Treadmills, Unseen Military Science, and the Inertia of "Forever Chemicals"

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Introduction

This paper examines political and economic configurations related to the military's nuclear weapons production and development and use of per- and polyfluoroalkyl substances (PFAS), a broad class of chemicals commonly known as "forever chemicals" that are driving global ecological change and causing widespread human health impacts. To do so, we bring together the treadmill of production (ToP) and the treadmill of destruction (ToD) theories, along with science and technology studies approaches to unseen and undone science. PFAS have violated "planetary boundaries" of chemical pollution and are globally distributed in surface water, rainwater, and soil at levels that exceed numerous health-based guidelines (Cousins et al. 2022), and bioaccumulate and biomagnify in wildlife and the food chain (Giesy and Kannan 2001). They can be found in the blood of virtually entire populations of developed countries (Graber et al. 2019; Botelho et al. 2025), and toxicological and epidemiological studies show links to many adverse health outcomes, including several types of cancers, reproductive, developmental and immune system effects, and thyroid and liver impacts (Fenton et al. 2021). PFAS contamination is both highly localized (near industrial and military sources) and widespread due to broad use in the food system, household products, and presence in drinking water (Garrett et al. 2022; Tokranov et al. 2025). The major application of PFAS in nuclear weapons production is a key part of this legacy.

The history of PFAS use was largely hidden from public view until recent decades. Despite internal industry research documenting PFAS toxicity and exposure concerns going back to the 1960s (Graber et al. 2019; Lyons 2007), the "social discovery" of the public and environmental health harms of PFAS did not emerge until the early 2000s. Unseen science – research that is produced but not shared beyond institutional boundaries - and a compromised US chemical regulatory framework resulted in nearly sixty years of research and inaction on fluorinated compounds (Richter, Cordner, and Brown 2018). Recent public and scientific attention has primarily focused on uncovering the hidden industrial and commercially-oriented sources of PFAS, and the unseen science documenting their public and environmental health consequences. While corporate malfeasance has been widely discussed, little attention has been given to the U.S. military's historical role in advancing the science and production of PFAS outside a focus on the military's contributions to the development of aqueous film-forming foam (AFFF) used at military bases as a fire suppressant (Jacqz et al. 2024). However, the fluorochemical industry has deeper historical ties to the U.S. military that warrant exploration. For example, DuPont, the nation's oldest company producing military weaponry, was also the pioneering firm in PFAS discovery, production, and marketing (Poudrier 2024).

While much of the attention around the Manhattan Project, the multi-pronged project that created atomic weapons, emphasizes nuclear physics and the mission to secure uranium, an

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underappreciated and often obscured aspect of the project involved the procurement of special materials involved in the complex and novel chemistry of nuclear weapons production (Jones 1985). Fluorochemistry existed only at an experimental scale before the Manhattan Project and nuclear weapons production. The Manhattan Project was the impetus for a boom in special chemicals production in 1943-1944, particularly fluorinated chemicals that met the strict parameters for cleaning, cooling, lubricating, and sealing in the K-25 gaseous diffusion project at the Clinton Engineering Works, later known as Oak Ridge (Jones 1985). The well-known PFAS polytetrafluoroethylene (PTFE, often known by the brand name Teflon) was only one of the dozens of fluoropolymers and fluorinated gases that were created, refined, and produced to build nuclear weapons (Manhattan District 1947a, b). Eighty years after the Manhattan Project, the Pentagon's role in establishing the science and manufacture of PFAS through a military-industrial-scientific complex remains largely obscured by national security, military secrecy doctrines, and limited independent scientific investigation. Furthermore, while dual patterns of, first, elite control and strategic use of science, and, second, treadmill of production and destruction dynamics are both evident in the case of PFAS, no research to date has explicitly linked these theoretical approaches to advance an understanding of PFAS as a product of the military-industrial-scientific complex.

This paper examines how undone and unseen science have shaped the emergence, disappearance, and transformation of PFAS treadmills over time. We present an overview of key environmental sociology theories and describe the expansionary dynamics of chemical production following World War II. We draw from research on the treadmill of production (Buttel 2004; Gould, Pellow, and Schnaiberg 2015) and the treadmill of destruction (Hooks and Smith 2004; Hooks, Lengefeld, and Smith 2021), and discuss how an interpretation of these theories allows for the identification of mechanisms of environmental and social harm which are historically contingent and culturally specific. We are interested in how the science of PFAS was harnessed, why the manufacture of PFAS unfolded as it did, the sources of social power shaping this process, and the social conditions that produced widespread but hidden environmental health consequences. After describing our methodological approach, we provide a thick description of sequences that characterize the synergy and interplay of these chemical treadmills that emerged after World War II.

Background and Theory

PFAS are a specific class of organic chemicals containing at least one fully-fluorinated carbon atom (OECD 2018). They exhibit chemical and physical resistance and amphiphobicity resulting from the extremely strong carbon-fluorine bond. In the environment, they are known to be persistent, bioaccumulative, and toxic (Cousins et al. 2020). The PFAS used in nuclear weapons production were formulated for nuclear science, some of which remain shrouded in military secrecy, while others have since been commercialized or have dual-use military and commercial applications. In the remainder of this section we briefly summarize prior treadmill research and recent work recasting them as critical realist mechanisms, and outline the relationship between treadmills of production and destruction in the US historical context.

Treadmills and Mechanisms

In environmental sociology, a treadmill refers to a process involving the accumulation of power and capital through the appropriation of nature, resulting in environmental degradation that is suppressed and distorted by treadmill-involved organizations. The core argument of the "treadmill of production" (ToP) framework is that capitalism's growth imperative drives corporations to make unsustainable withdrawals and additions that surpass the carrying capacity of local ecosystems and the global environment (Buttel 2004; Gould, Pellow, and Schnaiberg 2015). The alignment of labor, capital, and the state in bolstering technological innovation and economic expansion at the cost of the environment is central to the ToP (Leguizamón 2024). Moreover, corporations play a formative role in manipulating science to delay and prevent regulation of their activities. In tandem, states frequently enable corporations by passing environmental laws and regulations that legitimize and reinforce treadmill expansion (Lynch, Stretesky, and Long 2020). Scientists, policymakers, and treadmill actors engage in contentious struggles over science, environmental laws, and health outcomes, as demonstrated by research on contested illnesses (Brown et al. 2004; Brown 2007, 2012).

The "treadmill of destruction" (ToD) framework offers a friendly critique and extension of the treadmill of production (Hooks and Smith 2004, 2005; Lengefeld, Hooks, and Smith 2021). While acknowledging the importance of capitalism and market competition in explaining environmental harms and inequalities, the ToD points to the military-industrial complex and global arms race as significant drivers of environmental harm. This military-driven growth dynamic is not predominantly driven by economic pressures or motivations of the military (Clark and Jorgenson 2012; Givens 2014). Rather, the structural dynamics of militarism and the geopolitics of arms races accelerate environmental inequality in a qualitatively distinct way that cannot be reduced to capitalism, although capitalist firms are often positioned to benefit[4], and there is potential for synergy between the ToD and ToP (Smith, Hooks, and Lengefeld 2014, 2020). These two treadmill approaches are unique in their explanations of environmental degradation, but they are complementary in their focus on the mechanisms behind human activities that stress—and may surpass—the capacity of the environment. The central role of the military in the expansion of capitalism and state power is an important and enduring theme in sociology (Mills 1956; Skocpol 1979, 1988; Tilly 1990; Collins 1978, 2011; Mann 2012) and other scholarly work (Melman 1970, 1985). Given the powerful impacts of war-related activities on subsequent civil society and economic life, one could argue that modern ToPs are indebted to the ToD.

The treadmill of destruction (ToD) theory has been a key environmental sociology perspective for examining the environmental consequences associated with militarism. This area of research, which initially focused on militarism within the United States (Hooks and Smith, 2004), has expanded to consider the global and cross-national impacts of military activities (Hooks and Smith, 2012; Jorgenson and Clark, 2009; Jorgenson, Clark, and Givens 2012; Lengefeld and Smith, 2013; Smith and Lengefeld 2020). ToD scholarship has concentrated on

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[4] From the 1940s to the 1960s, economic and technological "spin offs" from the arms race benefitted the civilian economy, however, from the 1970s onward, military R&D was increasingly esoteric with few civilian applications. The transition to a "baroque arsenal" resulted in a military sector that is both insulated from and parasitic upon the larger economy. Although large revenues from DoD contracts are attractive to firms, there are significantly lower profit margins with defense contracts compared to other businesses, leading in part to excessive defense industry consolidation after the Cold War. See Allen, Gregory and Doug Berenson. 2024, "Why Is the U.S. Defense Industrial Base So Isolated from the U.S. Economy?", Online: Center for Strategic and International Studies. Retrieved 2/20/2025, (https://www.csis.org/analysis/why-us-defense-industrial-base-so-isolated-us-economy). See also Kaldor, Mary. 2019. "Research, Development and Production: The Baroque Arsenal in Perspective." Pp. 111-25 in *Technology and Strategy*: Routledge.

defense planning and military expenditure, energy consumption (Clark, Jorgenson, and Kentor 2010; Jorgenson et al 2023; Jorgenson and Clark, 2009, 2016; Jorgenson and Kentor, 2014; Smith, Hooks, and Lengefeld 2024), global freshwater use (Alvarez 2016), chemical weapons like Agent Orange in Vietnam and Southeast Asia (Frey 2013; Auerbach 2024) and chemical herbicides in the War on Drugs in Latin America (Smith, Hooks, and Lengefeld, 2014, 2020), and impacts on Native Americans (Hooks and Smith, 2004; Lengefeld 2018). Few studies have delved into the environmental health dimensions of military-driven production but exceptions include the "atomic veterans," the 1960s nuclear radiation and tooth study, studies of the Hanford "Green Run" (an intentional radiation release), studies on exposure and diseases from nuclear weapons production (Mix, Cable, Shriver and coauthors), Navajo Nation residnets health effects from uranium mining (Brugge and Benally), and environmental health effects on Alaska Natives from military sites (Miller et al. 2013).

Commented [GU1]: Miller, Pamela & Waghiyi, Viola & Welfinger, Gretchen & Byrne, Sam & Kava, Jane & Gologergen, Jesse & Eckstein, Lorraine & Scrudato, Ronald & Chiarenzelli, Jeff & Carpenter, David & Seguinot Medina, Samarys. (2013). Community-based participatory research projects and policy engagement to protect environmental health on St Lawrence Island, Alaska. International journal of circumpolar health. 72. 10.3402/ijch.v72i0.21656.

Although today treadmills appear to be both ubiquitous and temporally stable, the critical realist perspective argues instead that their emergence is historically contingent, and their absence, presence, and transformation are rooted in specific social and cultural conditions (Hooks, Lengefeld, and Smith 2021; Smith, Hooks, and Lengefeld 2014, 2020). Treadmills are idiosyncratic, and do not emerge under every context and circumstance where a capitalist political economy or a militaristic geopolitical arrangement exists. Although they can be synergistic, this synergy is not a foregone conclusion. Wars, and moments in wars, bear an internal logic and structure that can define conjunctures and catalyze change (Kestnbaum 2005). Attention to the macrosocial context gives insight into the forces propelling, sustaining, or inhibiting the emergence of a treadmill. For example, Tilly's (1990) work on capital and coercion demonstrates that extreme concentrations of capital can stall the accumulation of coercive means; correspondingly, a highly militarized social context can stall economic growth and development. In a similar vein, treadmills are distinct based on their macrosocial context, the organizations at their core, and the elites that command them. An insubordinate capitalist class or a state with a weak extractive capacity (or both) can stall the emergence of a ToD, just as a kleptocratic military organization can act parasitically upon a society's economic organization and inhibit a ToP.

In his initial work on the ToP, Schnaiberg (1980) observed that the rate of energy and chemical intensity of *production science* flourished in the U.S. post-war era, as World War II fundamentally changed the relationship between states, science, and militarism. From WWII and the Manhattan Project to the end of the Cold War in the early 1990s, national security and military objectives dominated the U.S. science and technology agenda (McLauchlan and Hooks 1995). Figure 1 shows the precipitous growth in average annual U.S. chemical production between 1919 and 2019. Annual US industrial chemical production more than doubled from 1939 to 1944; from the start of the Cold War in 1949 through peak Cold War R&D in 1963, industrial chemical production increased 95.32%~~, and the chemical activity barometer shows a 147.7% increase~~. The significance of military-directed science and technology in this era cannot be overstated: indeed, "… until the mid-1970s, government Research and Development (R&D) represented a larger share of the U.S. effort than that of the entire private sector" (McLauchlan and Hooks 1995:752). At the peak of Cold War R&D in 1963, ninety-three percent of federally funded R&D went to military topics, including nuclear energy, space, or defense (Branscomb 1993). As shown in Table 1, from the latter half of the 20th century to the present, federal spending on defense R&D has consistently outpaced non-defense R&D (American Association for the Advancement of Science 2022). Fluorochemicals were a subset of chemical industries that boomed during the Manhattan Project and were widely applied in commercial sectors and the civilian economy in the post-war era.

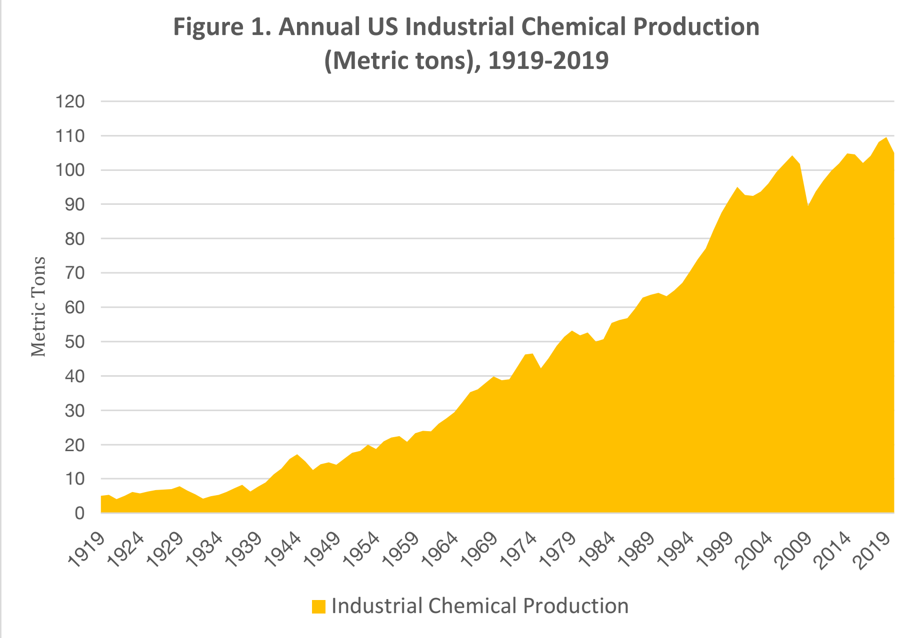
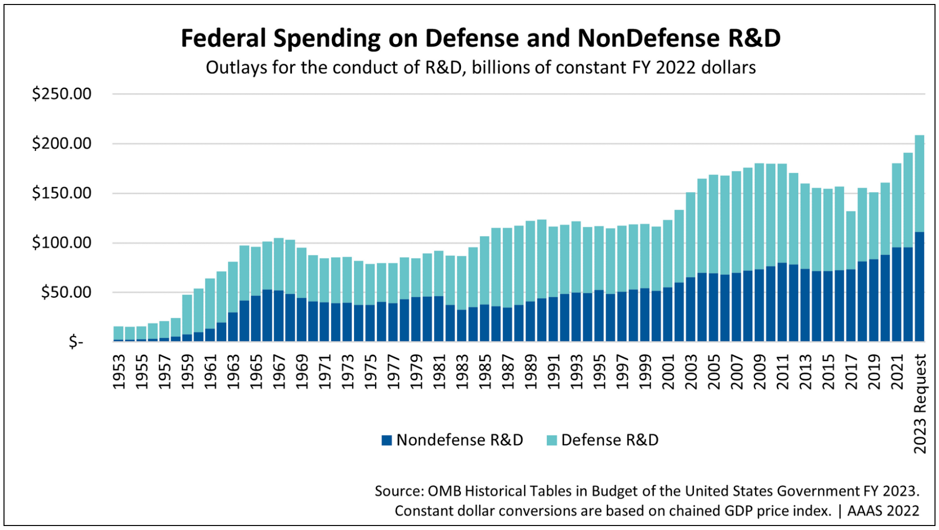


Figure 1 Data available from the Dryad Digital Repository (https://doi.org/10.6086/D12H4C)

Table 1.



Source: OMB Historical Tables in Budget of the United States Government FY 2023.
Constant dollar conversions are based on chained GDP price index. | AAAS 2022

As the preceding paragraphs indicate, the military-industrial-scientific complex was borne out of the geopolitical struggle of WWII and the Manhattan Project, with corporations and research universities playing a key role in a vertically integrated military-controlled bureaucracy. The national labs reconfigured the institutional framework of science into a system of government-sponsored labs operated through contracts with industrial firms, universities, and university consortia (Westwick 2003). These long-standing relationships between the military and both public and private contractors and support economies also blurred the lines between treadmills of production and destruction (Alvarez et al. 2021). This (geo)politicized "big science" was a key force in the vast expansion of chemistry and chemical production in the 20th century. Our analysis integrates treadmill theory with political-economic approaches in the "new political sociology of science" perspective, which is concerned with the inherent politicization of science and the visible and unseen social structures of power that shape scientific practices and organizations (Frickel and Moore 2006). We tap into related concepts of undone science (Frickel et al. 2010; Hess 2010) and unseen science (Richter, Cordner, and Brown 2018) which address ignored, underfunded, and/or obscured areas of scientific research and knowledge production. Undone science refers to research that is not pursued because it conflicts with elite interests, such as in the case of the "chlorine sunset" controversy related to phasing out the use of chlorine, "bucket brigade" models of public-directed environmental sampling, or research on environmental, rather than lifestyle or behavioral, causes of breast cancer (Frickel et al. 2010). Unseen science refers to research that has been conducted but is obscured because it is sequestered within institutional boundaries, identified by previous research on the PFAS controversy (Richter, Cordner, and Brown 2018, 2021). Unseen science plays a prominent role in other institutional contexts, such as national security doctrine and nuclear weapons (and PFAS) production in the Manhattan Project.

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Methods

We analyze data collected as part of a larger project on social and scientific questions related to PFAS, which includes in-depth interviews, data on activism and governance, and government archives and reports related to PFAS, industry research, and military research, including the Manhattan Project. Our case studies involve a thick narrative description of the processes that shaped fluorochemistry and PFAS production for the Manhattan Project (ToD) and a multitude of commercial industrial and consumer applications (ToP). We also identify related marketing and advertising campaigns. Our data comes from two main sources. First, we draw on qualitative interviews conducted as part of our larger research project that investigates the production of scientific knowledge and ignorance, governance issues, and activism around PFAS. Within this larger project, we have conducted 247 total interviews with scientists, impacted residents, regulators, legislators, environmental and health advocates, lawyers, journalists, industry representatives, and other stakeholders. These interviews were conducted between 2016 and 2025. Questions were semi-structured and focused on knowledge and perspectives on PFAS contamination, activism, research efforts and gaps, and challenges. This research was approved by the Institutional Review Board at X University. To protect confidentiality, interviewees are not identified and any information that mentions specific people is drawn from publicly available information.

Second, we draw on declassified and partially redacted U.S. government documentation of the Manhattan District History collected as part of a separate project on the history of nuclear weapons production (Lengefeld 2020; Lengefeld 2018). The Manhattan District History is a 36-volume history grouped into eight books which was originally commissioned in late 1944; it was first made publicly available in 1994 and was published online in 2013. It includes extensive annotations, statistical tables, charts, engineering drawings, maps, photographs, and detailed indices. Much of the data for the current project comes from the Book II Gaseous Diffusion (K-25) Project (Manhattan District 1947b), Book VII Feed Materials, Special Procurement, and Geographical Exploration (Manhattan District 1947a), and the Oak Ridge National Laboratory's Histories of the Analytical Chemistry and Chemical Technology Divisions (Oak Ridge National Laboratory 1990, 1993). Data from industry perspectives on DuPont's work for the Manhattan Project, including oral histories and interviews with key scientists, comes from the Chemical Heritage Foundation/Science History Institute (Renfrew 1987). Finally, we draw from the large number of archival data sources collected by Altman (2019).

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Our analysis utilizes two methodological approaches common in historical sociology: *path dependency* and *process sequencing*. In path dependence, early conditions are contingent, yet the sequences of path dependency can 'lock-in' to a causal pattern that is difficult to abrogate. Institutional reproduction is therefore caused by the initial conditions of institutional genesis and can persist even in the absence of those initial conditions (Mahoney 2000). This inertia bolsters institutional reproduction while also weakening the possibility for alternative configurations. A path-dependent sequence, or a "self-reinforcing sequence", occurs where initial conditions during a critical juncture trigger positive feedbacks or increasing returns (Pierson 2000; Mahoney 2004). Thus, the early contingent events in the sequence are the "critical" junctures which structure later events, where initial conditions trigger subsequent chains of events that are causally connected and lead to a "lock-in" where events that may have been possible at earlier points are not attainable further down the causal chain (Mahoney 2004). The historical narrative is a means to describe the 'plot' of a path-dependent sequence, from its breakpoint to its outcome, through specific causal paths (Mahoney 2000). Self-reproducing path-dependent sequences can take three forms: *continuous* processes involving an early event that is stable and reproduced over time, such as the perpetuation of a long-standing policy or organization; *self-amplifying* processes that results in the expansion or growth of an outcome over time, such as the spread of technological innovation; or *self-eroding* processes where a path leads away from an established process, such as institutional erosion or drift (Falleti and Mahoney 2015). As we argue in the case studies below, the PFAS ToD mechanism that emerged during the Manhattan Project was a self-amplifying process.

A process sequence or a "reactive sequence" occurs where "an initial outcome triggers a chain of temporally ordered and causally connected events that lead to a final outcome of interest" (Mahoney 2004: 91). Each event conditions reactions or responses in subsequent events, and the sequence is transformative because subsequent events can be fundamentally different and even reverse prior events (Sewell 1996). These reactive processes are identified and interrogated using inductive process tracing, which permits the researcher to coherently assemble historical sequences, while also allowing the discovery of unanticipated events in a sequence that can lead to novel theoretical insight (Falleti and Mahoney 2015). The ToP mechanism that emerged with the commercialization of PFAS - and the ToD involving AFFF use by the US military, involved reactive sequences.

Both approaches share a concern with temporality and the sources of exogenous and endogenous change that imbue actors and institutions to advance or limit change. They differ in their view of how sequences proceed through either cumulative endogenous patterns of "increasing returns" or exogenous events that produce reaction/counterreaction dynamics of "reactive" sequences (Howlett 2009; Falleti and Mahoney 2015). While some previous scholarship has considered these two approaches to be competitive (Howlett 2009), different cases or processes may have different levels of intractable inertia (path dependency) versus transformative causal chains (process sequencing). We look for evidence of both historical processes in the case of PFAS treadmills. Overall, these comparative methods are uniquely effective for allowing the use of counterfactuals in examining causal linkages, identifying necessary and sufficient conditions, testing hypotheses, and constructing theory through the identification of alternative paths or counterfactuals (Mahoney 2000).

Our analysis of PFAS production and use in the Manhattan Project are assisted by the *Guide for Investigating Historical and Current Uses of Per- and Polyfluoroalkyl Substances at DOE Sites* (U.S. Department of Energy 2023). As part of a team that produced this document for DOE's Legacy Management division, Dr. Eric Boyle was awarded the 2022 Secretary of Energy Achievement Award, in which the DOE historian discusses his discovery that PFAS were used in enormous volumes – 150,000 lbs – as a process gas, rather than as an inert material that was chemically resistant (Office of Legacy Management 2023). We are currently awaiting a response to a Freedom of Information Act request to DOE for information on this specific PFAS chemical (or chemicals). Table 2 identifies known and suspected PFAS used in the Manhattan Project in various capacities. We have positively identified at least 15 PFAS that were used for nuclear weapons production. Given the ongoing military secrecy around some of the Manhattan District's unreleased and redacted data, it is feasible that additional PFAS remain unidentified. For example, important and comprehensive accounts of hazardous substances released at the national laboratories do not include data on any of these substances (Makhijani et al. 1995).

Results

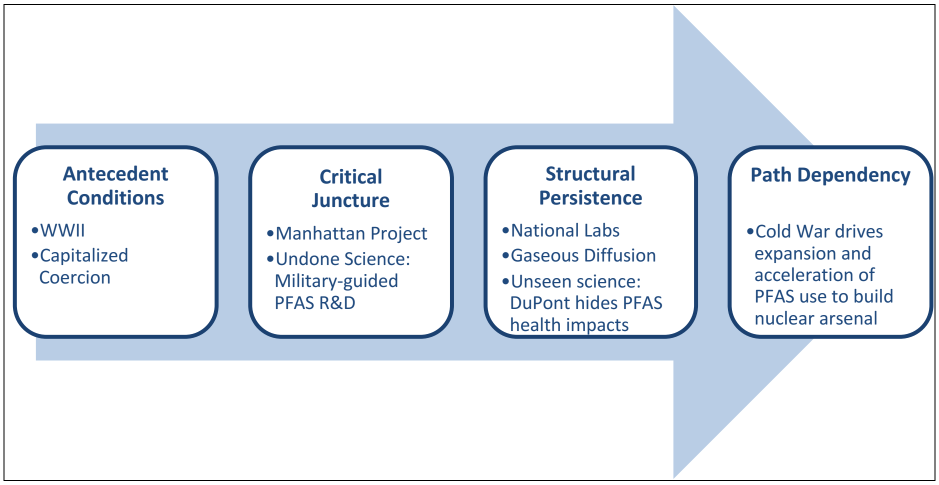
The History of PFAS Treadmills

A path-dependent, self-amplifying process proceeds through a set of sequences (Mahoney 2000; Pierson 2000). In the first stage, contingent historical and social factors shape the possible paths and selection processes. From this set of pre-existing conditions, a critical juncture or "breakpoint" results in the selection of a specific pathway among multiple possible alternatives. As the process proceeds down a certain pathway, it becomes structurally persistent as actors and institutions make specific investments in that pathway, leading to increasing returns, thus restricting the possibility of alternative pathways. We begin our analysis by establishing a timeline of events and processes involving the manufacture and use of PFAS (Table 2) and proceed by providing a thick narrative description of the PFAS ToD that emerged from the Manhattan Project. Subsequently, we examine the emergence of a ToP and the reactive sequences that characterized its growth, transformation, and intersection with the ToD.

Treadmill of Destruction Mechanism

More than 80 years after the Manhattan Project, scholars are just beginning to uncover the connection between PFAS and nuclear weapons production. Even DOE historians have been shocked by what has been uncovered in this history (Office of Legacy Management 2023). Diatomic and inorganic fluorine and PFAS have known uses in uranium enrichment. They are also presumptively used in numerous nuclear weapons production processes because of their extreme resistance to corrosion and heat. For example, Los Alamos recognized high priority areas that likely used PFAS include "the Chemistry and Metallurgy Research Facility (TA-3) and Plutonium Processing Facility (TA-55) effluents, which are transferred to the Radioactive Liquid Waste Treatment Facility (TA-50) for chemical processing" (Los Alamos National Laboratory 2020:9). The nuclear weapons production process involves: the mining and milling, chemical conversion, refinement, enrichment, processing, and fabrication of uranium for reactor fuel; plutonium and tritium production; plutonium and uranium reprocessing; the manufacture of components made of plutonium, beryllium, deuterium, lithium-6 and lithium deuteride, and mechanical, electrical, and plastic components; and waste management (Makhijani et al. 1995). Figure 2 outlines the path dependent processes which led to the ToD mechanism. In the paragraphs that follow we address each of these processes: we discuss the antecedent conditions of US warmaking during WWII; the critical juncture of the Manhattan Project and the undone science of nuclear weapons; the context of the broader trends in the institutional and infrastructural growth of the US military after WWII that led to structural persistence; and finally we situate the path dependence of military PFAS for nuclear weapons within these trends.

Figure 2. Path Dependent Processes in the Treadmill of Destruction Mechanism



PFAS were initially discovered by commercial researchers at IG Farben in 1934, and Teflon was created by accident by DuPont chemists in 1938, yet the chemicals weren't used for industrial or consumer applications until the 1950s (Interstate Technology Regulatory Council 2020). Two significant conditions shaped the path of military PFAS production in the US. First, the historical context involves the American entry into WWII and initiation of the Manhattan Project to create a nuclear weapon. Prior to the Manhattan Project, PFAS existed only at a laboratory scale, and their practical use-value was undetermined. At the onset of the Manhattan Project in 1942, fluorinated chemicals (including PFAS) were quickly recognized as invaluable for nuclear science and weapons production. This led to an enormous state investment and booming expansion of nuclear science and chemistry. Second, the American social and political economic context shaped the options available to Manhattan Project planners, and shaped the institutional foundation of US warmaking that persists to the present day. Our analysis is rooted in Tilly's (1990) logic of capitalized coercion, which signals the growth in the state's extractive capacity. The macrosocial context plays a decisive role in determining what pathways are possible for a nation-state to pursue a nuclear arsenal. As Tilly (1990) shows in his work on European state-building, extreme concentrations of capital can stall the accumulation of coercive means, or a highly militarized social context can stall economic growth and development.

The development of military PFAS is situated within the US political economy and institutional genesis of US warmaking beginning with WWII. Hooks and McLauchlan document the institutional foundation of US warmaking over three eras: an ascent to hegemony (1939-1945); the hegemonic era (1946-1970); and the era of relative decline (1971-1992). Through these three eras, the US state's ascent to hegemony was defined both by the expansion of the state's extractive capacity and the development of the state's infrastructural power was profound (Hooks and McLauchlan 1992). The US' capital reserves and its industrial economic dominance were a prerequisite condition for the Manhattan Project, tapping these resources for investment and expansion of industrial production, scientific research, and university infrastructures, and securing the military's postwar control of science (McLauchlan and Hooks 1995). At the end of WWII, the US capital advantage was even more profound; it was far and away the leading global economic and industrial power, as both Europe and the Soviet Union suffered devastating human, economic, and infrastructural losses.

The era of US hegemony witnessed a shift from a WWII mobilization strategy to a postwar nuclear deterrence strategy, and the Manhattan Project became the paradigm for national security state R&D (McLauchlan 1992; McLauchlan and Hooks 1995). Significant shifts in the organization and planning of the US military had consequences for the expansion and structural persistence of the nuclear arms race (and military PFAS production). In 1947 the armed forces were reorganized into the Department of Defense. The Air Force ascended as a coequal to the Navy and Army, but it also became the centerpiece of postwar military and national security strategy by asserting the importance of technological advantages of air power in the WWII victory and advances in areas such as nuclear weapons (McLauchlan 1989, 1992). The autarkic Pentagon implemented a de facto industrial policy, pursuing “an agenda distinct from both the client firms at the core of the military-industrial complex and the monopoly-sector firms with significant sales in both civilian and defense markets” by securing budgetary autonomy and authority that permitted it to act independently of other federal agencies (Hooks 1990). These changes led to the structural persistence of the nuclear arms race - and the expansion of chemistry R&D, uranium enrichment and chemical separation (reprocessing) technologies developed in the Manhattan Project.

The selection of the nuclear weapons strategy – which was tied to PFAS in weapons production - was partially driven by the U.S. political economy. Relative to other nation-states, the U.S. government’s extractive capacity was limited by relatively low tax rates, and the American public and legislators had long resisted strategies involving military conscription. The alternative to strategic nuclear weapons was conscription of a large U.S. military force, which would support the Marshall Plan and the rebuilding and defense of Europe. For national security planners, strategic nuclear weapons offered the path of least resistance, and the US pursued a strategy of “hegemony on the cheap” through science-intensive strategic nuclear weapons (Hooks and McLauchlan 1992). The US guided the design and manufacture of military technologies over several decades, creating “baroque arsenals” which became increasingly costly and technologically sophisticated, but offered diminishing returns in performance and had few civilian applications (Kaldor 1981, 2019). Contradicting the military Keynesian thesis - that military spending serves the needs of economic growth - empirical evidence shows that the Pentagon actively pursued a warmaking strategy first and foremost, with benefits that shaped the US economy (Galbraith 1967; Melman 1970, 1985; Hooks and McLauchlan 1992). The economic benefits were not the primary goal; they were a benefit secondary to the Pentagon’s pursuit of U.S. military dominance and a nuclear arms race. As economic hegemony began its decline in the 1970s and amid popular discontent with the Pentagon over the disastrous war in Vietnam, declining military R&D budgets reinforced the Pentagon’s efforts to maintain military superiority through expanding the strategic nuclear weapons arsenal and improving delivery systems (dramatically demonstrated by spaceflights to the moon). The expansion of PFAS use during the Cold War arms race was predicated upon the precipitous growth of the nuclear arsenal, and the investment in R&D on qualitatively unique thermonuclear weaponry and weapons delivery systems.

Critical Juncture: The Manhattan Project and Undone/Unseen Science

Returning to the Manhattan Project, this event was a path-dependent critical juncture resulting in the complete transformation of state warmaking from all previous eras of human warfare, redefining warfare in the latter half of the 20th century forward. For the first time in history, the state's apparatus established and guided a military-scientific-industrial complex that went beyond merely purchasing weapons to actively planning their research, development, and manufacture as de facto U.S. industrial policy (Hooks 1990). The US military negotiated with leading corporations and infused vast amounts of capital into the institutional expansion of modern scientific laboratories and university infrastructures:

> … a number of private research institutions (Johns Hopkins, MIT, Purdue) and chemical firms (American Cyanamid, Du Pont, General Chemical, Harshaw Chemical, Hooker Electrochemical, Kinetic Chemicals, Penn Salt) in the development and supply of the numerous fluorinated hydrocarbon chemical compounds —in the form of coolants, sealants, and lubricants—needed to operate the plants safely and efficiently with the highly corrosive feed material. (Jones 1985:314)

Not all corporations were keen on participating in war mobilization. The Du Pont Corporation, a key player in the construction and operation of the Hanford Site and also a leader in PFAS research and development (R&D), was initially reluctant, having been labeled as "merchants of death" for their munitions sales in WWI; however, wartime exigencies meant non-participation was not an option, and Du Pont agreed to build Hanford on a cost-plus-fixed fee, with a fixed fee of one dollar (Jones 1985).

The early history of chemical production for the Manhattan Project reveals the unseen and undone science of military PFAS. Several fuel programs for manufacturing fissionable materials (of uranium and plutonium) were considered: centrifuges; electromagnetic separation; thermal diffusion; and gaseous diffusion. Initially, leading officials in the bomb project evaluated gaseous diffusion as the lowest priority for success for several reasons. It was theoretically sound but implementation involved important practical problems, most importantly that a fully operational plant would be required to produce any materials, whereas the other processes could produce materials at the pilot stage. Heated exchanges between scientists at Berkeley, the University of Chicago, and Columbia University defended different fuel programs and their ability to produce military-grade materials. Du Pont doubted the feasibility of the plutonium process altogether, and to prompt Du Pont's participation, Groves appointed a committee headed by MIT chemist Warren Lewis and Du Pont engineers to review the different processes, (Gosling 1999). The Lewis Committee supported development of all the processes, but contradicting the leading officials on the project, they advocated for gaseous diffusion as the most likely option for success – conveniently, this was the most lucrative for Du Pont because it required enormous amounts of Du Pont's patented product Teflon (Blake 2025). President Roosevelt accepted the Lewis Committee's recommendation and gaseous diffusion became the top priority, and construction on the industrial-scale plant was started while the other fuel programs were to continue in the pilot phase.

Gaseous diffusion was dangerous for reasons related to both undone and unseen science. In addition to the risks associated with uranium ore processing, the effects of production of fluorine, fluorocarbons, and fluoroplastics were recognized among the first industrial hygiene problems of the Manhattan Project:

> The principal hazard in the diffusion processes arose from the employment of highly toxic substances, including uranium in its oxide and hexafluoride forms, radium, and several fluorocarbons. While their use in small quantities for pilot plant testing presented little danger, their employment in enormously increased amounts in the production plants posed much greater hazards. (Jones 1985: 418)

The Manhattan District's industrial medicine branch implemented protocols to protect workers from hazards including burns, lung irritation, and kidney failure. But broader harms to environmental and human health were overlooked in favor of military secrecy.

> … the Industrial Medicine Branch collaborated with construction and operating contractors to install closed ventilation systems and to develop special handling techniques. The Carbide and Carbon Chemicals Corporation, for example, had its gaseous diffusion plant workers use protective clothing and Army-type gas masks when they repaired the hundreds of pumps that were cooled and lubricated with toxic fluorinated hydrocarbons. (Jones 1985: 418)

The Manhattan Project had undergone labor shortages and unrest among workers at several facilities, but the production of Teflon and fluorocarbons at the Du Pont Deepwater factory in New Jersey was a highly significant source of labor unrest. According to classified documents (Bernstein 1944; Brundage 1945) and reporting by Blake (2025:44), workers had "fear of the physical consequences," dreading assignment to the Du Pont fluoride processing areas as "an exile to Devil's Island". Their fears were not unfounded. Fluorinated chemicals and fluorocarbons produced at Du Pont's Chambers Works facility were involved in explosions, deaths, and contamination events (Renfrew 1987; Blake 2025).

In the initial phases of the industrial-scale PTFE production, PFAS production involved a combination of unseen science, which sequestered knowledge about the risks due to military secrecy, and undone science which had not yet documented the range of environmental and human health effects. In 1943, the Manhattan Project contracted with DuPont to operate a fluorocarbon pilot plant at Kearny, NJ. During the pilot stage, three scientists died at Jackson Laboratory in DuPont's Deepwater, New Jersey factory from chemical exposure to Teflon processing waste gases (Renfrew 1987). The autopsy concluded the worker's lungs were "similar to a victim of WWI poison gas" (Bernstein 1944). Decades later, acute lung injury was associated with Teflon manufacturing in occupational health studies. For years, workers had complained of "Teflon flu," cases of which were studied and results withheld by DuPont (Gaber et al. 2023). Another incident involving Teflon resulted in an explosion at DuPont's Experimental Station in Arlington, Delaware; the rush to meet Manhattan Project demands led to human error and left two technicians dead (Renfrew 1987). Manhattan Project planners and scientists were not ignorant to the risks revealed by these incidents – they recognized that the enormous amounts needed at scale in production plants posed much greater hazards than the small quantities used at pilot plants (Manhattan District 1947b). Local downwinders were also affected by production at Deepwater, and in 1944 several farmers brought a lawsuit claiming there was widespread contamination and damage to peach crops and livestock, and farmworkers were becoming sick after eating produce from the fields (Blake 2025; Groves 1946).

Commented [ML4]: What was the outcome - MP didn't release data due to national security/military secrecy

Undone and unseen science also played a role in the (non)production of environmental health and toxicology knowledge around PFAS. Harold Hodge of the University of Rochester was hired to lead toxicology research on uranium and fluorocarbons. The secretive work involved an effort to generate data that would "strengthen the Government's interests" and undermine "medical legal" issues related to the production of fluorinated compounds (Blake 2025; Warren, 1945; Friedell, 1946). Moreover, Du Pont was reticent to provide information about their patented product. Internal Manhattan Project memos from 1944, written to the director of medical research, showed that Du Pont "considers that we were buying a 'packaged product' and is not interested in our investigating the toxicity of the materials involved" (Capt. Ferry to Col. Warren, 1944). The medical division sought to learn more about the deaths of workers exposed to Teflon, but Du Pont refused to provide samples. "DuPont is reluctant to release samples of their own commercially produced material since several of the components thus far identified give good promise for commercial uses" (Manhattan District Engineer Ruhoff to H.T. Wensel, 1944). These instances would foreshadow Du Pont's handling of public concerns around the commercial manufacture of PFAS.

As the construction of the gaseous diffusion plant was rapidly moving forward, a central chemistry problem remained: finding materials that could withstand highly caustic fluorine gas. Of the fifteen PFAS we identified in the Manhattan Project, several were most likely used in very large volumes as process gases and for coating equipment that encountered process gas. PTFE or Teflon (codenamed D-29, K419, or TFE in Manhattan Project documents) was the initial candidate, but it turned out to be far less useful than planners hoped. While initially optimistic about Teflon's ability to "meet the needs for a plastic material for gaskets, valve seats and the like which would be inert to fluorine and process gas," early research found that it was "not as satisfactory as originally expected and the quantity need would therefore be very [sic] much smaller" (Manhattan District 1947a: G.27). Importantly, the broader search for materials that were inert to fluorine and process gas was guided by the initial insight that "by far the most likely material would be a completely fluorinated substance" (Manhattan District 1947a: G.27).

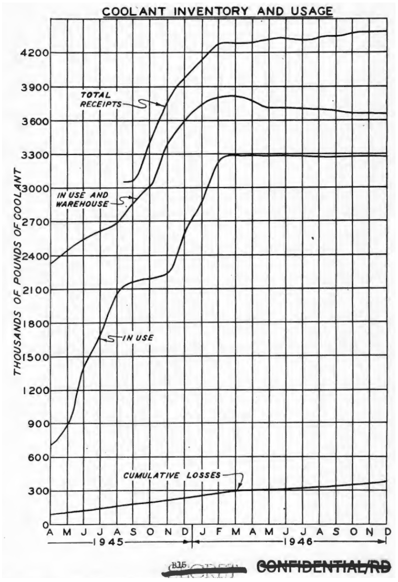
Data on the types and quantities of PFAS used during the entire Cold War is not publicly available, but their critical use in the Manhattan Project highlights their enduring importance in gaseous diffusion, a key process in uranium enrichment for both nuclear energy and nuclear weapons production. The Manhattan District History of the K-25 Gaseous Diffusion Project identifies several PFAS which were "principal special chemicals required at the gaseous diffusion plant" at Oak Ridge (Manhattan District 1947a). The procurement of these special materials was critical enough that two separate sections of the Madison Square Area Engineers Office were assigned to the task: the Special Materials Branch and the Special Projects Branch (Jones 1985). PFAS served an extremely wide range of processes. Some of these uses required very large volumes, such as process coolants, and others were as lubricants or sealants on virtually everything that came into contact with the volatile and highly caustic substances uranium hexafluoride or fluorine gas. We explore two of these uses in detail: the PFAS used in the greatest volumes at Oak Ridge as process coolants, and the PFAS used in more moderate volumes as lubricants, solvents, gaskets, and valve seals.

Gaseous Diffusion at Oak Ridge Nuclear Reservation

A nuclear warhead requires highly enriched uranium (or plutonium). During the Manhattan Project, three enrichment processes were used at the Clinton Engineering Works, or Oak Ridge, facility in Tennessee: electromagnetic separation at the Y-12 plant; thermal diffusion at the S-50 plant; and gaseous diffusion at the K-25 plant (Makhijani et al 1995). Gaseous diffusion was the only enrichment process used after 1946, primarily due to cost efficiency. While gaseous diffusion has been carried out at three US facilities, the high-level enrichment of 994 metric tons of uranium for nuclear weapons and naval reactors has occurred only at Oak Ridge (1944-1985) and Portsmouth (in Piketon, OH, 1954-1992), with Paducah (in Paducah, KY, 1952-2013) producing low-enriched uranium for both military and civilian reactors (Makhijani et al 1995). The K-25 gaseous diffusion facility involved over 1,000 pumps and stages in which a process gas was used to enrich uranium hexafluoride, by separating uranium-235 from other uranium isotopes to enrich it, and the end product was fabricated into fuel for nuclear reactors (U.S. Nuclear Regulatory Council 2025).

Oak Ridge Reservation is an enormous swath of land that housed three major sites: Oak Ridge National Laboratory; Y-12 National Security Complex; and the K-25 plant (now called the East Tennessee Technology Park). While the Pentagon is the world's largest low-rise office building (U.S. Department of Defense 2024), the main process building of K-25 surpassed it in size as a four-story U-shaped structure that was more than half a mile long, 1000 feet wide, and covered 44 acres. It housed 54 process and purge cascade buildings, and the full process involved 2,892 stages (Manhattan District, 1947a; U.S. National Park Service 2025). The Oak Ridge Reservation included factories for producing fluorinated chemicals, and the production of highly enriched uranium which occurred at five enrichment facilities. Rather than acquiring existing fluorine production sites, Manhattan Project leadership chose to build fluorine gas production plants at the Oak Ridge gaseous diffusion site for both practical and economic reasons: the volatility of fluorines in terms of both their production and use, the associated transportation risks, and the vast quantities needed for the gaseous diffusion process (Manhattan District 1947b). The Chemical Technology Division at Oak Ridge National Laboratory was a leading national institution, operated by private corporations, pioneering nuclear technologies and chemical engineering R&D (Oak Ridge National Laboratory 1993; see Figure 3). Throughout the Manhattan Project and the Cold War, a large network of private corporations, university laboratories, and subcontractors were responsible for facilities operations and training of personnel. J. A. Jones Construction Company built the K-25 complex. It was operated by: the Kellex Corporation; Union Carbide and Carbon Corporation; Du Pont; the University of Chicago Metallurgical Laboratory; Ford, Bacon, & Davis; and Hooker Electrochemical Corporation (Manhattan District 1947b; Oak Ridge National Laboratory 1993). Oak Ridge underwent enormous expansions during the Cold War and especially after the 1950 onset of the Korean War and the commensurate use of PFAS at Oak Ridge grew exponentially after 1950, and likely peaked in the late 1960s as the military's enriched uranium stockpiles became saturated.

Figure 3. Manhattan District Coolant inventory and Usage. Manhattan District History, Vol. II, 1947, Appendix B15



Three important PFAS were used as "dummy gas" and process coolants: perfluoroheptane (C-716[5]); perfluorodimethylcyclohexane (C-816), and hexafluoroxylene (P-45). The dummy gas, which had a similar density to uranium hexafluoride but was non-corrosive, was used as a test fluid and to train operators and test the system for leaks before uranium hexafluoride was used (Manhattan District 1947a). As noted, all of the equipment that came into contact with uranium hexafluoride or fluorine gas needed to be "conditioned," treated in a special facility that coated equipment with a heated mixture of fluorine and nitrogen gases. Such conditioned equipment was used in as many as 1,000 stages of the diffusion process as well as all of the pumps necessary to move the process gas through the system (Figure 4).

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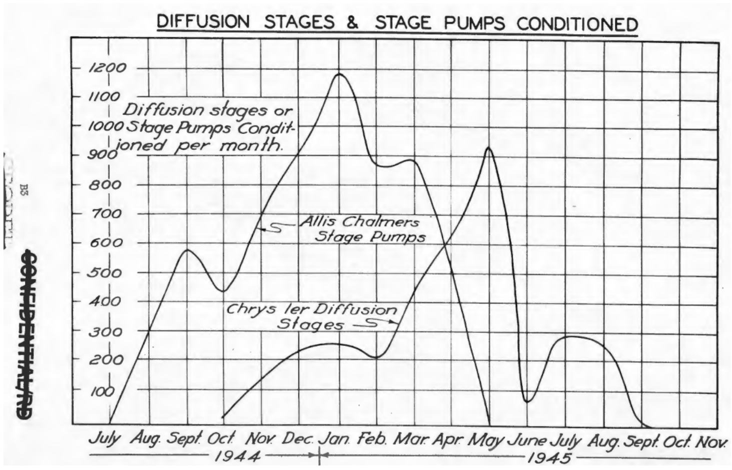
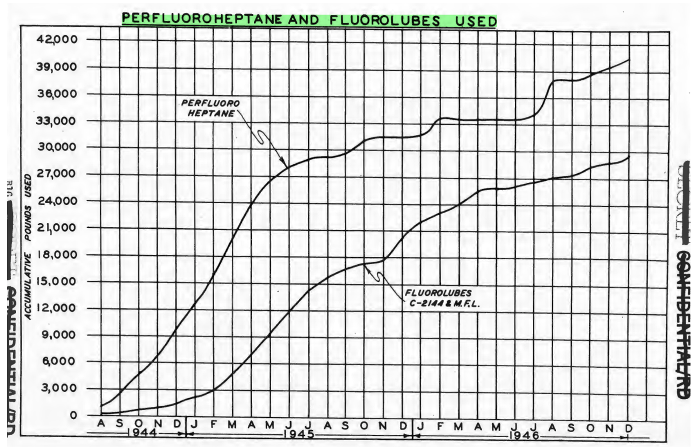
[5] Numbers indicate Manhattan District codenames used for these special materials. See Table

Figure 4. Manhattan District Gaseous Diffusion Stages and Pumps Conditioned. Manhattan District History, Vol. II, 1947, Appendix B3



Every pump required specialty lubricants and numerous gaskets and valve seats. Testing and lubricating the system required a considerable amount of perfluoroheptane and fluorolube (Figure 5). Du Pont's contract with the Manhattan Project required the construction of a special manufacturing plant for perfluoroheptane, resulting in the production of 20,280 pounds; additionally, 97,032 pounds of perfluoroheptane derivatives C-716-1 and C-716-2 were produced at the plant (Manhattan District 1947b). The rapid production of perfluoroheptane took precedence over cost efficiency. Planners remarked that an alternative cheaper process for producing perfluoroheptane was under development, and "Undoubtedly this process would have been used had it been possible to develop it in time since the cost of the material as a by-product would have been relatively low in any case" (Manhattan District 1947b: G.6).

Figure 5. Manhattan District Gaseous Diffusion Perfluoroheptane and Fluorolube Usage. Manhattan District History, Vol. II, 1947, Appendix B16



C-716 was the initial choice for process coolant, but the high cost and enormous volume needed facilitated the extension of R&D on perfluoromethylcyclohexane (C-816) which was taking place at Johns Hopkins and Purdue Universities and Hooker Electrochemical and Du Pont (Manhattan District 1947b). DuPont was chosen as the manufacturer of C-816 due to their extensive work with C-716 and C-816. Production schedules and requirements were in chaotic flux throughout the Manhattan Project:

> Requirement schedules were changed almost daily and especially in the latter part of 1944 and early 1945 these changes varied as work proceeded with the construction of various plants which required this material. Early in March 1945, instructions were given for reducing the plant capacity of C-816 in which about 75% of the facilities were to be shut down and placed in standby conditions … in the latter part of the same month, additional requirements were received and it was necessary to ask du Pont to increase production rates. In early April 1945, it was requested that C-816 be made at the rate of

> 150,000 pounds per month and at the same time it was thought that additional C-2144 would be necessary… requirements changed so that the C-2144 process was shut down entirely a little more than a month later. (Manhattan District 1947b: G.8-9)

A total estimated 4.4 million pounds of process coolant inventory was in use and warehoused during the Manhattan Project, including 3.9 million pounds of C-816 which were needed to fill the gaseous diffusion coolant systems (see Figure 3; Manhattan District 1947b: 5.6-5.9). Production of C-816 required large volumes of hexafluoroxylene (P-45), and Hooker Electrochemical was contracted to build and operate a plant near Lova Canal that produced P-45 and two useful derivatives, ultimately producing 2,729,846 pounds of P-45; 168,350 pounds of P-45CL, and 69,790 pounds of P-45CL-2 (Manhattan District 1947b).

Fluorolubes and Solvents

Fluorolubricants presented another unique scientific problem for the Manhattan Project, because the gaseous diffusion process required lubricants that could withstand the corrosive uranium hexafluoride. Prior research had not satisfactorily yielded an appropriate material, and Manhattan Project research proceeded slowly due to the difficulty and high cost of R&D. Numerous fluorolubes were researched, developed, and produced: 30,513 pounds of a fluorinated commercial oil lubricant, C-2144; 23,108 pounds per month of the polymerized fluorolube MFL, made of polymerized and fluorinated perfluorovinyl chloride (PVC); at least 357.4 pounds of fluorolube solvent (FLS); and MFP-10, another polymerized perfluorovinyl chloride which became the chemical of choice for valve seats (Manhattan District 1947b). Initially, DuPont was awarded the contract for building a plant that would produce the fluorolube C-2144, a fluorinated version of commercial oil lubricant, and a mixture of kerosene and fluorinated hydrocarbons known as fluorolube solvent (FLS) that was necessary for dissolving fluorolube in the manufacturing process. But expectations for production of C-2144 failed and "this process was never satisfactorily worked out since explosions and burn outs in the plant were a constant source of difficulty" (Manhattan District, 1947b: G.14-15). In attempting to work around the problems with C-2144, Hooker Electrochemical was contracted for the R&D and production of MFL, which appeared to have superior qualities to C-2144. The production requirements for MFL included 79,850 pounds of another PFAS, trifluorochloroethylene (P-539) and simultaneous with MFL R&D was research on the production of MFI, a "heavy vaseline-like grease obtained from the residues" of MFL production, of which 559 pounds were recovered and converted into MFL (Manhattan District 1947b).

Our analysis has focused on PFAS use in uranium enrichment, which is only one aspect of the nuclear weapons production process for which data was available. PFAS have numerous applications across the nuclear energy and weapons manufacturing processes which have yet to be fully uncovered, including serving as lubricants, gaskets, and seals in nuclear reactors and supporting reprocessing activities. The US operated eight plants that reprocessed spent nuclear fuel into bomb components, until the end of reprocessing in 1988: five at Hanford; two at the Savannah River Site; one at the Idaho Chemical Processing Plant which began operations in 1953; additionally, military reprocessing was carried out at a privately-owned reprocessing plant in West Valley, New York between 1966 and 1972 (Makhijani et al. 1995: 208). As of 2024, DOE has begun investigation of the historical uses of PFAS and results are forthcoming; publicly available testing of drinking water sources at the Hanford site have not detected PFAS (US DOE

2024). PFAS are highly likely to have been used at Los Alamos in the Chemistry and Metallurgy Research Facility and the Plutonium Processing Facility (Los Alamos 2020:9), and PFAS have been measured in drinking water and groundwater at exceptionally high levels at some sites at Los Alamos (Paskus 2021). PFAS are used in polymer-bonded explosives (and other munitions components), which are used as nuclear weapons detonators, and although PFAS may be destroyed by the heat of a nuclear detonation, their creation requires PFAS materials. The US created more than 60,000 nuclear weapons over the course of the Cold War (Makhijani et al. 1995). Many of these polymer-bonded explosives have been developed at National Labs and are named after them, such as LX-04 developed at Lawrence Livermore National Laboratory (Dobratz 1972). Given their utility in tolerating extreme environmental and chemical conditions, PFAS are likely used in nuclear waste management systems as well.

In this section, we have briefly outlined a ToD that emerged in the production of PFAS for the nuclear arms race. Our analysis highlights the antecedent conditions and macrostructural context of the US entry into WWII and the competition to create a nuclear weapon. The critical juncture of the Manhattan Project marked a deepening in the long-standing organization and manufacture of military weaponry through the fusion of industrialism and militarism - the military-industrial complex. But the dynamics of capitalism in the world's leading capitalist economy do not fully explain the creation of nuclear weapons, the postwar US military strategy, or the chemical treadmill of destruction that resulted from this effort. The infusion of US capital reserves into the Manhattan Project was a *sufficient* condition for the emergence of a PFAS treadmill. The *necessary* conditions were the enormous military-guided growth in fluorine chemistry (and nuclear physics), the geopolitical competition and arms race, and the transformational military organization of science, industry, and academic institutions towards the production of the bomb. As the US entered the Cold War arms race in the wake of WWII and competed to maintain its military dominance, it established the institutional foundation of warmaking by doubling down on its strategy of "hegemony on the cheap" through science-intensive strategic nuclear weapons (Hooks and McLauchlan 1992). Having the national labs and the nuclear reservations provided a strong institutional network of funding, science training, employment, and social legitimation that comprised the treadmill mechanism. PFAS were invaluable for nuclear weapons production and the goals of the national security state, and their use became more entrenched with every expansion of the nuclear arms race. Thus, PFAS production for the Manhattan Project and the Cold War arms race was a self-amplifying path-dependent process that resulted from a specific mechanism - a treadmill of destruction.

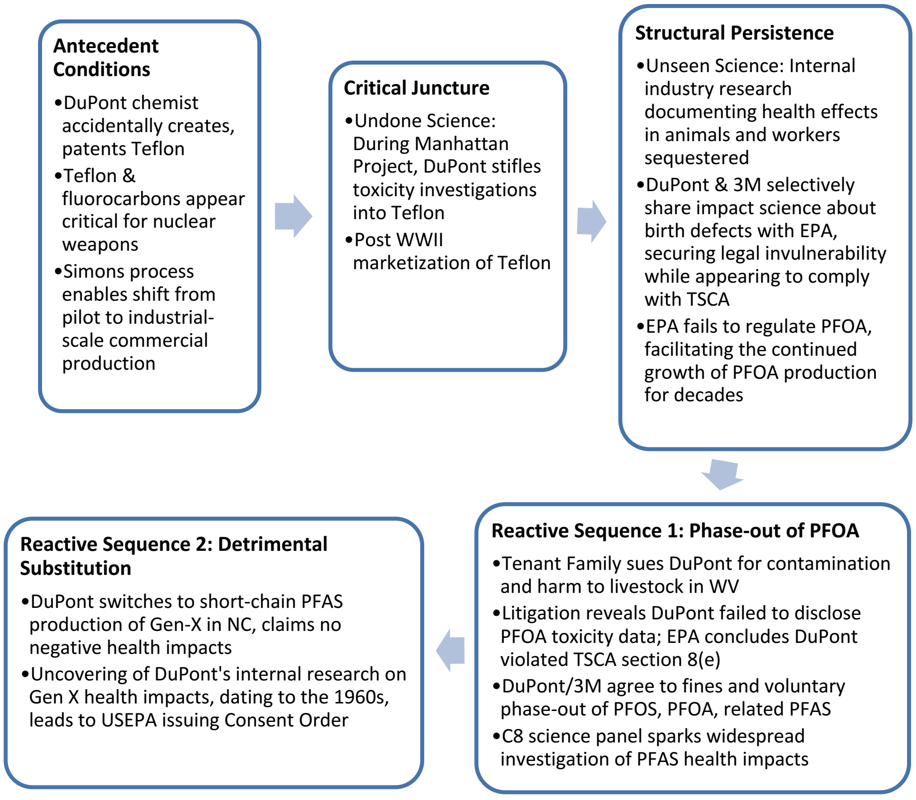
Treadmill of Production Mechanism

Thus far we have identified ToD mechanisms at play in the corporate-military entanglements that characterized the Manhattan Project and Cold War, focusing on the use of PFAS in nuclear R&D and production. We found clear evidence of path dependency in how the US military identified PFAS compounds as tools that fit their needs for various aspects of nuclear technology, and then integrated PFAS as requisite, widely used compounds. This history shows evidence of a self-reinforcing sequence in the US military's commitment to using PFAS as part of the gaseous diffusion process for nuclear weapons production – among other weapons processes – which reached manic heights during the Cold War nuclear arms race.

We now turn to ToP mechanisms at play in the commercialization of PFAS by major chemical companies. These companies certainly played consequential roles in ToD dynamics in the Manhattan Project and Cold War, but such PFAS use had natural limits. Going forward, it was the commercialization of PFAS that has contributed most significantly to the widespread nature of PFAS contamination today. We discuss two examples of PFAS-containing products that show how chemical companies actively sought to accelerate and then protect the production of these profitable compounds: the commercialization of Teflon as a product with myriad industrial and consumer applications, and the development of fluorinated AFFF firefighting foam. While both Teflon and AFFF both have military applications and entanglements, focusing on their commercialization outside state or military uses highlights ToP dynamics. Studying their production helps us in identifying reactive sequences - in contrast to ToD's self-reinforcing sequences - that defined companies' actions regarding the perpetuation and expansion of PFAS production.

We are far from the first to examine how chemical companies participate in the ToP. Such attention goes back to Schnaiberg's (1980) original writing on chemical intensity and production. Schnaiberg and Gould (1994) consider "*Basic* Chemical Company" as one of three archetypical organizations to fully conceptualize the industrial logic of the ToP, highlighting how a chemical company's environmental practices lead to environmental harms, and how they respond to and intervene regarding political, economic, and social pressures. Other scholars have applied ToP to case studies involving the chemical industry, including organic agriculture (Obach 2005) and coal mining (Bell and York 2012), and explored organizational characteristics that matter for companies' environmentally damaging behaviors, including chemical facility characteristics (Grant et al. 2010) and social embeddedness (Carrillo and Pellow 2021). In the paragraphs that follow we address the processes involved in a reactive sequence of the ToP mechanism: the antecedent conditions of Du Pont's Teflon discovery, its perceived importance for the Manhattan Project, and the development of the Simons process; the critical juncture of the Manhattan Project, the undone science of nuclear weapons and Du Pont's stifling of critical health research on Teflon; the structural persistence of PFAS production resulting from Du Pont and 3M's unseen science, and EPA's failure to regulate PFOA; and two reactive sequences in which Du Pont shifted to producing the replacement PFAS, Gen-X after the Tenant Family lawsuit and the C8 Study.

Figure 5. Reactive Sequences in the Treadmill of Production Mechanism



Antecedent Conditions

- DuPont chemist accidentally creates, patents Teflon
- Teflon & fluorocarbons appear critical for nuclear weapons
- Simons process enables shift from pilot to industrial-scale commercial production

Critical Juncture

- Undone Science: During Manhattan Project, DuPont stifles toxicity investigations into Teflon
- Post WWII marketization of Teflon

Structural Persistence

- Unseen Science: Internal industry research documenting health effects in animals and workers sequestered
- DuPont & 3M selectively share impact science about birth defects with EPA, securing legal invulnerability while appearing to comply with TSCA
- EPA fails to regulate PFOA, facilitating the continued growth of PFOA production for decades

Reactive Sequence 1: Phase-out of PFOA

- Tenant Family sues DuPont for contamination and harm to livestock in WV
- Litigation reveals DuPont failed to disclose PFOA toxicity data; EPA concludes DuPont violated TSCA section 8(e)
- DuPont/3M agree to fines and voluntary phase-out of PFOS, PFOA, related PFAS
- C8 science panel sparks widespread investigation of PFAS health impacts

Reactive Sequence 2: Detrimental Substitution

- DuPont switches to short-chain PFAS production of Gen-X in NC, claims no negative health impacts
- Uncovering of DuPont's internal research on Gen X health impacts, dating to the 1960s, leads to USEPA issuing Consent Order

Teflon production

The first ToP example is the commercialization of PTFE, a fluoropolymer whose extreme non-reactivity made it useful in a broad range of industrial and consumer applications, most famously Teflon as a non-stick coating but also for applications requiring non-corrosive, non-reactive surfaces (e.g., certain pipes), heat durability and electrical insulation (e.g., computer wiring), slipperiness (e.g., dental floss), and hundreds of other uses (Gluge et al. 2020). Perfluorooctanoic acid (PFOA) was used in the manufacture of PTFE and remained present in finished goods as a contaminant, though PFOA and Teflon are not equivalent.

The antecedent conditions involve a series of events that set the stage for both the creation - and industrial scale production - of Teflon and other fluorochemicals. Teflon was first synthesized in 1938, accidentally, by a Du Pont chemist attempting to make a fluorinated refrigerant (Altman 2019). Elsewhere in, 1940 a chemical engineer named Joseph Simons was being recruited for the Manhattan project to develop the electrochemical fluorination process, which held promise for the Manhattan Project to ramp up fluorochemical production to an industrial scale, and his process became sequestered by military secrecy (Penn State University 2025). In 1941 PTFE and the process used to create it was patented as "Tetrafluoroethylene Polymers" (Suiter Swanz IP 2018). Du Pont participated heavily in the construction and operation of facilities for the Manhattan Project beginning in 1942 – such as the K-25 gaseous diffusion plant - which involved constructing "hundreds of miles of pipe and tens of thousands of filters, seals, gaskets, and pumps", virtually all lined with fluorocarbons (Blake 2025:43). Though the company did this work for limited profit, they maintained the Teflon patent (Blake 2025:42), and trademarked the brand in 1946 (Suiter Swanz IP 2018). Meanwhile, Manhattan Project chemists derived methods other than the Simons process to produce military fluorocarbons for the bomb, and after the war Simons sold his process to 3M who patented it in 1948 (Altman 2019; Penn State University 2025). Both Teflon and the Simons process ultimately proved to be less useful for the Manhattan Project than initially hoped for, as Teflon did not meet performance specifications of uranium hexafluoride and Manhattan Project chemists chose another industrial scale process over than the Simons process. But Teflon was a necessary condition, and the Simons process was a necessary and sufficient condition, that set the stage for the commercial-industrial production of PFAS.

A critical juncture for the ToP mechanism occurred at the intersection of these two antecedent conditions (the discovery of Teflon and the development of the Simons process) and a key event: Du Pont's stifling of Manhattan Project toxicity investigations into Teflon and its byproducts, and the Manhattan Project officials' efforts to stymie potential lawsuits related to Du Pont's secret work and the resulting environmental health harms. During the war a series of worker deaths and nearby crop and livestock poisoning occurred. Following two worker deaths involving the inhalation of Teflon by-products, the medical division of the Manhattan Project requested Teflon samples, and Du Pont refused because the compounds showed "good promise for commercial uses" (Ruhoff 1944). Additionally, General Groves was concerned that the negative publicity of poisoned peach crops in Deepwater, New Jersey near the Du Pont plant would impact public perception of the bomb project; Manhattan Project officials lobbied the FDA not to ban the contaminated produce (Bryson and Griffiths Papers; Groves Memo; Deepwater files). It is plausible that, had the health effects of Teflon production been more thoroughly documented and explored, Du Pont would have facedgreater scrutiny of the

Commented [GU5]: Simons invented the ECF process in 1939. What is this "Penn State University 2025" source, and is this statement about military recruitment of Simons explicit and verifiable in that source? I ask because I know from diss research that 3M's commissioned historical account of the Simons process tells a somewhat different story, as do other sources that I consulted.

Regardless, here is the ECF patent that is the "Simons process""
https://patents.google.com/patent/US2519983A/en?inventor=Joseph+H+Simons
3M filed it in 1948, as you say later in the paragraph. We should cite the patent (and likely the Simons oral history interview transcript) in the next version of the paper if this discussion of Simons is retained as part of our argument in the next iteration of this paper. - GP

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Commented [GU8]: It is really not plausible that DuPont would have faced criminal or financial penalties given the government contract defense/immunity that came with being enlisted by the government as the core architect of Hanford, Savannah, etc.. Hagley has extensive documentation on this point that I can point to if needed.

commercialization and marketization of its newly patented product, and the government might have been pressured to redress the polluting activities of its contractors.

After World War II, Du Pont pursued the marketization of Teflon into consumer use products. Du Pont's commercial fluorocarbon production was still at the pilot scale, and only very small amounts could be produced at great expense. The pilot process was very dangerous and faced numerous setbacks, including poisoning and explosions (Blake 2025). Du Pont approached 3M with hopes that the Simons process could help refine their own Teflon production, purchasing PFOA, "a white, detergent-like powder and, in the Teflon process, it eased Teflon into formation" (Altman 2019). Industrial-scale Teflon production began at DuPont's Parkersburg, WV facility starting in 1951, using the 3M PFOA, while waste streams flowed into rivers, air, and local landfills that later contaminated the water supply (Altman 2019; Lyons 2007). Beyond the Manhattan Project, Teflon found numerous other military applications, including wire insulation for radar equipment and aviation (E.I. du Pont de Nemours & Company Plastics Department 1963:7; Poudrier 2024). In 1960-61, "Teflon gained public identification" through the release of non-stick frying pans (E.I. du Pont de Nemours & Company Plastics Department 1963:11). The company engaged the advertising firm N.W. Ayer & Son to develop a multi-pronged strategy centered around Teflon-lined "Happy Pans" as a tool for losing weight and reducing labor (Poudrier 2024:79). Additionally, advertising embraced the connection between Teflon and American nationalism, connecting the product to the space program and the Statue of Liberty (Poudrier 2024:82-83). The company sold 500 million pieces of nonstick cookware from 1961-1987 (Troy 1987).

The widespread marketing and use of Teflon in commercial products led to the structural persistence and acceleration of Teflon production. The company worked to move Teflon more directly into the public sphere, enhancing the visibility of the product both through overt marketing and highlighting otherwise invisible uses. For example, a company periodical, *The Journal of Teflon*, highlighted the disparate uses of the compound, from musical instruments to circuit-board production (E.I. Du Pont de Nemours & Company, Inc. 1962:1–8). In the words of a later DuPont pamphlet, "'Teflon' has hundreds of familiar uses, along with hundreds of unfamiliar ones" (E.I. du Pont de Nemours & Co. DuPont Building Files 1988).

Teflon production in this early period was characterized by an episode of unseen science (Richter, Cordner, and Brown 2018). Simultaneously with the acceleration of production and the marketing blitz, evidence emerged about Teflon and PFOA's toxicity. Starting in the 1950s, several cases of worker illness linked to Teflon were published in academic or government sources (Gaber 2023:6), and by the 1980s, significant toxicological research identified PFOA as a "serious health risk" for numerous health endpoints (Gaber 2023:7). Internal industry studies conducted as early as 1970 identified PFOA as "highly toxic" when inhaled (Gaber cite 90), and in 1981 a study identified significant birth defects in the pups of pregnant rats exposed to PFOA during pregnancy (Hegg 1981). In 1981, DuPont removed female workers from the Teflon division when several employees gave birth to children with birth defects (Karrh 1981; Lerner 2015; Richter et al. 2018). Though the company shared some internal animal toxicology data with USEPA, they did not disclose the information about their employees; although EPA staff expressed concerns about animal toxicology findings, no regulatory action was taken at this time (Blake, 2015; McKusick, 1982). An internal memo in 1994 encouraged the company to "evaluate replacement of C8 with other, less toxic materials" (Boone and DuPont 1994:5; see also Gaber et al. 2023).

Substantial action on PFOA, and by extension Teflon, was not rekindled until nearly two decades later, when the Tenants, a West Virginia farm family, engaged a lawyer to investigate DuPont's contamination of their land and harm to their livestock (Richter et al. 2018; Bilott 2019; Lyons 2007). As part of the subsequent litigation, internal DuPont documents revealed the company's failure to disclose data on PFOA's toxicity and harm to workers. DuPont and 3M agreed to substantial fines and a voluntary phase-out of PFOS, PFOA, and related PFAS effective in 2015 (U.S. Environmental Protection Agency 2013). While 3M announced in 2000 that it would stop producing PFOA altogether, DuPont produced the compound at a newly constructed Fayetteville, NC plant from around 2002 until an unknown date (DuPont 2001).

With PFOA use hindered but fluoropolymer production ongoing, industry sought a functional replacement chemical. DuPont's replacement for PFOA was a processing aid commonly referred to as "GenX chemicals" "or GenX technology" (Chemours 2023; U.S. Environmental Protection Agency 2021b). DuPont filed a Pre-Manufacture Notice (PMN) with the USEPA for GenX chemicals in 2008, and the company - now called Chemours after DuPont spun off its specialty chemicals division - has been producing GenX chemicals since 2009 (Chemours 2023).

Although the company initially claimed that GenX chemicals had a "favorable toxicological profile and very rapid bioelimination" (DuPont 2010:2), the company's own research points to toxicity and exposure concerns from soon after it first synthesized the compounds in the 1960s. In 1963, DuPont conducted an acute oral toxicity study in which male rats given a single dose of one of the GenX chemicals died following "discomfort, gasping and/or tonic convulsion" (Sherman 1963:2). Starting in the late 1990s, presumably as part of the company's search for a PFOA replacement, DuPont conducted acute lab animal toxicity studies (USEPA NCEA 2024). From 2006-2011, DuPont submitted 18 TSCA Section 8(e) filings related to potential risks, including results for short-term oral toxicity, dermal toxicity, inhalation toxicity, genotoxicity, and eye irritation tests in mammals, as well ecotoxicity tests in an aquatic invertebrate, with "reportable" findings including liver effects, hematological effects, and death (DuPont 2006-2019).

In response to DuPont's 2008 PMN for GenX Chemicals, USEPA issued a Consent Order concluding that the compounds "may present an unreasonable risk of injury to human health and the environment" (USEPA 2009:xv). The Consent Order required the company to provide certain pharmacokinetic and toxicology data, triggered by undisclosed production volumes, and further ordered the company to provide certain workers with personal protective equipment and to "recover and capture (destroy) or recycle" 99% of GenX chemical wastewater and air emissions from commercial production (p. vi). Further research, both internal industry studies and independent academic research, confirmed concerns about GenX chemicals' toxicity and exposure potential. In 2017, residents near the Fayetteville, NC Chemours facility learned about elevated levels of GenX chemicals in their treated drinking water (Sun et al. 2016:418). The resulting regulatory investigations led to a Consent Order with North Carolina state environmental and health agencies requiring Chemours to install and manage emission abatement technologies and to fund water clean-up efforts (NCDEQ 2025), but production continues at this facility.

Elsewhere we have argued that the case of GenX chemical substitution for the legacy chemical PFOA is a case not just of what is called "regrettable" substitution, in which the replacement of chemicals found to present human health hazards with other, unstudied chemicals with different or unknown hazards (Blum et al. 2019; Howard 2014; Maertens et al. 2021), but of *detrimental* substitution (Allgeyer et al. *under review*). Unlike "regrettable" substitution, which implies that results were unforeseen and unintended, detrimental substitution acknowledges that at least in some cases, those consequences were reasonably foreseeable by responsible parties but were deliberately disregarded in order to preserve or expand markets and profit potential. In cases of regrettable substitution, "harmful chemical substitution process results from structurally produced knowledge gaps that are attributable to three main factors: the capitalist growth imperative that incentivizes harmful corporate behavior, statutory limitations and loopholes, and self-imposed regulatory reticence" (Allgeyer et al. *under review*).

Intersecting Treadmills - AFFF production, Airports, and MilSpec

Having described the original applications of PFAS in the Manhattan Project and the commercialization of Teflon, we turn now to a more recent example of a PFAS treadmill, the DOD's historic use of PFAS-containing aqueous film forming foam (AFFF; pronounced "A-triple-eff"). Environmental releases of AFFF historically fell into four major categories: fire training, fire preparedness procedures (annual testing), fire suppression systems, and emergency fire responses (Anderson et al. 2016); it is now widely recognized that decades of historical AFFF releases by the DOD account for a substantial portion of contemporary PFAS contamination (Anderson et al. 2016, Houtz et al. 2013).

Scientific R&D on AFFF began in the 1960s in the US military-industrial complex as a research collaboration between the US Naval Research Laboratory (NRL) and two private corporations, the Minnesota Mining and Manufacturing Company (3M) and Ansul (MacKay 1991). Their research culminated in the development of 3M's "Light Water" AFFF, which gradually overtook protein-based foam to become the DOD's gold standard tool for extinguishing Class B (flammable-fuel based) fires. The DOD's use of 3M's "Light Water" AFFF (and later, competing AFFF brands) began in 1967 and continued for more than fifty years, causing widespread PFAS contamination in the US and globally (Back 2024).

A critical juncture occurred when a horrific fire aboard the U.S.S. Forestal created a window for institutionalization. The success of 3M's Light Water AFFF was not inevitable or guaranteed. Rather, after initial collaboration with NRL researchers, 3M aggressively pursued contracts and implementation within the military. The 1967 fire on the USS Forrestal aircraft carrier created an opportunity for 3M to pursue service-wide adoption of AFFF within the US Navy; as 3M historian Neil MacKay described, "the balance was tipped" in favor of 3M and their AFFF product (MacKay 1991:160). The Forrestal fire was particularly devastating for the Navy, killing 137 crew members, injuring 161 others, and causing an estimated $72 million in damages (cite). As Poudrier's sociological analysis of AFFF history shows, "the Navy's willingness to adopt Light Water increased rapidly" following the Forrestal fire; indeed, according to one account, military leadership and 3M representatives met in person to discuss Light Water the day after the Forrestal fire made headlines (Poudrier 2024:95-96). A few months later, newspapers publicized the arrival of Light Water on US carriers in Vietnam. Much of the immediate publicity misrepresented Light Water as an overnight breakthrough in fire suppression technology, developed by the military in a moment of crisis, rather than as a firefighting innovation that had already been in development for years (Poudrier 2024).

[treadmill expansion- AFFF set within MilSpec as the only product that would work; also set into Part 139 airport testing/training requirements; evidence of how chem companies actively sought new military requirements and new private/FF markets]

Following the Navy's adoption, 3M courted contracts from other military service branches and focused on breaking through US Air Force resistance to adopting AFFF (McKay). Concurrently, 3M and Ansul undertook additional efforts to expand their market of AFFF users beyond the US military and into commercial aviation, municipal fire departments, oil refineries, and other industries that deal in fuel-based fire hazards (Poudrier 2024). Both efforts paid off. In 1969, mil spec_________ effectively routinized adoption across the military. In ____, FAA /Part 139… [sentences about institutionalization of AFFF]. The promulgation of both specifications for AFFF effectively routinized environmental releases at scale, setting the stage for widespread PFAS contamination that is still being discovered. By September 1976, the *South China Morning Post* reported that 3M Light Water was "used extensively throughout all branches of the US Department of Defense, in municipal fire departments, in industrial plants, and in petroleum storage tank areas" (South China Morning Post 1976).

By the late 1970s, 3M scientists had clear evidence that PFOS was persistent, bioaccumulative, and toxic, and urged the company to perform carcinogenicity tests (Hansen 2023). Yet in product brochures distributed to potential customers during this period, 3M overtly represented Light Water as "biodegradable," "low in toxicity," and "environmentally neutral" (3M Company 1978). In 1988, a 3M Environmental Specialist penned an internal memo problematizing this disinformation: "I don't think it is in 3M's long-term interest to perpetuate the myth that these fluorochemical surfactants are biodegradable. It is probable that this misconception will eventually be discovered, and when that happens, 3M will likely be embarrassed, and we and our customers may be fined and forced to immediately withdraw products from the market" (Reiner 1988).

While DOD does not appear to have learned about PFOS toxicity from 3M, the military conducted its own suite of research studies on AFFF's environmental impacts, initially prompted by concerns about AFFF disposal methods and the potential impact of AFFF on aquatic environments and military lands. In the process of investigating these concerns, DOD research documented the environmental toxicity of AFFF releases starting in 1974 (Kroop and Martin 1974; LeFebvre & Inman 1974). 3M and Ansul played an outsized role in AFFF development (i.e., developing the inaugural military- grade AFFF formulas, compatible foam dispensing systems, and building markets outside the military), other chemical companies later joined them on the DOD Qualified Products List, manufacturing AFFF through an alternative PFAS synthesis method (explain 2 methods) and branding their own formulations, including National Foam, Angus, Chemgard, Kidde, and Buckeye. A second reactive sequence occurred as the military began phasing out AFFF in recognition of widespread use and contamination issues. 3M sought to undermine opposition and regulation while maintaining their capture of the market for as long as possible. One consequence of widespread AFFF adoption has been the ongoing discovery of PFAS contamination on sites where AFFF was historically discharged. According to Salvatore et al's (2022) analysis, PFAS contamination from AFFF releases is likely to be discovered on a range of sites not exclusive to the US military, including airports, fire training areas, railroad crash sites, petroleum refineries, chemical manufacturing plants, and bulk storage facilities.

DOD began the long process of transitioning from AFFF to a fluorine-free alternative following the 2020 National Defense Authorization Act (NDAA), which required that DOD cease using PFAS-containing AFFF on land-based installations by the end of 2024 (Nevitt & Percival 2022). In early July 2025, DOD announced its intention to submit the second of two allowable 1-year waivers in excess of the 2024 NDAA deadline, to enable the continued legal use of AFFF on select installations until October 2026 (Rizutto 2025).** [sentences about how this speaks to the inertia/lock-in of treadmills]also, military recognition of hazards, combined with legitimacy of NDAA inclusion, gave a big boost to non-military expansion of AFFF.

Discussion and Conclusion

Our analysis offers lessons for how undone/unseen science can advance Treadmill theory regarding the social construction of ecological harm and environmental health risks. ToP scholarship highlights the disregard for human, animal, and environmental hazards. It is not surprising that ToD activities would be even more likely to disregard those hazards, since claims of national security and military secrecy make it easy to move ahead quickly and deliberately in hazardous fashion. This is especially evident in the case of nuclear weapons production, where a myriad of national sacrifices were made under the guise of "national security" (Lengefeld 2018, 2020). Overall, research on military contamination shows rampant dumping of dangerous chemicals and lack of concern for communities that complained. The ToD represents a form of state violence, which we understand here as a multi-level process consisting of harms to the mining extractors and weapon producers, harm from the nuclear weapons, and future harms to all involved - what Altman (2019) called in her eponymous article "time-bombing the future."

We explored a set of counterfactuals in each case that demonstrate how interventions might have changed the path – and indicate where future interventions might prevent the emergence of treadmill dynamics. National security and military secrecy played a fundamental role in the ToD production and use of PFAS. Future interventions via policy needs to make the military subject to the same environmental protection rules as civil society, and overall environmental protection will need to recover from Trump-era retrenchment as well. Both the NDAA and the DOD's Congressional Directed Military Research Programs (CDMRP) need to add new mechanisms to support research in the history we have described here, including dose reconstruction studies to support multi-generational epidemiology research on exposed people and their descendants. They should also establish offices and programs for both intramural and extramural research on alternatives assessment in order to set standards for nontoxic or less toxic replacements.

Appendix

TABLE 2. Known and Suspected PFAS Used in the Manhattan Project						
Manhattan Project Label A	**Manhattan Project Label B**	**Common name**	**CAS**	**Chemical Formula**	**Manhattan Project Uses**	**Industrial uses**
C-2144	Fluorinated lube oil		N/A	$C_{21}F_{44}$	Uranium enrichment, plutonium production, nuclear operations,	lubrication
C-21445	Chlorofluorolube oil (from terphenyls)		N/A		"a substitute for C-2144"	Lubricating oils, heat transfer in transformers, plasticizers, flame retardants
C-714	Mixture of tetradecafluoromethylcyclohexane and tetradecafluoroethylcyclopentane	tetradecafluoromethylcyclohexane or perfluoro(methylcyclohexane)	355-02-2	C_7F_{14}		Various electronic industry, coolant, chemical synthesis, solvent for other PFAS
C-715CL	Chloro-pentadecafluoro-heptane		N/A		Coolant	
C-716	n-perfluoroheptane	Perfluoroheptane	335-57-9	C_7F_{16}	Uranium Enrichment, Plutonium Production, Nuclear Operations: sealant, inert gas, coolant	Paper manufacturing, coolant used in electronics industry
C-816	Perfluorodimethylcyclohexane	Perfluoro(1,3-dimethylcyclohexane)	335-27-3	C_8F_{16}	Uranium Enrichment, Plutonium Production, Nuclear Operations, Coolant	Solvent, polymer manufacturing, coolant in electronics industry, solvent used in cosmetic product manufacturing

FL	Fluorolube		N/A	N/A	Uranium Enrichment, Plutonium Production, Nuclear Operations -	metallic surfaces in applications that require stability and performance in strong acidic and/or oxidizing environments", nuclear industry, metal industries, coolant
FLS	Fluorinated lubricant solvent or fluorinated kerosene		N/A	N/A	Laboratory, "FLS being a fluorinated hydrocarbon in the kerosene range necessary for dissolving FL in the manufacturing process"	Cleaning and degreasing
		Perfluorokerosene-L	N/A	C_nF_{2n+2}	Laboratory	Mass-spec standard
MFL, MFI	Polymerised and further fluorinated trifluorochloroethylene (liquid) and (grease)	Polychlorotrifluoroethylene (PCTFE), Kel-F	9002-83-9	$(CF_2CClF)_n$	Membrane filtration, uranium enrichment, plutonium production, nuclear operations	Moisture barriers in electronic industry, plastic production, sealants and lubricants
P-45	Hexafluoroxylene	Product 45	433-95-4	$C_8H_4F_6$	Produced by Hooker Chemical at Love Canal between 1943 and 1946, P-45 was shipped to Oak Ridge for Manhattan Project, used in production of C-816	Today, appears to be used in electronics manufacturing for polishing
P-45CL	Monochlor P-45		N/A	Assumed $C_8H_3ClF_6$		
P-45CL$_2$	Dichlor P-45			$C_8H_2Cl_2F_6$		Electronics manufacturing

P-539	Trifluorochloroethylene	Chlorotrifluoroethylene	79-38-9	C_2ClF_3	Uranium Enrichment, Plutonium Production, Nuclear Operations, used to produce Kel-F and fluorolube	Resins and plastics production
Symalit		Ethylene Tetrafluoroethylene	25038-71-5	$(C_2H_4.C_2F_4)_x$		

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