving Beyond the Heuristic of Creative Destruction: Targeting Exnovation with Policy Mixes for Energy Transitions." *Energy Research & Social Science* 33:138–146. https://doi.org/10.1016/j.erss.2017.09.023.

DOE (Department of Energy). 1999a. *Nuclear Skills Retention Measures within the Department of Defense and Department of Energy*. Washington, D.C: Department of Energy. (The Chiles Commission).

DOE (Department of Energy). 1999b. *Stockpile Stewardship Program: 30-Day Review*. Washington, D.C: Department of Energy.

DOE (Department of Energy). 2017. "Fiscal Year 2018 Stockpile Stewardship and Management Plan Report to Congress." November. https://www.energy.gov/sites/default/files/2017/11/f46/fy18ssmp_final_november_2017%5B1%5D_0.pdf.

DSB (Defense Science Board). 1993. "Report of the Defense Science Board Task Force on the Defense Nuclear Agency." Office of the Under Secretary of Defense for Acquisition and Technology, U.S. Department of Defense, Washington, D.C.

DSB (Defense Science Board). 1998. "Report of the Defense Science Board Task Force on Nuclear Deterrence." Office of the Under Secretary of Defense for Acquisition and Technology, U.S. Department of Defense, Washington, D.C.

DSB (Defense Science Board). 2006. Report of the Defense Science Board Task Force on Nuclear Capabilities. Washington, D.C: Office of the Under Secretary of Defense for Acquisition and Technology, U.S. Department of Defense.

Elmet, D. 1994. *The Role of the Unrealisable: A Study in Regulative Ideals*. Basingstoke: Macmillan Press.

Finnemore, M. 1996. *National Interests in International Society*. Ithaca, NY: Cornell University Press.

Flank, S. 1993. "Exploding the Black Box: The Historical Sociology of Nuclear Proliferation." *Security Studies* 3 (2): 259–294. https://doi.org/10.1080/09636419309347549.

Frankel, M., J. Scouras, and G. Ullrich 2021. "Tickling the Sleeping Dragon's Tail: Should We Resume Nuclear Testing?" Johns Hopkins Applied Physics Laboratory. https://www.jhuapl.edu/Content/documents/DragonsTail.pdf.

Gaffney, F. 1991. "Self-Imposed Structural Disarmament: The Sorry State of the DoE Weapons Complex. House of Representatives Committee on Armed Services Hearing on 'National Defense Authorization Act for Fiscal Years 1992 and 1993- H.R. 2100'." April 18.

Garrity, P. 1991. "The Depreciation of Nuclear Weapons in International Politics." *Journal of Strategic Studies* 14 (4): 463–514. https://doi.org/10.1080/01402399108437465.

Geels, F. 2005. *Technological Transitions and System Innovations: A Co-Evolutionary and Socio-Technical Analysis*. Cheltenham: Edward Elgar.

Government Accountability Office. 2007. "Nuclear Weapons: Annual Assessment of the Safety, Performance, and Reliability of the Nation's Stockpile." GAO-07-243R. https://www.gao.gov/assets/gao-07-243r.pdf .

Gray, C. 1999. *The Second Nuclear Age*. London: Lynne Rienner.

Gusterson, H., and C. Besteman. 2019. "Cultures of militarism." *Current Anthropology* 60 (19): 3–14. https://doi.org/10.1086/700648.

Hamre, J. 1998. *DOD News Briefing, Deputy Secretary of Defense John J. Hamre*. Washington, D.C: U.S. Department of Defense.

Harahan, J., and R. Bennett. 2002. *Creating the Defense Threat Reduction Agency*. Washington, D. C: U.S. Department of Defense.

Harrington, A. 2011. "The Strategy of Non-Proliferation: Maintaining the Credibility of an Incredible Pledge to Disarm." *Millennium - Journal of International Studies* 40 (1): 3–19. https://doi.org/10.1177/0305829811413312.

Harrington, A., and M. Englert. 2014. "How Much is Enough? The Politics of Technology and Weaponless Nuclear Deterrence." In *The Global Politics of Science and Technology: Perspectives, Cases and Methods*, edited by M. Mayer, M. Carpes, and R. Knoblich, 287–302. Berlin: Springer.

Hecht, G. 2000. *The Radiance of France: Nuclear Power and National Identity After World War II*. Cambridge, MA: The MIT Press.

Hecker, S. 1992. "Prepared Statement by Dr Siegfried Hecker, Director, Los Alamos National Laboratory. Senate Committee on Armed Services Hearing on 'Department of Defense Authorization for Appropriations for Fiscal Year 1993 and the Future Years Defense Program'". 27 March.

Hecker, S. 1997. "Statement by Dr Siegfried S. Hecker. Senate Committee on Armed Services Hearing on 'Department of Defense Authorization for Appropriations for Fiscal Year 1998 and the Future Years Defense Program'." 19 March.

Herzfeld, C. 1990. "Statement of Dr Charles Herzfeld, Chairman, Nuclear Weapons Council. House of Representatives Committee on Armed Services Hearing on 'National Defense Authorization Act for Fiscal Years 1991- H.R. 4739'." March 20.

Hopkins, J. 2016. "Nuclear test readiness." *National Security Science* 9–16. https://www.lanl.gov/discover/publications/national-security-science/2016-december/assets/docs/NSS-dec2016nuclear-test-readiness.pdf.

Hughes, T. 1983. *Networks of Power: Electrification in Western Society, 1880-1930*. Baltimore: Johns Hopkins University Press.

IPNDV (International Partnership on Nuclear Disarmament Verification). 2018. "Food-For-Thought Paper: Achieving Irreversibility in Nuclear Disarmament. Working Group 1: Monitoring and Verification Objectives." International Partnership on Nuclear Disarmament Verification. https://www.ipndv.org/wp-content/uploads/2018/01/IPNDV-WG1-FFT-Irreversibility-Final.pdf.

Jasanoff, S., Ed. 2004. *States of Knowledge: The Co-Production of Science and Social Order*. London: Routledge.

Jordan, A., C. Green-Pedersen, and J. Turnpenny. 2012. "Policy Dismantling: An Introduction." In *Dismantling Public Policy: Preferences, Strategies, and Effects*, edited by M. Bauer, et al., 2–29. Oxford: Oxford University Press.

Joseph, R., and R. Lehman. 1998a. "U.S. Nuclear Policy in the 21st Century." *Strategic Forum* 145: 1–4 .

Joseph, R., and R. Lehman. 1998b. *U.S. Nuclear Policy in the 21st Century: A Fresh Look at National Strategy and Requirements*. Washington, D.C: National Defense University and Lawrence Livermore National Laboratory.

Koretsky, Z. 2023. "Dynamics of Technological Decline as Socio-Material Unravelling." In *Technologies in Decline: Socio-Technical Approaches to Discontinuation and Destabilisation*, edited by Z. Koretsky, P. Stegmaier, B. Turnheim, and H. van Lente, 15–42. London: Routledge.

Koretsky, Z., and H. van Lente. 2020. "Technology Phase-Out as Unravelling of Socio-Technical Configurations: Cloud Seeding Case." *Environmental Innovation and Societal Transitions* 37:302–317. https://doi.org/10.1016/j.eist.2020.10.002.

Krepon, M. 2003. *Cooperative Threat Reduction, Missile Defense and the Nuclear Future*. New York: Palgrave Macmillan.

Kull, S. 1988. *Minds at War: Nuclear Reality and the Inner Conflicts of Defense Policymakers*. New York: Basic Books.

Kyl, J. 1994. "National Defense Authorization Act for Fiscal Year 1995." *Congressional Record (House of Representatives)*, May 18.

Law, J. 1987. "Technology and Heterogeneous Engineering: The Case of Portuguese Expansion." In *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, edited by T. In Pinch, W. Bijker, and T. Hughes, 111–134. Cambridge: MIT Press.

Law, J. 2007. "Actor Network Theory and Material Semiotics." Working paper. http://www.heterogeneities.net/publications/Law2007ANTandMaterialSemiotics.pdf.

MacKenzie, D. 1993. *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance*. Cambridge, MA: MIT Press.

MacKenzie, D. 1999. "Theories of Technology and the Abolition of Nuclear Weapons." In *The Governance of Large Technical Systems*, edited by O. Coutard, 173–198. London: Routledge.

Markard, J., K. Isoaho, and L. Widdel. 2023. "Discourse Around Decline: Comparing the Debates on Coal Phase-Out in the UK, Germany and Finland." In *Technologies in Decline: Socio-Technical Approaches to Discontinuation and Destabilisation*, edited by Z. Koretsky, B. Turnheim, and H. van Lente, 119–144. London: Routledge.

McAdam, D., J. McCarthy, and M. Zald, Eds. 1996. *Comparative Perspectives on Social Movements: Political Opportunities, Mobilizing Structures, and Cultural Framings*. New York: Cambridge University Press.

Mehan, H., C. Nathanson, and J. Kelly. 1990. "Nuclear Discourse in the 1980s: The Unravelling Conventions of the Cold War." *Discourse & Society* 1 (2): 133–165. https://doi.org/10.1177/0957926590001002002.

Milliken, J. 1999. "The Study of Discourse in International Relations: A Critique of Research and Methods." *European Journal of International Relations* 5 (2): 225–254. https://doi.org/10.1177/1354066199005002003.

Olshanksky, S., and R. Williams. 1990. "Culture Shock at the Weapons Complex." *Bulletin of the Atomic Scientists* 46 (8): 29–33. https://doi.org/10.1080/00963402.1990.11459874.

PDD (Presidential Decision Directive). 1993. "NSC-15." The White House. Washington, D.C. November 3. https://irp.fas.org/offdocs/pdd/pdd-15.pdf.

Perkovich, G., and J. Acton. 2008. "Managing the Nuclear Industry in a World without Nuclear Weapons. In Perkovich & Acton." *International Journal of Offshore and Polar Engineering* 48 (396): 69–82. https://doi.org/10.1080/05679320802370248.

Pinch, T. 1998. "Theoretical Approaches to Science, Technology and Social Change: Recent Developments." *Southeast Asian Journal of Social Science* 26 (1): 7–16. https://doi.org/10.1163/030382498X00021.

Pretorius, J. 2023. "Staying the Course: Lessons from South Africa for Irreversibility of Nuclear Disarmament." Working Paper.

Price, R. 1995. "A Genealogy of the Chemical Weapons Taboo." *International Organization* 49 (1): 73–103. https://doi.org/10.1017/S0020818300001582.

Reis, V. 1996. *Prepared Statement of Dr Victor Reis. House Committee on Appropriations Subcommittee on Energy and Water Development. Hearing on 'Energy and Water Development Appropriations for 1997'*. Washington, D.C: U.S. Government Printing Office.

Reis, V. 1997. *Testimony Before the Senate Committee on Governmental Affairs, International Security, Proliferation, and Federal Services Subcommittee*. Washington, D.C: U.S. Government Printing Office.

Reis, V. 1998. *Prepared Statement of Dr Victor Reis, Assistant Secretary of Energy for Defense Programs*. Hearing on "Energy and Water Development Appropriations for 1998: Atomic Energy Defense Activities". Washington, D.C: U.S. Government Printing Office.

Richanbach, P., D. Graham, J. Bell, and J. Silk. 1997. *The Organization and Management of the Nuclear Weapons Program*. Alexandria: Institute for Defense Analysis.
Ritchie, N. 2009. *US Nuclear Weapons Policy After the Cold War: Russians, Rogues and Domestic Division*. Basingstoke: Routledge.
Ritchie, N. 2010. "Relinquishing Nuclear Weapons: Identities, Networks and the British Bomb." *International Affairs* 86: 2:465–387. https://doi.org/10.1111/j.1468-2346.2010.00892.x.
Ritchie, N. 2013. "Valuing and Devaluing Nuclear Weapons." *Contemporary Security Policy* 34 (1): 146–173. https://doi.org/10.1080/13523260.2013.771040.
Ritchie, N. 2018. "Inventing Nuclear Disarmament." *Critical Studies on Security* 7 (1): 73–77. https://doi.org/10.1080/21624887.2018.1468083.
Ritchie, N. 2022. "A Contestation of Nuclear Ontologies: Resisting Nuclearism and Reimagining the Politics of Nuclear Disarmament." *International Relations*. https://doi.org/10.1177/00471178221122959.
Robinson, C. P. 1999. *Statement of C. Paul Robinson, Director, Sandia National Laboratories. Senate Committee on Armed Services Hearing on 'Comprehensive Test Ban Treaty'*. Washington, D.C: U.S. Government Printing Office.
Roscow, S. 1989. "Nuclear deterrence, state legitimation, and liberal democracy." *Polity* 21 (3): 563–586. https://doi.org/10.2307/3234748.
Rosert, E., U. Becker-Jakob, F. Giorgio, and A. Schaper. 2013. "Arms Control Norms and Technology." In *Norm Dynamics in Multilateral Arms Control*, edited by H. Muller and C. Wunderlich, 122–172. Athens, GA: University of Georgia Press.
Shove, E., M. Pantzar, and M. Watson. 2012. *The Dynamics of Social Practice: Everyday Life and How It Changes*. London: Sage.
Sims, B., and C. Henke. 2012. "Repairing Credibility: Repositioning Nuclear Weapons Knowledge After the Cold War." *Social Studies of Science* 42 (3): 324–347. https://doi.org/10.1177/0306312712437778.
Sovacool, B., K. Lovell, and M. Ting. 2018. "Reconfiguration, Contestation, and Decline: Conceptualizing Mature Large Technical Systems." *Science, Technology and Human Values* 43 (6): 6, pp. 1066–1097. https://doi.org/10.1177/0162243918768074.
Spence, F. 1994. "The Clinton Administration and Nuclear Weapons Policy: Benign Neglect or Erosion by Design?" *Congressional Record (House of Representatives)*, June 8.
Spinardi, G. 1994. *From Polaris to Trident: The Development of US Fleet Ballistic Missile Technology*. Cambridge: Cambridge University Press.
Spinardi, G., and D. MacKenzie. 1995. "Tacit Knowledge, Weapons Design, and the Uninvention of Nuclear Weapons." *American Journal of Sociology* 101 (1): 44–99. https://doi.org/10.1086/230699.
Steeves, G. 2020. "Ready, Set, Getting to Go: US Nuclear Test Readiness Posture." *Strategic Studies Quarterly* 14 (3): 22–48. https://www.jstor.org/stable/26937410.
Stegmaier, P. 2023. "Conceptual Aspects of Discontinuation Governance: An Exploration." In *Technologies in Decline: Socio-Technical Approaches to Discontinuation and Destabilisation*, edited by Z. Koretsky, P. Stegmaier, B. Turnheim, and H. van Lente, 78–116. London: Routledge.
Stegmaier, P., S. Kuhlmann, and V. Visser. 2014. "The Discontinuation of Socio-Technical Systems as a Governance Problem." In *The Governance of Socio-Technical Systems*, edited by S. Borrás and J. Edler, 111–133. Elgar: Cheltenham.
Stirling, A., and P. Johnstone. 2018. "Interdependencies Between Civil and Military Nuclear Infrastructures." *SPRU Working Paper Series (SWPS)* 13:1–18. https://doi.org/10.2139/ssrn.3230021.
Sturm, R. 1993. "Nuclear Power in Eastern Europe: Learning or Forgetting Curves?" *Energy Economics* 15 (3): 183–189. https://doi.org/10.1016/0140-9883(93)90004-B.
Thurmond, S. 1991. *Senate Committee on Governmental Affairs Hearing on 'DOE Nuclear Weapons Complex Reconfiguration Study'*. Washington, D.C: U.S. Government Printing Office.

Turnheim, B. 2023. “Destabilisation, Decline and Phase-Out in Transitions Research.” In *Technologies in Decline: Socio-Technical Approaches to Discontinuation and Destabilisation*, edited by Z. Koretsky, P. Stegmaier, B. Turnheim, and H. van Lente, 43–77. London: Routledge.
United Nations. 2007. “Model Nuclear Weapons Convention. Working Paper Submitted by Costa Rica to the Preparatory Committee for the 2010.” Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons. NPT/CONF.2010/PC.I/WP.17. Vienna. May 1.
van der Vleuten, E. 2009. “Large Technical Systems.” In *A Companion to the Philosophy of Technology*, edited by J. Olsen, S. Pederson, and V. Hendricks, 218–222. Oxford: Blackwell Publishing.
Walker, P. 2016. “Cooperative Threat Reduction in the Former Soviet States: Legislative History, Implementation, and Lessons Learned.” *The Nonproliferation Review* 23 (1–2): 115–129. https://doi.org/10.1080/10736700.2016.1178442.
Walker, W. 2000. “Entrapment in Large Technology Systems: Institutional Commitment and Power Relations.” *Research Policy* 29 (7–8): 833–846. https://doi.org/10.1016/S0048-7333(00)00108-6.
Walker, W. 2020. “On Nuclear Embeddedness and (Ir)reversibility: A Working Paper.” Program on Science and Global Security, Princeton University.
Weiner, S. 2011. *Our Own Worst Enemy: Institutional Interests and the Proliferation of Nuclear Weapons Expertise*. Cambridge, MA: The MIT Press.
White House. 1962. “‘Blueprint for the Peace Race: Outline of Basic Provisions of a Treaty on General and Complete Disarmament in a Peaceful world’.” Washington, D.C. http://ucf.digital.flvc.org/islandora/object/ucf%3A5074/datastream/OBJ/view/Blueprint_for_the_peace_race__Outline_of_basic_provisions_of_a_treaty_on_general_and_complete_disarmament_in_a_peaceful_world.pdf.
White House. 1995. *Joint Statement on the Transparency and Irreversibility of the Process of Reducing Nuclear Weapons*. Washington, D.C: The White House.
Wilton Park. 2023. “Irreversibility in Nuclear Disarmament.” Wilton Park Conference. Details at https://www.wiltonpark.org.uk/event/irreversibility-in-nuclear-disarmament-2 .
Winner, L. 1980. “Do Politics Have Artifacts?” *Daedalus* 109 (1): 121–136.
Winner, L. 1986. *The Whale and the Reactor: A Search for Limits in an Age of High Technology*. Chicago: University of Chicago Press.