Tritium Matters: Constructing Nuclearity & Navigating Ambivalence of a Unique Material

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ABSTRACT

This dissertation surveys the history of tritium beginning in Ernest Rutherford's lab in 1934 with its discovery and ending at the Fukushima Daiichi disaster site in 2023 when TEPCO began releasing tritiated wastewater into the Pacific ocean. In this time, expert conceptions of tritium have experienced interdependent and overlapping phases. Each phase is characterized by a dominant “nuclearity” and situated in context of “nuclear exceptionalism” (Hecht 2014) that directly and indirectly affects material conditions, elite decision-making, and radiological impacts on the environment and human health. Because it is pervasive, diffuse, and laborious to measure, a great deal of uncertainty surrounds tritium’s contribution to radiological risks. Beyond various commercial and scientific uses, it is also integral to both nuclear energy as a waste and nuclear weapons as a mechanism for dramatically increasing explosive yields. This versatile and powerful material operates at the technological nexus of two existential risks for humanity: climate change and nuclear weapons.

I divide the history of tritium into three distinct phases. First, super nuclearity characterizes early designs for the “superbomb” by Manhattan project scientists who believed vast amounts of tritium would be required. This phase extends to the late 1950s when thermonuclear warheads based on more feasible designs requiring significantly less tritium were beginning to be incorporated into the U.S. nuclear weapon stockpile. Second, special nuclearity describes the status of tritium throughout the Cold War as a critical nuclear weapons material that was referred to and treated as a special nuclear material (SNM) in practice even though it was never legally defined as such. Third, byproduct nuclearity is the current post-Cold War paradigm defining tritium as a form of incidental waste or as an innocuous “other accountable material” intentionally produced by the nuclear fission process. While tritium’s super nuclearity proved to be an animating fiction with political and material impacts on the early U.S. post-war nuclear weapons program, tritium’s special and byproduct nuclearities have since been fully embodied in technological artifacts—primarily nuclear weapons and nuclear power plants—and remain in dynamic tension.

Tritium does not fit neatly into existing nuclearity narratives. It is accurately referred to as both “highly” and “weakly” radioactive. Having a half-life of ~12 years and being the lightest radioisotope, it has high activity by weight, but when it decays into stable helium-3 it emits only a relatively weak beta particle which poses a potential risk as internal dose. I argue that the nuclearity processes constituting various conceptualizations of tritium provide insight into navigating the complex sociotechnical relationships between humans and nuclear technology. Additionally, I anticipate tritium’s next nuclearity transformation as reactor fuel for a still nascent fusion power industry. I argue that rather than allowing fusion energy proponents to dictate the next phase of tritium’s nuclearity, efforts should be made to assess and synthesize salient aspects of this unique material to provide a more holistic accounting of its risks, benefits, and tradeoffs.

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GENERAL AUDIENCE ABSTRACT

Hydrogen is the most abundant element in the universe. It fuels the stars and forms compounds like water that are essential to life. Most atoms of hydrogen contain one proton and one electron, but hydrogen also has two less common, naturally occurring "heavy" forms that additionally contain neutrons. One is deuterium, which contains one neutron and can be concentrated to make heavy water. The other type of hydrogen is tritium, which contains two neutrons. This dissertation is about tritium, an extremely rare and valuable material that can be used to produce a faint green light source without electricity, to increase the explosive power of nuclear weapons, or to fuel fusion power reactors. Tritium is also a radioactive waste material produced by both military and civilian nuclear activities.

I divide the history of tritium into three phases: super, special, and byproduct. When tritium was first discovered in 1934, it was an exotic scientific curiosity. During the 1940s, scientists with the Manhattan Project began working out how tritium could be weaponized into a "superbomb" that would be vastly more powerful than the atomic bombs the U.S. dropped on Japan in WWII. While the "superbomb" designs proved to be unviable, powerful hydrogen weapons were developed in the 1950s that relied on tritium alongside specially prepared masses of uranium and plutonium. To limit the spread of nuclear weapons, these special forms of uranium and plutonium have been tightly regulated as special nuclear material (SNM). Tritium, on the other hand, never met the legal definition of SNM but was nonetheless treated as a "special" material throughout the Cold War until the 1990s. Tritium has remained a critical material for all modern nuclear weapons, but in the last thirty years it has been primarily thought of and regulated as a byproduct material.

Because the radiological risks posed by tritium are ambiguous and technically challenging to measure at low concentrations, many proponents of nuclear technologies suggest that they are negligible and, at the same time, anti-nuclear activists claim that more research is needed to show tritium's dangers clearly. I argue that it is important to prioritize a more thorough assessment of tritium's radiological risks and role in nuclear weapons before the implementation of large-scale fusion technologies that will require the production of many thousands more times the amount of tritium currently available in the world.

For Rebecca & Evan, who make all this possible and give me the courage to ~~imagine~~ build a better world.

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Introduction

This dissertation is about tritium, a radioactive isotope of hydrogen. Tritium is a key component of virtually all modern nuclear warheads, a commercial product useful for radioluminescent applications, a tracer material suitable for biological and medical research, and a routine part of nuclear power plant waste. Also, tritium has the potential to fuel a future fusion power industry. This versatile and powerful material operates at the technological nexus of two existential risks for humanity: climate change and nuclear weapons. Because it is pervasive, diffuse, and laborious to measure tritium poses challenges for assessing radiological risks. Better understanding tritium's unique properties will provide essential insight into navigating the complex sociotechnical relationships between humans and nuclear technology.

In this dissertation I argue that expert conceptions of tritium—expressed and afforded by constructions of its nuclearity—have experienced interdependent and overlapping phases of development. These phases range from Manhattan Project era designs for the "Super" nuclear weapon, to the inclusion of tritium in the scope of "special nuclear material" alongside uranium and plutonium, and to a more benign existence as a "byproduct material." Each phase is characterized by a dominant nuclearity that directly and indirectly affects material conditions, elite decision-making, and radiological impacts on the environment and human health. I further argue that rather than allowing fusion energy experts to dictate the next phase of tritium's nuclearity that efforts should be made to assess and synthesize salient aspects of this unique material to provide a more holistic accounting of its risks, benefits, and tradeoffs.

I approach the topic through the interdisciplinary theories of Science & Technology Studies (STS) that have emerged alongside and in large part in response to the post-war conditions of the so-called Nuclear Age. Early critiques of nuclear technologies and infrastructures were an equal and opposite reaction to the secrecy, militarism, and authoritarian technics that produced them. Activists, scholars, and experts pushed for greater transparency, abolition, and greater democratic participation. Near the turn of the century, some of the previous abolitionist extremism gave way to a democratically responsive coexistence with nuclear technologies. Just as tritium can help trace biological and environmental processes, so can its nuclearity constructions and raw materiality trace one boundary of our nuclear world.

In nature, tritium is extremely rare but ubiquitous. The vast majority of naturally occurring tritium is produced by cosmic ray interactions with gases in the upper atmosphere where it can be incorporated into water molecules and fall to Earth's surface. Considering this atmospheric production rate and radioactive half-life of tritium decay, the total volume of naturally occurring tritium tends to an equilibrium of approximately 3.8 kg dispersed over the entire Earth.[1] In practice this means, according to Martin Kalinowski, "it is not possible to find any water sample which does not contain tiny amounts of

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[1] Olivier Seignette and Mikaël Lafontan, "Tritium and the Environment" (Institut de radioprotection et de sûreté nucléaire (IRSN), December 18, 2010), 4, https://www.irsn.fr/EN/Research/publications-documentation/radionuclides-sheets/environment/Documents/Tritium_UK.pdf.

tritium."[2] Merely detecting the presence of tritium in a sample is meaningless without comparing the relative concentration to this naturally occurring background condition.

With a half-life of ~12.3 years, tritium transforms through a beta decay process into stable Helium-3 (He-3) at a rate of ~5% each year. Beta decay occurs when a neutron in the nucleus emits a small packet of negatively charged energy (basically an electron), which changes the neutron's charge from neutral to positive, becoming a proton. The newly created He-3 nucleus now contains two protons and one neutron. He-3 poses virtually no risk and even has valuable properties which are useful for cryogenic cooling and portal monitors to detect the illicit transfer of some nuclear materials. The beta particle is relatively low energy and can only produce damage in living organisms when the process occurs directly inside the body. Of course, since tritium is everywhere, to some small degree the process of tritium beta decay has always and will always occur inside our bodies. Just like detection in an environmental sample, tritium poses discrete radiological risks not by its mere presence but in its relative concentrations in the body.

The life of tritium began in a lab. Before its natural occurrence in the environment was confirmed in the 1950s, tritium was synthetically produced through nuclear experimentation in 1934 by Ernest Rutherford, M.L. Oliphant, and Paul Harteck.[3] Like many origin stories in the physical sciences, there was not a discrete unarguable "Eureka!" moment. In retrospect it became clear that they did successfully produce tritium, but Rutherford had initially believed that he had identified a *radiologically stable* hydrogen isotope containing one proton and two neutrons. In fact, he had confused tritium's decay product, He-3 with tritium itself and would be under this mistaken impression for several years. It was not until 1939, that Luis Alvarez and Robert Cornog experimentally demonstrated that tritium was an unstable isotope.[4] Once the *radioactivity* of tritium was firmly established as scientific consensus, efforts to accurately measure its half-life and find useful applications of this new substance began.

In a data book entry dated June 26, 1944, a researcher from the "100 Area" plutonium production reactors at Hanford, Frank A. Valente, noted that the "Half-life of H^3 is variously taken as 10-30 years; it is not well known at the present time."[5] Valente also expressed uncertainty about whether or not tritium is desired in a purified form and suggests "a probable use of Tritium is that of tracer work."[6] While high-level discussions and calculations for hydrogen bombs had begun as early as 1942, this potential application for tritium had clearly not been made known to or suspected by researchers like Valente who were hard at work providing materials necessary for the A-bomb. Approximately 8 years later, production from the B reactor at the Hanford 100 Area would supply the tritium used in the first

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[2] Martin Kalinowski, *International Control of Tritium for Nuclear Nonproliferation and Disarmament*, Science and Global Security Monograph Series, v. 4 (Boca Raton: CRC Press, 2004), 3.

[3] C M Hoffman and G L Stewart, "Quantitative Determination of Tritium In Natural Waters," Geological Survey Water-Supply (U.S. Department of the Interior, 1966), https://pubs.usgs.gov/wsp/1696d/report.pdf. D1.

[4] Luis W. Alvarez and Robert Cornog, "Helium and Hydrogen of Mass 3," *Physical Review* 56, no. 6 (September 15, 1939): 613–613, https://doi.org/10.1103/PhysRev.56.613.

[5] F.A. Valente, "Data Book 100 Areas," April 15, 1946, 32, DOE Public Reading Room - Hanford Battelle, https://www.osti.gov/opennet/detail?osti-id=16463738.

[6] Valente, "Data Book 100 Areas."

hydrogen bomb test.[7] In September of 1945, Dr. Joseph G. Hamilton[8] requested 5 millicuries (~0.5 μg)[9] of tritium for medical isotope experimentation at the University of California Berkeley Donner Lab.[10] This request would be aggregated and processed the following year by the Isotopes Research Division of the newly created Atomic Energy Commission (AEC). In this request, Dr. Hamilton lists the half-life of tritium as "31 yrs." The glossary of a Manhattan District History published on April 29, 1947 (parts of which were not declassified until 2013) states that tritium has "a half-life of *about twenty years*, and therefore *does not occur in nature*."[11] Half-life estimates began narrowing to today's accepted value in a technical brief from the chemistry division of Argonne National Laboratory (ANL) dated July 16, 1947, where it is listed as 11.8 years.[12] Precisely determining the half-life of tritium was nontrivial because it was costly to produce, challenging to purify, difficult to measure, and restricted for distribution for several years.

Parallel to fundamental research into tritium's characteristics and efforts to find applications, often as a marker or tracer in biological research, there was an on-going, secretive push for the hydrogen bomb, also known as the "super."[13] In a 1949 letter to President Truman, Senator Brien McMahon starts the clock for the super in 1942 when Edward Teller, Robert Oppenheimer, and Hans Bethe had begun making initial calculations.[14] While Teller would later go on to champion post-war hydrogen bomb research, the exigencies of the time directed all material and intellectual resources toward the creation of the first fission bombs. Sen. McMahon gestured to this early date to illustrate how work on the super had already begun and that it was intimately connected with the ongoing legacy of the Manhattan Project. There is a wide array of Manhattan Project histories, biographies, video series, and movies that cover this fascinating and unprecedented era. These depictions and discussions provide important context, but in many historical accounts of "the bomb," tritium gets overshadowed by the mushroom cloud. This dissertation draws from these histories and many primary documents to provide a technically coherent and systematic account of the story of tritium.

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[7] "Manhattan Project: Places > Hanford Engineer Works > 100 Area: Plutonium Production Reactors," accessed December 4, 2023, https://www.osti.gov/opennet/manhattan-project-history/Places/Hanford/hanford-reactors.html.

[8] "Joseph G. Hamilton - Nuclear Museum," *Https://Ahf.Nuclearmuseum.Org/* (blog), accessed December 3, 2023, https://ahf.nuclearmuseum.org/ahf/profile/joseph-g-hamilton/. Notably, "Hamilton had a large role in the controversial human plutonium injection experiments that began during the war."

[9] I will use the approximation of 10,000 Ci ≈ 1 g of tritium throughout this paper.

[10] J.G. Hamilton, "List of Radio-Elements Together with Appropriate Methods of Production in Amounts That Could Be Profitably Used Within the University During the Next Year," September 24, 1945, NNSA/NSO Nuclear Testing Archive, https://www.osti.gov/opennet/servlets/purl/904738.pdf.

[11] *Manhattan District History*, vol. Vol. 2 Technical, VIII-Los Alamos Project (Y) (Atomic Energy Commission, 1947), 485, https://www.osti.gov/includes/opennet/includes/MED_scans/Book%20VIII%20-%20Volume%202%20-%20Technical.pdf. Emphasis mine.

[12] W.K. Crane, "Research and Development Technical Briefs" (Atomic Energy Commission (AEC), July 28, 1947).

[13] In many accounts the terms "super," "superbomb," hydrogen bomb, thermonuclear bomb, and several others are somewhat conflated, but they represent a range of different technologies, both imagined and built. I will preserve original terms in sources when clarifying would be largely pedantic. However, when I discuss tritium's roles and quantities used in various designs, weapons, and tests, I will provide the most technically appropriate term along with sufficient information to differentiate it from others.

[14] Brien McMahon, "Brien McMahon Chairman of Joint Congressional Committee on Atomic Energy Discusses Building of a 'Super' Atomic Bomb" (United States: White House, November 21, 1949), 4, U.S. Declassified Documents Online, http://link.gale.com/apps/doc/CK2349318169/USDD?sid=bookmark-USDD&xid=c43b60c5&pg=1.

In Chapter 1, I present theoretical approaches to nuclear technology from STS and argue that classic approaches typified by Langdon Winner offer a reductive critique. Rather than deepening our collective understanding of these highly complex technologies, they tend to be dismissed as paramount and irredeemable examples of Lewis Mumford's authoritarian technics. Then, I consider more recent nuclear-specific frameworks by Gabrielle Hecht and Itty Abraham and explore the *nuclearity*, *nuclear exceptionalism*, and *nuclear ambivalence* that exemplify this unique material. Importantly, I divide nuclear exceptionalism into two typologies, *peaceful* and *military*, to provide additional explanatory power to tritium's propensity to a Janus-faced phenomenology.

In Chapter 2, applying the theoretical frameworks from the previous chapter, I consider the scientific emergence of tritium as a laboratory produced specie and how tritium's nuclearity was constructed as both a technoscientific entity and a key component in nuclear weapons. During the Manhattan Project and the rise of the post-war nuclear secrecy regime, military exceptionalism became dominant over the ostensibly peaceful exceptionalism of basic scientific research and commercial applications. I argue that tritium created internal material constraints for the paradigm shift from fission-only weapons (A-bomb) to thermonuclear weapons (H-bomb) and external motivations in support of vertical proliferation from the specter of a possible Russian superbomb made possible by the espionage of Klaus Fuchs. This early phase is characterized by the construction of tritium's *super* nuclearity—a material and technoscientific entity considered to be the crucial ingredient for unlocking the near limitless potential of nuclear weaponry. Additionally, the tension between public and restricted data on tritium specifically — embedded in its military nuclear exceptionalism and its nonpareil super nuclearity—was a central element to discussions of early nuclear secrecy and, I argue, these tensions remained largely unresolved until the mid-1990s.

Despite the intellectual efforts of world-leading physicists and the intensive calculations performed by one of the first programmable computers, the construction of tritium's super nuclearity remained an abstraction. The principle of deuterium-tritium (D-T) fusion was the only *real* throughline from the classic super designs to functional hydrogen bombs. Super nuclearity proved to be an animating fiction that inspired early efforts toward the production of hydrogen weapons of devastating potential. After Teller's plans for a post-war research crash course for the super confronted significant limitations in early tritium production work and, ultimately, an inherently flawed design, the tritium paradigm shifted to "boosted" fission weapons and more feasible thermonuclear warhead designs. The construction of tritium's nuclearity became more commensurate with highly enriched uranium (HEU) and plutonium-239. Then, tritium entered a phase of *special* nuclearity where tritium was commonly considered—and referred to as—special nuclear material (SNM) even though it has never met the legal definition.

By the late 1980s, all tritium production in the U.S. had ceased after the shutdown of the K Reactor at the Savannah River Site (SRS). During this time of uncertainty for the nuclear weapon enterprise, tritium's peaceful nuclear exceptionalism began to hold more political sway. Tritium's practical status as a SNM gave way to a more innocuous *byproduct* nuclearity—which has more in common with radioactive wastes than nuclear bomb materials. In the early 2000s, the U.S. transitioned to tritium production in commercial light water reactors (CLWR) which has been on-going for the past twenty years. More recently, a growing contingent from the still nascent nuclear fusion industry has embraced tritium's byproduct nuclearity and seeks to maintain its associated regulatory scope for the development of first-of-a-kind fusion reactors.

In Chapter 3, I consider the case made by Martin Kalinowski for a greater and systematic role for tritium control in commercial applications and nonproliferation regimes. These systems, he refers to as the International Tritium Control System (ITCS) and Integrated Cutoff Agreement (ICO) respectively, would offer a simultaneous and holistic approach to global tritium management. I argue that they would rebalance the peaceful and military exceptionalism aspects of tritium and allow for a nuclearity coextensive with both its special and byproduct constructions. Additionally, Kalinowski's diagnosis that tritium's historical neglect in nonproliferation regimes is primarily due to the nuclear secrecy regime offers only a partial and unsatisfactory answer. I argue that tritium's nuclearity in transition—its ambivalent flexibility—led to a complex and uncertain material status. Is it *super*lative and unique? Is it a material equivalent of HEU and plutonium? Is it an *other*, a byproduct, with useful applications?

In Chapter 4, I analyze another aspect of byproduct nuclearity that lies behind and interconnects all other incidence and use of tritium: its capacity as radioactive pollution. I argue that several constructions of this byproduct nuclearity attempt to conflate the very real and distinct risks posed by tritium with a broad array of other radiological risks. I present a high-level overview of how most anthropogenic tritium is produced, how it behaves when it enters the environment, and what ecosystem and biological consequences are suggested in the latest research. Then, I examine the phenomenology of tritiated water in a case study of the Fukushima Daiichi wastewater releases that were first initiated in August 2023. In the final section of this chapter, I do a deep dive into Arjun Makhijani's 2023 book *Exploring Tritium's Dangers: Health and Ecosystems Risks of Internally Incorporated Radionuclides* and evaluate his construction of tritium's nuclearity in the context of the paradigms explored above.

In Chapter 5, I look ahead to tritium's role in possible fusion futures and total nuclear disarmament. Throughout the history of constructing tritium's nuclearity particular configurations of purity, quantity, and concentration have influenced its associated value, utility, and risk. Commercial fusion energy presents an unprecedented large technological infrastructure moving, containing, and accounting for quantities of tritium several orders of magnitude above the current scale of tritium use and trade. Will the technical requirements, personnel/public safety demands, and nuclear safeguards be met under a regulatory regime designed for byproduct materials of a vastly different scope and scale? How will nonproliferation and disarmament regimes respond to an environment of tritium abundance? I propose steps that we can take now to ensure that the next iteration of tritium's nuclearity emerges from a holistic consideration of the many facets inherent in this ambivalent and unique material.

Chapter 1: Science & Technology Studies Approaches to Nuclear Questions

Tritium Anecdote I: Beginning in the Middle

In 2012, I was in training to be an Assistant Unit Operator (AUO) at Browns Ferry Nuclear (BFN) Plant. My training cohort and I had just finished one of several lectures on reactor physics that provided technical fundamentals for the processes occurring inside an operating reactor. In this lecture we were introduced to the "fission yield curve" (Figure 1), which shows the distribution of possible outcomes when a neutron interacts with an atom of Uranium-235 (U-235), the primary fuel isotope powering most nuclear reactors. Typically, when a neutron causes a U-235 atom to fission the atomic nucleus splits into two uneven parts, one heavier and one lighter atom, and two or three additional neutrons are released (2.43 neutrons on average) that can create additional fission events. Occasionally an unusual fission reaction occurs which yields three products, a process known as ternary fission. The third product is either Helium-4 or Hydrogen-3, a radioactive isotope known as tritium which has two neutrons and one proton in its nucleus. It is helpful to remember that these processes occur inside a solid-state material, a ceramic pellet of uranium oxide, and these fission products predominantly remain trapped inside this solid matrix, though there is some outgassing in the space surrounding the pellets inside the welded fuel pin. As the smallest and lightest element, some hydrogen will invariably permeate through these solid materials and enter the reactor coolant, which for the boiling water reactors at BFN means ordinary water, albeit specially cleaned, monitored, and controlled. Tritium produced in this way can also enter the coolant or spent fuel pools via small defects and cracks in fuel pins that can develop over time. This is one process that makes a minor contribution to the amount of tritium that nuclear power plants release into the environment on a regular basis. I evaluate the various mechanisms of incidental tritium production in nuclear reactors in more detail in Chapter 4.

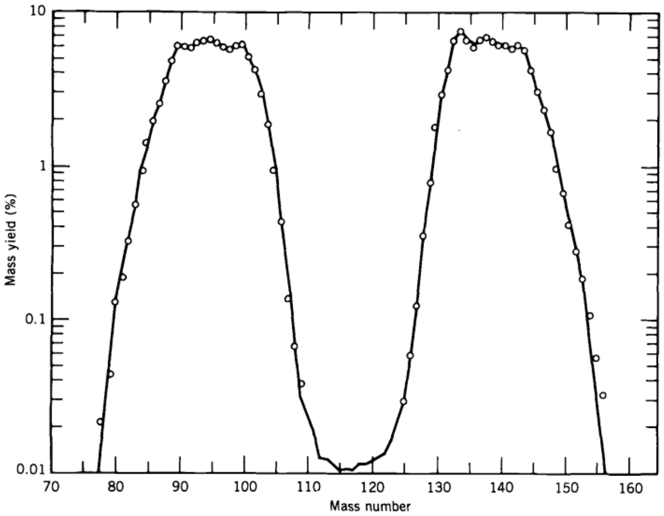

Figure 1: Thermal Neutron Fission of U-235 Product Yield Curve[15]

Having completed an M.S. in Science & Technology Studies (STS) several years prior, I was learning not only how to operate a nuclear power plant but also how the boundaries between the complex

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[15] K.S. Krane and D. Halliday, *Introductory Nuclear Physics*, vol. 465 (New York: Wiley, 1988), 485.

sociotechnical infrastructure of a large nuclear power station and the environment are maintained. Of note, I discovered how the intricate and overlapping "fission product barriers" required to protect the public from the nuclear fission process has some inherent and normal porosity, at least with respect to tritium containment. The controlled and monitored releases from the plant, both in liquid and gaseous forms, transform byproduct materials like tritium into background environmental conditions, which are always already a tenuous amalgam of natural and human activity.

While pondering all of this and speaking with my instructor after the lecture, he made an offhand comment: "You know, they produce tritium at Watts Bar for nuclear weapons." Along with BFN, the Watts Bar and Sequoyah Nuclear Plants make up the nuclear fleet for the largest public utility in the U.S., the Tennessee Valley Authority (TVA). I, in fact, did not know that this was going on "up the river," and my burgeoning understanding of nuclear power experienced a jarring re-orientation. My superficial sense of what is commonly known as dual use technology, meaning materials and processes having both peaceful and military applications, did not encompass at that time a directly coupled, on-going process inside a commercial power reactor. That this had been going on for over a decade with minimal attention and concern from the public I also found baffling.

All technologies, particularly large-scale technologies, have tradeoffs, and a nuclear power plant is no different. Presently, I make no attempt to rehash the wide array of factors commonly constitutive of nuclear power's cost-benefit analysis but suffice to say the introduction of tritium production explicitly for use in nuclear weapons further complicates already contentious arguments for and against nuclear energy. Throughout my training and time as an AUO, we routinely invoked the mission mantra "to protect the health and safety of the public," and I would often wonder how coherently TVA's environmental obligations to the public were in concert with the national security mission for tritium production.

STS on Nuclear Technology

Complex, large-scale nuclear technologies emerged through the work of the prototypical combination of big science and big technology that took place under the guise of the Manhattan Project. From the advent of “the Bomb” and subsequent deployment of the “peaceful atom,” nuclear technologies have become the subjects of intense debates and rightfully so. In the field of STS, a pivotal figure in this discourse is Langdon Winner. To orient an understanding of more recent nuclear scholarship, I will begin by contextualizing Winner’s influential contributions to the terms of the debate.

For Winner, nuclear technology is not simply a matter of scholarly interest but is an animating force in his life. His 1980 essay “The Whale and the Reactor: A Personal Memoir” reified an epiphanic metaphor of seeing, juxtaposed in the distance, a grey whale surfacing and spraying a mist from its blow hole with the tandem domes of the Diablo Canyon NPP. The Whale’s semiotic resonance conveyed to Winner an anthropomorphic guilt-trip for not doing more:

> As the grey whale surfaced, it seemed to be asking: "Where were you?" The sight of the reactor itself, the experience of the thing's presence in a particular time and a particular

> place said infinitely more than all of the studies, analyses and findings of all the sophisticated work I had been reading ever could.[16]

Under the influence of what William James would have called a religious experience, Winner came into possession of an ineffable knowledge that Diablo Canyon was intrinsically evil and had irreversibly desecrated "the values of nature and our common humanity."[17] He then acknowledges his "virtual heresy" against his STS discourse community because he had pre-determined an inestimable loss without considering first the possibilities and risks of loss. The idea that anything might be *gained* was an unthinkable possibility, at least to Winner and anyone who he would deem a colleague.

Winner would go on to publish one of his most seminal essays later that same year where he mused "Do Artifacts Have Politics?"[18] From page one, he deploys Lewis Mumford's *technics*[19] to delineate between authoritarian nuclear power and democratic solar power and offers little pretense in mocking technocratic cheerleaders like David Lilienthal who extoled big science and big technology as "democratizing, liberating forces."[20] He later invokes the "obvious example" and "special case" of the atom bomb as "an inherently political artifact."[21] The security and operational demands of such uniquely destructive and lethal artifacts necessitate strict authoritarian control, requiring carve outs and firewalls within otherwise democratic political structures. Even if, Winner argues, society manages to benefit from nuclear power while minimizing technological risks, its inherent authoritarian features would exact a steep cost on our collective liberty.[22]

These two essays were collected in *The Whale and the Reactor: A Search for Limits in an Age of High Technology*, first published in 1986. Now issued in a second edition, which arrived 40 years after their original publication, Winner provides a brief afterward where he takes a victory lap about the imminent closure of the Diablo Canyon NPP. Then, in May 2019, Winner highlights some key I-told-you-so's: authoritarian China is the only country investing in new nuclear, democratic California is leading the way to a nuclear free world, and "nuclear energy has a substantial carbon footprint." The latter point is delivered as a veritable *Gish gallop* of carbon intensive activities associated with generating nuclear energy without pretending to quantify or even suggest a scale of any such emissions.[23] The proof, he thought, was in the pudding.

A little over three years later, the situation has shifted dramatically. The Conference of the Parties (COP) to the UN Framework Convention on Climate Change (UNFCCC), also known as COP28, recently ended with more than twenty countries pledging to triple nuclear power generation by 2050. Whether or not

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[16] Langdon Winner, "The Whale and the Reactor: A Personal Memoir," *Journal of American Culture* 3, no. 3 (Fall 1980): 454, https://doi.org/10.1111/j.1542-734x.1980.0303_446.x.
[17] Winner, 454.
[18] Langdon Winner, "Do Artifacts Have Politics?," *Daedalus* 109, no. 1 (Winter 1980): 121–36.
[19] Lewis Mumford, "Authoritarian and Democratic Technics," *Technology and Culture* 5, no. 1 (1964): 1–8, https://doi.org/10.2307/3101118. Mumford invokes "technics" to refer to whole systems of technologies and associated practices in a society.
[20] Winner, "Do Artifacts Have Politics?," 121.
[21] Winner, 131.
[22] Winner, 135.
[23] In my opinion, pedantically arguing that nuclear power is not literally zero-carbon or carbon-free was not, in 2019, the gotcha that Winner believed it to be. The full life-cycle emissions of nuclear power are estimated and accounted for in every serious discussion comparing electrical generation sources for mitigating climate change.

such a goal is achievable, it's clear that nuclear generation has growing global support. The EU has designated nuclear energy as a "net-zero technology" in the Net Zero Industry Act proposed in 2023.[24] The Japanese Diet passed a series of Green Transition (GX) bills in 2023 that prioritized restarting many operational power plants that have been idled. Furthermore, in a January 2024 policy speech, Japanese Prime Minister Kishida Fumio referred to nuclear power as "an effective measure toward decarbonization" and stressed that Japan "will continue use of nuclear power with priority on safety."[25] Even Diablo Canyon, as of 2024, has a new lease on life and Unit 1 and Unit 2 will be allowed to continue operation until October 2029 and October 2030, respectively. It appears the rumors of nuclear energy's demise have been greatly exaggerated. However, it is important to keep in mind that in the wake of the Fukushima Daiichi disaster in 2011 the much-lauded nuclear renaissance of the early 21st century stumbled at the starting gate. Will Russia's military occupation of Zaporizhzhia Nuclear Power Plant (ZNPP) in Ukraine lead to additional public uncertainty or private industry uranium supply chain woes for the next nuclear renaissance cycle? Will another nuclear disaster on the scale of Fukushima Daiichi put nuclear growth on hold again? That remains to be seen.

The key takeaways are not that Winner is biased against nuclear technologies or that he's wrong. Though, he is most certainly biased and ultimately neither right nor wrong; Winner's voice and influence are an important part of the nuclear conversation. Instead, Winner's disciplinary deficiency is his inability to sincerely imagine things could be other than they are. Within Winner's conception of these technologies, he appears only able to entertain heretical ideas when they comfortably conform to the lessons drawn from his ineffable whale experience. Perhaps an unprecedented Beyond Design Basis (BDB) earthquake will occur tomorrow and Diablo Canyon NPP will succumb to the same natural forces that severely damaged three reactors at the Fukushima Daiichi site, but odds are against it. More likely, the plant will operate another 10-20 years and be decommissioned. In the former, Winner and others may feel vindicated in their precaution and pushback, and, in the latter, nuclear proponents might exhale slightly and say "see, there was nothing to worry about." Neither reaction appears to genuinely consider the actual possibility of the other. As I said in *Anecdote I* above, large-scale adoptions of technology always involve tradeoffs. Many continue to critically evaluate the real and probabilistic tradeoffs between nuclear power and the real and probabilistic risks represented by a steadily warming world driven by CO_2 emissions.

Joseph G. Morone and Edward J. Woodhouse offer a more balanced consideration of nuclear energy and its possible compatibility with democratic technics in *The Demise of Nuclear Energy? Lessons for Democratic Control of Technology* (1989).[26] Privileging neither position, they consider technology to be less deterministic than enthusiasts like Lilienthal imply and more malleable than critics like Winner contend. Instead, drawing from Thomas Hughes and others, large-scale nuclear technologies are amenable to democratic intervention before *inertia* sets in, when the system begins exhibiting soft

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[24] "Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on Establishing a Framework of Measures for Strengthening Europe's Net-Zero Technology Products Manufacturing Ecosystem (Net Zero Industry Act)" (2023), https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023PC0161.

[25] "PM Kishida States Clear Commitment to Using Nuclear," *Japan Atomic Industrial Forum, Inc.* (blog), February 8, 2024, https://www.jaif.or.jp/en/news/6901; "GX Decarbonization Power Supply Bill Approved by Committee on Economy, Trade and Industry," *Japan Atomic Industrial Forum, Inc.* (blog), May 16, 2023, https://www.jaif.or.jp/en/news/6466.

[26] Joseph G. Morone and Edward J. Woodhouse, *The Demise of Nuclear Energy? Lessons for Democratic Control of Technology* (New Haven: Yale University Press, 1989).

deterministic characteristics. Morone and Woodhouse argue that the U.S. decision to focus on the construction of large gigawatt-scale light water reactors (LWR) emerged as the result of largely non-democratic processes. Decisions in the 1950s and 60s related to reactor safety, design, and siting could have resulted in technologies embedded with very different character. All the situated factors that provoked Winner's dismal assessment of nuclear energy might have emerged very differently. Increased democratic decision-making may have slowed nuclear growth to a more sustainable trajectory. Instead of a coalition of private companies the U.S. might have transitioned to the public utility model similar to the Tennessee Valley Authority (TVA), and sites with complex hazards like Diablo Canyon may have never been developed in the first place.

The historical evidence for nuclear industry inertia and built-in undemocratic latencies are copious. Early reactor design choices at the national labs prioritized the potential for fuel "breeding"[27] over safety, the selection of pressurized water reactors (PWR) for civilian power plants was driven by the proven viability of nuclear submarine reactor technology, and the early Atomic Energy Commission (AEC) was more of a promoter of nuclear energy than a proper regulator.[28] Following the Three Mile Island (TMI) partial nuclear meltdown in 1979, the Institute for Nuclear Power Operations (INPO) was formed to promote and support industry-wide excellence above and beyond the legal minimum required for regulatory compliance. However, it would take many years before the legacy of poor operational mentalities of production over safety and prioritizing equipment reliability would transform the industry from having a generating capacity factor (CF) of mid-80% to 92+%. CF is the measure of the power generated as a percentage of theoretical maximum output of a site in a given year. A consistently high CF exemplifies a healthy industry. It is somewhat ironic that sites that start inculcating a culture of safety over production would, over time, result in better overall performance, but that is precisely what happens when the complex operations of an NPP is approached with humility and intentionality. The industry that Morone and Woodhouse observed throughout the 1980s exhibited many worrying signs that left its "demise" a valid and open question.

Despite the inertia and path dependent legacies in-built in the industry, two significant events transformed the nuclear industry in the 21st century. First, the terrorist attacks of September 11, 2001, caused a sea change in both nuclear security and engineered system resilience. Second, the disaster at Fukushima Daiichi as a result of the Tōhoku earthquake on March 11, 2011, prompted a re-evaluation of Beyond Design Basis Events (BDBEs), strategies available for Severe Accident Mitigating Guidelines (SAMGs), and deployable resources available at secure regionally situated sites. Even if the siting of Diablo Canyon NPP near a previously unidentified seismic fault could not be corrected, the plant could be made marginally more secure, safe, and reliable.

The next generation of nuclear decisions appear to be attempting to redress many of the anti-democratic mistakes highlighted by Morone and Woodhouse. Most notably, the federal government in partnership with private companies are seeking consent-based siting of waste storage, exploring potential reparations for past harms to indigenous people and lands, and promoting smaller and safer

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[27] Breeder reactors are capable of burning fuel such as U-235 and producing new fuel materials such as Pu-239 in the same process.

[28] Morone and Woodhouse, *The Demise of Nuclear Energy?*, 29–66.

reactor designs.[29] The bipartisan Radiation Exposure Compensation Reauthorization Act passed the U.S. Senate in March 2024 in a 69-30 vote. The official title of the Act is "a bill to extend the period for filing claims under the Radiation Exposure Compensation Act and to provide for compensation under such Act for claims relating to Manhattan Project waste, and to improve compensation for workers involved in uranium mining."[30] This Act would reauthorize and expand the original Act H.R.2372 from 1990 and successive amendments that had broadened the scope of claimants—including nuclear testing and cleanup in the Marshall Islands and other "downwinders"—and simplified the compensation process. The legacies of nuclear technologies are linked both materially and abstractly. Public fears and concerns of radiation exposure and nuclear catastrophe must contend with an unknown future of next generation nuclear energy, the pernicious legacies of the past, and everything in between. Truly democratic accountability for nuclear energy may mean a nuclear-free Germany and a resurgent nuclear Japan as democratic societies contend with the tradeoffs inherent in large-scale technological systems.

Nuclear weapons, by contrast, were "born secret" in decidedly undemocratic fashion and have largely remained under the purview of a political and military elite, insulated from democratizing forces. As the primary existential threat to humanity, these weapon technologies are in dire need of democratic oversight. The institutional and technological inertia of the nuclear weapon complex is so pervasive that nuclear-weapon states (NWS)[31] have refused to even participate in discussions about and meetings of the Treaty on the Prohibition of Nuclear Weapons (TPNW), the landmark international framework for banning nuclear weapons introduced in 2017 which entered into force in 2021. While there were never any illusions that NWS would join the TPNW and begin unilaterally disarming, it is remarkable that no NWS nor any state falling under the "nuclear umbrella" of various extended deterrence regimes has engaged in the process in any meaningful capacity. It may very well be true that the TPNW is counter-productive to the long-standing regime of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), as claimed by some analysts in the U.S. and elsewhere, but total disengagement with the humanitarian vanguard of nuclear disarmament does not bode well for the future of democratic accountability and governance of nuclear weapons.

Contemporary STS Approaches

In general, STS scholars have tended to consider nuclear technologies as *sui generis* boundary markers for advanced technology. More recent scholarship from Adriana Petryna, Itty Abraham, and Gabrielle Hecht have challenged monolithic notions of nuclear technology and "the bomb" by exploring the varieties of sociopolitical life that have emerged in the so-called "atomic age." While Petryna and Hecht examine the lived experiences and material conditions of workers/citizens laboring and living within nuclear infrastructures under specific systems of governance and categorization, Abraham considers the

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[29] Until these first-of-a-kind reactors are built the *actual* safety performance is merely theoretical. Hypothetical reactors are 100% safe unless you count the danger of papercuts.

[30] Josh [R-MO Sen. Hawley, "S.3853 - 118th Congress (2023-2024): Radiation Exposure Compensation Reauthorization Act," legislation, March 11, 2024, 2024-02-29, https://www.congress.gov/bill/118th-congress/senate-bill/3853/all-info.

[31] The technical meaning of the term "nuclear-weapon state" as defined by the 1968 Treaty on the Non-Proliferation of Nuclear Weapons is "[a state] which has manufactured and exploded a nuclear weapon or other nuclear explosive device prior to 1 January 1967." (Article IX.3) This definition applies to only five states: United States, Russia (formerly USSR), United Kingdom, France, and China.

nuclear order from a more geopolitical context. Each provides much needed nuance and circumspection to the inherent complexities and contradictions of nuclear answers to human questions.

Hecht has contributed two significant monographs to better understanding nuclear technologies. The first, *The Radiance of France: Nuclear Power and National Identity after World War II* originally published in 1998 explores nuclear development as what Michel Callon refers to as a "hybrid sociotechnical *agencement*"—an arrangement of material production and political affordance.[32] The second, *Being Nuclear: Africans and the Global Uranium Trade* originally published in 2012, zooms out from the national sociotechnical locus of *Radiance* to a consideration of global material supply chains supporting nuclear infrastructures. In each case, the nuclear reactor serves as a nexus of transformation for both technology (bombs, materials, and energy) and politics (identity, prestige, and power). These transformations are entangled but not fixed in the seemingly deterministic relationships supposed by Winner and other anti-nuclear ideologs. To be certain, Hecht's analyses are highly critical of nuclear technologies, knowledges, and practices, but still manage to depict them as particular to specific regimes of control and production that could be otherwise. In other words, while much of the nuclear world order is rooted in forms of colonial exploitation, the work of nuclearity is on-going; several African-led initiatives are attempting to transplant the nuclear economy into indigenous soil, and Hecht does not suggest an outcome predetermined by any inherent characteristics of nuclear technologies.[33]

In this dissertation, I appeal to Hecht's concepts of *nuclearity* and *nuclear exceptionalism* developed in *Being Nuclear*. Nuclearity is the process by which materials and activities become designated as "nuclear" and nuclear exceptionalism is the systematic insistence that possessing the designation of "nuclear" signifies "an essential nuclear difference" in a person, place, thing, or process. [34] Nuclearity is not simply a material property synonymous with radioactivity, but rather a diffuse parameter that encompasses materials, environments, work practices, workers themselves, geography, geology, governance, and degrees of radiological risk. Hecht clarifies:

> *Radiation* is a physical phenomenon that exists independently of how it is detected or politicized. *Nuclearity* is a *technopolitical* phenomenon that emerges from political and cultural configurations of technical and scientific things, from the social relations where knowledge is produced.[35]

We are exposed to radiation doing mundane things like breathing, eating a banana, sleeping next to someone, or walking in sunlight. We all emit radiation from our bones and various trace radioisotopes that are integrated in our bodies. Though, these activities could be made "nuclear" if they are framed a certain way. To someone with a family history of melanoma, walking around Denver, Colorado in the midday sun might be considered more of a radiological cancer risk but to others merely risks the nuisance of a sunburn. When this person applies sunblock to minimize exposure to solar radiation, they are engaging in safety practices to mitigate risk like how a mine worker might don a respirator to reduce exposure to the particulate daughter products of radioactive radon gas. In Chapter 2, I will analyze how

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[32] Gabrielle Hecht, *The Radiance of France: Nuclear Power and National Identity after World War II* (Cambridge, Mass.: MIT Press, 2009), xiii.
[33] Gabrielle Hecht, *Being Nuclear: Africans and the Global Uranium Trade* (Cambridge, MA: MIT press, 2014), 336.
[34] Hecht, 6.
[35] Hecht, 15. Emphasis in original.

tritium's nuclearity is constructed as a technopolitical phenomenon in various contexts and moments in time.

Tritium's nuclear exceptionalism is much more ambiguous. Nuclear weapon states in general, and the U.S. in particular, consider tritium availability as a non-negotiable requirement of national security—a tenet of its military exceptionalism. Virtually all modern nuclear weapons require tritium to meet design specifications and stockpiles cannot be maintained without it. Tritium has also found use in trivial consumer products like watch dials, radioluminescent lights, and gun sights. When tritium is routinely released from nuclear power plants as effluent waste, it is transformed through the process of dilution and environmental diffusion into a naturalized background condition. Tritium is exceptional when it needs to be, ordinary when it performs a useful function, and natural when sociotechnically convenient.

Where Hecht diverges from Winner's artifactual politics of nuclear technologies is that a great deal more ambiguity is at play. Winner primarily characterizes nuclear technologies such as power plants and bombs like binary toggles. Hecht retorts, "[h]ere's the problem: this unreflective reflex, this historiographical and philosophical certainty about what things fall into the domain of the 'nuclear'—along with the certainty concerning the exceptionalism of those things—does not correspond to technopolitical practices."[36] In this critique, she is also responding to Bruno Latour's assertion that "the atom bomb is the ultimate THING in which people think of the relation between science and politics."[37] Importantly, while both Winner and Hecht consider nuclear artifacts as part of larger technopolitical systems, only Hecht contends that "[t]he things in which nuclearity gets distributed are not all connected to each other. Their networks do not always match up."[38] Hecht's granular consideration of nuclearity provides much greater resolution for analyzing nuclear enterprises, which allows for a spectrum of analysis beyond an intractable nuclear dichotomy.

Another point of theoretical refinement in Hecht's work is an expansion and deepening of themes from Itty Abraham's analysis on nuclear weapons, particularly his concept of *nuclear ambivalence*. The tendency of experts to analyze and characterize a nation-state "going nuclear" as flipping a binary switch obfuscates how "nuclear" and "non-nuclear" infrastructures are interconnected and interdependent.[39] Allowing for nuclear ambivalence provides space for a multiplicity of technological affordances and policy-making processes that are not reducible to elite decision-making for or against acquiring "the bomb."[40]

Adriana Petryna anticipates some of the socio-political implications of Abraham's nuclear ambivalence and Hecht's nuclearity in her insightful ethnography in post-Soviet Ukraine, *Life Exposed: Biological Citizens After Chernobyl,* where she applies the concept of biological citizenship to the legacy of the worst nuclear disaster in history.[41] Bodies become sites of radiological damage, transformed both biologically and legally, into recognized entities for compensation and/or medical treatment. A more

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[36] Gabrielle Hecht, "A Cosmogram for Nuclear Things," *Isis* 98, no. 1 (2007): 101, https://doi.org/10.1086/512834.
[37] Hecht, 101. Here she is citing a statement from Bruno Latour and Peter Weibel's "Making Things Public" exhibit at ZKM Karlsruhe, 2005.
[38] Hecht, 106.
[39] Itty Abraham, "The Ambivalence of Nuclear Histories," *Osiris* 21, no. 1 (January 2006): 55, https://doi.org/10.1086/507135.
[40] Abraham, 56.
[41] Adriana Petryna, *Life Exposed: Biological Citizens after Chernobyl*, 2013 ed. (Princeton, NJ: Princeton University Press, 2003).

recent intersection between nuclearity and of what has also been called biocitizenship can be seen in the wake of the nuclear disaster at Fukushima Daiichi because of the 2011 Tōhoku earthquake and tsunami. Now over 12 years later, a major point of contention in the release of treated wastewater from the Daiichi site into the ocean is the tritium content. Protests in Japan, South Korea, and China have viscerally characterized this action as an irreversible harm, with governments in Hong Kong and China going so far as to ban seafood imports from Japan. All the while, dozens of nuclear power plants in South Korea and China continue to release several orders of magnitude more tritium into the environment during normal operation. The implication is that the wastewaters from Daiichi are somehow *marked* and the people and environments exposed to them will be uniquely and unalterably polluted.

STS provides key tools to make sense of nuclear matters and trace the knowledge-making process of tritium's nuclearity. Because these processes are grounded in the inherent materiality of tritium it is important to understand its physical boundaries and effects in the real world. However, the context and meaning attributed to this reality consists of human choices, values, and stories. Artifacts *do* have politics and studying tritium allows for greater insight into the vast infrastructures supporting the peaceful atom and the bomb.

Methods

Overview

The research foundation for this project began during collaborations under the Nuclear Policy Project (NPP), a Virginia Tech +Policy Network-funded transdisciplinary team of scholars which included Sonja Schmid, Paul Avey, Patrick Roberts, and me. From 2020-2021, Prof. Sonja Schmid and I reviewed over 160 documents on tritium, the bulk of which were government reports and technical analyses on tritium production in the United States spanning from the 1980's to the 2020's. We focused our research on the U.S. decision to produce tritium in commercial light water reactors (CLWR); the scope of my dissertation extends this work to consider tritium in broader contexts.

Two key texts on tritium provided an excellent orientation for both research projects: Ken Bergeron's *Tritium on Ice: The Dangerous New Alliance of Nuclear Weapons and Nuclear Power* (2002)[42] and Martin Kalinowski's *International Control of Tritium for Nuclear Nonproliferation and Disarmament* (2004).[43] Each text provides well-researched arguments rich with substantial primary and secondary source materials. Additionally, Bergeron's proactive Freedom of Information Act (FOIA) requests produced important documents with respect to the decision-making process for producing tritium in a commercial reactor.

Beyond these two monographs, there are two other significant works addressing tritium that play an important role in the framing of my research. The first is the *Tritium Factor: Tritium's Impact on Nuclear Arms Reductions* (1989), which records the proceedings of a high-level workshop of U.S. experts addressing the provocative notion of allowing the natural decay of tritium to drive nuclear disarmament. This account provides the candid discussions of a veritable who's-who of nuclear weapon experts at a highly uncertain historical moment: the Soviet Union had not yet collapsed, and the U.S. had recently

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[42] Kenneth D. Bergeron, *Tritium on Ice: The Dangerous New Alliance of Nuclear Weapons and Nuclear Power* (Cambridge, Mass: MIT Press, 2002).
[43] Kalinowski, *International Control of Tritium for Nuclear Nonproliferation and Disarmament*.

shut down its sole tritium production reactor. The second is Arjun Makhijani's *Exploring Tritium Dangers: Health and Ecosystem Risks of Internally Incorporated Radionuclides*, which provides a recent overview of tritium's radiological risks.[44] Among these texts, a great deal is left to explore such as a thorough account of the history of tritium in the U.S. nuclear weapons program and what has been happening over the last twenty years.

Given a dearth of academic literature on the topic, we soon realized that we would need to interview relevant experts in the tritium production decision/transition and tritium's role in nuclear weapon infrastructures. Additionally, I have also submitted three FOIA requests to TVA to fill knowledge gaps in publicly available documents.

Parallel to these joint efforts, I researched the history of tritium more broadly, drawing sources from many digital archives including those from several government agencies, academic databases, professional organizations, and various independent scholar repositories. Contemporary controversies and discourses surrounding tritium leaks at nuclear power plants and the recent treated wastewater discharges from the Fukushima Daiichi site have foregrounded public concerns with the radiological risks posed by tritium in the environment. These developments have not emerged in isolation and are deeply connected with the historical evolution of nuclear technologies and infrastructures. Moreover, the expert and layperson understanding of tritium will also influence the direction of still nascent nuclear fusion futures. Because of this my document search also includes more speculative research into fusion power technologies.

My research has also been positively affected by meeting experts through webinars, workshops, and interactions on social media. The community of nuclear weapon experts and scholars is small but very engaged. The prevalent norm is generosity and encouragement, particularly with early scholars. The many open doors, helpful suggestions, and thoughtful advice that I have encountered have led me to salient references and valuable resources that I may not have otherwise discovered.

Archives/Databases/Resources:

The DOE Office of Scientific and Technical Information (OSTI.gov) has been an invaluable source of publicly available documents related to tritium production and nuclear weapons. Many of the technical reports referenced for this research have come from this on-line database. Additionally, OSTI also hosts OpenNet, a separate archive of declassified documents, including information obtained from FOIA requests. If not for Alex Wellerstein's thorough and detailed advice on locating specific Atomic Energy Commission (AEC) staff papers, I may not have come across this vital and relevant archive until months later.[45] After a few hours searching for "tritium," "hydrogen bomb," and several related terms, I was able to address several gaps in my research into the historical status of tritium in the U.S. weapons program and identify key documents indicating notable shifts.

The public-facing NRC Agencywide Documents Access and Management System Web-based ADAMS provides unparalleled insight into commercial power plant operations in the U.S. NRC reporting

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[44] Arjun Makhijani, *Exploring Tritium Dangers: Health and Ecosystem Risks of Internally Incorporated Radionuclides* (Washington, D.C.: Opus Self-Publishing Services, 2023), https://ieer.org/wp/wp-content/uploads/2023/02/Exploring-Tritum-Dangers.pdf.

[45] I had been under the mistaken impression that the OSTI archive offered a unified search of all publicly available DOE documents concerning nuclear science and technology.

mandates require all but the most sensitive safeguards and trade-secret documents to be available to the public. The vast quantities of documents also create significant research challenges. The ADAMS search engine is non-intuitive and requires some trial and error to develop efficient and effective search parameters. By crossing into the NRC-regulated domain (outside the National Nuclear Security Administration (NNSA)), tritium production has produced a substantial paper-trail much of which can be found in this database. Key search terms include “tritium,” “tritiated,” “TWST,” and “TPBAR.”[46] Additionally, since the purview of the NRC is nationwide, it is helpful to narrow results to match the docket numbers for Watts Bar Units 1 & 2. My professional experience in nuclear power operations also greatly informed which documents were particularly valuable, such as the Updated Facility Safety Analysis Report (UFSAR), Core Operating Limits Reports (COLR), Technical Specifications (TS), and Technical Requirements Manual (TRM), and which documents would be unlikely to contain relevant information.

Conveniently, Virginia Tech Libraries trialed Gale U.S. Declassified Documents, an archive containing unique and valuable documents for understanding the historical evolution of thermonuclear weapon designs and public vs. restricted information on tritium’s role in these weapons. During the trial, I found several memos and documents that provide additional historical depth to my research.

Other archives and databases that I have benefitted from digital access to include: Secure NEPA Documents, a unique post-9/11 artifact established to shield potential terrorist targets from identification[47]; Institut de radioprotection et de sûreté nucléaire (IRSN), a French radiation protection institute that provides some of the best available information on tritium effects on the environment; the IAEA, the International Atomic Energy Agency provides an excellent reference database (where full-text has not been available the Virginia Tech Inter-library Loan (VT ILLiad) office has been helpful in tracking them down); The Declassified Document Retrieval System with the DOE Public Reading Room, a valuable archive of declassified DOE technical documents; The digital Research Library for Los Alamos National Labs, a helpful resource when searching for specific references originating from LANL; The DOE Directives, Guidance, and Delegations database, an essential reference for understanding current and archived DOE documents including the document lineages and interconnections between them; Pfeiffer Nuclear Weapon and National Security Archive, Marty Pfeiffer is a PhD candidate at the University of New Mexico who actively cultivates a colorful social media presence and provides a unique data trove generated by his many FOIA requests and expertise in nuclear anthropology.

Each of these databases, archives, and resources had their own idiosyncratic search and content filtering functionality. Often after failed attempts of locating relevant primary documents, I would successfully return results later using a different approach and/or new search terms or parameters that emerged during my research. On several occasions, when I suspected my negative results were due to an error or oversight on my part, I posted messages on social media to seek help from other nuclear scholars who

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[46] Tritium Producing Burnable Absorber Rods (TPBARs) are the fuel bundle inserts that create tritium through interactions between lithium and the neutron flux in the core. The Tritiated Water Storage Tank (TWST) is a 500,000-gallon tank addition to the Watts Bar site implemented around 2011-12 that was paid for entirely by the DOE. The TWST allows for the storage of a greater volume of tritiated water and strategic releases into the environment when the river flowrate is high.

[47] Secure NEPA Documents no longer serves its original purpose but continues to exist as a holdover. To access the few dozen documents in the database a researcher must request the documents over email.

were familiar with these resources. Many hours of frustration were saved due to the generous responses of other scholars.

All the resources above are either digital or have been made digital through the irreplaceable services provided by the intrepid interlibrary loan workers. Of the twenty-two requests I submitted, VT ILLiad successfully located and provided all but two.[48] I have accumulated over 500 documents and references related to tritium using the resources referenced above. While I am certain there are valuable and important documents related to tritium that remain to be discovered in physical archives, I did not encounter a research thread in my dissertation that would have benefitted from the time, energy, and financial investment necessary to uncover them. On the contrary, I find that I have more primary documents on the history and science of tritium than can be effectively used in the scope of this research project.

Conclusion: Why Tritium?

As an object of inquiry, tritium is understudied and underappreciated not only in STS but also in nonproliferation and radiological risk discourse. While I highlight the few but robust tritium monographs in Chapter 2, I derive the bulk of my analysis from primary source materials, many of them historical and technical documents which have only been declassified in the last 20-30 years. I also draw from many other publicly available but highly specialized reports on tritium that have rarely been brought into conversation with one another. The result is a holistic story of tritium over time that builds a unique typology of tritium's nuclearity and its practical consequences.

Nuclear materials such as uranium and plutonium have been exhaustively analyzed, regulated, and incorporated into international safeguards. The relative success of the nonproliferation regime for limiting the growth of nuclear weapon possessing states from the five original states to nine currently[49] was partially due to controlling dual-use technologies related to fissile material production and enrichment. As I describe in Chapter 2, tritium has been an integral part of nuclear weapon stockpiles since at least 1955 and has not received attention from experts and policymakers commensurate to this role. I argue that understanding how tritium's nuclearity has been historically constructed and how it has shifted over time offers additional explanatory power for why tritium has been overlooked. Then, in Chapter 3, I argue how and why tritium should be more fully incorporated into nonproliferation regimes.

A significant dimension of uranium's nuclearity, as elucidated by Hecht, is the construction of its radiological risks. Tritium's risks prove much more challenging to assess and construct. In Chapters 4 and 5, I explore the intersection between nuclear activities and the release of tritium into the environment. These releases produce both local and aggregate global effects and unlike most other pollutant radioisotopes they cannot easily be removed from effluents. Nuclear proponents tend to emphasize how tritium pollution is lost in the noise of natural background levels through diffusion, and nuclear critics tend to focus on much higher tritium concentrations measured at the release sources. Without

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[48] One of the two "failures" was due to COVID mitigations at the hosting archive. The other was because the document remained classified and not publicly available.

[49] Originally, there were five nuclear-weapon states as defined by the NPT: U.S., U.K., France, U.S.S.R. (now Russia), and China. Currently, the states known to possess nuclear weapons include India, Pakistan, North Korea, and Israel. Even though Israel officially maintains "nuclear ambiguity" of whether they possess nuclear weapons, most experts believe that they do. Notably, South Africa possessed several nuclear weapons before they dismantled them and ended their nuclear weapon program in 1989.

clear epidemiological evidence of the effects of tritium exposure on human health, both proponents and critics resort to inference to account for "safe levels" and risk thresholds. Despite these disagreements and insufficient information, decisions will still need to be made and regulatory policies will need to be enacted in response to tritium-intensive technologies such as fusion energy. Because fusion research and development will take many more years before commercial generation is viable, we collectively have the potential to assess and weigh-in on these large-scale, potentially transformative technologies before they become normal features of our hybrid sociotechnical *agencement*.

Chapter 2: Tritium in the Nuclear Order

Introduction

In the early 21st century, three important texts on tritium were published. The first, *Tritium on Ice: The Dangerous New Alliance of Nuclear Weapons and Nuclear Power* by Ken Bergeron[50] focuses on the United States' decision to produce tritium in a commercial light water reactor (CLWR) for nuclear weapons. The second, *International Control of Tritium for Nuclear Nonproliferation and Disarmament* by Martin Kalinowski[51] makes the case for a systematic approach to the monitoring, verification, and control of tritium as a part of the international nuclear nonproliferation regime. Both texts foreground tritium as a critical concern but with different historical presuppositions and visions of the future. The third, *Exploring Tritium Dangers: Health and Ecosystem Risks of Internally Incorporated Radionuclides* by Arjun Makhijani reassesses the commonly downplayed radiological risks of tritium by examining existing risk models and considering potentially underexplored mechanisms for harm.

As a retired reactor safety expert, Bergeron voices two central criticisms of this change in US tritium policy: (1) Producing tritium for nuclear weapons in a civilian reactor breaches a long-held norm of the separation between military and civilian nuclear technologies and (2) the reactor at Watts Bar Nuclear Plant is based on an uncommon containment design that requires an exotic ice condenser to dissipate heat in the event of an accident. His book is rooted in an activist concern for reactor safety for what he considers an unnecessarily risky design that is further exacerbated by the unprecedented incorporation of tritium production.

In this dissertation I make no case for or against the ice condenser safety concerns, but I am keenly interested in Bergeron's policy postmortem which exposes tritium as an ambivalent material with a contested identity. Is tritium a troublesome pollutant with relatively benign use cases, such as remote runway lighting, exit signs, radioluminescent watch dials, and gun sights? Or is it an essential material for nuclear weapons with national security implications? Will breaching the so-called firewall between civilian and military nuclear infrastructures undermine core principles of the nonproliferation regime and prompt rogue proliferators to follow suit? Or, as the Department of Energy (DOE) argues, will new modes of tritium production allow for the necessary maintenance of nuclear stockpiles while on the long path to complete disarmament?[52]

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[50] Bergeron, *Tritium on Ice*.

[51] Kalinowski, *International Control of Tritium for Nuclear Nonproliferation and Disarmament*.

[52] "Negotiations required for further reductions in United States nuclear weapons and, ultimately, total nuclear disarmament, will likely stretch well into the next century. United States production of tritium in a CLWR will support the U.S. nuclear weapons stockpile during this process. Such support of a decreased nuclear weapons stockpile *is not inconsistent with* the long-range goal of total nuclear disarmament." "The Final Environmental

As a physicist, Kalinowski meticulously assesses tritium as a bomb material and situates this materiality in the language and logic of existing international treaties. In his exhaustive analysis, the recent move by the U.S. to produce tritium in CLWR is simply one of many tritium production mechanisms. Also, as a dual-use material, he considers the various commercial uses of tritium and proposes a unified framework for trade and end-use regulation. The political status of tritium has been fragmented into relatively innocuous commercial products and an irreplaceable component in all extant nuclear arsenals. Kalinowski argues that this bifurcation emerged because of the regime of nuclear secrecy surrounding tritium's use in nuclear weapons:

> During the negotiations for the Nonproliferation Treaty (NPT) the significance of tritium for nuclear weapons was not generally known. It took nearly 30 years from the first release of tritium from military production to civilian use before the relevance of tritium to proliferation was recognized at the 4th NPT Review Conference in 1990.[53]

While it is true that many technical details were not officially declassified until 1972 and 1974[54] around the time J. Carson Mark's "A Short Account of Los Alamos Theoretical Work on Thermonuclear Weapons, 1946-1950" was published, a great deal of expert speculation had been on-going in the public sphere from at least January 1950 when Pres. Truman announced his directive to the AEC to continue work on the "so-called hydrogen or superbomb."[55] I argue that technical information on tritium's role in nuclear weapons was sufficiently available to support its usefulness for nonproliferation, and its relatively late arrival to policy discourse is due to a persistent siloing of expertise between technical military and civilian policy domains. This disconnect is exemplified by the construction of tritium's *special* nuclearity whereas strict adherence to policy excludes tritium from the category of Special Nuclear Material (SNM). Experts in nuclear weapons have tended to consider tritium SNM both in word and practice. In the following, I survey primary documents and some of the many histories already written on the early years of the nuclear weapon program in the U.S. to trace the nuclearity of tritium with respect to the nuclear exceptionalism of "the bomb" variously conceived.

Makhijani's exploration of tritium's dangers will be considered in Chapter 4: "Byproduct Nuclearity." The so-called Atomic Age brought forth a concomitant age of nuclear risks that have evolved over time and left persistent legacies on the Earth and many communities and ecologies directly affected by nuclear activities, whether the atoms in question were "peaceful" or otherwise. In the present chapter, I will avoid lengthy discursions into these real and important concerns. This is not intended to sanitize nuclear history but, rather, to properly highlight the unique challenges posed by understanding the roles and effects of tritium against a backdrop of myriad other radiological risks in a later chapter.

Born Nuclear

Gabrielle Hecht coined the term nuclearity in *Being Nuclear: Africans and the Global Uranium Trade*. Long before the radioactivity of uranium was determined by Henri Becquerel in 1896, it "began life as a metal of marginal value" when it was used in glass/ceramics for coloring, in various applications for its

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Impact Statement for the Production of Tritium in a Commercial Light Water Reactor" (Department of Energy (DOE), March 4, 1999), S-8. Emphasis mine.

[53] Kalinowski, *International Control of Tritium for Nuclear Nonproliferation and Disarmament*, 14.

[54] "Restricted Data Declassification Decisions 1946 to the Present," January 1, 2002, 27.

[55] Harry S. Truman, "Statement by the President on the Hydrogen Bomb" (The American Presidency Project, January 31, 1950), https://www.presidency.ucsb.edu/documents/statement-the-president-the-hydrogen-bomb.

metallic properties, as fishing weights for its mass, or simply wasted in the tailings of gold mines.[56] Uranium's non-nuclear beginnings allowed for a patchwork of nuclearity constructions to emerge at the local level of each mine and processing site. Tritium, on the other hand, was *born nuclear* in the laboratory and all its practical applications are rooted in its radioactive properties.[57]

One of the earliest descriptions of the discoveries of hydrogen's heavy isotopes, deuterium and tritium, appeared in The Scientific Monthly, vol. 39 in October 1934.[58] Hugh S. Taylor, a chemistry professor at Princeton University, first recounts that laboratory measurement discrepancies of Carbon-13 in 1929 led to hypothesizing that 1:4,500 hydrogen atoms have a mass of 2, meaning the nucleus would contain one proton and one neutron. Taylor remarks on the technoscientific merits of these discoveries:

> That the pace of this scientific development is prodigious all must realize when they remember that only a year ago the deuterium isotope was not yet isolated. Today it has a still rarer brother, tritium; it has itself given rise to this and to other new isotopes, some radioactive, some not; it has made possible a new branch of chemistry, the chemistry of isotopes, which already has markedly enriched our knowledge of general and physical chemistry; it is *a potent weapon of attack* also on physiological and biological problems.[59]

Note that even though no military application was even alluded to at this early date, martial language was assigned to the scientific use of deuterium and tritium. In less than a decade hence, industrial-scale production of heavy water (water made with deuterium, or D_2O) would prove to be a significant technological concern of World War II. The use of heavy water reactors would become a plausible pathway for plutonium production for first generation nuclear weapons. Few would anticipate that deuterium and tritium posited above as transformative tools (or *weapons*) of scientific inquiry would themselves establish the foundation for a subsequent generation of nuclear weapons that would transform the world.

A key document for assessing this period is "Policy and Progress in the H-Bomb Program: A Chronology of Leading Events," a document produced by the Joint Committee on Atomic Energy (JCAE) on January 1, 1953, and not declassified until 1992.[60] This report provides a slightly different "Super" origin story than Senator McMahon's letter to Truman referenced in the introduction. In a series of conversations in early spring 1942, Edward Teller and Enrico Fermi conceptualized the possibility of using an "A-bomb as a means of igniting a mass of deuterium."[61] Early calculations made such a device appear feasible, but it would require significant temperatures to "ignite" the deuterium-deuterium (D-D) fusion process. Later that summer, Emil Konopinski suggested "to lower the ignition temperature of deuterium by the admixture of artificially-produced tritium (hydrogen 3)." This was when the principle

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[56] Hecht, *Being Nuclear*, 319.

[57] It is important to note that all large-scale tritium production currently depends on the mining and trading of uranium and/or lithium. The production of tritium in heavy-water reactors does not require lithium.

[58] Hugh S. Taylor, "Protium-Deuterium-Tritium the Hydrogen Trio," *Annual Report of Smithsonian Institution*, U.S. Congressional Serial Set, 9974 (1935): 119-[x]. Reprint of original article.

[59] Taylor, 127. Emphasis mine.

[60] "Policy and Progress in the H-Bomb Program: A Chronology of Leading Events" (Joint Committee on Atomic Energy (JCAE), January 1, 1953), https://blog.nuclearsecrecy.com/wp-content/uploads/2019/12/1953-01-01-Policy-and-Progress-in-the-H-bomb-Program.pdf. Courtesy of Alex Wellerstein.

[61] "Policy and Progress in the H-Bomb Program: A Chronology of Leading Events," 4.; German A. Goncharov

of D-T fusion was first introduced, which proved a key innovation in successfully building and testing this new class of terrifying weaponry. Additionally, during the winter of 1943-1944, a significant problem arose with plutonium that required all hands, while this work critical to the fission bomb mission was being done "two members of the British wartime mission to Los Alamos performed the most extensive new calculations concerning tritium and deuterium."[62] The hydrogen bomb like all "national" nuclear projects for peace or war has always been born in part from international collaboration both materially and intellectually. This is an early example of what Itty Abraham calls *nuclear ambivalence*, "a permanent feature of the nuclear condition."[63] Valuable work toward the weaponization of fusion was completed by two unnamed British scientists who brought their own personal and national interests to the task. The nuclear age was never a monolithic U.S. achievement.

The conceptual progress on the advantages of D-T fusion provided sufficient motivation for Oppenheimer, Gen. Groves, and C.H. Greenewalt of the duPont Company to decide in May 1944 to begin "experimental tritium production" at the Clinton Pile "using surplus neutrons."[64] These *extra* neutrons were put to work in the same way the *surplus* British scientists were—these efforts would meaningfully advance the timeline toward a possible hydrogen weapon without slowing the pace toward the A-Bomb. Ample and reliable tritium production would prove to be a significant technical challenge for several years. The proposed weapon designs also proved to be a moving target. Estimated amounts of tritium required for the "super" would rise several times before other possible hydrogen weapon designs began to appear more desirable for their apparent need for far less. The economic tradeoffs between fission and fusion work would change dramatically after the successful Trinity test and subsequent atomic bombings of Japan.

In the days following the bombings of Hiroshima and Nagasaki, the "Smyth Report" was released as part of Gen. Groves's meticulously planned Manhattan Project propaganda effort.[65] Authored by Henry DeWolf Smyth, Chair of the Dept. of Physics of Princeton University, this report was intended to provide a general and technical history of the development of the bomb without revealing critical bomb-making information not already deducible from publicly available scientific literature. The nuclear historian Alex Wellerstein writes "[Smyth] was granted unusual freedom to circumvent the compartmentalization policies that prevented others from gaining a 'full view' of the work."[66] In other words, Smyth had the expertise and access to produce an authoritative and unprecedented book to be published as a publicly accessible *proof* that scientists worldwide would acknowledge its plausibility and soundness.

With respect to tritium, the Smyth Report is almost entirely silent. Given its focus on the development of the fission bomb, it might be tempting to consider that tritium was irrelevant or beyond the scope of the work. However, on closer examination, its absence appears more conspicuous. Smyth touts the importance of the discovery of deuterium in 1932 and notes the unprecedented success in 1940 of the large-scale isotopic separation of hydrogen, "*whose two isotopes differ in mass by a factor of two*."[67]

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[62] "Policy and Progress in the H-Bomb Program: A Chronology of Leading Events," 5.
[63] Abraham, "The Ambivalence of Nuclear Histories," 55.
[64] "Policy and Progress in the H-Bomb Program: A Chronology of Leading Events," 5.
[65] H. D. Smyth, *Atomic Energy for Military Purposes*, 1945, https://www.osti.gov/opennet/manhattan-project-history/publications/smyth_report.pdf.
[66] Alex Wellerstein, *Restricted Data: The History of Nuclear Secrecy in the United States* (Chicago: The University of Chicago Press, 2021), 100.
[67] Smyth, *Atomic Energy for Military Purposes*, 35. Emphasis mine.

The discovery of tritium in 1934 would have been well known to most scientists, chemists and physicists in particular. Implying there are only two isotopes of hydrogen is curious by itself, but he also briefly mentions "a rare isotope of helium" whose mass number is not "at least twice as great as [its] atomic number."[68] This reference is obviously to He-3 which primarily comes from tritium decay and less commonly from other nuclear reactions. The only oblique reference to the existence of tritium is found in a short list of "a few other types of reaction" in the introduction which includes "(d, H^3)."[69] The projectile deuterium (d) interacts with a target nucleus (which would appear to the left of the open parenthesis) and emits a triton (H^3) leaving a remainder (which would appear to the right of the close parenthesis).[70] Smyth likely considered the production of tritium by deuteron bombardment to be innocuous enough to include in the report because this reaction could not be used to produce quantities sufficient for weapons uses.

Given that Smyth studied under Lord Rutherford, who co-discovered tritium, and was a full professor and soon to be Physics department chair when Princeton's "new and specially refined mass spectrograph" measured 1:200,000 tritium atom concentration in the "purest heavy water," it would be impossible for him to be unaware or disinterested in tritium.[71] Smyth was also appointed by Gen. Groves to a "Committee on Postwar Policy" in 1944, which discussed the possibility of "thermo-nuclear bombs of ten thousand fold greater power" than fission bombs and meticulously considered the pros and cons of postwar secrecy.[72] Furthermore, the "rules for public release" provided by Gen. Groves to Smyth were sufficiently general enough that mentioning tritium would have likely satisfied two necessary criteria for inclusion: I(b) "of true scientific interest and likely to be truly helpful to scientific workers in this country" and II(a) "already known generally by competent scientists."[73] The most plausible explanation in my assessment is that tritium was *de facto* off-limits due to its relevance to the then nascent "super bomb." Otherwise, the existence of tritium would have been remarked upon at least in passing despite its lack of direct relevance to the state of fission weapons in 1945. It would not be until later that year when tritium science would receive a more thorough consideration for declassification.

In a memo addressed to Gen. Groves dated November 17, 1945, summarizing a meeting of the Committee on Declassification chaired by Richard C. Tolman, information was classified into three categories and various aspects of tritium science were considered.[74] The three categories were:

Class I: Information recommended for immediate declassification.

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[68] Smyth, 6.
[69] Smyth, 20.
[70] One of the Russian translations of the Smyth Report available online mistakenly transcribes H^3 as H^2 here, but other versions have it rendered correctly without comment. Thanks to Alex Wellerstein for pointing this out. Smythe, H. D. "Атомная Энергия Для Военных Целей," 1946. https://www.e-reading.club/bookreader.php/1006999/Smit_-_Atomnaya_energiya_dlya_voennyh_celey.html.
[71] Taylor, "Protium-Deuterium-Tritium the Hydrogen Trio," 123.
[72] Richard C. Tolman et al., "Report of Committee on Postwar Policy," December 28, 1944, 8, https://blog.nuclearsecrecy.com/wp-content/uploads/2023/07/CTS-R04-T06-F03-Interim-Committee-and-Scientific-Panel.pdf.
[73] L.R. Groves and Richard C. Tolman, "General Rules Governing the Information to Be Contained in the Document Under Preparation by Dr. H.D. Smyth" (Courtesy of Alex Wellerstein, July 9, 1945).
[74] Along with Tolman, the committee members included: R.F. Bacher, E.O. Lawrence, F.H. Spedding, A.H. Compton, J.R. Oppenheimer, H.C. Urey, and J.R. Ruhoff.

> Class II: Information whose declassification would conduce to the national welfare and to long term national security, so that the date of declassification should depend on estimates as to the probability and imminence of war.
> Class III: Information not at present recommended for declassification, and whose declassification should await a real reduction in the threat of atomic warfare.

The report further explains:

> Class I includes basic scientific information which has little direct application to the problems of production or military utilization. Class II includes certain basic scientific information which would be of great value to the development of science but which has a direct bearing on production or military utilization. It also includes technological information which would be of great importance for the peacetime utilization of atomic energy but which also has importance for production or military utilization. Class III includes information which has immediate application to the problems of military utilization but for the most part has little application to the development of science or to peacetime utilization. Included in this class are statements with regard to production capacities, amounts of active material on hand, present output of bombs, stock pile (sic) of bombs, etc. This inclusion in Class III is made in order to reserve to the President and the Congress the formulation and disclosure of national military policy.[75]

These definitions demarcate between three distinct use cases: basic science, atomic energy, and military. Furthermore, they also incorporate geopolitical considerations such as “the probability and imminence of war,” “threat of atomic warfare,” and “peacetime.” The tensions between these contexts would define the trajectory and tenor of the Cold War for several decades. Class II and III were in a state of flux. The categorization of tritium and associated notes on the list of classified substances illustrates dynamics embedded in this classification scheme.

With respect to Basic Chemistry, Basic Physics, and Nuclear Physics, tritium is classified as Class I, recommended for immediate declassification. However, in a note under the Nuclear Physics column, the committee highlights its only apparent disagreement: “In the case of the D-T cross section, recommendation for Class I was not unanimous.”[76] In other words, information with respect to the probability of deuterium-tritium fusion given appropriate conditions was considered sensitive with respect to the potential for “military utilization” to at least one committee member.

One of the committee members in support of the immediate declassification of tritium’s nuclear physics related information including the D-T cross section was likely Robert J. Oppenheimer. According to 1961 memorandum by Lewis Strauss, a founding member of the Atomic Energy Commission (AEC):

> At a meeting of the General Advisory Committee in October of 1947, Dr. Oppenheimer being Chairman, the Committee recommended to the Commission that *all information*

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[75] Richard C. Tolman et al., “Memo to Major General L. R. Groves, Subject: Report of Committee on Declassification” (Atomic Energy Commission (AEC), November 17, 1945), 4–5, https://www.osti.gov/opennet/servlets/purl/1244263.pdf.

[76] Tolman et al., 6.

> *on the nuclear properties of Tritium should be declassified*. Commissioner Strauss opposed this when it came before the Commission but was out voted. Dr. Oppenheimer stated for the GAC that the military applications of thermonuclear reactions which might seem to warrant retaining the properties of Tritium as classified information were a very long-range problem.[77]

Strauss prepared the memo as a contribution to the "Oppenheimer" file because it contained information not addressed in the security clearance hearings but which provided facts he felt were germane to Oppenheimer's alleged obstruction of the development of thermonuclear weapons. The apocryphal story of Teller vs. Oppenheimer in the development of this new class of hydrogen weapons has been satisfactorily debunked by others including Peter Galison, Barton Berstein, and Anne Fitzpatrick.[78] In the context of the present work, better understanding the material challenges posed by scaling tritium production to meet the high projected demand provide additional justification for Oppenheimer's assessment of near-term feasibility.

Tritium's only recommendation for Class III was under the Technology column. The committee defined technology as "[including] descriptions of actual manufacturing operations and laboratory work from which the nature of these operations could be clearly inferred."[79] Even here a note delineates that "small scale production methods are in Class II." The differentiating factor appears to be that small scale tritium production methods have legitimate applicability and possibly "great value" for scientific research, but even such methods might allow for quantities sufficient for military use. Furthermore, under the category of "Military Utilization Project," the committee recommended discussion of "the 'super" as a weapon" to be a Class III topic. This prohibition would continue until Pres. Truman's brief public statement on January 31, 1950.

It should also be noted that lithium (in any isotope or compound) does not appear in the list of classified substances or even as a subject for discussion. However, it is critically important to tritium production targets[80] and ultimately to the design of thermonuclear bombs (in the form of a lithium deuteride in the secondary), but this innovation would come several years later. It is possible that lithium may have been covered by the Class II/III Technology designation for tritium, but it is unclear from the text of the meeting summary.

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[77] "Memorandum by Lewis L. Strauss Regarding Facts Not Brought out in the Oppenheimer Hearings, Compiled from 'A Chronology of the Thermonuclear Weapons Program to November 1952,' Dictated by Strauss on 8/14/53." (United States: Atomic Energy Commission, January 10, 1961), U.S. Declassified Documents Online, http://link.gale.com/apps/doc/CK2349123484/USDD?sid=bookmark-USDD&xid=2e8f60a8&pg=1. Emphasis mine.

[78] Peter Galison and Barton Bernstein, "In Any Light: Scientists and the Decision to Build the Superbomb, 1952-1954," *Historical Studies in the Physical and Biological Sciences* 19, no. 2 (1989): 267–347, https://doi.org/10.2307/27757627; Anne C. Fitzpatrick, "Igniting the Light Elements: The Los Alamos Thermonuclear Weapon Project, 1942-1952," July 1, 1999, https://doi.org/10.2172/10596.

[79] Tolman et al., "Memo to Major General L. R. Groves, Subject: Report of Committee on Declassification," 6.

[80] Early tritium production targets or "slugs" were in the form of lithium fluoride, and later research considered other forms such as lithium aluminum alloys, lithium aluminate, and even a "lead-lithium mixture." ["Production Office Diary July 17, 1944 Through January 24, 1946," January 24, 1946. DOE Public Reading Room - Hanford Battelle. https://www.osti.gov/opennet/detail?osti-id=16421692. 186.] Lithium silicate and the lithium containing mineral petalite were also tested in related programs. Johnson, Jr, T. J. Kabele, and W. E. Gurwell. ["Tritium Production from Ceramic Targets: A Summary of the Hanford Coproduct Program." Battelle Pacific Northwest Labs., Richland, Wash. (USA), August 1, 1976. https://doi.org/10.2172/7125831. 1.]

Under these declassification recommendations, Smyth would have been free to mention tritium and provide basic scientific information. However, since these guidelines were developed several months after the publication of the Smyth Report, Smyth appears to have been operating under informal, precautionary considerations with respect to the topic of tritium. The lesson later learned when editors removed references to "pile poisoning" from the subsequently issued Princeton University Press edition of the Smyth Report is that they would only inadvertently draw more Soviet attention to the topic.[81] In other words, since discretely concealing information after the fact only appeared to make matters worse, it was thought to be better to say little or nothing on matters potentially sensitive to national security.

The tension between scientific transparency and military secrecy produced additional tensions. To maintain appropriate control of even small-scale tritium production some small quantities were eventually released to university labs. Many radioisotopes requested were producible by a university's own cyclotrons, but the much more efficient pile production and other methods available to the AEC and U.S. Government would save hundreds to several thousand hours of cyclotron operation to produce equivalent amounts.

A chronology of early post-war tritium production is summarized in a *History of the Activities of the Manhattan District Research Division: Oct. 15, 1945 – Dec. 31, 1946*, which covers the almost 15-month period between the Research Division's creation to when it was transferred to the newly established AEC.[82] In 1945, the Clinton Pile, also known as the X-10 graphite reactor, in Oak Ridge, TN originally supplied tritium exclusively to Los Alamos "which manifested an increasing demand for it."[83] By July 1948, Hanford had taken over tritium production and had increased it to a rate which far exceeded the needs of Los Alamos.[84] The Research Division have received material requests from the University of California, the National Bureau of Standards, and even ANL, who had manufactured the lithium fluoride (LiF) slugs that were used to produce the tritium in the first place:

> Following a comprehensive review of the problem, including future anticipated supply and demand at Los Alamos, the Division recommended to the Washington Office on December 11, 1946, that current District policy be modified to permit the initiation of a coordinated program at other research installations involving fundamental research with H^3, and that excess material be made available for this purpose. *From a security standpoint it was felt such a policy would deemphasize the District's interest in this*

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[81] Wellerstein, *Restricted Data*, 127–28.

[82] "History of the Activities of the Manhattan District Research Division: Oct. 15, 1945 - Dec. 31, 1946," December 31, 1946, NNSA/NSO Nuclear Testing Archive, https://www.osti.gov/opennet/detail?osti-id=16111638.

[83] "History of the Activities of the Manhattan District Research Division: Oct. 15, 1945 - Dec. 31, 1946," Chp. IV, 39.

[84] George G. Reed Jr., "History of the P-10 Project as of 02/01/1951," January 4, 1952, 3, D198108143, https://reading-room.labworks.org/Files/GetDocument.aspx?id=D198108143. During this period of early tritium production, this P-10 history is in partial disagreement with the "History of the Activities of the Manhattan District" which places the tritium production transition to Hanford in 1946. Since Reed's P-10 History was produced later and focused exclusively on tritium production, I considered its chronology to be more likely to be both accurate and precise.

> *important material more effectively than the present policy under which all use is frozen [except] for Los Alamos.*[85]

Being cognizant that the Soviets were paying close attention to activities of the vast infrastructure of the U.S. nuclear weapons complex, those administering the Manhattan District Research Division were beginning to understand that this included the negative space of topics avoided along with materials and technologies that were tightly restricted. Supplying tritium for scientific research outside the nuclear weapons complex demonstrated that it was no different than other radioisotopes commonly made available. Furthermore, it may have even signaled a position of strength—if the Soviet's suspected tritium was useful for nuclear weapon designs, the U.S. would appear to have an overabundance of this rare and costly material.

In a November 10, 1947 meeting of the Committee on Nuclear Science of the National Research Council, a staff designee of the Director of the Isotopes Division at the AEC, Paul C. Aebersold, presented statements on the isotope distribution program's progress. Note that this was an unclassified meeting with public and private stakeholders. The penultimate update from the AEC in a list of 15 items reads:

> Tritium is still not available for distribution. A number of problems in production, handling, and packaging are yet to be solved—particularly for routine processing. One difficulty is finding qualified personnel to put to work on the overall job. Since very tiny quantities will have a high activity, the problem of providing tritium labeled compounds will be more difficult than for C 14 (sic) and hence more important.[86]

In this instance, Aebersold was accurately but vaguely representing the challenges for tritium production and distribution. The LiF slugs, or targets, were challenging to work with, had limited irradiation capacity,[87] and tritium extraction required a wide range of personnel. Beyond personnel with scientific, technical, and material know-how, *skilled glassblowers* were also required. The following month he provided slightly more detail in a presentation at the Conference on the Use of Radioactive Isotopes in Agricultural Research:

> Tritium is not yet available through Commission facilities. There are many tricky problems in its production, (sic) and in its packaging. The material is quite active per unit volume. A millicurie is about a cubic millimeter, so that it will require very specialized handling. Consequently, it may be necessary to develop means of distributing this isotope only in the form of labeled compounds. Small amounts of tritium can be obtained from cyclotron laboratories by recovery from beryllium targets that have received long bombardment.[88]

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[85] "History of the Activities of the Manhattan District Research Division: Oct. 15, 1945 - Dec. 31, 1946," Chp. IV, 41. Emphasis mine and "[except]" included to disambiguate meaning.

[86] "Minutes of the Meeting of the Committee on Nuclear Science of the National Research Council, on 10 November 1947," November 10, 1947, 106, NNSA/NSO Nuclear Testing Archive, https://www.osti.gov/opennet/detail?osti-id=16005370.

[87] Targets developed later allowed for longer irradiation times. The longer slugs can be irradiated in a pile the more tritium they will produce. Also, the LiF slugs had the tendency to pressurize and potentially rupture the cans that contained them inside the irradiation tubes.

[88] P.C. Aebersold, "Speech: 'Isotopes Available for Research' (Presented At Conference On The Use Of Radioactive Isotopes In Agricultural Research, Alabama Polytechnic Institute, Auburn, Alabama)" (Atomic Energy Commission

At least two details stand out in his explanation. First, he established the possibility that tritium may not ultimately be distributed in purified form but in "labeled compounds," meaning compounds formed with tritium atoms in positions normally filled by ordinary hydrogen. Second, he stated suggestively that "small amounts of tritium" can be obtained in another way. This latter suggestion does not appear to violate the Declassification Committee's Class II recommendation for "small scale production" because such a method requires stocks of "beryllium targets that have received long bombardment," which would not readily be replenishable if one wanted to use a cyclotron for anything else. Aebersold, at least in words, was able to delicately manage the fine line between scientific transparency and the sui generis requirements of the emerging "Restricted Data" regime of nuclear secrecy.

On September 27, 1948, the recommendation from the Research Division nearly two years prior was affirmed by the AEC and both tritium and He-3 isotopes were made available for distribution for research purposes.[89] The conspicuous absence of tritium was finally amended. In the chronology of the 1953 "Policy and Progress in the H-Bomb Program" report, the deliberations surrounding this decision were labeled "The 1947-48 tritium episode."[90] Among the General Advisory Committee (GAC), the Military Liaison Committee (MLC), and the AEC "a controversy developed" requiring "extended discussion and meetings" to assess how the Soviets would interpret tritium availability or unavailability for general research. They finally settled on two key decisions: they could adjudicate the matter without "[referring] to the President for final solution" and "on balance, tritium should be added to the list of isotopes shipped to private users."[91] Even though they ultimately decided against it, the fact that they considered running the matter by the President demonstrated the seriousness of their deliberations. Over a year before the Soviet's shocked experts with their first A-bomb test on September 23, 1949, there was already high anxiety over the race toward hydrogen weapons. They knew tritium would be the key.

While tritium was *born nuclear* within the technoscientific laboratory context, for nearly 15 years its weaponization potential and importance to the vertical proliferation of nuclear weapons remained a closely guarded secret.[92] In this way, tritium's nuclearity was bifurcated between public small-scale experiments devoted primarily to research functions as a medical tracer and the highly secret industrialized production dedicated for use in the development of the "super." During this time, the military nuclear exceptionalism of tritium interfered with its general availability as a research material. Furthermore, with many prominent scientists sworn to secrecy, expert discourse on tritium was also significantly stifled.

(AEC), December 18, 1947), 11, NNSA/NSO Nuclear Testing Archive, https://www.osti.gov/opennet/detail?osti-id=905953.

[89] "Minutes of the Meeting of the Committee on Nuclear Science of the National Research Council, on 09 November 1948" (United States Dept of Navy, November 9, 1948), 137, NNSA/NSO Nuclear Testing Archive, https://www.osti.gov/opennet/detail?osti-id=16005373.

[90] "Policy and Progress in the H-Bomb Program: A Chronology of Leading Events," 21.

[91] "Policy and Progress in the H-Bomb Program: A Chronology of Leading Events," 21.

[92] Vertical proliferation can refer to an increase in quantity or quality of nuclear weapons. In this case, it is the latter as tritium was the key to unlocking the efficiencies of boosted fission weapons and the devastating yields of thermonuclear warheads.

Super Nuclearity

In response to the successful Soviet A-bomb test that arrived several years before expert estimates, President Truman announced to the world on January 31, 1950:

> It is part of my responsibility as Commander in Chief of the Armed Forces to see to it that our country is able to defend itself against any possible aggressor. Accordingly, I have directed the Atomic Energy Commission to continue its work on all forms of atomic weapons*, including the so-called hydrogen or superbomb*. Like all other work in the field of atomic weapons, it is being and will be carried forward on a basis consistent with the overall objectives of our program for peace and security.
>
> *This we shall continue to do until a satisfactory plan for international control of atomic energy is achieved.* We shall also continue to examine all those factors that affect our program for peace and this country's security.[93]

The "hydrogen or superbomb" quickly became a potent symbol of technological superiority and global dominance. Additionally, this weapon was explicitly positioned as a bargaining chip in the ongoing U.S. effort to re-tool these technologies of war for peaceful ends. Truman's statement would be one of the dashed lines connecting the ill-fated Baruch Plan from 1946 to President Eisenhower's "Atoms for Peace" speech in 1953.

A month following Truman's speech, Senator McMahon, chairman of the Joint Committee for Atomic Energy (JCAE), expressed his uncertainties and anxieties with Soviet progress in a meeting with General Bradley:

> Now, I am constantly bedeviled by the thought that they have done their hydrogen and atomic developments contemporaneously, and any idea that they aren't ahead of us, while I think the chances are that they are not, but how do I know?
>
> We say, 'Well, *where would they get the tritium?' And I believe that is the best assurance that we have got* that, so far as we know—our intelligence, for instance—*they haven't been in that particular business*, but we don't know.[94]

Chairman McMahon's great assurance that the Soviets were behind in the race to the H-bomb relied not on scientific sophistication, technological superiority, or any other material advantage except for the fact that the U.S. had *the tritium*. The U.S. was in the tritium business, and business was booming.

The U.S. would complete two tests using tritium as part of Operation Greenhouse in May 1951. The first, *George*, established the D-T fusion response produced by a large fission explosion. The second, *Item*, would be the first test of a true fusion "Booster" which "established the probable utility of small amounts of tritium in improving the yield of moderate-sized A-bombs."[95] The following year the Operation Ivy Mike test shot would successfully demonstrate the full capabilities of a thermonuclear

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[93] Truman, "Statement by the President on the Hydrogen Bomb." Emphasis mine. While Klaus Fuchs had confessed his Soviet espionage of the U.S. hydrogen bomb program to British agents only a few days before, it is unclear if Pres. Truman knew about it when he made the superbomb announcement. Regardless, fears emerging from the Fuchs affair proved to be a motivating force in the U.S. race to the H-bomb.

[94] "Policy and Progress in the H-Bomb Program: A Chronology of Leading Events," 42. Emphasis mine.

[95] "Policy and Progress in the H-Bomb Program: A Chronology of Leading Events," 54.

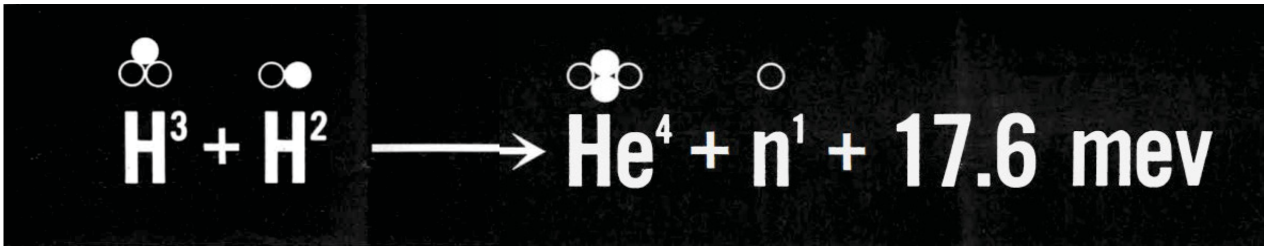
bomb—while its fusion yield relied heavily on a large amount of cryogenically-cooled deuterium, a small amount of tritium was also used. Initial assessments of Mike's yield were "at least 6 megatons and may have been as high as 11 megatons," which was "300-550 times" the yield of the Trinity test 7 years earlier.[96]

Having successfully tested the first thermonuclear device, the U.S. had maintained the nuclear initiative. An early investment in tritium production had been a major factor in being able to test when they did. Much of the account above has only been possible due to the declassification of significant documents and the Freedom of Information Act (FOIA) requests of diligent nuclear scholars. To evaluate the validity of Kalinowski's thesis that the proliferation relevance of tritium was neglected until the 90s due to this secrecy, I will now turn to evaluate the public speculation of the H-bomb. Even if such secrets were not strictly knowable—how close were the educated guesses and how did these assessments affect public constructions of tritium's super nuclearity?

James C. Beckerley, Director of Classification, divides his concerns with these public speculations into two categories in his March 1, 1950 "Comments on H-Bomb Articles" memo:

1. Speculation on the reactions involved in an H-bomb and the effects accompanying its explosion.
2. Speculation on the program (cost, time, etc.) necessary to produce H-bombs.[97]

With respect to the first category, Beckerley pinpoints a key phrase of concern in Louis N. Ridenour's "The Hydrogen Bomb" published just weeks prior in *Scientific American*: "a certain mixture of deuterium and tritium to fuel the fusion process."[98] At that time the Classification Division's "position with respect to the D-T reaction is that all information on the reaction which is obtainable with a few cc's of tritium is declassifiable."[99] This accommodated for the unavoidable realities coupled with the decision to release tritium for research.[100]



[101]

Figure 2: D-T fusion illustration in Ridenour's Scientific American article that spanned two pages.

Beckerley reasons that while every competent scientist should already know "that tritium is very likely to be involved in a thermonuclear bomb," the "<u>significance</u> must be concealed."[102] He does not explicitly

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[96] "Policy and Progress in the H-Bomb Program: A Chronology of Leading Events," 88.
[97] James G. Beckerley and Salisburg Morse, "Comments on H-Bomb Articles," Memo (United States: Atomic Energy Commission, March 1, 1950), U.S. Declassified Documents Online, http://link.gale.com/apps/doc/CK2349433239/USDD?sid=bookmark-USDD&xid=ba2da8eb&pg=1.
[98] Beckerley and Morse.
[99] Beckerley and Morse, 2.
[100] Beckerley and Morse, 2.
[101] Louis N. Ridenour, "The Hydrogen Bomb," *Scientific American* 182, no. 3 (March 1950): 14–15.
[102] Beckerley and Morse, "Comments on H-Bomb Articles," 2. Emphasis in original.

spell out precisely what the significance entails in this document, but it appears to be a logical conclusion based on disclosing the fact that H-bombs *require* tritium. From this starting point, an adversary attempting to build their own H-bomb might correctly conclude that "the D-D reaction alone may not work," thus potentially saving them time and resources researching dead end designs.[103] Additionally, one might also reason that tritium production infrastructure is integral to building and maintaining an H-bomb stockpile. Beckerley also expresses concern that unambiguous information released regarding the project's use of tritium would remove the last remaining "buffer" to classified information on H-bomb activities, which might lead to lax operational security around the sharing of other project information.[104] In this way, tritium was important not only for its material properties but also for its *obscurity at scale*. By circumscribing increasingly specialized and discrete domains of secret knowledge, scientists may feel comfortable providing general knowledge, which might aid a clever audience in discerning their boundaries and contours.

To better illustrate Beckerley's concern here is an event that occurred in 1980. A seemingly innocuous breach of tritium secrecy concerning D-T fusion ignition temperatures was included as an example of how "completely benign conversations can turn into uncomfortable situations in China" in a 2004 *Intelligence Threat Handbook*. George A. Keyworth, the chief physicist at LANL, visited China to lecture in an academic capacity on fusion.[105] While he was careful to avoid sensitive weapons-relevant specifics during questions, he still inadvertently divulged at a "cocktail party thrown in his honor" that D-T ignition temperatures were so low "that you could just about get ignition by dropping them on the floor."[106] Keyworth contended in a 1999 New York Times article that all his discussions with Chinese counterparts were "absolutely unclassified," he had voluntarily reported the conversation out of concern of being near the boundary of propriety.[107] The broader context here was that this information was the suggestion that this may have aided Chinese weapon designers in developing novel approaches to so-called "neutron bombs." In theory, a large quantity of tritium and deuterium coupled with minimal amounts of fissile material could produce low explosive yields and significant amounts of high-energy neutron radiation which would penetrate armored vehicles and other shielding structures and disproportionately damage living things in the effective blast area. Such bombs were developed and tested by NWS but are widely believed to be abandoned because they lack clearly advantageous use cases.

With respect to the second category regarding speculation on program timelines, costs, and materials, Beckerley addresses public comments made by Hans Bethe and Robert S. Allen which alluded to possible timelines for the first H-bomb. While these statements do not directly relate to tritium, Beckerley connects tritium to overall cost and production tradeoffs that will adversely affect fissionable material available for A-bomb production, both the use of uranium fuel to produce neutrons and the use of those neutrons to produce tritium rather than plutonium.[108] In a report from August 1950, Teller and John

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[103] Beckerley and Morse, 2.

[104] Beckerley and Morse, 3.

[105] James Risen, "In China, Physicist Learns, He Tripped Between Useful Exchange and Security Breach," *The New York Times*, August 1, 1999, sec. World, https://www.nytimes.com/1999/08/01/world/in-china-physicist-learns-he-tripped-between-useful-exchange-and-security-breach.html.

[106] *Intelligence Threat Handbook*, Operations Security Information Series (Interagency OPSEC Support Staff (IOSS), 2004), 26–27, https://nsarchive.gwu.edu/document/21414-document-18.

[107] Risen, "In China, Physicist Learns, He Tripped Between Useful Exchange and Security Breach."

[108] Beckerley and Morse, "Comments on H-Bomb Articles," 2.

Wheeler quantify the production tradeoff of 1 kg of tritium “costing the same number of Hanford neutrons as 80 kg of plutonium.”[109]

Three months after Ridenour’s technical assessment in *Scientific American*, William L. Laurence who has been described as “part huckster, part journalist, all wild-card” delivered his bombastic take on the new hydrogen bomb.[110] Like Smyth, Laurence had been granted special access to Manhattan Project sites and scientists—even witnessing the Trinity test and the Nagasaki bombing from an observation plane—in order to provide propaganda for Gen. Groves’s PR operation.[111] Unlike Smyth, his write-ups required heavy editing for style to be fit for purpose due to his hyperbolic technological enthusiasm, and as a result, they would often go unused. Even though Laurence’s project access had ended in 1945, there was concern that his reporting on tritium and the hydrogen bomb would be seen with unwarranted authority.[112] Was Laurence’s “Truth About the Hydrogen Bomb” true enough to matter?

Building off his brief and provocative “IT’S A TRITON BOMB, MIGHTIEST POSSIBLE” op-ed published in the New York Times the day after Truman’s announcement, Laurence weaves technical matters with the titillating story of Fuchs, the Soviet spy, who violated the “sanctum sanctorum of Los Alamos” stealing away its H-bomb secrets.[113] With respect to tritium, Laurence correctly reports that D-T “catches fire much faster than the deuterons alone,” but offers outlandish estimates on the needed material for three potential variants, D-D, D-T, and T-T:

> To make a bomb 1000 times more powerful than the A-bomb would require 1000 kilograms of deuterium at a cost of $4,500,000; 91 kilograms of deuterium, and 136 kilograms of tritium at a total cost of $132,328,410,000; or 333 kilograms of tritium at a total cost of most than $324,000,000,000 at the current production price. These costs, of course, are over and above the cost of the A-bomb trigger.[114]

For context, estimates of annual tritium production at the Savannah River Plant (SRP)[115] between 1955-1984 average between 4.6-6.9 kg/year with a total tritium inventory in 1984 estimated between 72.2-90.0 kg.[116] Just one of the D-T bombs described by Laurence would require more tritium than the U.S. has possibly ever possessed at any given time. Furthermore, the tritium production methods used at the Clinton Pile, ANL, and Hanford reactors before 1955 were far more experimental and less scalable than production at SRP. The cost was equally outlandish: the $132 billion price tag in 1950 would equate to >$1.7 trillion in 2024![117] Laurence tells a good story, but his wild calculations were far from reality. It

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[109] Fitzpatrick, “Igniting the Light Elements,” 223. This report is being cited from Fitzpatrick’s work because the document in question is “Secret-RD.” Hirsch and Matthews (1990) provide the estimated ratio of 1:70 kg for production equivalency between tritium and plutonium (25).

[110] Alex Wellerstein, “The Improbable William Laurence,” *Restricted Data: The Nuclear Secrecy Blog* (blog), October 30, 2015, https://blog.nuclearsecrecy.com/2015/10/30/the-improbable-william-laurence/.

[111] Wellerstein.

[112] Wellerstein, *Restricted Data*, 235.

[113] William L. Laurence, “IT’S A TRITON BOMB, MIGHTIEST POSSIBLE,” *The New York Times*, February 1, 1950; William L. Laurence, “The Truth About the Hydrogen Bomb,” *Saturday Evening Post* 222, no. 52 (June 24, 1950): 18.

[114] Laurence, “The Truth About the Hydrogen Bomb,” 90.

[115] Later referred to as the Savannah River Site (SRS).

[116] Thomas B. Cochran et al., *Nuclear Weapons Databook: U.S. Nuclear Warhead Production*, vol. II (Cambridge, Mass: Ballinger, 1987), 180.

[117] According to the U.S. Bureau of Labor Statistics: https://www.bls.gov/data/inflation_calculator.htm

seems he even overestimated his own popular appeal. Despite Laurence's insistence that the name "Hell Bomb" was catching on, it appears "hydrogen bomb" was and continues to remain the preferred nomenclature.

When the Soviets tested their first H-bomb in 1955, three years following the U.S. Mike shot, the provocative tale told by Laurence, namely that Fuchs provided crucial information to accelerate the development timeline, was widely accepted as true. It was not until Hans Bethe's 1952 "Memorandum on the History of the Thermonuclear Program" was declassified and released to a FOIA request in 1990 that this popular narrative was questioned.[118] Daniel Hirsch and William G. Mathews at University of California, Santa Cruz published an exposé based on the memo that revealed that the "classical Super" design that Fuchs provided the Soviets had several fundamental flaws that weren't discovered until the hydrogen bomb work began in earnest following Truman's announcement.[119] Because it soon became obvious that tritium would be required to ignite the fusion process, Stanislaw Ulam and his assistant Cornelius Everett began making calculations that led to the conclusion that "'spectacular' quantities of tritium would be needed, far greater than that assumed by Teller's group and enough to make 'the economic soundness of the H-bomb highly questionable.'"[120]

The estimated quantities of tritium previously calculated for the Super are unfortunately deleted in the released version of Bethe's 1952 memo. Additionally, key unclassified edited documents "Prima Facie Proof of the Feasibility of the Super," "Report of Conference on the Super," and "Ignition of Deuterium-Tritium Mixtures: Numerical Calculations Using the ENIAC"[121] have similarly excised information related to tritium quantities.[122] The only clue to these amounts that I have found are in Anne Fitzpatrick's 1999 dissertation "Igniting the Light Elements," which cites "Secret-RD" versions of the above documents. Fitzpatrick references a conclusion from the April 1946 Super conference "indicating—based on a minority of the individual ENIAC calculations—that the Super would ignite with *less than 400 grams of tritium present in its booster and primer parts*."[123] By 1947, subsequent calculations from ENIAC would indicate "more than 400 grams of tritium would be needed to ignite the Super."[124] Furthermore, the "spectacular" quantities of tritium required according to Ulam and Everett's February 1950 calculations

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[118] Hans A. Bethe, "Memorandum on the History of the Thermonuclear Program," May 28, 1952, https://www.proquest.com/dnsa/docview/1679125783/abstract/5AF229C51CB348BAPQ/5.

[119] Daniel Hirsch and William G. Mathews, "The H-Bomb: Who Really Gave Away the Secret?," *Bulletin of the Atomic Scientists* 46, no. 1 (January 1990): 23.

[120] Hirsch and Mathews, 25.

[121] The Electrical Numerical Integrator and Computer (ENIAC) was one of the first programable computers.

[122] S. Frankel, "Prima Facie Proof of the Feasibility of the Super (Unclassified Edited Version)" (Los Alamos National Lab. (LANL), April 15, 1946), https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-00551_DEL; S. P. Frankel et al., "Report of Conference on the Super, April 18-20, 1946 (Unclassified Edited Version)," C, February 16, 1950, https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-00575_DEL; S. Frankel, N. Metropolis, and A. Turkevich, "Ignition of Deuterium-Tritium Mixtures: Numerical Calculations Using the ENIAC (Unclassified Edited Version)" (Los Alamos National Lab. (LANL), February 11, 1947), https://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-00525_DEL.

[123] Fitzpatrick, "Igniting the Light Elements," 122. Emphasis mine. Later in Fitzpatrick's dissertation (pg 193), she writes in a footnote: "The obvious vagueness in my description of the specific amounts of [tritium] examined the ENIAC problems is due to classification of the amounts in grams" [sic]. It is unclear if she is referring to different ENIAC calculations than she quantifies elsewhere, or if the footnote was mistakenly retained from an earlier draft that did not include these values.

[124] Fitzpatrick, 128.

"showed that Teller's previous estimates *ranging between 300 and 600 grams of tritium* were not nearly enough to make the Super ignite."[125] While I am unable to corroborate these values because they appear to be taken from documents classified as Restricted Data in their unexcised forms, the quantities roughly correspond to publicly available information on scaling of "roughly twice as large" between 1946 and 1947 calculations.[126]

Shortly after Norris Bradbury succeeded Oppenheimer as LANL director in 1945, Teller had suggested if H-bomb work received similar resources to the A-bomb efforts then they could be ready to use ~212 g of tritium[127] for "preliminary experiments" in 1-2 years, and following another 1-2 years of accelerated tritium production at a rate of ~1.27 kg/year, they could build a successful Super model.[128] Bradbury did not consider this a serious recommendation and "even Teller acknowledged this as a 'fantastic' venture given present supplies."[129] Three years later, in the 10th GAC meeting, Enrico Fermi suggested a reasonable tritium production rate for hydrogen bomb research was closer to 10 g/year. The following year, on October 5, 1949, Lewis Strauss reiterated Teller's crash course suggestion in a memo read by other AEC Commissioners, Sen. McMahon, and even President Truman:

> It seems to me that the time has now come for a quantum jump in our planning (to borrow a metaphor from our scientist friends)—that is to say, that we should now make an intensive effort to get ahead with the <u>super</u>. By intensive effort, I am thinking of a commitment in talent and money comparable, if necessary, to that which produced the first atomic weapon. <u>That</u> is the way to stay ahead.[130]

Strauss and others saw the "super" as a crucial element to remaining "ahead" in the nuclear arms race with the Soviets. Note that in Strauss's admittedly *non*-scientist perspective that "talent and money" were sufficient ingredients for the scheme, saying nothing of the uncertainties and material constraints inherent in the tritium required to make it work.

Actual tritium production quantities at Hanford were aggregated from production data by Anne M. Nolan in personal notes in 1982. These notes and associated reports were declassified and approved for public release between 1998-2002.[131]

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[125] Fitzpatrick, 146–47. Emphasis mine.

[126] J.C. Mark, "Short Account of Los Alamos Theoretical Work on Thermonuclear Weapons, 1946-1950," July 1, 1974, 8, https://doi.org/10.2172/4283999.

[127] This calculation is based on Teller's reference to needing 1 liquid liter of tritium. Assuming nominal temperature of 0°F, I multiplied the mass of ordinary liquid hydrogen by three times, which should be sufficiently precise to provide a sense of scale. Los Alamos also had cryogenic equipment which could have lowered the temperature and nominally increased the tritium mass per unit volume.

[128] Fitzpatrick, "Igniting the Light Elements," 190. Here I am referencing a "Letter from Bradbury to Groves" from November 23, 1945, that Fitzpatrick quotes from LANL Archives.

[129] Fitzpatrick, 190.

[130] "Policy and Progress in the H-Bomb Program: A Chronology of Leading Events," 26. Emphasis in original.

[131] Anne M. Nolan, "RPR Program Personal Notes," September 23, 1980, D8211885, https://reading-room.labworks.org/Files/GetDocument.aspx?id=D8211885; Anne M. Nolan, "Hanford Production Levels from 1945 to Present," February 25, 1982, D9022124, https://reading-room.labworks.org/Files/GetDocument.aspx?id=D9022124; A.M. Nolan, "Historical Annual Production Quantities," January 7, 1985, D197048411, https://reading-room.labworks.org/Files/GetDocument.aspx?id=D197048411.

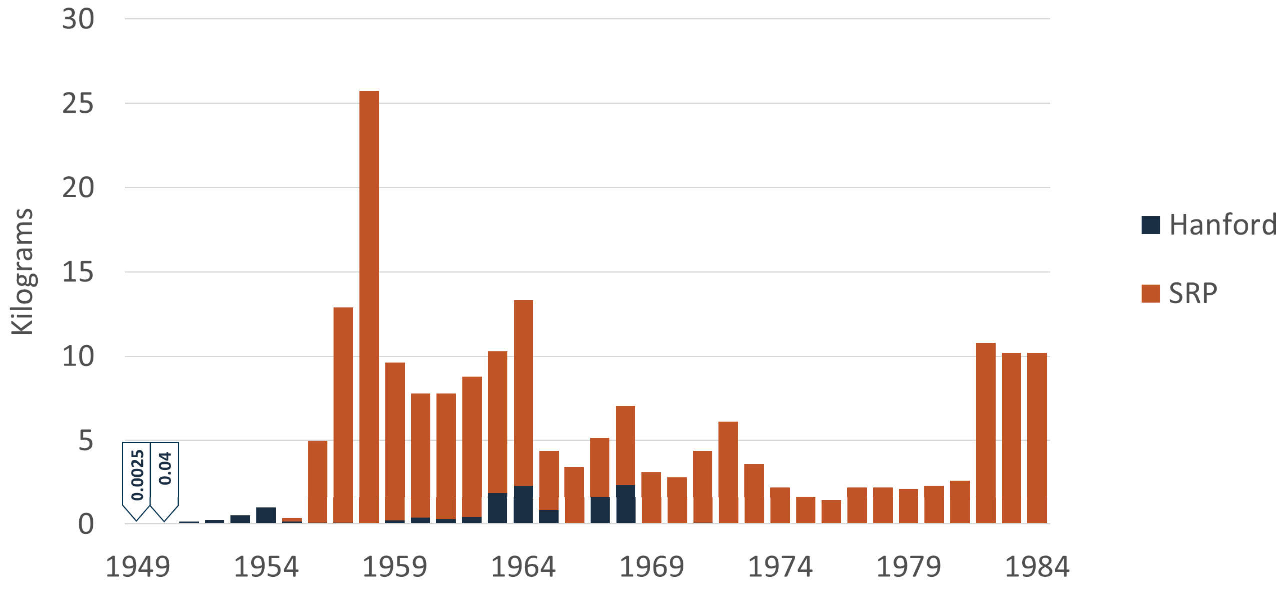

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Figure 3: Historical Tritium Production at Hanford and SRP, 1949-84

Covering monthly production/extraction amounts for both plutonium and tritium and often indicating quantities attributed to specific reactors, these documents are particularly rich and granular with few redactions. Following Fermi's 10 g/year suggestion, Hanford only extracted 2.5 g in 1949[133] but managed 40 g in 1950. The tritium available for Operation Greenhouse George and Item and the Operation Ivy Mike test, quantities extracted from 1949-1952, would total ~463 g.[134] Tritium production at Hanford continued until 1971, when it's total integrated production of 12.7 kg represented ~10% of all tritium produced by the U.S.—an estimated 121 kg had been produced at the SRP by that time.

The rapid increase in tritium production was the result of a combination of at least three factors: material/process innovations, reactor capacity expansions, and Pres. Truman's elite discretion. Around 1949-50, Tritium production rates benefitted from a material shift from LiF to lithium aluminum alloy (LiAl alloy), also known as SR-65 or "P-10 alloy."[135] In a project proposal for a new LiAl alloy production line from staff at Hanford, advantages over LiF were noted "(1) the yield of tritium is 2.5 times higher,

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[132] Nolan, "RPR Program Personal Notes"; Cochran et al., *Nuclear Weapons Databook, Vol. II*, vol. II, app. C. Hanford quantities are based on empirical data compiled by Anne M. Nolan, and SRP quantities were estimated by Thomas Cochran, et al. based on publicly available data.

[133] S. P. Gydesen, "Tritium Extraction Throughput at Hanford, 1949-1954" (General Electric Co., Richland, WA (United States). Hanford Atomic Products Operation, February 24, 1994), 3, https://doi.org/10.2172/10170899. This source lists 16.56077 liters (4.46 g) for 1949 Hanford tritium extraction totals. Amounts and totals from 1950-52 almost exactly correspond Anne M. Nolan's tabulations. However, there are several quantities for 1953-54 that do not match. Some discrepancies may be due to tritium extraction moving to the SRP in the 1954-55 time frame, but unless the source documents are declassified, I cannot determine which is more accurate.

[134] Uncorrected for decay.

[135] J.S. McMahon, "Project Proposal-Facilities for Manufacture of Lithium - Aluminum Alloy Slugs - Project C-334," April 27, 1949, 2, https://www.osti.gov/opennet/detail?osti-id=16427403. P-10 was the codename for the tritium production program. This name was abandoned in the fall of 1950 because its significance was considered compromised.

and (2) the gas purity exceeds 80%, versus 50% maximum with LiF."[136] Given similar irradiation constraints considered by Fermi in his 10 g/year estimate, this material replacement alone would allow for 25 g/year production levels and require less work to purify the extracted tritium. Two reactors were brought on-line, H-reactor was added in October 1949 and DR-reactor was added in November 1950. Adding to B, D, and F-reactors, this brought the Hanford production reactor total to five. With the clear Presidential directive to create a first-of-a-kind hydrogen weapon, the U.S. nuclear infrastructure began retooling and adapting to the emerging demand for tritium.

These new technological capabilities were immediately put to use even before their efficacy and safety could be properly evaluated. A "History of the P-10 Project" by George G. Reed, Jr. published as a classified report on January 4, 1952, describes this transition in the following passage:

> The advance of the tritium program from the first laboratory experiments at Argonne National Laboratories to the operation of a plant at Hanford required the solution of several major and minor problems, *most of which were unduly complicated by the requirement that design and construction proceed concurrently with research and development work. For example, alloys [sic] slugs with six months exposure were not available for experimental work until after the plant had been designed and built.*
>
> The control or elimination of radiation hazards was the most important problem in the design and construction of extraction facilities. Two separate radiation problems were present, the handling of radioactive slugs and the handling of highly radioactive tritium. Although the solution of the slug handling problem required a large amount of careful and detailed design work the only really complicating effect was the limitations placed on the design of the extraction furnace. The radiation problems associated with the handling of some thousands of curies of tritium per day were more difficult to solve.
>
> Although at the end of 1949 a process had been developed and a plant was being operated for the production of substantial quantities of high purity tritium, a considerable amount of development work remained to be done before the full potentialities of the process and plant could be developed and the operation placed on a routine basis.[137]

Parallel to the novel weapon requirements emerged a new paradigm of radiological risks "associated with the handling of some thousands of curies of tritium per day." Concerns with acute exposure from accidental intake of the relatively small quantities of tritium previously used in research and development had to be expanded to consider daily risks to workers that could lead to potential chronic exposures. Never in human history had such "substantial quantities of high purity tritium" ever existed at a single site. Under the secretive conditions of nuclear weapon development, tritium's *byproduct* nuclearity as a pollutant was being constructed to characterize these new risks. This byproduct nuclearity is considered more fully in Chapter 4. During the race to the H-bomb, the radiological risks posed by tritium were relegated to a second order concern.

Teller's original vision for the Super program was not only based on a fundamentally flawed design but also required significant quantities of tritium that would not be possible until 1956 after tritium

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[136] McMahon, 5.

[137] Reed, "History of the P-10 Project," 5–6. Emphasis mine. This report was declassified on February 1, 1994.

production began at the SRP.[138] Following Ulam and Everett's pessimistic calculations in early 1950, work on the classical Super was abandoned and efforts were refocused on boosters and other promising hydrogen weapon designs requiring far less tritium. Pres. Truman's "superbomb or hydrogen bomb" rhetoric implied that the President and leaders like Commissioner Strauss cared less about the nomenclature or technological particulars of the device and more about achieving the hydrogen weapon milestone before the Soviets.

Based on Bethe's 1952 memo and interviews with nuclear weapon scientists, Hirsch and Mathews further contend that a plausible source other than Fuchs's espionage for the secrecy failure of the successful Teller-Ulam H-bomb innovation was Soviet analysis of fallout from U.S. tests. Rather than relying on high ignition temperatures to initiate D-T fusion, the Teller-Ulam design leveraged the significant radiation released by a fission explosion to compress the hydrogen fuel to begin and propagate the fusion reaction. The peculiarities of the successful design configuration were considered by Bethe and others to be more the result of good fortune than rigorous scientific analysis, and they believed it was highly unlikely that the Russians could independently create a similar design.[139] On the contrary, had the Soviets *followed the science* based on initial assumptions of the super—which were well known to Fuchs—they would have more than likely concluded that thermonuclear weapons were not possible. Once any such *impossible* technologies are successfully demonstrated—as was the case of the atomic bombs dropped on Hiroshima and Nagasaki and the Mike H-bomb test—the scientific question shifts from *could it be done* to *how was it done*. Declassified Soviet nuclear secrets have since indicated that their fallout sampling program was not established until after the Mike test. Historian Gennady Gorelik and other experts have more recently suggested alternate explanations for the Soviet's "suspiciously fast" progress to their first thermonuclear bomb test.[140]

At least part of the explanation appears to be rooted in an important material innovation that overturned the assumptions of U.S. experts. In 1996, German Goncharov's 3-part series in *Physics Today* on the H-bomb race concluded that the Soviets were first to use LiD (enriched in Li-6) in tests in 1953 and 1955. The infamous Castle Bravo test in 1954 was the first U.S. device to use LiD (and tritium), the largest U.S. test at 15 MT, and a significant radiological disaster. The 1955 Soviet test, referred to as RDS-37, was the first thermonuclear airdrop test (meaning a test of a potentially *deliverable* weapon) yielding 1.6 megatons *without using tritium in the design*.[141] Senator McMahon's confidence that the U.S. led the Soviets in 1950 was based on the false assumption reinforced by the belief of Teller and

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[138] Cochran et al., *Nuclear Weapons Databook, Vol. II*, vol. II, app. C. Cochran, et al, estimate SRP tritium production at ~4.9 kg in 1956.

[139] Bethe, "Memorandum on the History of the Thermonuclear Program," 12.; In the words of J. Robert Oppenheimer: "My feeling about the delay in the in the [sic] hydrogen bomb, and I imagine you want to question me about it, is that if we had had good ideas in 1945, and had we wanted to, this object might have been in existence in 1947 or 1948, perhaps 1948. If we had had all the good ideas in 1949, I suppose some little time might have been shaved off the development as it actually occurred. *If we had not had good ideas in 1951, I do not think we would have it today*." "In the Matter Of: Classified Testimony of: J. Robert Oppenheimer" (Atomic Energy Commission (AEC), August 13, 1954), 263, https://www.osti.gov/opennet/detail?osti-id=1159674. Emphasis mine.

[140] Gennady Gorelik, "The Riddle of the Third Idea: How Did the Soviets Build a Thermonuclear Bomb So Suspiciously Fast?," Scientific American, August 21, 2011, https://www.scientificamerican.com/blog/guest-blog/the-riddle-of-the-third-idea-how-did-the-soviets-build-a-thermonuclear-bomb-so-suspiciously-fast/.

[141] German A. Goncharov, "Thermonuclear Milestones: (3) The Race Accelerates," *Physics Today* 49, no. 11 (November 1, 1996): 60, https://doi.org/10.1063/1.881532. The first U.S. thermonuclear airdrop test was in 1956.

other proponents of the “superbomb or hydrogen bomb” that significant tritium resources would be required for success. While this necessity appears to have been correct, the Soviet shortcut of producing all the tritium *in situ* as the bomb explodes was not considered. This conceptual failure is further evidenced by the declassification committee’s fixation with the D-T cross section and large-scale production methods of tritium while ignoring lithium, the material most useful for producing tritium. For the U.S. at least, tritium existed for the better part of a decade under a regime of super nuclearity where it was both the solution to the hydrogen bomb problem of initiating D-D fusion and a material limitation that would secure American leadership in the nuclear arms race. As functional and deliverable hydrogen weapons began being developed and stockpiled, tritium’s nuclearity transitioned to a supporting role in design optimization and production shifted from retrofitted lithium slugs producing tens of grams / year to industrial production of tens of kilograms / year in purpose-built reactors at SRP.

The phase of super nuclearity dominance was characterized by pervasive secrecy and high technology. For nearly 6 years, Manhattan district scientists would only vaguely mention tritium until the “1947-48 tritium episode.” After a series of intensive interagency discussions concluded that excessive tritium secrecy was inadvertently signaling its military importance, small quantities of tritium began being released to civilian laboratories. The first tasks assigned to the ENIAC were superbomb calculations estimating tritium requirements. The super proved to be a seductive fiction constructed from Teller’s shared fixation, unprecedented feats of computation, and a post-war fervor for staving off annihilation from the Soviets. The only material constraint believed to be limiting progress toward a weapon of near limitless destructive power was tritium. However, such weapons were never built, never tested, and presumably would not have worked if they had been. Tritium ultimately did serve an essential role in the advent of hydrogen weapons, but it was relegated to a supporting role alongside uranium and plutonium.

Nuclearity in Transition

The year following the U.S. H-bomb success with the Operation Ivy Mike shot, Pres. Eisenhower kicked off another geopolitical contest later dubbed by Pres. Kennedy as the “Peace Race.” Pres. Eisenhower delivered his landmark “Atoms for Peace” speech before the United Nations in Dec. 1953. In this speech the newly minted hydrogen weapons were touted as possessing explosive power “in the ranges of millions of tons of TNT equivalent,” which, along with growing nuclear arsenals around the world, threatened “the annihilation of the irreplaceable heritage of mankind handed down to us from generation to generation, and the condemnation of mankind to begin all over again the age-old struggle upward from savagery towards decency, and right, and justice.”[142] Alternatively, he argues, the nations of the world should join forces to promote and develop peaceful atomic energy “to hasten the day when fear of the atom will begin to disappear from the minds [of] the people and the governments of the East and West.”[143] The establishment of the International Atomic Energy Agency (IAEA) within the United Nations (UN) emerged from this proposal. Eisenhower envisioned nuclear power plants as ploughshares to be forged from the swords of these unspeakably powerful weapons. The reality would be the growth of both military and civilian nuclear technological infrastructures operating in dynamic and evolving tensions. Within this relationship, tritium undergoes translation into civilian sociotechnical

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[142] Pres. Dwight D. Eisenhower, “Atoms for Peace Speech” (470th Plenary Meeting of the United Nations General Assembly, IAEA, December 8, 1953), https://www.iaea.org/about/history/atoms-for-peace-speech.

[143] Eisenhower.

constructions, expanding beyond the confines of its previous super nuclearity and creating points of friction with the industrialization of nuclear power. Later, in the early 1960s, tritium also becomes a practical and novel commercial product.

From some of the earliest discussions regarding the establishment of the IAEA the tensions between military and peaceful nuclear technologies were evident. In a series of internal position papers and memos circulated among the Atomic Energy Commission (AEC) and the Military Liaison Committee (MLC) regarding "forthcoming international technical discussions on safeguarding peaceful uses of atomic energy" the question was raised if "the complete absence of reactor-produced tritium from the agenda" might conspicuously signal to the Russians that U.S. negotiators are not engaging in good faith.[144] This recasts the secrecy concerns voiced in 1946 by the Manhattan District Research Division with the diplomatic concerns for transparency and mutual respect. The District was concerned that controlling tritium material and science too strictly would inadvertently expose its importance. This recommendation later led to the distribution of small quantities of tritium for scientific research. C.D.W. Thornton, then the AEC Operations Analysis Chief, suggested that any "discussions should be kept general and purposely vague" regarding tritium in two out of six potential subject matters:

> (4) No comments should be made disclosing the relative interest of the U.S. in one or another of various dangerous materials even under the guise of power reactor discussions. Such statements might have intelligence significance as regards U.S.A. thorium vs. uranium ore procurement, our interest in U-233, lithium, tritium, etc. *particularly since present capabilities of AEC plants might be involved in meeting future multiple objectives involving the integration of peacetime applications with military uses*.
>
> (5) No discussion of the mechanics of producing other possible reactor products such as tritium, particularly as regards the metallurgical matrix in which such material might be produced, the separations techniques for such products, or the possible use of such materials in peacetime thermonuclear or other devices of the sort being discussed on an unclassied [sic] basis at the Geneva conference by other nationals.[145]

Note the perfunctory nonchalance of "integrating peacetime applications with military uses." During this era of international engagement prior to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) in 1968, the boundary between military and the emerging peaceful infrastructures was much more unabashedly porous. Thornton also highlights the material significance of lithium and the "metallurgical matrix" used in tritium production. Much of this tritium production information would not be declassified until 2003 and 2004 when the U.S. began production at Watts Bar and even then only because legally required disclosures and publicly accessible information would strain the credulity of the classification system.[146] In other words, because Watts Bar is a commercial power facility its power history, radioactive effluents, and fuel usage are publicly available then any tritium production would be

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[144] W.B. McCool, "Position Paper for Guidance of U.S. Participants in Forthcoming International Technical Discussions on Safeguarding Peaceful Uses of Atomic Energy Under Proposed Charter of International Atomic Energy Agency," August 23, 1955, 12, HS61-2012-0270, https://www.osti.gov/opennet/detail?osti-id=1048890.
[145] McCool, 14–15. Emphasis mine.
[146] Martin Pfeiffer, "HQ-2019-00482-F_Responsive_Documents.Pdf" (Open Science Framework, December 20, 2019), Pfeiffer Nuclear Weapon and National Security Archive, https://osf.io/u3dq4.

readily discernable. To maintain tritium production secrecy in this context would be a wasteful and improper use of classification.

In a 1960 "NSC Meeting on Nuclear Cut-off" with Pres. Eisenhower, where a possible fissionable material cut-off agreement with the Soviets was discussed, there are several telling passages on the contested status of tritium. Throughout this discussion the only weapon materials named are plutonium, U-235, and tritium. Gen. Twining, then Chairman of the Joint Chiefs of Staff, worried that any such cut-off agreement would also place restrictions on tritium production, and Pres. Eisenhower retorted "that we should not always assume we will lose in the bargaining or that we will not have the determination to do what is necessary such as continuing to make tritium."[147] Later in the same meeting John N. Irwin, then Assistant Secretary of Defense for International Security Affairs, had a complex exchange on the unsettled role of tritium in potential agreements, which I reproduce in full:

> Mr. Irwin spoke at some length regarding the tritium proposal and expressed concern that world opinion would be reluctant to distinguish between fissionable material and fusionable material. *Since the H-bomb is considered worse than the A-bomb we would be charged with holding on to the worst material*. He urged careful study of the military implications before agreeing to the cut-off.
>
> The President said that perhaps we might be pushed into agreeing to stop tritium production also. In that case the Soviets would have to stop too and that might really lead to inefficiency of the Soviet thermonuclear weapon stockpile and thus cut down Soviet ability to destroy the United States. Perhaps on the other hand tritium is more important to us than the Soviets. In either case we have to try to make a start. We can't go on the way we are with the nuclear build-up and spread of capabilities.[148]

Mr. Irwin presents the provocative notion that tritium is the "worst material" in the context of "world opinion" of nuclear weapons. "World opinion" when used here should be understood as how other nations view the geopolitical standing of the U.S. in contrast with the U.S.S.R. The emerging ideological clash between U.S. democracy and Soviet communism might disadvantage the U.S if "holding on to" tritium production overshadowed efforts to reduce nuclear risk with a fissionable material cut-off. Pres. Eisenhower responds that even if including tritium in a cut-off agreement has undesirable asymmetric effects, the "nuclear build-up and spread of capabilities" status quo might be more undesirable yet. In Eisenhower's assessment, tritium production was seen as a necessity only to be given up if it meant a halt to an accelerating nuclear arms race.

The ramp up of tritium production rates in the late 1950s, which were possibly as high as ~12 to ~25 kg / year in 1957 and 1958 respectively,[149] allowed for creating a commercial market with material in excess of military requirements. In 1959, the AEC sold 100 g of tritium through Oak Ridge National Laboratory (ORNL); between 1948-58 only a little more than 5 grams total had been sold.[150] When levels of extracted tritium exceeded military and scientific needs, then the only remaining options were to let it

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[147] "NSC Meeting on Nuclear Cut-Off" (Department of State, February 18, 1960), 3, NN00304, https://www.proquest.com/dnsa/docview/2246166888/abstract/7930F7B874C948E0PQ/15.
[148] "NSC Meeting on Nuclear Cut-Off," 4. Underlining in original and italics are my own.
[149] Cochran et al., *Nuclear Weapons Databook, Vol. II*, vol. II, app. C.
[150] Kalinowski, *International Control of Tritium for Nuclear Nonproliferation and Disarmament*, 5.

decay or sell it. The global consumption of commercial tritium grew to ~400 g / year in the mid-90s. In 2024, the only source of commercially available tritium is separating tritium from heavy water reactor coolant. Only two industrial-scale facilities for tritium separation currently exist: one is the Wolsong Tritium Removal Facility (WTRF) in Korea and the other is the Darlington Tritium Removal Facility (DTRF) in Canada.

The U.S. perspective on a possible fissionable material cutoff agreement was further developed and refined in an October 18, 1965, position paper from the U.S. Arms Control and Disarmament Agency (ACDA). The ACDA was formed by an Act of the U.S. Congress in 1961 to create an independent agency that "must have the capacity to provide the essential scientific, economic, political, military, psychological, and technological information upon which realistic arms control and disarmament policy must be based," before being merged with the U.S. State Department in 1999.[151] In this formulation of policy, the U.S., U.K., and U.S.S.R. would suspend all production of fissionable materials except for "non-weapons uses," and tritium production would continue for weapons use as needed to account for decay and for other non-weapons use.[152] Additionally, the inspections required to verify plutonium cutoff adherence would also subject any tritium production reactors to on-going scrutiny since they would remain capable of plutonium production. This document also proposes a verification mechanism for the non-production of plutonium which could potentially be useful for tritium accountancy: "studies conducted by AEC contractors, according to preliminary results, determined that the only practical source of helium-3 in significant quantities is the decay of tritium."[153] The nation offering proof that a given reactor is *only* producing tritium could provide a He-3 gas sample of sufficient mass that would indicate a proportional mass of tritium produced (and decayed) in a given timeframe. Any subterfuge by providing samples of He-3 from pre-existing stockpiles would be unsustainable without on-going tritium production. Tritium production can simultaneously maintain operability of remaining nuclear stockpiles and support disarmament efforts. If tritium production rates are sufficiently high for a given reactor's power capacity, then there would not be spare neutrons available for plutonium production. Even in such a scenario of increased transparency and cooperation among nuclear weapon possessing states, the paper concludes that a key step to "[preventing] the disclosure of sensitive weapon design data" would be the "removal of gaseous tritium before submitting weapons for the destruction process."[154] While uranium and plutonium remain the essential materials required for fission weapons, details related to tritium (mass, D-T ratios, production, etc.) continued to be some of the most closely guarded secrets of weapon designs.

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[151] "Arms Control and Disarmament Act," Pub. L. No. H.R. 9118 (1961), https://www.govinfo.gov/content/pkg/STATUTE-75/pdf/STATUTE-75-Pg631.pdf; "Repeal of the Arms Control and Disarmament Agency's Regulations," Federal Register, April 1, 1999, https://www.federalregister.gov/documents/1999/04/01/99-8129/repeal-of-the-arms-control-and-disarmament-agencys-regulations.

[152] "A Cutoff of Production of Fissionable Materials for Weapons Use with Demonstrated Destruction of Nuclear Weapons and Transfer of Fissionable Material Therefrom to Non-Weapons Uses" (U.S. Arms Control and Disarmament Agency, October 18, 1965), 4, NN01344, https://www.proquest.com/dnsa/docview/2246168766/abstract/7930F7B874C948E0PQ/9.

[153] "A Cutoff of Production of Fissionable Materials for Weapons Use with Demonstrated Destruction of Nuclear Weapons and Transfer of Fissionable Material Therefrom to Non-Weapons Uses," 8.

[154] "A Cutoff of Production of Fissionable Materials for Weapons Use with Demonstrated Destruction of Nuclear Weapons and Transfer of Fissionable Material Therefrom to Non-Weapons Uses," 12.

Also, during this era of nuclearity transition, the General Electric Company initiated the Coproduct Program at the Hanford Site in 1963. The “coproducts” in question were tritium and plutonium. Initially, irradiations under this program began in one of the K Reactors at SRP but transitioned to the powerful and versatile N Reactor at Hanford from 1965-1967. Since the SRP had successfully demonstrated sufficient tritium production capacity for weapons use, the program at Hanford produced tritium “intended for use in energy production” and “intended to provide comprehensive engineering data on the optimal characteristics of lithium-based irradiation targets to be used for tritium production in parallel with both plutonium and electrical energy production.”[155] Anne M. Nolan’s personal notes aggregating Hanford production showed an average of >1 kg for this time period with the highest peak production quantities ever achieved of 2,318 g in 1964 and 2,336 g in 1968. Interestingly, in this same document Nolan separates plutonium production quantities into “Defense” and “Non-Defense” categories, but annual tritium production quantities are only represented by a single, otherwise uncategorized number.[156] The fusion energy production research of the Coproduct Program focused primarily on identifying the best lithium-based targets for tritium breeding rather than using the produced tritium for fuel directly.

According to an appendix from a June 2006 PNNL report on the sources and legacies of radioactive wastes at the Hanford site:

> The fate of any waste generated by the Coproduct Program research activities, *including the extracted tritium itself*, remains unknown. Record keeping during that time period was at best limited, and many of the disposal records from that time period have been destroyed during several past space-saving records purges. In addition, the fact that work was performed under conditions of strict classification further complicates the situation. It is, thus, possible that some record of material accountability has yet to be declassified; however, that is unlikely since researchers investigating the plutonium inventory of the burial ground have already concluded that even the safeguards related special nuclear materials records from that period have been destroyed; so, *it is probable that tritium target disposal records suffered a similar fate.*[157]

The substantial amounts of tritium produced at Hanford during this program of experimentation do not appear traceable through declassified or presumably even *classified* sources. One exception to this traceability appears to be the final full power (4,800 MWth) test of the N Reactor during the Coproduct Program which discharged 759 g of tritium in April 1967[158], and “the entire load was shipped to Savannah River for extraction.”[159]

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[155] Charles T. Kincaid et al., “Inventory Data Package for Hanford Assessments,” June 1, 2006, app. D.6, https://doi.org/10.2172/896352.

[156] Nolan, “Historical Annual Production Quantities,” 2.

[157] Kincaid et al., “Inventory Data Package for Hanford Assessments,” app. D.6-D.7. Emphasis mine.

[158] Nolan, “RPR Program Personal Notes,” 13.

[159] Kincaid et al., “Inventory Data Package for Hanford Assessments,” app. D.6. The production quantity for this test was inferred by comparing this source with Nolan’s “RPR Program Personal Notes.” In app. D, authored by John Evans, he references that the full power test “was calculated to be on the order of 60 million curies of tritium per year,” which would be approximately 6 kg. The monthly production data from Nolan shows April as the all-time highest tritium production month at Hanford, which should exactly correlate with the full power test. This would

Special Nuclearity

A key contention confronted by Ken Bergeron in *Tritium on Ice* is that tritium is not legally considered special nuclear material (SNM). A July 1998 interagency review authored by Joan Rohlfing concluded that

> tritium is not a fissionable material capable of sustaining a nuclear reaction. Thus, it is not classified as a special nuclear material and is therefore not subject to the prohibition in the Atomic Energy Act of 1954, as amended, on the use of such materials for nuclear explosive purposes if produced in a commercial light water reactor.[160]

This is an important distinction since the 1983 Hart-Simpson Amendment to the Atomic Energy Act "expressly prohibited the use of special nuclear material (SNM) derived from commercial reactors for nuclear arms."[161] Instead, Rohlfing argues in the report,

> under the law, tritium falls within the definition of a *byproduct material*. Section 11(e) of the Atomic Energy Act defines byproduct material as (1) any radioactive material (except SNM) yielded in or made radioactive by exposure to the radiation incident to the process of producing or utilizing SNM and (2) the tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content.[162]

Defined as byproduct material tritium becomes legally innocuous and the decision on how to produce it is conveniently reduced to economics—what's the most cost-effective way? The fact that this material is designated for use in the nuclear stockpile is irrelevant. However, the SNM category which provides a legal boundary for byproduct material is not based solely on fixed material properties and is open to amendment. The transition to byproduct nuclearity is explored more fully in Chapters 4 and 5.

In the Atomic Energy Act of 1954, SNM is defined as "plutonium, uranium enriched in the isotope 233 or in the isotope 235, and any other material which the Commission, pursuant to the provisions of section 51, determines to be special nuclear material, but does not include source material."[163] The provisions in section 51 read:

> The Commission may determine from time to time that other material is special nuclear material in addition to that specified in the definition as special nuclear material. Before making any such determination, the Commission must find that such material is capable of releasing substantial quantities of atomic energy and must find that the determination that such material is special nuclear material is in the interest of the common defense

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allow for ~4 months of downtime between production runs throughout the year to approximately equal 6,000 kg for 8 months of full power production.

[160] Joan Rohlfing, "Interagency Review of the Nonproliferation Implications of Alternative Tritium Production Technologies Under Consideration by the Department of Energy," A Report to the Congress, July 1998, 2, https://fissilematerials.org/library/doe98.pdf.

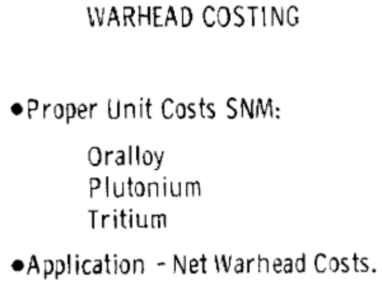
[161] Rohlfing, 6.

[162] Rohlfing, 7.

[163] "Atomic Energy Act of 1954 [As Amended Through P.L. 117–286, Enacted December 27, 2022]" (United States Congress, December 27, 2022), 11, https://www.govinfo.gov/content/pkg/COMPS-1630/pdf/COMPS-1630.pdf.

> and security, and the President must have expressly assented in writing to the determination.[164]

Note the incongruency between the AEC definition of SNM cited by Rohlfing and her paraphrasing. There is no technical prerequisite for SNM to be “fissionable” or “capable of sustaining a nuclear reaction.” SNM is not a scientifically bound category but a political one. The Commission must ascertain that a “material is capable of releasing substantial quantities of atomic energy,” and that the SNM designation serves “common defense and security.” Even then, to designate a new material as SNM, the elite discretion of the President is required. In my assessment, there are no policy-based reasons or material properties of tritium that exclude it from the SNM category. However, since at least the 1960s when the U.S. sold unprecedented quantities of tritium, the broad availability and commercial use of tritium and tritium-production technologies has made SNM categorization a nonstarter. Tritium has never been defined by the law as SNM. However, that has not stopped it being called and treated like SNM in many instances and in different contexts. In high-level meetings, tritium has been discussed alongside fissionable materials as essential and complementary. For defense planning and stockpile stewardship tritium has been explicitly referred to as SNM, for international dialogues on warhead dismantlement it has been considered separately from SNM, and for material control and accountancy (MC&A) regimes it has held a more ambivalent position over time. In the following, I consider each of these frameworks and how the use and characterization of SNM has evolved.



WARHEAD COSTING

- Proper Unit Costs SNM:
    - Oralloy
    - Plutonium
    - Tritium
- Application - Net Warhead Costs.

Figure 4: Tritium categorized as Special Nuclear Material.

Weapons designers and planners have long considered tritium an SNM both in word and practice. In the “Proceedings of the Tactical Nuclear Weapons Symposium” held at Los Alamos between September 3-5, 1969, representatives of a multi-contractor group based in Oak Ridge, TN (AECOP) repeatedly refer to tritium as SNM:

Two retired military Colonels, Sid C. Bruce and H. E. Shaw, presented “Warhead Costing” and “Availability of Special Nuclear Materials” respectively. In each, tritium production was discussed alongside and in relation to “oralloy,”[165] the common name of HEU, and plutonium. While actual material quantities are heavily redacted throughout, Col. Shaw provides important context on the tritium/plutonium relationship:

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[164] “Atomic Energy Act of 1954 [As Amended Through P.L. 117–286, Enacted December 27, 2022],” 18–19.

[165] The term “oralloy” is derived from Oak Ridge Alloy, which refers to the location of the Y-12 site where most HEU was sourced.

> In planning for production of reactor products, one must balance the production of tritium and plutonium as they compete for neutrons in the reactors. Because tritium decays significantly and plutonium does not, *production planning is normally optimized on the tritium requirements to avoid overproduction of this material*. Then, the resulting plutonium production is compared with the plutonium demands.[166]

During this time in the late 1960s, both materials were in demand. Notably, tritium and not plutonium dictated the production schedule, and both depended on neutrons from low enriched uranium (LEU). Additionally, Col. Shaw referenced potential economic impacts of the projected LEU demand for civilian power fuel from 1970-80.[167] Whether or not tritium was technically SNM, its production was clearly situated in complex material relationships with both plutonium and uranium. Furthermore, since the commercialization of fusion power technology may still today be several decades off, tritium's dual use ambivalence leaned much more heavily toward its dominating special nuclearity and military exceptionalism.

The economic and strategic importance of tritium is further reinforced by Restricted Data declassified in the 1990s regarding barters under the 1958 *United States—United Kingdom Mutual Defense Agreement*. Tritium, plutonium, and HEU had exchange equivalences that appeared to support desired national material balances in the promotion of mutual defense between the two allied nations. When the U.S. had apparently *overproduced* tritium, then they were able to trade for plutonium with the U.K. to correct for this unnecessary production investment. In a series of three trades from 1960-79, the U.S. gave the U.K. 6.7 kg of tritium and 7,500 kg of HEU in exchange for 5,366 kg of plutonium.[168] One trade, "Barter A," was 6 kg tritium for 480 kg of plutonium—this is exactly the production equivalence, 1 kg of tritium for 80 kg of plutonium, that Teller had described in 1950. However, the only other trade involving tritium, "Barter C," was only 0.7 kg of tritium for 813 kg of plutonium, which was less than 7% of the equivalent amount of tritium. Presumably the "Barter B" exchange of U.S. HEU for UK plutonium may have accounted for the value difference, but it is not explicitly noted in the declassification report.

Again, in a final report of the DOD/DOE Long Range Resource Planning Group, "Long Range Nuclear Weapon Planning Analysis" from 1980, tritium is repeatedly referred to as SNM. The authors of the report go so far as to acknowledge that their use of the term does not correspond with the legal definition:

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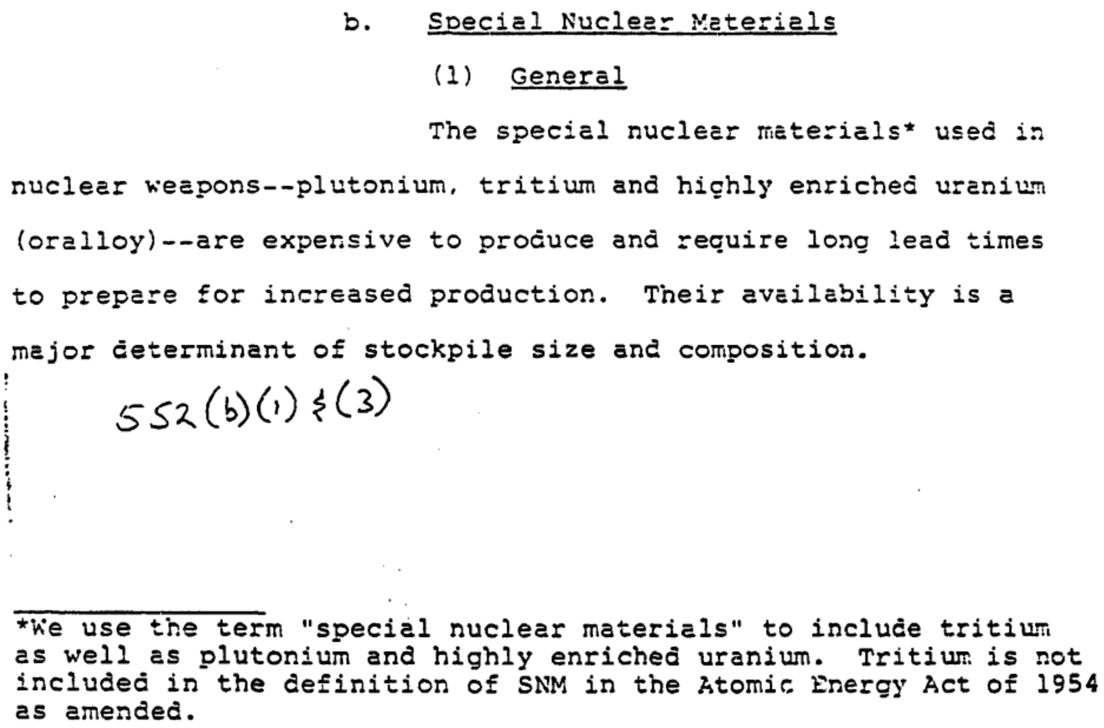
[166] "Proceedings of the Tactical Nuclear Weapons Symposium" (Los Alamos, NM: Los Alamos National Lab. (LANL), September 3, 1969), 358–59, HS61-2012-0001, https://www.osti.gov/opennet/detail?osti-id=1042614. Emphasis mine.

[167] "Proceedings of the Tactical Nuclear Weapons Symposium," 347.

[168] "Restricted Data Declassification Decisions 1946 to the Present," 24.



b. Special Nuclear Materials

(1) General

The special nuclear materials* used in nuclear weapons--plutonium, tritium and highly enriched uranium (oralloy)--are expensive to produce and require long lead times to prepare for increased production. Their availability is a major determinant of stockpile size and composition.

552(b)(1) & (3)

*We use the term "special nuclear materials" to include tritium as well as plutonium and highly enriched uranium. Tritium is not included in the definition of SNM in the Atomic Energy Act of 1954 as amended.

[169]

Figure 5: Special nuclear material disambiguation in a joint DOD/DOE report.

When they use the term, they are talking about materials whose “availability is a major determinant of stockpile size and composition”—a practical rather than a legal matter.

In 1981, Alfred T. Peaslee, a former LANL Group Leader for TD-7 Foreign Technology (related to thermonuclear weapons), published a politically charged report, “Some Political Issues Related to Future Special Nuclear Materials Production.” The report postulates three possible options for the future “production of two special nuclear materials—plutonium and tritium.”[170] Peaslee is primarily concerned with preserving the continuity of operations requiring these essential, reactor-produced materials, and his general tone suggests that he resents public scrutiny involved in making these necessary decisions:

> The topic of special nuclear materials production has the possibility of attracting attention not only from those who desire general or nuclear disarmament, regardless of the consequences, but also from those who are against nuclear power or modern technology in general.[171]

To Peaslee, the political dimensions of SNM production decisions are inconvenient problems to solve and not legitimate concerns to address. Even so, he does not attempt to disentangle tritium from plutonium and the SNM category despite citing the Atomic Energy Act of 1954 that defines it.

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[169] “Long Range Nuclear Weapon Planning Analysis for the Final Report of the DOD/DOE Long Range Resource Planning Group,” July 15, 1980, 60, https://www.proquest.com/dnsa/docview/1679139290/abstract/2DB04D71C95A4A88PQ/9.

[170] Alfred T. Peaslee, “Some Political Issues Related to Future Special Nuclear Materials Production” (Los Alamos National Lab. (LANL), Los Alamos, NM (United States), August 1, 1981), 2, https://doi.org/10.2172/6052534.

[171] Peaslee, 7.

Furthermore, Peaslee considers Eisenhower's efforts from the 1950s-60s for a "cutoff of fissionable material production" as a cautionary tale of what would happen if production facilities were allowed to "deteriorate into a nonoperating condition."[172] In this context, he poses perhaps the first public consideration of a "tritium freeze" scenario:[173]

> *The public sector of the disarmament community has generally ignored another facet of a special nuclear materials production cutoff*; namely, that all nuclear weapons dependent upon tritium for successful operation will decay to some extent just as tritium decays… Besides nuclear weapons that might depend on tritium-driven thermonuclear reactions for a major part of their explosive yield, tritium is used in the "boosting"… of fission nuclear weapons. At present, tritium for nuclear weapons use is produced only at the Savannah River Plant, although coproduction of tritium and plutonium could be accomplished at the Hanford N Reactor... Thus, a cutoff of special nuclear materials production at the defense production reactors would mean the certain disablement, in approximately a decade, of one-half of the nuclear weapons stockpile that uses tritium. Such a prospect would probably be attractive to the followers of the "disarm regardless" political stripe.[174]

A minor point worth noting is Peaslee's shift in nomenclature from "fissional material" cutoff to "special nuclear material" cutoff. In contrast with tritium's ambiguous status in Eisenhower's NSC meeting, Peaslee assumes any such cutoff would naturally include tritium. He also foreshadows the work of J. Carson Mark,[175] Paul Leventhal, and others who proposed this exact tritium cutoff scenario, referred to as the "Tritium Factor," in September 1988.[176]

I emphasize another subtle but important part in the passage quoted above, where Peaslee states that the "public sector of the disarmament community" has failed to understand tritium's significance to nuclear weapons. This suggests that Kalinowski's diagnosis of tritium's neglect is partially correct and that there is at least some technical deficiency in the disarmament community's understanding of tritium's role in nuclear weapons. It is not until technical and scientific experts turned activists like J. Carson Mark joined these public sector efforts that their formerly siloed technical knowledges became integrated with the broader disarmament community. The technical experts' predilection for tritium's special nuclearity predisposed them to consider its material significance alongside HEU and plutonium, whereas others might be more inclined to deemphasize tritium and focus on materials that were by definition SNM.

The question of tritium's status as an SNM comes up again in a June 1988 DOE memo included as an appendix in the *Tritium Factor* workshop proceedings. The memo was produced at the request of the Deputy Assistant Secretary for Intelligence, U.S. DOE, and sets an unambiguous tone in the first paragraph:

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[172] Peaslee, 7–8.

[173] Note that the Eisenhower "NSC Meeting on Nuclear Cut-Off" (1960) cited above was not declassified until 1999, and Peaslee's report was not restricted when it was issued in August 1981.

[174] Peaslee, "Some Political Issues Related to Future Special Nuclear Materials Production," 8. Emphasis mine.

[175] J. Carson Mark was a Leader of the Theoretical Division at LANL during Peaslee's tenure at the lab.

[176] J. C. Mark et al., "The Tritium Factor as a Forcing Function in Nuclear Arms Reduction Talks," *Science* 241, no. 4870 (September 2, 1988): 1166–68, https://doi.org/10.1126/science.241.4870.1166.

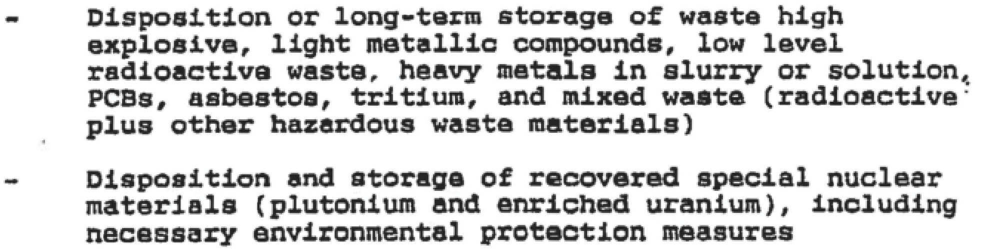
> An old arms control idea has surfaced again. This is a dangerously simplistic idea that threatens US security. It is being called “The Tritium Factor" this time, but it has been floated before under other names, such as a tritium freeze. Influential nongovernment arms control advocates are briefing it right now to administration officials. It is very important to set the facts straight immediately.[177]

The memo continues by considering arguments in support of a “tritium freeze” and providing stark counterpoints. In response to the claim that “tritium is a Special Nuclear Material (SNM) and subject to international regulation” the author states:

> Tritium is not an SNM. The framers of world atomic energy policy *carefully excluded tritium from the beginning*. Tritium has many legitimate uses, and worldwide regulation would be very complex. The International Atomic Energy Agency (IAEA) has no current responsibility for tritium control and would have to develop new technologies and procedures for verification purposes.[178]

In my research, I have not come across evidence that policymakers “carefully excluded tritium from the beginning,” but rather tritium’s exclusion and neglect were primarily the unintended consequences of its Janus-faced nuclearity. The rest of the statement remains largely true today, but several promising monitoring and verification techniques have been developed in recent decades.[179]

When it came time to consider warhead dismantlement, tritium appears to be rendered *ordinary* yet again. In a November 8, 1991, memo (declassified in March 2016) submitted to General John Gordon on the National Security Council (NSC), the Office of Arms Control presents recommendations on “Nuclear Warhead Dismantlement/Destruction” procedures and on-going discussions with the Soviet Union.[180] Compare the following two line items for discussion:



- Disposition or long-term storage of waste high explosive, light metallic compounds, low level radioactive waste, heavy metals in slurry or solution, PCBs, asbestos, tritium, and mixed waste (radioactive plus other hazardous waste materials)
- Disposition and storage of recovered special nuclear materials (plutonium and enriched uranium), including necessary environmental protection measures

[181]

Figure 6: Description of the disposition of tritium waste separate from SNM.

In the first item, the disposition of tritium is bundled with a wide array of “mixed waste.” In the second item, SNM is “recovered” separately from these wastes. The separate consideration of tritium from plutonium and uranium during dismantlement procedures is incongruent with their aligned treatment

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[177] Sharon Tanzer Leventhal, *The Tritium Factor: Tritium’s Impact on Nuclear Arms Reductions* (Nuclear Control Institute & The American Academy of Arts and Science, 1989), 149.

[178] Leventhal, 151.

[179] For an overview of current technologies and procedures for tritium verification see Appendix A.

[180] Anthoy F. Czajkowski, “Department of Energy, Memorandum for John Gordon, ‘Nuclear Warhead Dismantlement/Destruction,’” November 8, 1991, https://nsarchive.gwu.edu/document/22066-document-21.

[181] Czajkowski, 4.

with respect to construction and maintenance of nuclear weapons. However, it is important to note that in the context of collaborations on dismantlement with Soviet/Russian counterparts, U.S. experts may be more inclined to strictly follow legally recognized material designations where appropriate.

Tritium's treatment under U.S. MC&A regimes has shifted over time. These changes were aptly summarized in an "Assessment of Challenges for Tritium Accountancy and Control in Fusion Energy Systems" from May 2023.[182] From the 1980s up until 2011, "tritium was treated the same as a Category III SNM":

> Tritium is a nuclear material of strategic importance; therefore, graded safeguards programs for tritium shall be established and followed equivalent to the following categorizations:
>
> Category III—Weapons or test components containing reportable quantities of tritium. Deuterium-tritium mixtures, or metal tritides that can be easily decomposed to tritium gas, containing greater than 50 grams of tritium (isotope) with a tritium isotopic fraction of 20 percent or greater.
>
> Category IV—All other reportable quantities, isotopic fractions, types, and forms of tritium.[183]

The "material of strategic importance" language here echoes the practical assessment of defense planners above, and tritium maintained its functional status as an SNM in all but name. This also exclusively frames tritium accountancy in terms of military interests. Then in 2011, tritium was declared "other accountable nuclear material" to be "protected in a graded manner consistent with [its] strategic and *monetary importance*," and the reportable quantity was raised from 0.01 g to 1 g.[184] The value of tritium here is expanded to include not only its strategic value of defense but also its financial value. In the current version (Feb. 7, 2023) of the DOE Directive on Nuclear Material Control and Accountability, the language of "graded safeguards" and "graded manner" of protection for tritium and other accountable nuclear material is dropped entirely to focus on bureaucratic reporting requirements and program management.[185]

The authors of the assessment only describe this transition in policy without offering an explanation behind the changes. It is unclear what has driven this relaxation of tritium accountancy requirements, but I have two plausible theories. The first theory is as tritium production has scaled-up at Watts Bar NPP the reporting requirements may have become increasingly burdensome or potentially problematic. The 2011 timeframe is when DOE was becoming more concerned with tritiated water management on-site, and they fully funded and built a 500,000-gallon Tritiated Water Storage Tank (TWST) to provide greater operational margins for releases. Though, to be entirely clear the tritium contained in this

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[182] R. L. Sindelar et al., "Assessment of Challenges for Tritium Accountancy and Control in Fusion Energy Systems," May 2023, https://sti.srs.gov/fulltext/SRNL-STI-2023-00217.pdf.

[183] "DOE 5633.3B Control and Accountability of Nuclear Materials" (Washington, D.C.: Department of Energy (DOE), September 7, 1994), I–9, https://www.directives.doe.gov/directives-documents/5600-series/5633.3-BOrder-b/@@images/file.

[184] "DOE 474.2A Nuclear Material Control and Accountability" (Washington, D.C.: Department of Energy (DOE), February 7, 2023), 2-II–3, https://www.directives.doe.gov/directives-documents/400-series/0474.2-BOrder-a/@@images/file. Emphasis mine.; "DOE 5633.3B Control and Accountability of Nuclear Materials," I–2.

[185] "DOE 474.2A Nuclear Material Control and Accountability," 2-II–3.

storage system would likely be exempt from reporting requirements since it was “used as a moderator in a nuclear reactor.”[186] It is unclear if the tritium contained in the several hundred Tritium Producing Burnable Absorber Rods (TPBARs) would qualify as a “reportable quantity” if the tritium remained sequestered inside the physical matrix of the rod. If “any item that contains nuclear material that rounds to a reportable unit for that nuclear material is accountable,” then after irradiation each TPBAR would be accountable as they typical contain slightly less than 1 g.[187] The second theory is a stepwise relaxation of reporting requirements in response to the increasing research and development into fusion power. Substantial amounts of tritium will be required to develop and implement fusion technologies, and if/when commercial-scale reactors become viable, tritium supplies will be more commonly on the scale of kilograms vs. grams. In this case, I would expect the reporting requirement to shift further.

Whether technically *special* or not, the common argument against strict and cumbersome control and accountancy of tritium is that absent particular configurations of SNMs such as plutonium and uranium tritium cannot by itself be weaponized. This argument presupposes that the sole goal of nuclear nonproliferation is the prevention of *horizontal* proliferation, keeping new nation states and highly sophisticated non-state actors from joining the “nuclear club.” Mitigating *vertical* proliferation more often than not is relegated to a second or third order concern. In most instances, vertical proliferation, which is the increase in an existing stockpile in quantity and/or technological sophistication, is assumed to be at the discretion of the five officially designated NWS. In other words, as long as NWS provide *any* reassurances that they are working toward NPT Article VI obligations of advancing the long-term goal of complete disarmament, short-term investments in vertical proliferation are often rationalized as “modernization.” These Article VI rationalizations have been a key driver for the creation and ratification of The Treaty on the Prohibition of Nuclear Weapons (TPNW)—disarmament proponents were tired of waiting for NWS to act in good faith to fulfill their legal obligations under the NPT. What the current environment inadvertently allows for is a lax regime of tritium control and accountancy that might benefit de facto nuclear weapon states like Israel, India, Pakistan, North Korea, and perhaps even Iran before long by allowing easier access to tritium and/or the accumulation of tritium for weapons use without excessive international scrutiny commonly reserved for SNM.

Conclusion: Nuclearities in Tension

In contrast with Kalinowski, I do not believe that the benign neglect of tritium in the context of proliferation has been primarily or largely due to the regime of nuclear secrecy surrounding the “significance” of tritium’s role in nuclear weapons. The idea that tritium was important if not integral to hydrogen weapons was widely suspected if not conclusively known. Furthermore, the U.S. reluctance to overemphasize tritium, particularly in bilateral agreements with the Soviets, was likely two-fold. First, uranium and plutonium were seen as the more critical material constraints on increasing weapon stockpiles, and their verification and monitoring alone already posed significant technical and diplomatic challenges. Second, U.S. leaders were concerned with the disruption of tritium production because it was considered necessary to on-going stockpile maintenance requirements.

As I have argued above, the bifurcation of tritium’s nuclear exceptionalism between peaceful and military contexts led to material ambivalence beyond typical *dual use* considerations. In other words,

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[186] “DOE 474.2A Nuclear Material Control and Accountability,” 2-II–3.
[187] “DOE 474.2A Nuclear Material Control and Accountability,” 2-II–3.

the graded approach to tritium accountancy shifted over ~40 years from strategic to monetary and then finally to a more bureaucratic orientation. During this time, the central role of tritium in nuclear weapons remained entirely unchanged. What did change was the signing of bilateral Strategic Arms Reduction Treaties (START I & II) in 1991 and 1993 between the U.S. and U.S.S.R./Russia, which led to the reduction of nuclear weapon stockpiles by half by the early 2000s.[188] This allowed the U.S. to rely on recycled tritium from decommissioned warheads during 1988-2003 when the last military production reactor for tritium had been shut down. While tritium production was starting in civilian reactors, there was also increasing interest and investment in peaceful nuclear fusion technologies that rely on tritium for fuel.

The transition to CLWR for tritium production in the U.S. also prompted important changes in tritium secrecy. Because these reactors are regulated by the Nuclear Regulatory Commission (NRC) and they "operate in an unclassified environment" significant safety-related information could no longer legitimately be concealed without "[casting] doubt on the credibility of the classification system."[189] In effect, these declassification determinations made available key performance data indicating the number of TPBARs being irradiated each cycle and how much tritium was produced. Previously, under defense production regimes researchers had to estimate minimum and maximum levels inferred from related publicly available data.[190] In addition to this expansion of domestic transparency, the production of tritium in a commercial reactor would allow for International Atomic Energy Agency (IAEA) inspections under the "Voluntary Offer," where the U.S. has agreed to allow inspections of "non-defense nuclear facilities."[191] The Voluntary Offer is intended to minimize the discriminatory effect of the Treaty on the Non-proliferation of Nuclear Weapons (NPT) regime *requiring* all non-nuclear weapon states (NNWS) nuclear facilities to accept IAEA inspections for verifying, monitoring, and safeguarding any SNM. While tritium, by definition, would not be subject to this oversight role, it should still be considered significant that a facility in a nuclear weapon state (NWS) producing nuclear weapons material is eligible for IAEA inspections at all, which is not the case for defense facilities. For the time being, the Voluntary Offer remains merely a political gesture because the IAEA has not exercised the option and for many reasons is unlikely to do so in the future. The IAEA is a global UN agency with a broad mandate, limited resources, and no enforcement powers. Their scant nuclear safeguard resources have been largely devoted to inspections in Iran and for the past year they have also maintained a continuous presence at ZNPP to further assure the world that Russia's military occupation of the plant will not devolve into a nuclear catastrophe. NWS already legitimately possess weapons, materials, and processes disallowed to non-NWS—there is very little incentive to expend resources to inspect NWS facilities.

In chapter 3, I consider how the various constructions of tritium's nuclearity in peaceful and military applications have influenced the neglect and resistance to tritium control in nonproliferation regimes.

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[188] Additionally, with the collapse of the Soviet Union in 1991, Cold War mentalities were being reimagined in the emerging post-Soviet geopolitical context. The future of nuclear weapons played a central role in these global narratives.

[189] Pfeiffer, "HQ-2019-00482-F_Responsive_Documents.Pdf," 3,7.

[190] Cochran et al., *Nuclear Weapons Databook, Vol. II*. One notable exception is the declassification of material production quantities at Hanford between 1945-1971.

[191] Rohlfing, "Interagency Review of the Nonproliferation Implications of Alternative Tritium Production Technologies Under Consideration by the Department of Energy," 8.

Chapter 3: Nonproliferation Policy & Paths Forward

Tritium Anecdote II: A Study in Tritium

In 2015, I was training to become a Senior Reactor Operator certified instructor (SRO Cert), and one of my qualifying tasks was to complete an instructor certification class with the Institute of Nuclear Power Operations (INPO). Formed in the aftermath of the Three Mile Island (TMI) Nuclear Power Plant partial meltdown, INPO is an organization that promotes U.S. nuclear industry performance well above the minimal legal standards required by the Nuclear Regulatory Commission (NRC). A robust and accredited training program plays a central role in the operation of any licensed nuclear power plant (NPP). INPO instructor certification, involving several weeks of synchronous on-line learning followed by a two-day on-site experiential learning capstone, is a core element of this process.

For my capstone project, I had prepared a lesson on tritium production at Watts Bar Nuclear Plant (WBN). My cohort consisted of operators, engineers, and maintenance workers from all over the country, there was even an engineer from NuScale, a company that has yet to build an operational reactor. My audience mostly recognized tritium as an incidental byproduct of NPP operation and had not considered its use in nuclear weapons or that it might be intentionally produced in a commercial nuclear reactor for this purpose. After providing a general introduction to tritium, what it is, and why it is used in nuclear weapons, a maintenance instructor from Wolf Creek NPP raised his hand and asked, “don’t we have international agreements and treaties that prevent us from doing this?” That, I told him, was an excellent question, and I had been asking it myself.

At the time, my research was limited, but two key documents addressing this question were a Government Accountability Office (GAO) report on “unobligated uranium” and the Final Environmental Impact Statement (FEIS) for the production of tritium at Watts Bar NPP.[192] Arguments hinged on the fact that even though tritium is used in nuclear weapons it is not defined as Special Nuclear Material (SNM) by the Atomic Energy Act of 1954. In accordance with this foundational legal framework, most treaties governing nuclear weapons reserve the strictest limitations for SNM, leaving out so-called byproduct materials like tritium. The only point of contention was whether or not the U.S. could use uranium fuel subject to treaty obligations—meaning any reactor fuel disallowed from producing weapons material—or would “unobligated” fuel, entirely domestically produced, be required in a reactor producing tritium for weapons.[193]

As an existing nuclear weapon state (NWS) defined under the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), the legitimacy of the U.S. possession and maintenance of nuclear weapons is sacrosanct. How an NWS decides to maintain its stockpile and the dividing boundary between its civilian and military nuclear infrastructures was simply a matter of national discretion without meaningful

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[192] “GAO-15-123 Interagency Review Needed to Update U.S. Position on Enriched Uranium That Can Be Used for Tritium Production,” Report to Congressional Requesters, Department of Energy (DOE) (Government Accountability Office (GAO), October 2014), https://www.gao.gov/products/GAO-15-123; “The Final Environmental Impact Statement for the Production of Tritium in a Commercial Light Water Reactor.”

[193] A bookkeeping processing known as “flag swapping” is also commonly used to designate “unobligated” fuel. Because uranium used in nuclear fuel is considered a fungible asset, U.S. “flagged” material might exist in DOE storage somewhere and like-for-like “swaps” could assign any treaty obligations to the stored material while essentially transferring the domestic-origin property to international sourced materials. U.S. flagged material is rapidly diminishing because there is insufficient domestic uranium enrichment to replenish these stores.

implications for practices or processes prohibited for non-nuclear weapon states (NNWS). After all, even if a NNWS comes into possession of significant quantities of tritium it cannot be weaponized without SNM, and furthermore, due to its decay rate, it cannot be stockpiled in anticipation of establishing a clandestine nuclear weapon program.[194]

In transitioning tritium production from dedicated military production reactors to commercial reactors at WBN, the U.S. sidestepped considering important nonproliferation implications of tritium production. Despite the considerable efforts of Martin Kalinowski and a few others, tritium continues to be neglected in nonproliferation discourse. In the emerging multipolar geopolitics of U.S. parity with Russia, mutual vulnerability with China, and nuclear weapon possession taking on an increasingly overt, coercive role, it is critical that we do not disregard a potential role for tritium monitoring, verification, and control in the next generation of arms control agreements.

Tritium Matters for Nonproliferation Policy

The definitive text on tritium and nonproliferation is *International Control of Tritium for Nuclear Nonproliferation and Disarmament* by Martin Kalinowski. Published in 2004, it is the culmination of over a decade of work beginning with his PhD research in nuclear physics.[195] An earlier version of his research on tritium and nonproliferation appeared in an extensive journal article co-authored with Lars Colschen in 1995.[196] The key insight provided by Kalinowski and Colschen, further explicated in Kalinowski's later book, was that in order to control military tritium production and use it would be necessary to establish international systems clearly demarcating military and civilian tritium supply chains. Instead of allowing tritium's ambivalent nuclearity to shift between military and civilian domains, there would be fixed international control paradigms providing greater clarity of material accountancy and end use obligations. To be clear, there have been few instances of the diversion of peaceful-use tritium for weapons use.[197] However, the existing patchwork of international regulations governing tritium production, trade, and use have afforded material ambiguities, as I argue in Chapter 2, that have inhibited a thorough reckoning of tritium's potential in nonproliferation regimes.

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[194] One caveat to the prospect of stockpiling tritium is that an NWS could choose to maximize tritium production well beyond defense requirements in the short-term and then cease tritium production for several years. Eventually decay would reduce the stockpiled tritium back to levels requiring new production. Several nations have the commercial nuclear power infrastructure to produce high levels of tritium but only an NWS could do so with impunity under the NPT. Also, a significant tradeoff in such a scenario is the infrastructure and personnel required to produce large quantities of tritium could not simply be restarted as needed. Maintaining at least a minimum level of tritium production would be necessary to avoid the degradation of these capabilities.

[195] Martin Kalinowski, "Nuclear Weapons Uses of Tritium and Multilateral Control Measures," ed. G. Bonizzoni and E. Sindoni, *Tritium and Advanced Fuels in Fusion Reactors: Proceedings of the Course and Workshop Held at Villa Monastero, Varenna, Italy, September 6-15, 1989*, 1990.

[196] Martin B. Kalinowski and Lars C. Colschen, "International Control of Tritium to Prevent Horizontal Proliferation and to Foster Nuclear Disarmament," *Science & Global Security* 5, no. 2 (August 1995): 131–203, https://doi.org/10.1080/08929889508426422.

[197] Kalinowski, *International Control of Tritium for Nuclear Nonproliferation and Disarmament*, 12; to United States. Department of State, "FRG Firms Charged with Illegal Export of Tritium and Nuclear Equipment to Pakistan," Cable, December 22, 1988, https://www.proquest.com/dnsa/docview/1679126944/abstract/2DB04D71C95A4A88PQ/2. In the mid-1980s, a German firm illegally transferred 0.8 g of "apparently weapons grade" tritium to Pakistan along with other tritium-related equipment.

Kalinowski argues for the parallel and simultaneous implementation of an Integrated Cutoff Agreement (ICO) and an International Tritium Control System (ITCS) to systematically monitor and control tritium in military and civilian domains respectively. While the concept for an ICO is based on the precedent and failed efforts of establishing a Fissile Material Cutoff Treaty (FMCT), Kalinowski differentiates his proposal from a so-called “tritium freeze” which would ban all tritium production. This approach was thoroughly discussed in the 1988 *Tritium Factor* workshop and recently revisited by one of the original participants, Robert Kelley.[198] Kalinowski argues “a more realistic approach is the integrated cutoff, which can be negotiated in a way that takes into account that fresh tritium supplies may be necessary after some decades.”[199] An ICO need not require an absolute prohibition on tritium production if significant quantities (SQ) were defined—with respect to each NWS ICO signatory—as amounts required to meaningfully expand their operational stockpiles (vertical proliferation). Once any existing tritium reserves were initially assessed in an NWS, then only future production capacities and quantities would need to be monitored and verified. If these quantities did not exceed replacement levels necessary due to decay, then tritium production could be allowed to continue without risking prohibited and unexpected increases in nuclear weapon stockpiles.

Kalinowski’s proposed implementation of an ICO would initially cut off tritium production completely. Because of American and Russian nuclear stockpile reductions during the 90s and early 2000s sufficient supplies of recycled tritium were available to refurbish the remaining arsenals. This allowed the U.S. to maintain their nuclear stockpile for ~15 years without on-going tritium production. A 1993 report from the Resources, Community, and Economic Development Division (RCED) of the General Accounting Office (GAO) projected that tritium recycling “will enable DOE to service the planned nuclear arsenal through 2012 without the need for producing any additional tritium. In 2012, however, a source of tritium *must be* available.”[200] Later that year, DOE Secretary Hazel O’Leary pushed the “must be available” date up to 2008.[201] By 1996, the Nuclear Weapons Stockpile Plan (NWSP) established “the need for a new tritium production source by *approximately 2005*.”[202] Because tritium requirements/reserves have been and remain closely guarded secrets, it is difficult to audit the fidelity of these statements. Kalinowski estimates that the U.S. tritium stockpile remaining in 2003 to be between 26-54 kg, and the “inventory available to support requirements for the nuclear weapons stockpile on pre-START II levels and a five-year tritium reserve will be at least 45 kg in 2005 when the first batch of freshly produced tritium becomes available.”[203]

In the hindsight of 2024, the optimistic tritium production projections in the U.S. have not evolved as anticipated. Due to unexpected and excessive tritium permeation through the TPBAR cladding in early tests, the DOE tried to design better performing components before scaling tritium production to target levels. When these redesigns proved inadequate to fully mitigate undesired leakage levels, a 500,000

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[198] Leventhal, *The Tritium Factor*; Robert E. Kelley, “Starve Nuclear Weapons to Death with a Tritium Freeze | SIPRI,” August 28, 2020, https://www.sipri.org/commentary/topical-backgrounder/2020/starve-nuclear-weapons-death-tritium-freeze.

[199] Kalinowski, *International Control of Tritium for Nuclear Nonproliferation and Disarmament*, 53.

[200] “Nuclear Arsenal Reductions Allow Consideration of Tritium Production Options,” Report to Congressional Requesters, Nuclear Materials, August 1993, 1. Emphasis mine.

[201] Kalinowski, *International Control of Tritium for Nuclear Nonproliferation and Disarmament*, 111–12.

[202] “The Final Environmental Impact Statement for the Production of Tritium in a Commercial Light Water Reactor,” S-14. Emphasis mine.

[203] Kalinowski, *International Control of Tritium for Nuclear Nonproliferation and Disarmament*, 112.

gallon tritiated water storage tank (TWST) system was constructed at the Watts Bar site to better control tritium releases into the environment. The total cost of this project, ~$20 million, was paid for by the DOE.[204] Previously, TVA had assured the NRC that the existing liquid waste storage capacities totaling more than 287,000 gallons were "adequate to obtain the necessary dilution for liquid tritium discharges to the environment."[205] The fact that the DOE paid to upgrade tritiated waste handling that almost tripled original design capacities signaled that the tritium production mission being conducted at a TVA facility was largely responsible for elevated levels of tritium in the site's radwaste system.[206] Furthermore, the DOE also made a commitment to build a similar TWST at the Sequoyah nuclear site if tritium production was ever expanded to the site.[207] After successfully starting up Watts Bar Nuclear Unit 2 and scaling tritium production to required levels at the site, the DOE has since removed the option of expanding production to the Sequoyah reactors.[208]

Another reason why an ICO makes sense in the context of an FMCT is the ambivalence of military production reactors used to produce plutonium and/or tritium.[209] Both the U.S. and Russia have been able to shutdown plutonium production reactors—a de facto cutoff—in part because they have developed alternative pathways for ongoing tritium production.[210] Recent analysis from Alex Glaser and Julien de Troullioud de Lanversin suggest that Israel's on-going operation of the clandestine Dimona reactor may be for the sole purpose of tritium production.[211] Irreversibly shutting down plutonium production reactors even if that means nuclear weapon possessing states shift tritium production to commercial reactors, as the U.S. has done, creates a paradox *supporting* the irreversible disarmament goals of The Treaty on the Prohibition of Nuclear Weapons (TPNW) while *enabling* the continued refurbishment, maintenance, and modernization of nuclear weapon stockpiles.[212] This perhaps provides

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[204] "FOIA Request 23-FOI-00001 for DCN 59397 Tritiated Water Storage Tank Design Costs and Responsible Agency" (Tennessee Valley Authority (TVA), October 4, 2022).

[205] "Watts Bar Nuclear Plant - Responses to RAI Regarding Tritium Production - Interface Issues 14 and 15 (TAC No. MB1184)," December 7, 2001, E-2, https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML013520461.

[206] "TVA 2005 Annual Report," March 1, 2006, Information Sheet 15, https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML060650126. "TVA has a long-term interagency agreement with DOE to utilize TVA's Sequoyah and Waits Bar Nuclear Plants to irradiate TPBARS This agreement, ending in 2035, requires DOE to reimburse TVA for costs incurred plus a fee per TPBAR produced for irradiation services."

[207] "Tennessee Valley Authority; Watts Bar Nuclear Plant, Units 1 and 2," Federal Register, February 11, 2019, https://www.federalregister.gov/documents/2019/02/11/2019-01859/tennessee-valley-authority-watts-bar-nuclear-plant-units-1-and-2.

[208] "Amended Record of Decision for the Production of Tritium in Commercial Light Water Reactors" (Department of Energy (DOE), National Nuclear Security Administration (DOE/NNSA), September 14, 2023), https://www.govinfo.gov/content/pkg/FR-2023-09-14/pdf/2023-19909.pdf.

[209] See Chapter 2 for further discussion of the relationship between tritium and plutonium production.

[210] "Global Fissile Material Report 2022 Fifty Years of the Nuclear Non-Proliferation Treaty: Nuclear Weapons, Fissile Materials, and Nuclear Energy" (International Panel on Fissile Materials (IPFM), July 29, 2022), 41, https://fissilematerials.org/library/gfmr22.pdf. The last U.S. production reactor was shutdown in 1988 and the last Russian production reactor was shut down in 2010.

[211] Alexander Glaser and Julien de Troullioud de Lanversin, "Plutonium and Tritium Production in Israel's Dimona Reactor, 1964–2020," *Science & Global Security*, November 15, 2021, 1–18, https://doi.org/10.1080/08929882.2021.1988325.

[212] "Treaty on the Prohibition of Nuclear Weapons" (United Nations (UN), July 7, 2017), https://undocs.org/pdf?symbol=en/A/CONF.229/2017/8.

some credence to the DOE claim that "such support of a decreased nuclear weapons stockpile is not inconsistent with the long-range goal of total nuclear disarmament."[213] However, if and when a "decreased" stockpile is no longer the prevailing condition, this argument will be much more difficult to make in good faith.

Even under the auspices of a de facto fissile material cutoff, monitoring and verifying tritium used in nuclear weapons would provide additional value to the nonproliferation regime. Since tritium is the key ongoing nuclear weapon material requirement reliant on extensive irradiation infrastructure, verifiable information about its production could be shared equitably. Such exchanges could build confidence and provide verification mechanisms for assessing stockpiles and supplementing national technical means. While new bilateral or multilateral agreements, particularly in the untested waters of tritium monitoring and verification, seem unlikely given the current state of geopolitics it is essential to continue developing the policies and technologies necessary for tritium monitoring and verification so that they can be called upon when the political climate improves.

Conclusion: Paths Forward

An exhaustive technical report on "Nuclear Proliferation and Civilian Nuclear Power" from the Nonproliferation Alternative Systems Assessment Program (NASAP) conducted by DOE and Energy Research and Development Administration (ERDA) was published in June 1980.[214] The NASAP operated from 1977-1980, drew from "over 50 interrelated studies…performed by 7 national laboratories, 13 independent research organizations, 10 companies from the nuclear industry, and 5 universities," and produced a 9-volume set of over 1,000 pages.[215] The scope of the program is explicitly broad:

> The contribution that nuclear power programs can make to nuclear weapons programs depends upon the presence of sensitive materials and facilities in any of the processes associated with nuclear electrical power. *Sensitive material is weapons-usable material; examples are highly enriched uranium or plutonium. Sensitive facilities are those that can produce, or can be easily modified to produce, weapons-usable material; examples are enrichment or reprocessing plants for reactor fuel.* The proliferation risks arise because of the technical similarities between nuclear-power and nuclear weapons materials and facilities, and the opportunities for abuse that those similarities provide.[216]

The term "sensitive material" as used here is not as restrictive as "special nuclear material," which would technically exclude tritium. Therefore, it appears that there is no programmatic reason for the exclusion of the consideration of tritium as "weapons-usable." However, tritium is almost exclusively

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[213] "The Final Environmental Impact Statement for the Production of Tritium in a Commercial Light Water Reactor," 1–10.

[214] "Nuclear Proliferation and Civilian Nuclear Power. Report of the Nonproliferation Alternative Systems Assessment Program. Volume I. Program Summary" (Department of Energy, Washington, DC (USA). Assistant Secretary for Nuclear Energy, June 1, 1980), https://doi.org/10.2172/5320308.

[215] "Nuclear Proliferation and Civilian Nuclear Power. Report of the Nonproliferation Alternative Systems Assessment Program. Volume I. Program Summary," iii.

[216] "DRAFT: Nuclear Proliferation and Civilian Nuclear Power: Report of the Nonproliferation Alternative Systems Assessment Program. Executive Summary" (Department of Energy, Washington, DC (USA), December 1, 1979), iii, https://doi.org/10.2172/5536575. Emphasis mine.

referred as a potential problem pollutant as a byproduct material and only briefly as a potential fuel for fusion reactors. Nowhere is the use of tritium in nuclear weapons mentioned—even in Vol. VIII: Advanced Concepts where "large amounts of tritium" required to fuel a conceptual tokamak fusion-fission hybrid is considered.[217] One estimate from a 1976 EPA study indicated that "tritium inventories in large fusion power systems are expected to be *on the order of tens of kilograms*. At approximately 10^7 Ci per kg, *this represents amounts of tritium much greater than ever handled previously*."[218] Tritium's byproduct nuclearity, which will be discussed in Chapter 4, appeared to exclude other constructions in this study even though its use in nuclear weapons had been well-established in public discourse and officially declassified several years before publication.

In the preface to Kalinowski's book, Frank von Hippel estimates that for a global fleet of fusion reactors to replace the power generated by fission would require "about *40 million grams* of tritium."[219] Twenty years later, viable fusion power technologies are "still beyond the horizon," but the horizon of our possible fusion future is perhaps closer than it once was. Before vast amounts of purified tritium become embedded in our technological infrastructures, nonproliferation regimes should contend with this very real possibility. Integrated and systematic approaches to tritium control, monitoring, and verification will provide great value to the nonproliferation regime whether fusion power proves successful or not. In the event that fusion power infrastructures do emerge, having an international plan for tritium will be essential.

Chapter 4: Byproduct Nuclearity

Tritium Anecdote III: Tritium Leak at BFN

In January 2015, during my last week as an on-shift Assistant Unit Operator (AUO) at BFN before I started a developmental training program to become a Senior Reactor Operator Certified (SRO Cert) Instructor in Operations Training, my nightly rounds took me through the refuel floor. This large, cavernous room is near the top of the reactor building allowing access to all three units spent fuel pools and, during refueling outages, the reactor pressure vessels themselves. On the first night of my shift, I immediately noticed something unusual had happened on the previous shift. A steady leak was coming from up near the ceiling, several dozens of feet above, and dripping down onto interior wall sections that overhung the outside wall of the reactor building. A catch device, known as a "witch's hat," marked with a temporary equipment tag was in place to catch the leak and direct it to the reactor building drain system. Although a noticeable amount of water appeared to be missing the witch's hat and falling directly onto the overhang. When I later spoke with the reactor operator in the control room, I learned two things: first, the leak was coming from a failing air relief valve beneath the condensate head tank

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[217] "Nuclear Proliferation and Civilian Nuclear Power. Report of the Nonproliferation Alternative Systems Assessment Program. Volume VIII. Advanced Concepts" (Department of Energy, Washington, DC (USA). Assistant Secretary for Nuclear Energy, June 1, 1980), 98, https://doi.org/10.2172/5320307.

[218] Bruce J Mann, "Environmental and Safety Aspects of Alternative Nuclear Power Technologies - Fusion Power Systems," Technical Note (Las Vegas, NV: U.S. Environmental Protection Agency (EPA), May 1976), 8, https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=9101MEK7.txt. Emphasis mine.

[219] Kalinowski, *International Control of Tritium for Nuclear Nonproliferation and Disarmament*, xii. Emphasis mine.

and, second, the leak had apparently gotten worse since the previous shift. The operator then dispatched radiation protection laborers to expand the leak collection coverage area.[220]

Unless you know a little about the operation of nuclear power plants and the accompanying legal obligations, you may be surprised to know that the scenario described above led to a required notification of the Alabama Radiological Protection Department and Alabama Department of Environmental Management.[221] On January 7, 2015, operators sampled an on-site well and detected peak tritium concentrations of 7,520,000 pCi/L (278,240 Bq/L) which significantly exceeded the EPA limit for tritium in drinking water of 20,000 pCi/L (740 Bq/L). Approx. 200 gallons of water had seeped through the wall panels and down the outside of the exterior wall of the reactor building.[222] If we conservatively attribute 100% of the activity to the leak, then we can estimate that, at most, ~0.57 µg (micrograms) of tritium leaked from the reactor building into the ground. The source of the water was the condensate system. In a boiling water reactor (BWR), water is heated inside the reactor and the resultant steam flows down large pipes (known as steam lines) to rotate the blades of the turbine-generator and then condenses back to water to be cooled, cleaned, and recycled back into the reactor. To ensure the condensate system remains full, a 10,000-gallon head tank sits on the roof of the reactor building, just above the refuel floor. The leak occurred near where the piping for this tank penetrated the roof. One of the primary radioactive contaminants found in condensate that cannot be removed by the highly effective mechanical filtration system required before the water can return to the reactor is tritium. So, even if the cause of elevated tritium levels in on-site wells is unknown, then one of the likely suspects would be an unidentified leak from the condensate system. As of September 2017, the NRC reported tritium levels for the same on-site well had lowered to 3,493 pCi/L (~129 Bq/L).

Introduction

Tritium is a pernicious pollutant—a byproduct material—resulting from a wide array of global nuclear activities. Most other radionuclides in waste streams can be significantly mitigated through a combination of time, filtration, adsorption, decanting, and various other chemical and physical processes. Tritium, on the other hand, is predominantly contained within the molecular bonds of water and there are no known industrial-scale technologies that can readily separate ordinary water from tritiated water.

It is important to note that many analyses of the radiological risks posed by tritium use the U.S. EPA tritium drinking water limit of 20,000 pCi/L (740 Bq/L) as a frame of reference. A reader should not understand this to mean that levels *below this limit* are safe or that levels *above this limit* are dangerous. Many of the water samples referenced are not drinking water and are often from purpose-built wells on-site at nuclear facilities or other sampling locations in the surrounding environment intended to be an early indication of a leak. Moreover, readers should also note that the U.S. limit is currently one of the most conservative national tritium drinking water limits. The highest limit being

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[220] It is important to note that this condition was covered in the shift turnover process, but my position that night did not include rounds on the refuel floor. I had only gone through the area to access the stairwell to the reactor building roof. Otherwise, my noticing the existing condition might be interpreted as the result of a poor turnover process.

[221] "2015 Annual Radioactive Effluent Release Report" (Browns Ferry Nuclear Plant: Tennessee Valley Authority (TVA), April 30, 2016), ML16123A149, https://www.nrc.gov/docs/ML1612/ML16123A149.pdf.

[222] "List of Leaks and Spills at U.S. Commercial Nuclear Power Plants - September 2017." (Nuclear Regulatory Commission (NRC), September 2017), ML17236A511, https://www.nrc.gov/docs/ML1723/ML17236A511.pdf.

Australia at >2,000,000 pCi/L (76,100 Bq/L) with the next lowest limits being Canada and Russia at ~190,000 pCi/L (7,000 Bq/L) and ~208,000pCi/L (7,700 Bq/L) respectively.[223] Most European Union nations set a drinking water *guideline* (not a standard) of ~2,700 pCi/L (100 Bq/L) intended only as an potential indicator of other water quality problems. These limits are based on possible annual doses received by the public often derived from different calculation methods; they *do not* indicate *typical* levels of tritium in drinking water in the respective country. Moreover, the radiological risks embedded in these calculations are based on chronic exposure over decades and not acute exposure concerns. Regardless, tracking tritium and its various sources provides valuable environmental data useful for assessing potential risks and indicating inefficiencies or failures of barriers between nuclear activities and the public.

Because heavier radionuclides can be effectively removed from effluents and tritium cannot, tritium's contribution to the total radioactivity released into the environment from peaceful nuclear activities is proportionately large. Arjun Makhijani describes this relationship in his book *Exploring Tritium's Dangers*:

> Tritium is the most common radioactive pollutant routinely discharged in the largest quantities as measured by radioactivity. For instance, the total radioactivity of tritium in the discharges of polluted water from the Braidwood nuclear power plant in Illinois in 2019 was more than *75,000 times the discharges of all other fission and activation products*. The total radioactivity of routine gaseous releases of tritium in the form of water vapor from the Braidwood nuclear power plant in Illinois in 2019 were more than one hundred times that of all other gaseous fission products and activated radioactive gases.[224]

There are some important caveats to the provocative multiples used here. Makhijani refers to Braidwood nuclear power plant in Illinois because his organization, Institute for Energy and Environmental Research (IEER), commissioned an analysis of the tritium releases at the site.[225] Additionally, these percentages are highly variable from year to year at the same site and between different sites. Part of the reason a *large* number (like 75,000) can be emphasized in italics is because all other fission and activation products released are relatively low and can be directly affected by the efficiency of radwaste cleaning processes in ways that tritium cannot. In 2020, the U.S. site with the highest tritium releases in liquid effluent was Watts Bar at 7,130 Ci (~264 TBq).[226] This represents >2,000,000 times the total radioactivity released from other fission and activation products during that same time. Relatively this is a large number, but its magnitude results from the fission and activation product liquid releases being an order of magnitude *lower* than Braidwood and releasing over 3 times as much tritium in the same year. Hence, these relative terms tend to obfuscate rather than inform when presented out of context of absolute values, trends, and nuclear industry norms.

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[223] Maria Florencia Ferreira et al., "Tritium: Its Relevance, Sources and Impacts on Non-Human Biota," *Science of The Total Environment* 876 (June 2023): 4, https://doi.org/10.1016/j.scitotenv.2023.162816.

[224] Makhijani, *Exploring Tritium Dangers*, 4. Emphasis in original.

[225] Makhijani, app. B.

[226] J. Davis, "Radioactive Effluents from Nuclear Power Plants Annual Report 2020," June 2023, 3–18, https://www.nrc.gov/docs/ML2316/ML23164A219.pdf.

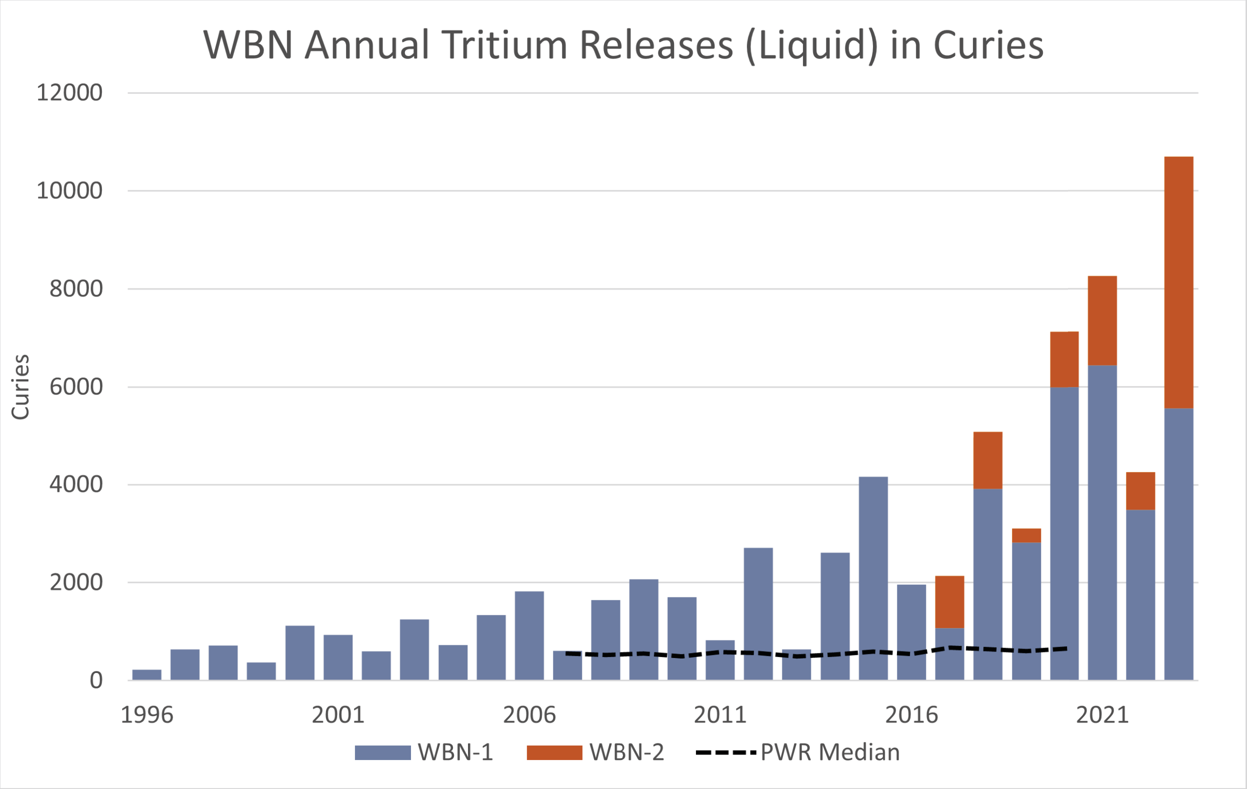

Figure 7: WBN Annual Tritium Releases (Liquid) in Curies.

For reference, I've compiled the chart in Figure 7 from annual reports for the first 26 years of operation for the Watts Bar Nuclear (WBN) site. Additionally, from 2007-2020, the NRC issued consolidated reports for all operating nuclear power plants in the U.S. The dashed black line shows the median value for tritium in liquid releases for all pressurized water reactors (PWR). Releases from the second reactor, WBN-2, were added after it achieved initial criticality in 2017. Since 2008, WBN has more often than not been the highest emitting plant in the U.S. Once the consolidated reports are released for 2021-2023, I fully expect they will remain a top emitting plant. Even so, these relatively high releases remain well under the site license limits.

One common way of communicating how "extremely radioactive" tritium is with the following examples:

> For a given mass, it is, for instance, about 150,000 times as radioactive, in terms of disintegrations per unit time, as plutonium-239. *One teaspoon of tritiated water (as HTO) would contaminate about 100 billion gallons of water to the U.S. drinking water limit; that is enough to supply about 1 million homes with water for a year.*[227]

These comparisons might suggest to the layperson that tritium is more dangerous than plutonium-239 and that even *small amounts* of tritium can contaminate *huge volumes of water*. The amount of tritium

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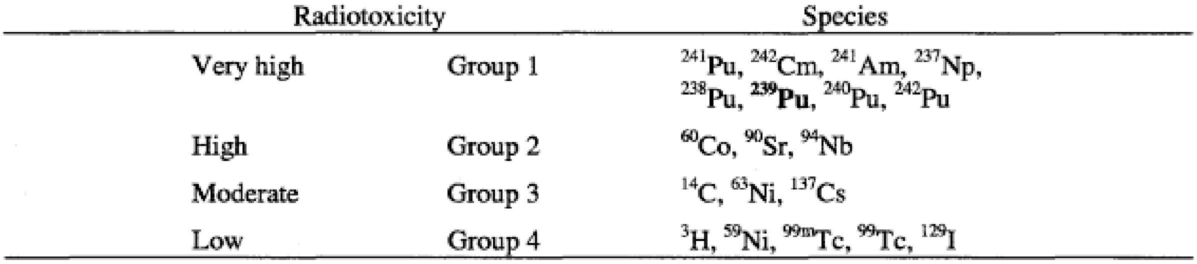
[227] Makhijani, *Exploring Tritium Dangers*, 4–5. Emphasis in original. Later in the text Makhijani uses a slightly different example to make this same point: "*one gram (the weight of about one-fifth of a teaspoon of water) of tritium in tritiated water (as HTO) will contaminate almost 500 billion liters of water up to the U.S. drinking water limit of 20,000 picocuries per liter*" (21).

sufficient to contaminate that much water is ~0.779 g (~278 TBq)—this is, in fact, a *vast amount* of tritium that would only exist in the form of pure HTO in special, purpose-built facilities. This amount is roughly equal to the *total tritium released* from the Watts Bar site in 2020. Furthermore, the total volume of Chickamauga reservoir where WBN discharges its liquid effluent is ~240 billion gallons which is constantly flowing downstream toward a dam that has the capacity to spill ~300 billion gallons in a day. Yes, 100 billion gallons is a lot of drinking water, but it is a veritable drop in the bucket of the hydrosphere. While Makhijani is careful to qualify the comparison between tritium and plutonium-239 "for a given mass…in terms of disintegrations per unit time," unless a layperson understands (1) the high improbability of ever being exposed to large amounts of tritium and (2) that tritium's biological half-life is measured in days and plutonium-239's is measured in years—they may come to the erroneous conclusion that, in general, they should be more worried about exposure to tritium than plutonium.[228] Among the "host of reasons to pay careful attention to the dangers of tritium," 4 of 14 numbered reasons provided by Makhijani explicitly and implicitly link tritium to plutonium, which is commonly considered "'the most toxic substance known to man.'"[229]



Radiotoxicity		Species
Very high	Group 1	^{241}Pu, ^{242}Cm, ^{241}Am, ^{237}Np, ^{238}Pu, **^{239}Pu**, ^{240}Pu, ^{242}Pu
High	Group 2	^{60}Co, ^{90}Sr, ^{94}Nb
Moderate	Group 3	^{14}C, ^{63}Ni, ^{137}Cs
Low	Group 4	^{3}H, ^{59}Ni, ^{99m}Tc, ^{99}Tc, ^{129}I

[230]

Figure 8: Radiotoxicity comparison between Pu-239 & tritium.

The radiotoxicity table above indicates the relative biological damage from intaking the respective radionuclides into the human body. Pu-239 is in the "Very high" group and tritium (H^3) is in the "Low" group—at opposite ends of the spectrum. In a recent virtual book talk hosted by Nuclear Energy Information Service (NEIS), an anti-nuclear power activist group, Dr. Makhijani, to his credit, was quick to correct his audience reading too much into these comparisons, though at least one person seemed to muse that the "teaspoon of tritium" example would be useful for the group's anti-nuclear power messaging.[231]

Tritium's byproduct nuclearity as waste is constructed by anti-nuclear advocates (against both power and weapons) in ways that emphasize its risks and dangers—how it *contaminates* water, air, and living

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[228] J. P. Adams and M. L. Carboneau, "National Low-Level Waste Management Program Radionuclide Report Series, Volume 17: Plutonium-239," March 1, 1999, 17–27, https://doi.org/10.2172/14779. "Once [Pu-239] is absorbed into the human body, it will tend to stay, with only minor removal, as long as the person is alive."

[229] J. P. Adams and M. L. Carboneau, 17–30. The authors argue that the dangerous reputation of Pu-239 is "undeserved" with respect to short term risks. However, since it is a reputation that plutonium isotopes commonly evoke, it is relevant to the context of communicating tritium's dangers.

[230] J. P. Adams and M. L. Carboneau, 17–18; Robert Granier, Denis-Jean Gambini, and Robert Granier, *Applied Radiation Biology and Protection*, Ellis Horwood Series in Physics and Applications (New York: Horwood, 1990), app. 2.

[231] The recorded video from the November 30, 2023 "Night with the Experts, featuring Dr. Arjun Makhijani," is not yet publicly available.

things. Whereas supporters of nuclear technologies tend to stress tritium's *naturalness*, how it is everywhere and how we are exposed to radiation from both natural and medical sources far exceeding any dose an individual might conceivably receive from the weak beta decay of tritium. In this chapter, I present the context of this contested nuclearity and consider the case of the treated wastewater ocean discharges from Fukushima Daiichi that began in 2023. The presence of tritium in the environment also functions as a *signal* or proxy of nuclear effects whether from nuclear weapons testing or the operation of nuclear facilities. The 12.3-year half-life of tritium ensures a temporal frame-lagging effect where new injection into the environment begins a ~85-year process until its virtual elimination from decay.[232] I argue that the tensions between these constructions of tritium's nuclearity remain unresolved and are likely to become even further polarized as fusion technologies reliant on vast amounts of tritium for fuel are further developed.

Tritium in the Environment

The example described in Tritium *Anecdote III* represents one path for anthropogenic tritium to enter the environment: a system leak inside secondary containment (the reactor building) that bypasses radwaste drains and finds a path that breaches containment. The typical flow path for any such leak is through a building drain system that is routed to radwaste for treatment, storage, and disposition. Most heavy radioactive isotopes are removed from radwaste liquids by treatment with a demineralizer. However, water molecules formed with tritium (commonly referred to as tritiated water in diluted form and super-heavy water in its pure form) behave essentially like all ordinary water and cannot be further separated from non-tritiated water by any practical technological process. The treated water is stored in tanks, sampled, and released into the environment through a controlled and monitored process.[233] The liquid effluent release process is not typically continuous and most often achieved in batches throughout a year. This allows for some tritium decay during storage and for releases to be planned for maximum dilution, for example, when a river's flowrate is particularly high.

In Tritium *Anecdote I* from Chapter 1, I describe how the fission process produces small quantities of tritium within the fuel that can partially permeate cladding and leak into coolant, but the majority of mobile, anthropogenic tritium from nuclear power plants results from neutron interactions with the moderator and coolant. I will nominally describe how this process looks in three major types of nuclear reactors: boiling water reactors (BWR), pressurized water reactors (PWR), and heavy-water reactors (such as CANDU).[234]

BWR – ordinary water serves as both the reactor coolant and neutron moderator. Just like all water molecules in the natural environment, a small fraction of the water is formed by heavier deuterium hydrogen atoms. When these highly diluted heavy water molecules interact with neutrons generated from the fuel, there is a chance they will absorb the neutron and form tritium. This process (also known as *deuterium activation*) will initially raise levels of tritiated water in the coolant and then tend toward a steady-state equilibrium. Maximum levels of accumulated tritium

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[232] The time it takes for a radioisotope to functionally *disappear* is typically 5-7 half-lives. After 5 half-lives, less than 3% of the original mass should remain. After 7 half-lives, it is mostly gone.

[233] While this is typical of most nuclear power plants, there are several so-called "zero release" plants that process, store, and dispose of liquid radwaste through practices other than environment releases.

[234] For the sake of simplicity, I will not explain the process of "neutron moderation" in any detail. Suffice to say, moderators interact with neutrons to promote a predictable and controllable fission process in the fuel.

in the reactor coolant will commonly be <10% of levels found in PWR coolant.[235] The reactor coolant/moderator boils into steam that flows from the reactor to the turbine where it is condensed, forming condensate. The entire cycle from reactor coolant/moderator to steam, from condensate to feedwater forms a balanced loop of inputs and outputs to and from the reactor pressure vessel (RPV).

PWR – ordinary water mixed with boric acid (forming borated water) serves as both the reactor coolant and neutron moderator. Some neutrons produced from fission will interact with boron to produce tritium in the coolant. However, in contrast with BWR coolant flow paths, PWR coolant remains in liquid phase (higher pressures inhibit boiling) circulating through a primary loop, which exchanges heat through tube walls inside a steam generator to produce steam in a secondary loop to drive the turbine. Because of this separation between primary and secondary loops, PWR condensate systems will not contain tritium under normal conditions. PWRs produce tritium from the same deuterium activation *plus* the additional boron reactions. Incidental tritium production in a PWR occurs at a faster rate than in a BWR. 80-90% of all tritium produced in PWR reactor coolant comes from the boron reactions and almost entirely accounts for the PWR/BWR differences.[236] Additionally, the lithium hydroxide (LiOH) added to PWR coolant to control pH makes a small contribution from the tritium produced by lithium neutron reactions. Tritium will tend to build-up in the reactor coolant during a fuel cycle, and during refueling outages this borated water with elevated tritium levels will be processed and exchanged. The resulting tritiated wastewater can be stored and released in a similar fashion to BWR sites.

CANDU – heavy water serves as both the reactor coolant and moderator.[237] CANDUs differ in another significant way from both BWRs and PWRs in that the moderator and coolant functions are maintained by two independent heavy water systems operating in parallel. Heavy water functioning as moderator is exposed to more neutrons than the heavy water in the coolant system. As such, tritium levels in the coolant tend to be 20-30 times lower than in the moderator.[238] Since pure heavy water consists entirely of water molecules made of deuterium atoms, deuterium activation is the dominant mode of tritium production. The natural prevalence of deuterium versus ordinary hydrogen is one in ~7,000 atoms.[239] The relatively rare event of deuterium activation that occurs both in BWRs and PWRs is amplified in a CANDU reactor by the greatly increased deuterium concentration. In CANDU reactors, tritium will continue to build up over time and will need to be

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[235] Greg Jones, "Tritium Issues in Commercial Pressurized Water Reactors," *Fusion Science and Technology* 54, no. 2 (15 2008): 331.

[236] Anthony Monterrosa et al., "Boron Use and Control in PWRs and FHRs" (University of California, Berkeley, May 5, 2012), 3, http://fhr.nuc.berkeley.edu/wp-content/uploads/2014/10/12-007_Boron_Use_in_PWRs_and_FHRs.pdf; Jones, "Tritium Issues in Commercial Pressurized Water Reactors," 329.

[237] While some proposed advanced CANDU designs use heavy water solely as a moderator and light water as a coolant, most currently operating CANDU reactors use heavy water in both roles.

[238] Allan Everatt, Ramesh Sadhankar, and Robert Munro, "CANDU Station Tritium Removal Facility. Optimal Design and Utilization," in *Progress in Cryogenics and Isotopes*, vol. 11 (The 11th International ICIT Conference Progress in Cryogenics and Isotopes Separation, Romania: National R and D Institute for Cryogenics and Isotopic Technologies, 2005), 11.

[239] M. Coleman and M. Kovari, "Global Supply of Tritium for Fusion R&D from Heavy Water Reactors" (FIP/P3-25, 27th IAEA Fusion Energy Conference, Ahmedabad, India, October 24, 2018), 1, https://nucleus.iaea.org/sites/fusionportal/Shared%20Documents/FEC%202018/fec2018-preprints/preprint0461.pdf.

> cleaned or exchanged with pure heavy water to minimize the radiological risks posed by higher levels of tritium to nuclear workers and undesirable impacts on reactor physics. Because heavy water itself is much more valuable than ordinary light water CANDU sites will either store the heavy water to allow for sufficient tritium decay or process the coolant through large-scale tritium removal facilities (TRF). Only two such facilities currently operate in the world, one in Canada and one in South Korea. The detritiation process separates tritium from the heavy water allowing it to be reused in the reactor. The separated tritium can then be made available for various uses. The Canadian government has dedicated the tritium separated at their facility for peaceful use, the bulk of the production capacity and reserves are planned to fuel the ITER experimental fusion reactor being built in France by an international consortium.

The differences between the amounts of tritium incidentally produced by these types of reactors are significant. PWRs produce about ten times as much tritium as BWRs, and CANDUs produce over a hundred times as much as PWRs. These are crude estimates meant to illustrate orders of magnitude, and specific production rates will depend on reactor type, power output, and several other factors. Also, it is important to remember that, while CANDU production rates are much higher, the Korean and Canadian TRFs allow for the separation and purification of substantial amounts of tritium for use rather than being expelled as waste from the plant. Even still, at every step in each reactors' operation cycle some tritium leaks and eventually finds its way into the environment either through gaseous or liquid releases. In accordance with various regulatory regimes, a key operational objective is to ensure that any such releases are controlled and monitored. The balance sheet between all the tritium production mechanisms validated by periodic system surveillances and all releases into the environment measured by qualified and calibrated instrumentation and processes should indicate only allowable discrepancies. The final backstop for any excessive, unaccounted tritium leakage is the wide array of environmental monitoring and sampling in areas surrounding the sites. The on-site well monitoring described in the anecdote above is one of the earliest indicators of any such problems.

Operating NPPs are a major contributor to environmental tritium levels, however other nuclear facilities, including fuel reprocessing plants, also release some tritium as well. According to a report from the Institut de Radioprotection et de Sûreté Nucléaire (IRSN), "worldwide, the quantity of tritium released is still low, but can result in high concentrations in localized areas."[240] Historically, atmospheric nuclear weapon testing contributed significantly to environmental tritium levels:

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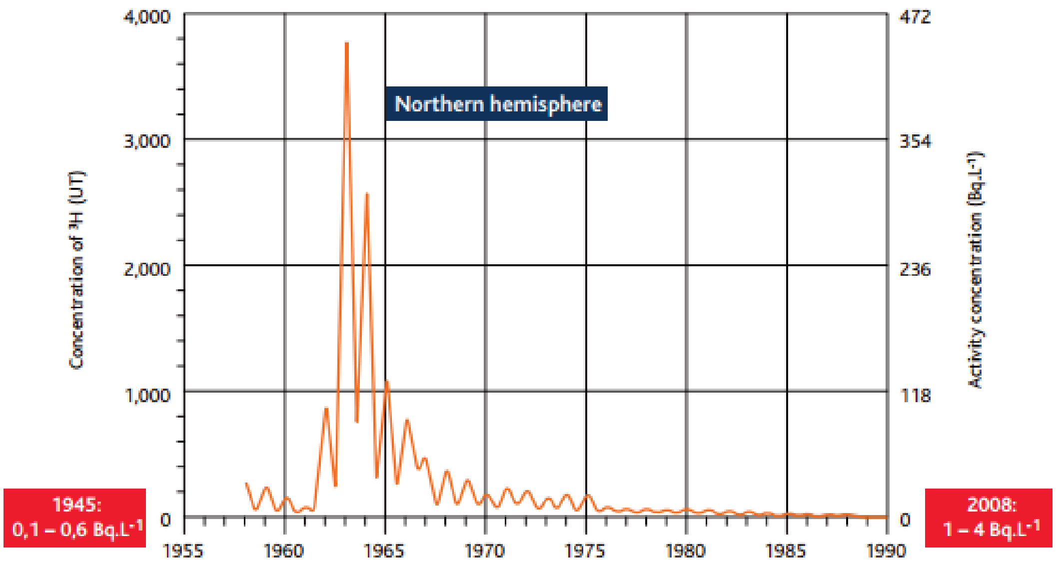
[240] Seignette and Lafontan, "Tritium and the Environment," 5.



[241]

Figure 9: changes in tritium concentrations in rainwater in the northern hemisphere between 1945 and 2008 (values given in red are for natural background levels in 1945 before nuclear testing and for current levels in 2008). from ISRN, 2010.

The peak tritium concentrations in 1963 depicted above (Figure 7) is equivalent to 12,500 pCi/L (~462 Bq/L). In other words, the average tritium concentration in *rainfall* across the entire northern hemisphere was >60% of the EPA limit for drinking water at 20,000 pCi/L (740 Bq/L). Because nuclear weapon testing was severely curtailed and almost entirely stopped by the mid-1990s levels of environmental tritium produced from nuclear explosions have significantly reduced through natural decay, and by 2044 will be almost entirely gone.

What happens to anthropogenic tritium when it enters the environment? Tritium behaves just like other hydrogen isotopes, which disperse throughout water and air. Tritium in gaseous states diffuse widely and pose very little radiological risk. Any tritium gases that an organism breathes in will more than likely just be exhaled. Tritium also forms chemical bonds with oxygen to make water and various other common hydrogen compounds. Any tritiated water as T_2O or HTO will tend to reside in organisms for longer periods which are characterized by a biological half-life. A biological half-life is like the radioactive half-life but instead of measuring the decay process it measures the time radioactive materials reside in the body before they are expelled through typical biological processes. Each radioisotope may have widely varying biological half-life values because the duration will depend on the specific radioactive compound's behavior inside different types of organisms. Typically, the biological half-life of many tritiated compounds is about 10 days. This means that after a month almost 90% of a single intake (acute exposure) will be excreted and essentially 100% after two-and-a-half months.[242] Longer-term chronic exposures to elevated levels in the environment will lead to an increased equilibrium level based on the biological half-life rate.

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[241] Seignette and Lafontan, 5.

[242] Makhijani, *Exploring Tritium Dangers*, 38.

Importantly, tritium can also form bonds in organic molecules and become integrated into living organisms. These compounds are referred to as organically bound tritium (OBT). The typical biological half-life of OBT is 40 days.[243] A research review from experts at IRSN from 2017 concluded that

> [as] far as OBT is concerned, although the vast majority of the observed environmental concentrations are explained by HTO concentrations in the surrounding environment, the compartments that store organic matter (aquatic plants, plants that are long-lived or have slow metabolisms, soils and sediments) may show significantly higher OBT concentrations than expected, evidence for the persistence of tritium emitted by historical releases or inputs. The fate of these forms in the environment seems to depend on the kinetics of the metabolic processes and of the decomposition rate of organic matter. Uptake of these forms by living organisms is directly linked to the use that organisms make of organic compounds.

In other words, the imbalance between non-organic tritiated compounds, like HTO, and OBT in most instances is explainable by the differences in the biological half-life. “Significantly higher OBT concentrations than expected” in some organic material can be attributed to the localized persistence of significant historical emissions. The behavior of OBT is extremely complex, and every researcher that considers it suggests *more study is needed* to determine causal linkages with environmental impacts and human health.

The good news is that there are no definitive and obvious epidemiological effects from environmental tritium and OBT, but that does not mean that adverse impacts can be ruled out. Arjun Makhijani poses a plausible pathway for OBT becoming incorporated into a cell and damaging mitochondrial DNA. I examine Makhijani’s construction of tritium’s byproduct nuclearity in terms of radiological risk in the final section of this chapter. The next section considers the case of Fukushima Daiichi as a case study of tritium’s pollutant nuclearity on a global scale.

Tritium in Releases from Fukushima Daiichi[244]

On August 24, 2023, Japan’s Tokyo Electric Power Company (TEPCO) began releasing the first batch of treated wastewater from the Fukushima Daiichi site. This comes over twelve years after the Tōhoku earthquake and tsunami that occurred on March 11, 2011, resulting in the partial meltdown of fuel at three power reactors of the six-reactor site. While much of the damage occurred in the immediate aftermath and several weeks that followed, in many senses Fukushima Daiichi is the site of an on-going disaster that must be continually mitigated and managed. A key aspect of the mitigation plan has been the on-site storage and treatment of many millions of gallons of water being used to cool the damaged fuel. At 1,000 m^3 each of over 1,000 total tanks on site, the current accumulated volume is ~1,000,000 m^3 of treated wastewater or >260 million gallons.

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[243] “IAEA Comprehensive Report on the Safety Review of the Alps-Treated Water at the Fukushima Daiichi Nuclear Power Station,” 2023, 129, https://www.iaea.org/sites/default/files/iaea_comprehensive_alps_report.pdf.

[244] “IAEA Comprehensive Report on the Safety Review of the Alps-Treated Water at the Fukushima Daiichi Nuclear Power Station.” This IAEA report is my primary source for chronology and basic facts. Because a subset of scholars and experts find both TEPCO and IAEA unreliable sources of information I will attempt to state as matter of fact only uncontested information. Additionally, I will limit the consideration of any broad organizational criticisms to specific points of contention that are relevant to tritium.

The wastewater is being treated via the Advanced Liquid Processing System (ALPS) along with several other systems and processes to remove almost all heavier radionuclides except for tritium. Because the tritium levels are already very low there are no existing, industrial-scale technologies that can further lower the tritium levels. Faced with the prospect of indefinitely expanding the number of storage tanks on site, the Japanese government developed a plan in April 2021 to discharge the treated wastewater into the sea. The five-part conclusion to the report begins by stating that the plan is necessary and should not be delayed followed by three paragraphs focused on responding to "adverse impacts on reputation."[245] The "reputations" in question were not just of TEPCO and the Japanese government but also the many stakeholders who voiced their concerns from the general public to "the production association of agricultural, forestry and fishery industries."[246] The initial batch release of ALPS treated wastewater was met with notable civil protests and policy reactions from regional governments.

Releasing the water into the ocean was one of several alternatives considered. After a six-year study, the TEPCO Tritiated Water Task Force and Subcommittee on Handling ALPS treated water (ALPS subcommittee) narrowed down alternatives to five choices: geosphere injection, discharge into the sea, vapor release, hydrogen release, and underground burial. The default option of continuing to store water in tanks on site was rejected due to limited space, and the possibility of expanding storage to off-site facilities was dismissed due to the time projected to secure "business permission" and the "understanding of the municipalities."[247] Both vapor release (evaporation) and sea discharge were seen as feasible options, and the other options either lacked established monitoring regimes or raised unexplored regulatory questions. Only the sea discharge approach had a clear regulatory track record and substantial operational precedent.[248]

One outside the box idea suggested by the Independent Expert Panel to the Pacific Islands Forum in August 2022 was that the treated wastewater should be used in general-use concrete for construction on-site and across Japan to avoid "transboundary impacts" to countries without nuclear power plants.[249] Their proposal differed from the "underground burial" option previously considered that would have also solidified the water in concrete in that the original position would use untreated wastewater instead of ALPS treated water. While the group suggests that "some or *much* of the ALPS treated water" could be used for on-site concrete needs, it is unclear what percentage of the proposed 3.2 million tons of cement is suggested by "much."[250] All other off-site uses would involve transporting the "radioactively contaminated water" to construction sites for use across Japan over a projected period of 10 years. In their June 12, 2023, paper, they do not address various issues cited in TEPCO's 2021 "Basic Policy" report for rejecting alternatives to sea discharge including similar business and municipality permissions that would be needed, evaporation of water during solidification of concrete, and concerns

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[245] "Basic Policy on Handling of Alps Treated Water at the Tokyo Electric Power Company Holdings' Fukushima Daiichi Nuclear Power Station (Provisional Translation)" (The Inter-Ministerial Council for Contaminated Water, Treated Water and Decommissioning issues, April 13, 2021), 14, https://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/bp_alps.pdf.

[246] "Basic Policy on Handling of Alps Treated Water," 5.

[247] "Basic Policy on Handling of Alps Treated Water," 4.

[248] "Basic Policy on Handling of Alps Treated Water," 4.

[249] Arjun Makhijani et al., "Minimizing Harm: The Concrete Option for Solving the Accumulation of Radioactively Contaminated Water at the Fukushima Daiichi Nuclear Power Plant Site," June 12, 2023, 3, https://cafethorium.whoi.edu/wp-content/uploads/sites/9/2023/06/Concrete-paper-Final-2023-06-12-v-2.pdf.

[250] Makhijani et al., 3. Emphasis mine.

about reputational damage. If *any* sea discharge of the treated wastewater would produce additional reputational harm to the area and its stakeholders, then how might millions of tons of *radioactive concrete* that would remain in place 100+ years be perceived? The ostensible conclusion of the Independent Expert Panel is that TEPCO and the Japanese government have an obligation to consider their "concrete option," and they have failed to do so. I will return to this proposal in the conclusion to this chapter. For now, I will turn to tritium's broader environmental context in the nuclear disaster at Fukushima Daiichi.

In the aftermath of the Tōhoku earthquake, Japan suspended operation for 19 of the remaining 33 operational reactors.[251] I conservatively estimate that between 2011-2023 these suspensions have avoided the release of ~1,554 TBq of tritium.[252] The Japanese government has set an annual tritium sea discharge limit for ALPS treated water of 22 TBq. Therefore, if the maximum amount of tritium is released each year over the projected 30-year period, then total amount of tritium released would be 660 TBq, or less than half of the total releases already avoided during the past 12 years. Note also that these are only aggregate total releases, and in order to calculate effects on regional inventories of tritium in sea water correcting for decay would be required. With respect to tritium, actions by the Japanese government in all likelihood have significantly lowered their national contribution to the equilibrium in the regional environment for the last 12 years and releasing 22 TBq/y of tritium from the Fukushima Daiichi site would be insufficient by itself to reverse that trend. This comparison should not be taken as a dismissal of concerns for tritium's potential radiological risks but as a frame of reference for proportion and context.

Critics of the Japanese decision to release treated wastewater tend to invoke tritium as illustrative of the severity of contamination and as a proxy for "more dangerous isotopes."[253] Ken O. Buesseler, a member of the Pacific Islands Forums mentioned above, published a critique in *Science* August 7, 2020 detailing associated tritium risks:

> Fortunately, tritium is relatively harmless because it emits a low-energy β particle that does little damage to living cells. As a result, tritium has the lowest dose coefficient for those radioactive isotopes reported in the tanks…and higher allowable release limits... *These properties do not detract from the potential for large amounts of tritium to have harmful effects, and debates remain about the potential health effects*.
>
> The total amount of tritium contained in the tanks also matters, which is reported to be around 1 PBq (PBq = 10^{15} Bq)...That total is far less than the 8000 PBq of tritium still remaining from global atmospheric nuclear testing in the 1960s or the 2000 PBq from

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[251] "IAEA|CNPP Japan 2023," 2023, https://cnpp.iaea.org/public/countries/JP/profile/preview; "Radioactive Effluent and Environmental Reports," NRC Website, accessed January 22, 2024, https://www.nrc.gov/reactors/operating/ops-experience/tritium/plant-info.html. Accessed on 01/22/2024. Data for this section is drawn from the IAEA Country Nuclear Power Profile (CNNP) of Japan and the NRC Annual Radioactive Effluent Summary Reports found at the links above.

[252] This estimate is based on U.S. data on median releases of tritium for the type of plant suspended (PWR or BWR) for each respective year. This approach is conservative because the U.S. median release values are relatively low, and the actual values would likely be higher but within the same magnitude. 1,554 TBq (terabecquerels) of tritium is roughly equivalent to 42,003 Ci or a little over 4 g.

[253] Ken O. Buesseler, "Opening the Floodgates at Fukushima," *Science* 369, no. 6504 (August 7, 2020): 621, https://doi.org/10.1126/science.abc1507. Emphasis mine.

> natural interactions between cosmogenic particles and nitrogen that form tritium in the atmosphere. In addition, all nuclear power facilities emit tritium that, depending on plant design, can be several PBq per year, or even higher, as in the case of nuclear fuel reprocessing plants such as at Cap de La Hague.

Tritium is both "harmless" and potentially "harmful" in "large amounts." Hence, Buesseler offers comparisons that appear to suggest that the Fukushima Daiichi total tritium content (1 PBq) and proposed release rate (22 TBq/year) do not qualify as large amounts but "debates remain."

On August 24, 2023, the Chinese government issued a strongly worded condemnation of the Fukushima Daiichi release as well:

> The ocean belongs to all humanity. To forcibly start the ocean discharge is an extremely selfish and irresponsible act in disregard of the global public interest. By dumping the water into the ocean, Japan is spreading the risks to the rest of the world and passing an open wound onto the future generations of humanity. By doing so, Japan has turned itself into a saboteur of the ecological system and polluter of the global marine environment. It is infringing upon people's rights to health, development and a healthy environment, which violates Japan's moral responsibilities and obligations under international law. *From the moment Japan started the discharge*, it has put itself in the dock in front of the international community and is bound to face international condemnation for many years to come.
>
> The Chinese government always puts our people's wellbeing first and will take all measures necessary to safeguard food safety and the health of our people.[254]

From the Chinese government's perspective, the effect of the releases were instantaneous, global, and irrevocable. Accompanying this press releases was an announcement that China had suspended "the import of all aquatic products originating from Japan." At a press conference the day before the releases began, the Foreign Ministry Spokesperson Wang Wenbin responded to a question asked by a member of the Associated Free Press (AFP):

> AFP: Independent nuclear experts have told AFP that the levels of tritium expected to be released by Japan are well below the WHO drinking water standards. And Japanese media have also reported that levels of tritium recorded in wastewater from Chinese nuclear plants in 2021 exceeded the maximum levels for the treated water that will be released by Japan. So in this case, can you tell us what's the scientific basis for China's opposition to Japan's plan?
>
> Wang Wenbin: Like we have said many times, *there is a fundamental difference between the nuclear-contaminated water that came into direct contact with the melted reactor cores in the Fukushima nuclear disaster and the water released by nuclear power plants in normal operation. They are different in nature, come from different sources and require different levels of sophistication to handle.* Japan deliberately compares the

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[254] "Foreign Ministry Spokesperson's Statement on the Japanese Government's Start of Releasing Fukushima Nuclear-Contaminated Water into the Ocean," August 24, 2023, https://www.fmprc.gov.cn/eng/xwfw_665399/s2510_665401/2535_665405/202308/t20230824_11131325.html.

> Fukushima nuclear-contaminated water with water released by nuclear power plants in normal operation, which only proves that Japan is not handling the issue scientifically and is deliberately misleading the international community.[255]

Spokesperson Wenbin does not directly address the question on tritium, nor does he state any other specific isotopes of concern. Instead, he asserts an essential difference between the sources of radiologically contaminated water. He goes on to say that "China and other stakeholders have pointed out on multiple occasions that if the Fukushima nuclear-contaminated water is truly safe, Japan wouldn't have to dump it into the sea—and certainly shouldn't if it's not."[256] One could wonder the same thing about water released by nuclear power plants.

Another expert from the Independent Expert Panel, Ferenc Dalnoki-Veress, also asserts this essential difference:

> But [Fukushima Daiichi's] water is different, as it has come into direct contact with molten nuclear fuel and has been contaminated as the result of an accident. Consequently, *many different types of radionuclides may be present.* Justifying the release from Fukushima on the basis of normal practice sets a terrible precedent for future nuclear accidents, which are bound to occur.[257]

A common thread throughout these expert and political critiques is the accusation, warranted or not, that Japan, TEPCO, the IAEA, or some subset of the three cannot be trusted to follow past commitments and suggestions for alternative courses of action—that would then also need to be trusted by the international community. Japan appears to be in a technoscientific and political Catch-22 of their own making.

The tritium content of the treated wastewater taken in isolation would generally be within the scope of "normal" NPP byproduct nuclearity—and in fact would be much lower than a typical operating plant. However, tritium also exhibits the highest activity and mobility of all radioisotopes from the anticipated releases. Therefore, tritium measurements (both HTO and OBT) in the ocean environment will provide the strongest signal of the extent of the radioisotope diffusion. As Japan continues to restart their nuclear fleet, it is likely even that signal might be lost in the new "normal" background conditions. Tritium's byproduct nuclearity is a hinge point in the Fukushima Daiichi ocean release debate as some experts accuse Japan and TEPCO of emphasizing the tritium content to distract from other potential isotopes of concern. If Japan, TEPCO, the IAEA, and other independent analysts begin detecting unexpected levels of any of these isotopes in the environment, they can stop. With a projected 30-year completion timeline for all planned ocean releases, there will be ample opportunity for international intervention if the facts on the ground warrant it.

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[255] "Foreign Ministry Spokesperson Wang Wenbin's Regular Press Conference on August 23, 2023," August 23, 2023, https://www.fmprc.gov.cn/eng/xwfw_665399/s2510_665401/2511_665403/202308/t20230823_11130960.html. Emphasis mine.

[256] "FM Spokesperson Wenbin."

[257] Ferenc Dalnoki-Veress, "It Is Not Too Late for Japan to Change Course on Fukushima Water," Nikkei Asia, August 24, 2023, https://asia.nikkei.com/Opinion/It-is-not-too-late-for-Japan-to-change-course-on-Fukushima-water.

Exploring Remaining Debates: Natural vs. Byproduct

The latest contribution to the debates surrounding tritium is Dr. Arjun Makhijani's *Exploring Tritium Dangers: Health and Ecosystem Risks of Internally Incorporated Radionuclides* (2023). In his book, self-published by IEER, Makhijani assesses and refutes arguments from those who have long-contended—as his Pacific Island Forum Expert Panel colleague Dr. Buessler does above—that tritium in low amounts is "relatively harmless." To this end, he deconstructs the radiological risk frameworks responsible for producing tritium's benign byproduct nuclearity and suggests that such a conclusion is only possible because pregnant individuals, embryos, and fetuses have been neglected by the "Reference Man" model. He hypothesizes that the radiological risks posed by tritium to these understudied and vulnerable populations is much higher than previously assumed and the best way to protect these groups is to lower drinking water limits for tritium in the U.S. from 20,000 pCi/L (740 Bq/L) to 400 pCi/L (15 Bq/L). In this section, I analyze Makhijani's (de)construction of tritium's byproduct nuclearity and consider possible rapprochements between these competing paradigms.[258]

Makhijani frames the scale of tritium's global material balances by directly comparing "the natural total inventory of tritium [of] less than 10 kilograms" with the "five million trillion kilograms" of mass in Earth's atmosphere. This is the only time he refers to tritium's vanishing *dilution* act in the vastness of the environment. The apparent implication is that this natural nuclearity relies on the existence of "very minute amounts" and byproduct nuclearity emphasizes that "man-made quantities of tritium far exceed those in nature."[259] One nuclear industry presentation from 2006 used an outdated metric of 100-300 pCi/L (~4-11 Bq/L) to represent the remaining tritium background from nuclear weapon testing.[260] In actuality, Makhijani argues, the "modern-day levels" cited in 2006 should be closer to 27-108 pCi/L (1-4 Bq/L), and that the slightly higher levels suggested would allow "[attribution of] tritium contamination in many areas to 'background' even if it is largely or even mainly due to nuclear power plant emissions and discharges."[261] It should be noted that typical values of Minimum Detectable Concentrations (MDC) cited by the EPA for assessing tritium in precipitation and drinking water is ~137 pCi/L (~5 Bq/L); there may be practical considerations and resource limits for producing useful "non-nuisance" results from specific detection methods.[262] Makhijani estimates the environmental inventory remaining from nuclear weapon testing in 2020 was about 20 kilograms. Unless Russia or another NWS decides to restart atmospheric nuclear testing, over the next 20 years this amount will dwindle to parity with the scant quantities from natural processes.

Of the remaining sources of tritium in the environment, Makhijani considers routine emissions from spent fuel pools and gaseous and liquid effluent releases from PWRs in the U.S. As I note above, BWR

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[258] Please note that despite Makhijani's book being published in 2023 many of his presuppositions are based on several outdated scholarly and policy references—some of which are 30 years old and have been superseded several times—I attempt to balance considering his arguments in good faith and providing updated references where appropriate.
[259] Makhijani, *Exploring Tritium Dangers*, 3–4.
[260] Ken Sejkora, "Atmospheric Sources of Tritium and Potential Implications to Surface and Groundwater Monitoring Efforts, Entergy Nuclear Northeast – Pilgrim Station" (The 16th Annual RETS-REMP Workshop, Mashantucket, CT, June 26, 2006), 6, https://documents.pub/document/atmospheric-sources-of-tritium-and-potential-implications-to-surface-and-groundwater.html.
[261] Makhijani, *Exploring Tritium Dangers*, 20.
[262] "RadNet Search | Envirofacts | US EPA," accessed February 19, 2024, https://enviro.epa.gov/envirofacts/radnet/search.

sites generate substantially less tritium during operation and subsequently have much lower environmental releases. In 2015, a high concentration of tritium from water "dripping from an icicle near the north end of the Hope Creek Turbine building" was identified and reported by Public Service Electric and Gas (PSEG), the nuclear plant operator. The sample was measured at 10,000,000 pCi/L (370,000 Bq/L). Based on this anomalous reading, Makhijani suggests:

> Such high concentrations in precipitation may indicate high episodic releases, raising questions about whether such releases are being adequately captured by monitoring. As noted above, the reported release to the atmosphere in 2008 was a small fraction of a curie. Thus, high year-to-year variations are also indicated if the source was the Hope Creek plant.
>
> There is another nuclear power plant very near the Hope Creek plant – the Salem plant, which has two PWRs. The NRC document does not examine whether the highly contaminated rainfall came from Hope Creek emissions or Salem emissions or some combination of both.[263]

Because this concentration roughly corresponds to 20-50 million pCi/L typical for PWR spent fuel pool water, Makhijani further suggests that spent fuel pool fuel evaporation combined with local meteorological conditions may have been the source. The implication is that such "high episodic releases" might provide an ineffectively monitored contamination pathway to groundwater and ultimately drinking water for any nearby households reliant on well water which are not required to be routinely monitored for radioisotopes by the NRC or EPA.[264]

The other major tack of Makhijani's argument considers radiological risks to pregnant individuals, embryos, and fetuses due to tritium intake and its incorporation into organically bound tritium (OBT). The limitations of Makhijani's presuppositions become evident when a reader begins assessing the sources relied upon to expose the antiquated "Reference Man" radiological risk paradigm. He notes:

> The official advice upon exposure has been to reduce the impact by drinking beer or other beverages: "Although the average biological half-life [of tritiated water] is 10 days, it can be decreased by simply increasing fluid intake, especially diuretic liquids such as coffee, tea, beer, and wine." Not wrong advice, of course; *yet, it is noteworthy that there are no cautions for women who are pregnant. In fact the words "pregnancy," "embryo," and "fetus," do not appear in this official handbook for "safe handling" of tritium.*

Having worked in the nuclear power industry from 2012-2019, I immediately thought that the omission of "pregnancy" from radiological worker concerns was highly suspect. The source he cites here is a 1994

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[263] Makhijani, *Exploring Tritium Dangers*, 27.

[264] Makhijani, 28. He cites a single recorded instance of tritium migrating offsite a nuclear power plant site and contaminating a private well. The results of the investigation were performed and reported by Exelon Nuclear. In 13 of 14 private wells measured below 142 pCi/L (presumed to be the Lower Limit of Detection). The well that showed detectable levels was tested three times ranging between 1,151-1,524 pCi/L. "Braidwood Station: Groundwater Tritium Investigation" (Braidwood Station: Exelon Nuclear, December 20, 2005), 5, https://www.nrc.gov/docs/ML1024/ML102450690.pdf.

"DOE Handbook: Primer on Tritium Safe Handling."[265] This document provides good, albeit dated, general information on tritium, and as of October 1, 2001, it has been designated "Archived" in the publicly accessible document database of the DOE Technical Standards Program.[266] While this document is not explicitly superseded by any other documents in the database hierarchy, it is referenced within other current documents covering the safe handling of tritium. In particular, "DOE Handbook: Tritium Handling and Safe Storage," introduced in 1999 with the latest revision in 2015, includes an updated version of the "Primer" in Appendix G. Not only are "declared pregnant workers" included in the current document, but it also references several other documents relevant to radiological cautions for pregnant workers. Key documents that are explicitly referenced to be used with this up-to-date reference include: "Radiation Protection Programs Guide," "Radiological Control Programs for Special Tritium Compounds," "Radiological Training for Tritium Facilities," and "Internal Dosimetry."[267] All but "Radiological Training for Tritium Facilities" includes reference to "declared pregnant workers," Workers who are pregnant or intend to become pregnant can voluntarily disclose this information to their supervision, and any such declaration will be accompanied by different work assignments or dosimetry requirements as appropriate. Additionally, this guide explicitly covers possible tritium exposure to an Embryo/Fetus:

> If an intake of radioactive material occurs, or occurred between conception and the declaration of pregnancy, the equivalent dose to the embryo/fetus should be determined as follows. The equivalent dose to the embryo/fetus from radionuclides in the embryo/fetus and in the mother that are relatively uniformly distributed, such as Cs-137 and compounds of H-3 and C-14 that are not organically bound, may be considered to be the same as the equivalent dose to the mother because, under these circumstances, the same energy would be deposited per gram of tissue in both the mother and the fetus. Refer to ICRP Publication 88*, Doses to the Embryo and Fetus from Intakes of Radionuclides by the Mother,* (ICRP 1998) for methodologies for estimating dose to the embryo/fetus. If other methods are used, the basis for their use in demonstrating an equivalent or better level of protection should be documented.[268]

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[265] "DOE Handbook: Primer on Tritium Safe Handling Practices" (Department of Energy (DOE), December 1994), 19, https://www.osti.gov/servlets/purl/10196000. Makhijani's error is likely attributable to relying on the more expansive, general document archive provided at OSTI.gov rather than the official database maintained for the DOE Technical Standards Program. This "primer" is widely cited, but it is also outdated with respect to the specific concerns Makhijani addresses in his book.

[266] "DOE Technical Standards Program," Page, accessed February 19, 2024, https://www.standards.doe.gov.

[267] John Blaikie, "Radiation Protection Programs Guide for Use with Title 10, Code of Federal Regulations, Part 835, Occupational Radiation Protection," Directive, July 8, 2011, https://www.directives.doe.gov/directives-documents/400-series/0441.1-EGuide-01c-admchg1; "DOE Handbook: Radiological Control Programs for Special Tritium Compounds," June 2006, https://www.standards.doe.gov/standards-documents/1100/1184-bhdbk-2004-cn1-2006/@@images/file; "DOE Handbook: Radiological Training for Tritium Facilities" (Washington, D.C.: Department of Energy (DOE), January 2007); "Internal Dosimetry," DOE Standard (Department of Energy (DOE), November 2022), https://www.standards.doe.gov/standards-documents/1100/1121-AStd-2008-cn1-2013-reaff-2022/@@images/file.

[268] Blaikie, "Radiation Protection Programs Guide for Use with Title 10, Code of Federal Regulations, Part 835, Occupational Radiation Protection," 102.

The International Commission on Radiological Protection (ICRP) Publication 88 referred to is also the reference cited by Makhijani as providing "the established fact of maternal to fetal radionuclide transfers."[269]

Basic radiation worker practices such as As Low As Reasonably Achievable (ALARA) also serve a blanket precautionary role against tritium exposure. In my experience in the nuclear power industry, declared pregnant workers were typically placed in the lowest dose roles for the duration of their declaration. Tritium risks are already emphasized by the additional practice of radiobioassay (bioassay):

> Measurement of the amount or concentration of radionuclide material in the body or in biological material excreted or removed from the body and analyzed for purposes of estimating the quantity of radioactive material in the body.[270]

In lay terms, this means pooping in a bag and peeing in a jug for radiological analysis. For facilities with the possibility of workers intaking radioactive contamination, including tritium, "as a verification, it may be desirable to obtain a special bioassay upon receipt of a pregnancy declaration, with a follow-up special bioassay at the conclusion of pregnancy if the worker continues to be exposed to possible intakes."[271] Not only is the minimization of occupational dose universally practiced through ALARA and further emphasized through lower-dose work assignments of declared pregnant workers, but also monitoring programs serve to validate the success of these practices. In summary, current radiation worker practices in the U.S. are more precautionary toward potential tritium exposures to a developing embryo/fetus than Makhijani implies in his book.

With respect to the critique of "the use of Reference Man, a hypothetical 20 to 30 year old Caucasian male, in radiation protection regulations and guidelines," Makhijani poorly represents his own previous work on the subject and seems to imply, if a reader takes *Exploring Tritium Dangers* in isolation, that little to no effort has been made to revise or improve on this antiquated paradigm established in 1975.[272] In fact, several of the recommendations he posed to the NRC, DOE, and EPA in a 2008 report critical of "Reference Man" have made some progress, albeit with characteristic bureaucratic lethargy. *Exploring Tritium Dangers* would have been an excellent opportunity to revisit these issues as they relate to tritium regulations and risk assessments. Instead, his critique appeared to be as static and reductive as the radiological risk model he was challenging.

The byproduct nuclearity relied on and further constructed in *Exploring Tritium Dangers* is also readily apparent in the book's accompanying blurbs. The oppositional tone in these excerpts is clear:

> Efforts to trivialize the potential effects of tritium in the environment ignore organic-binding, the uptake, trophic transfer and bio-accumulation by marine organisms, and

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[269] Makhijani, *Exploring Tritium Dangers*, 69.

[270] "Internal Dosimetry," 15.

[271] "Internal Dosimetry," 59.

[272] Arjun Makhijani, "The Use of Reference Man in Radiation Protection Standards and Guidance with Recommendations for Change, Rev. 1 (April 2009)" (Institute for Energy and Environmental Research (IEER), December 2008); Arjun Makhijani, Brice Smith, and Michael C Thorne, "Science for the Vulnerable Setting Radiation and Multiple Exposure Environmental Health Standards to Protect Those Most at Risk" (Takoma Park, MD: Institute for Energy and Environmental Research (IEER), October 19, 2006).

> effects on the cells within individuals who eat contaminated seafood products, including on nuclear DNA, mitochondrial DNA, RNA and signaling proteins. -Dr. Robert Richmond
>
> For decades, it has been claimed that tritium is a minor hazard, dispersing widely in water, that its beta radiation is not penetrating and relatively weak. With harder to assess exposures and risks, such internal emitters have often not been adequately addressed by radiation protection standards. -Tilman Ruff
>
> Highly recommended for anyone looking to understand the need for higher standards in radiation protection. -Dr. Ferenc Dalnoki-Veress[273]

I agree that there is a vocal minority of nuclear power proponents, sometimes derogatorily referred to as “nuke bros” on social media, who persistently trivialize and downplay radiation risks, including risks associated with tritium. They commonly deploy arguments that reduce tritium exposure to a dose value without considering risks to vulnerable populations beyond lifetime cancer rates. I share the author’s and reviewers’ exasperation with these bad faith actors. However, I disagree with them that this exasperation should extend to scholars, professionals, and experts diligently working in the radiation protection domain. As I have argued and demonstrated above, many radiological concerns stemming from the outdated “Reference Man” model are actively being addressed and revised. There is certainly more work that needs to be done, and Dr. Makhijani’s work, despite its deficiencies, is important because it highlights critical humanitarian issues of understudied radiological risks to women, children, and developing fetuses/embryos. Establishing a more robust understanding of risks posed by tritium *today* will provide a better foundation for safety-related design considerations, responsible regulation, and informed stakeholder consent necessary for the possible deployment of commercial fusion power *tomorrow*. Tritium-intensive technologies, like all technologies, are not inevitable but are the result of many human decisions. These decisions should be based on the best available data that consider holistic social concerns and long-term effects on public health.

Conclusion: Unresolved Tensions

In the environmental and human health contexts, tritium’s byproduct nuclearity and natural nuclearity have historically been conflated through the *dilution* approach to tritiated wastes. Radiological protection experts in the 21st century have been improving environmental measurements, promoting best worker practices, reevaluating risk assumptions, and considering unique and under researched OBT concerns. Scientists and activists like Dr. Makhijani play an important role in maintaining democratic accountability for large-scale technological projects and infrastructures. The tritium debate that I frame in competing nuclearities is merely one salient of that struggle. More science—even citizen science—is unlikely to resolve these tensions, but it may offer more clarity of the stakes and tradeoffs.

Chapter 5: Fission, Fusion, and the End of Nuclear Weapons

Fusion Futures

In June of 2022, the NRC hosted a public meeting on “Developing a Regulatory Framework for Fusion Energy Systems.” Participants included representatives of the Fusion Industry Association (FIA), the Fusion Energy Systems Working Group, the Nuclear Innovation Alliance, the Office of Nuclear Material

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[273] Makhijani, *Exploring Tritium Dangers*.

Safety and Safeguards (NMSS), Savannah River National Lab (SRNL), and the Fusion Technology Institute at University of Wisconsin-Madison, along with representatives from fusion startups Commonwealth Fusion Systems, Helion Energy, as well as the established "defense and diversified technologies company" General Atomics (GA).[274] Most of the presentations stress the fact that tritium nor any other radioactive material used in fusion facilities would be classified as *special nuclear material*. The special nuclearity often informally attributed to tritium by nuclear weapon practitioners, highlighted in chapter 2, becomes anathema to the peaceful exceptionalism embraced by fusion power advocates. Statements to this effect are often emphasized in bold and colored text.

Typical fission NPP are regulated under 10 CFR 50—Domestic Licensing of Production and Utilization Facilities based on the use of enriched uranium as fuel, the production of plutonium during irradiation, and the need for nuclear criticality controls. Fusion facilities, according to industry proponents, should instead be regulated under 10 CFR 30—Rules of General Applicability to Domestic Licensing of Byproduct Material. Fusion plasma ignition (or another analogous fusion process) is qualitatively different than fission chain reaction criticality—for example, there is no risk of uncontrolled power increases for fusion processes (e.g. no potential for fuel "meltdown"). Furthermore, because no uranium is used to generate fusion energy, even the incidental production of plutonium can be categorically excluded. This regulatory position echoes the "byproduct material" arguments for tritium production in a CLWR from Chapter 2. As defined in 10 CFR 30.4: "*Byproduct material* means— (1) Any radioactive material (except special nuclear material) yielded in, or made radioactive by, exposure to the radiation incident to the process of producing or using special nuclear material."[275] This approach also creates a chicken-or-the-egg dilemma for fusion regulation. Is there a meaningful technical difference between large quantities (several tens of kilograms) of purified tritium being used as fuel and tritium being produced as a *byproduct* of these nuclear processes?

The distinctions between SNM-enmeshed fission facilities and prospective fusion power designs carry with them regulatory advantages. 10 CFR 30 is already used to govern tritium use and production, which would reduce regulatory uncertainty. Also, the stigma and safeguards associated with SNM can be avoided. The alternatives, licensing fusion facilities under 10 CFR 50 or drafting entirely new guidelines, would add additional compliance burdens to an already unproven, uncertain, and expensive class of first-of-a-kind technologies. Even under an ideal regulatory regime, significant questions remain with respect to how the byproduct nuclearity of tritium will scale with the vast quantities required.

Only Laila El-Guebaly, the academic representative from University of Wisconsin-Madison, emphasized tritium's byproduct nuclearity in terms of pollution, spending considerable time evaluating potential waste concerns with fusion power. In her exhaustive analysis, she highlights the need for U.S. disposal sites designed for tritiated radwaste. While the SRNL offered their "extensive experience handling tritium at the quantities required for fusion machines" as a "resource to the fusion community and

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[274] "Developing a Regulatory Framework for Fusion Energy Systems," https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML22159A269. Unless otherwise noted, information from this section is taken from the slide presentations for this meeting.

[275] "10 CFR 30.4 Definitions," NRC Web, accessed March 8, 2024, https://www.nrc.gov/reading-rm/doc-collections/cfr/part030/part030-0004.html. Emphasis in original.

NRC," how this expertise—and waste streams—might scale from bespoke defense facilities to a fleet of civilian fusion power reactors remains to be seen.[276]

With respect to tritium's dual use capabilities, the meeting participants appear to be generally unconcerned with the nonproliferation risks, at least with respect to facilities operating in the U.S. Throughout the day-long meeting, the special role of tritium in virtually all modern nuclear weapon designs is never directly addressed in the presentation slides and only referenced obliquely with the term "dual use." The Helion presentation cites existing control regimes as being sufficient to control for proliferation risks posed by tritium and "thermonuclear knowledge." The presentation by Commonwealth Fusion Systems goes so far as to assert "no substantive connection to common defense and security":

- **Commercial fusion devices do not use special nuclear material or source material as the NRC defines these terms**
    - Fusion energy machines as designed will not be capable of producing fissionable materials
    - *Using any neutrons released in fusion reactions to produce fissionable materials would be an extraordinarily challenging way to create weapons material*
        - *Manufacturing weapons materials would require a complete re-design of a fusion machine*
        - *First, one needs to have access to either special nuclear material or source material in violation of the safeguard regime*
        - *Moderation of neutrons would be needed since the fission cross-section is higher than capture for both uranium/thorium*
        - *Fission fragment isotopes necessitate a separate reprocessing step done in a separate facility which would require transportation of highly radioactive material off-site*
        - *Fission fragment isotopes would likely also cause operational issues since the blanket systems are not designed for this and they would take neutrons away from re-generating tritium which is needed for fusion power operation*[277]

Tritium and lithium-6 (although the presenters stress other isotopes of lithium could be used) are not characterized as materials required to produce thermonuclear weapons. Only "fissionable materials" are highlighted as defense related. The SNM category is again treated as both a physical property of the materials and synonymous with "weapons material" writ large, rather than an artifact of policy based on some materially sufficient parameters. As a reminder of the discussion in Chapter 2, provision 51 of the AEA allows for Presidential discretion in assigning any additional materials to the SNM category. If any President had deemed it necessary for national defense, tritium could have been designated SNM. Even though such a decision would have been much more conceivable before tritium was made commercially available by Oak Ridge National Lab in 1962 than it would be today, this dimension of nuclear policy should guard against essentializing SNM as a scientific property.

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[276] "Developing a Regulatory Framework for Fusion Energy Systems," 148. Since a single commercial-scale fusion power reactor might require more tritium on an annual basis than the U.S. currently possesses in tritium reserves, it is unclear here what is meant by "at the quantities required" in this context.

[277] "Developing a Regulatory Framework for Fusion Energy Systems," 110. Emphasis in original.

The scope of this meeting concerned best practices for domestic regulation and policy concerning fusion power in the U.S. Therefore, international dimensions of tritium and fusion technologies with respect to the NPT, IAEA, Nuclear Suppliers Group, or other global organizations, entities, and agreements served as a reference point for domestic considerations. In almost every instance, these references were made to illustrate how tritium and fusion are excluded or otherwise sufficiently covered under global regimes. It is perhaps unsurprising that representatives of the nascent fusion industry would bracket out nonproliferation concerns as largely irrelevant and primarily rooted in concerns with the potential for fusion technologies to be used in the production of fissile SNM. Experts from Helion shared a pre-print of an in-depth technical paper that came to similar conclusions:

> the current dual-use export control regime is an appropriate path to look to for fusion, in large part because any potentially significant malicious misuse of the fusion technology from a nonproliferation perspective would require significant material changes to the underlying technology by rogue actors. Applying and modifying a dual-use export controls approach as necessary alongside the NPT—including potentially developing a "controls by design" usage-based controls regime for fusion—can more effectively support the safe deployment of this essential technology rather than applying the ill-fit, fission-specific nonproliferation regime.[278]

From the standpoint of byproduct nuclearity, it is rational to change policies only "as necessary" to prevent "malicious misuse." In other words, the goal is to control risks by safeguarding the boundary between these domains of nuclearity. Now, compare this with Martin Kalinowski's recommendations for harmonizing tritium's special nuclearity in the context of nonproliferation and disarmament regimes with its byproduct nuclearity for commercial applications.[279] Safeguarding industrial applications for peaceful use must then be balanced with potential benefits of tritium control policies for nonproliferation regimes. Policies such as Kalinowski's ICO and ITCS might exceed what is considered necessary for commercial interests, but if they provide additional tools in support of the ultimate goal of total nuclear disarmament, then they may yet serve both commercial and human interests in the long term.

On April 13, 2023, the NRC commissioners unanimously voted "to license and regulate fusion energy systems under the [NRC]'s byproduct material framework contained in 10 CFR Part 30." This will require developing and expanding the byproduct regulation to include language covering "all near-term fusion energy systems that are within the NRC's jurisdiction, reducing regulatory uncertainty."[280] The limited-scope rulemaking process does offer important caveats that "larger, higher hazard commercial fusion energy systems that differ from the characteristics of near-term facilities noted above may require application-specific exemptions, license conditions, or hearing orders".[281] While near-term facilities likely to be developed, which will include first-of-a-kind and demonstration plants, will be governed by the byproduct regulatory framework, the larger commercial facilities that will follow may require a different approach. This allows the NRC to reduce regulatory uncertainty for the burgeoning fusion

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[278] Michael Y. Hua et al., "Nonproliferation and Fusion Power Plants" (July 28, 2022), 2, https://arxiv.org/abs/2207.14348v3.

[279] See chapter 4.

[280] Daniel H. Dorman, "Options for Licensing and Regulating Fusion Energy Systems," Policy Issue (Notation Vote), January 3, 2023, 18, https://www.nrc.gov/docs/ML2227/ML22273A163.pdf.

[281] Dorman, 18.

industry while maintaining the clear regulatory position that commercial-scale facilities may require additional regulations. Additionally, the Commission has directed NRC staff to "develop a new volume of NUREG-1556, 'Consolidated Guidance About Materials Licenses,' dedicated to fusion energy systems".[282] This document will provide guidance (not prescriptive advice) on approaches to meet these newly developed regulatory requirements. The current trajectory of fusion power regulation in the U.S. appears to be heavily invested in interpreting tritium, and future fusion energy, in terms of byproduct nuclearity.

In my own work, I attempt to harmonize tritium's special and byproduct nuclearities from the standpoint of the emerging material needs of peaceful fusion energy technology. In my essay "Speculating on Tritium Futures: Why Defense Material Should Fuel Fusion Innovation," I argue that U.S. military tritium reserves and production capacity should be strategically made available to ensure tritium supplies for fusion research and development. My proposed *Gigatons-to-Gigawatts* program—inspired by the successful Megatons-to-Megawatt program that downblended Russian HEU to fuel U.S. reactors—would create a pathway for military material to support critical energy infrastructure and long-term decarbonization goals.

Conclusion: Tritium Disentangled

At least part of the reason that tritium is both chimerical and misunderstood is that it does not fit neatly into existing narratives of nuclearity. Like uranium, tritium exists in the natural world, but unlike uranium it is not mineable or extractable by any known technology or conventional means. Instead, it must be produced in a reactor like plutonium, but unlike plutonium, tritium rapidly decays on the scale of years rather than thousands of years. While "weapons grade" plutonium is most easily produced in dedicated military production reactors, the U.S. has demonstrated that tritium can be produced more easily and cheaply inside commercial power reactors. With a half-life of 12.3 years, tritium is much more highly radioactive than common isotopes of both uranium and plutonium with half-lives ranging from thousands to millions of years. Even though it decays much faster, it only emits a weak beta particle (and no gamma rays) decaying into a stable, inert atom of He-3, and adverse health effects of tritium exposure are difficult to measure; Whereas, uranium and plutonium isotopes exhibit complex decay chains producing much more highly radioactive isotopes like Polonium-210, which the Russian government allegedly used in the high-profile assassination of Alexander Litvinenko, and Radon-222, which is a significant occupational health hazard in uranium deep-mining operations.

In the introduction, I explicitly link tritium production with uranium fuel and Hecht's analysis in *Being Nuclear: Africans and the Global Uranium Trade*. Without uranium, tritium would be little more than a scientific curiosity meticulously produced and sparingly used in laboratory settings. While there are other methods of tritium production such as cyclotrons, linear accelerators, and breeding blankets in fusion reactors, the only methods ever used for industrial-scale production rely on uranium fuel. Even if tritium breeding in fusion reactors becomes viable for producing tritium without uranium, there will remain an important connection with lithium that deserves further analysis. While much of current scholarship on lithium extraction centers on batteries and the so-called electric vehicle (EV) revolution, lithium has played and continues to play a crucial support role in the tritium supply chain for nuclear

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[282] Brooke P. Clark, "Staff Requirements – Secy-23-0001 – Options for Licensing and Regulating Fusion Energy Systems," April 13, 2023, https://www.nrc.gov/docs/ML2310/ML23103A449.pdf.

weapons.[283] Lithium deuteride (LiD) compounds also serve as powerful *in situ* tritium generators for some of the most powerful explosive devices ever designed and tested. Tritium's complex relationship to and interactions with other key nuclear weapons components are central to its nuclearity constructions.

Long considered and intermittently referred to as a special nuclear material (SNM), tritium has never met the definition establish by the Atomic Energy Act of 1954 and has never otherwise been legally declared as such.[284] Furthermore, I have been reminded by notable experts that, as Alan Robock told me, "you can't build a bomb with just tritium."[285] Tritium is simultaneously a critically important and essential material for the stockpile stewardship and maintenance of nuclear weapons and an insufficient and minor detail to nonproliferation experts and policy-makers.[286] As I argue in chapter 4, this dissonance is in part due to an overemphasis on the horizontal proliferation concerns of "nuclear breakout" in non-nuclear states. This focus neglects the vertical proliferation and disarmament potential for coherent and global tritium control regimes such as those proposed by Martin Kalinowski. After all, any horizontal proliferation failure then becomes a vertical proliferation problem. In North Korea, for example, the concern has shifted from preventing nuclear weapon acquisition to mitigating the technical sophistication of their stockpile.[287] It is inarguable that the vast majority of the latent yield of all nuclear weapons is directly attributable to the unique capabilities afforded by tritium. Yet, these thermonuclear weapons are often treated as if they are just tweaked or upgraded fission bombs rather than the *sui generis* that they are.

The historical phenomenology of tritium began when it was born nuclear in the lab and proceeded through constructions of super nuclearity, special nuclearity, and byproduct nuclearity. Tritium's story is also marked by phases of military and peaceful exceptionalism that have allowed for a convenient ambivalence serving the needs of the nuclear weapon state. The current dominant paradigm of peaceful byproduct nuclearity is conducive to the emergence of the commercial fusion energy model but resistant to holistic consideration within nonproliferation regimes. This same byproduct nuclearity is a salient attack vector for anti-nuclear activists because of its outsized representation in routine NPP waste. The world is soon arriving at a critical juncture in the next 20 years when the vast quantities of tritium produced from atmospheric nuclear weapon testing will have effectively decayed away, and all remaining quantities and local areas of concentration will be attributable to current nuclear activities and legacy facilities that have operated since the 1960s. This era between now and 2044 will likely determine whether an unprecedent tritium economy will emerge to power a fusion future. The choice is to either let these existing narratives define our tomorrow or to tell a new story that sets us more assuredly on the path to total nuclear disarmament and builds a more equitable model of the risks and rewards of this ambivalent, unique material.

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[283] Thea Riofrancos, "The Security–Sustainability Nexus: Lithium Onshoring in the Global North," *Global Environmental Politics* 23, no. 1 (February 1, 2023): 20–41, https://doi.org/10.1162/glep_a_00668.

[284] "Atomic Energy Act of 1954 [As Amended Through P.L. 117–286, Enacted December 27, 2022]."

[285] Alan Robock, "Climatic and Humanitarian Impacts of Nuclear War."

[286] Notable exceptions include Martin Kalinowski, Bob Kelley, Rob Goldston, Sharon Weiner, Frank von Hippel, and me.

[287] "Producing Tritium in North Korea," *Trust & Verify*, no. 152 (March 2016), https://www.vertic.org/media/assets/TV/TV152.pdf.

Conclusion: Nuclearity Reimagined, Next Steps, & Tritium Matters

Nuclearity Reimagined:

Telling the story of tritium has been a satisfying project. While several scholars and experts have given the topic considerable attention, my contribution is the first broad, interdisciplinary account of this multifaceted material. The theoretical approaches from STS allow for a unique synergy of self-ethnography, history, philosophy, sociology, and policy grounded in technoscientific coherence. Furthermore, my experience as a nuclear technology practitioner informed every stage of my research. Nuclear technologies *are* special and unique, and they deserve thorough accounting through expert discourse and public scrutiny.

The field of STS once known for its reactionary responses to the twin juggernauts of Big Science and Big Technology has evolved following the so-called Science Wars that peaked with Alan Sokal's infamous hoax in 1996 where he viciously mocked the incoherence of science-critical discourse. Since then, STS has been steadily moving beyond its deconstructionist tendencies to establish veins of critique more grounded in technoscientific practices and the unavoidable tradeoffs inherent in our collective technological choices. I position my present work as a materially rooted project in this *reformed era* of STS where my research conclusions provide additional explanatory power and policy insight.

Gabrielle Hecht's vanguard work articulating nuclearity in the context of the global uranium trade provides analytical approaches already well-suited for understanding tritium. The material lineage of tritium production is directly connected to these same uranium infrastructures, but tritium also inhabits the world on distinctly different spatial and temporal scales. Tritium is produced in gram quantities in discrete locations rather than extracted from a vast network of mining operations and processed by the metric ton. Also, tritium subverts the fears of the long-lived legacies of radioactive materials and wastes by steadily vanishing over the span of a single lifetime. Just two commercial reactors at Watts Bar provide all the tritium required for maintaining one of the largest nuclear weapon stockpiles in the world, while still meeting their power generation mission. A single national lab site at Savannah River facilitates all the extraction and processing necessary to prepare this unique material for military use. Tritium's nuclear status is unambiguous, but its nuclearity exists in a state of flux tending toward a transgressive technopolitical logic allowing for its special/byproduct duality.

Since its commercialization in the 1960s, tritium has in-part escaped the Restricted Data realm of nuclear weapons. Given its relative ubiquity and many scientific and banal uses, reclassifying tritium as an SNM is neither practicable nor advisable. The international SNM control regime is more fit for purpose with its current scope of fissile materials; introducing tritium would create more problems than it solves. However, regulating tritium as a dual-use byproduct material fails to adequately address its *special* role in nuclear weapons and vertical proliferation. There is a reason that nuclear weapon practitioners and policymakers treated tritium as an SNM for several decades. The relatively rapid and recent changes in tritium's material control and accountancy requirements that I describe in Chapter 2 are indicative of an identity crisis. Will this crisis be resolved by fully embracing tritium's byproduct nuclearity in promotion of fusion power, or will there be a turn back to tritium's special nuclearity embedded in nuclear weapon infrastructures? Alternatively, I argue, we could embrace the middle path suggested by Martin Kalinowski to regulate both domains through parallel and complementary systems. This would allow for both the responsible development of fusion technology and create a greater role for tritium control in future arms control regimes.

Next Steps:

This dissertation will serve as a springboard for a 2-year Carnegie grant beginning in Fall 2024 to research the military/civilian nuclear divide. My role will be as a postdoctoral researcher and Co-PI alongside Sonja Schmid. Our research agenda spans the global nuclear domain, and we will solicit analysis from topical and regional experts on the interconnections and interdependencies between "the bomb" and the peaceful atom and how that boundary has been cultivated and maintained. Sonja and I will expand our research into the U.S. decision to produce tritium in civilian NPPs to better understand this critical nexus and what significance it holds for the international nuclear order.

My Gigatons-to-Gigawatts policy brief published in 2023 with New America offers one practical application of this technological arrangement that would allow for material flows of military tritium back to the peaceful domain for fusion R&D.[288] This policy recommendation emerges from a cautiously optimistic technological enthusiasm and a moral inclination to facilitate the forging of swords to ploughshares. Tritium has the potential to release vast stores of atomic energy for peaceful and low-carbon energy production, but over the past 70 years our reality has fallen short of Vannevar Bush's "Endless Frontier" vision.[289] The vast majority of tritium reserves possessed by nation states remains dedicated to maintaining nuclear weapons and the persistent existential threats they represent. The path to total nuclear disarmament must contend with the material realities of tritium both its production and tenuous reserves. If policy provides mechanisms for the immediate repurposing of tritium for peaceful use, then successful disarmament efforts would allow for the additional benefit of providing this costly and rare material for potentially transformative research. Any delay in this transition would result in the inevitable decay of a precious resource.

During the grant tenure, Sonja and I also plan to visit several of the sites associated with U.S. tritium production. We hope to tour facilities at Watts Bar to see for ourselves the "visually unclassified" status of TPBARS in fresh fuel assemblies and how these unique components affect refueling operations, on-site radiological conditions, and liquid waste releases. In coordination with Oak Ridge National Labs (ORNL) and the Savannah River Site (SRS), we hope to tour Y-12 facilities associated with tritium and lithium enrichment/recycling and the unclassified areas associated with tritium extraction and processing at SRS. Primary documents, even highly detailed and technical records, fall short of providing a full sense of the material conditions and technological practices involved in the tritium production infrastructure. This infrastructure involves the movement of materials and personnel back and forth across the civilian/military boundary. Material custody, governing procedures, and operational authority transition across this conceptual boundary in both visible and invisible ways. Witnessing these spaces and practices will provide essential insight into better understanding this unique civilian/military partnership.

Tritium Matters:

Throughout my research, particularly in the context of nuclear weapon reports and analyses, references to tritium were surprisingly sparse. With the notable exception of Peter Lobner's thorough blog posts

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[288] Taylor Loy, "Speculating on Tritium Futures: Why Defense Material Should Fuel Fusion Innovation," New America, April 24, 2023, http://newamerica.org/political-reform/briefs/tritium-fuel-futures/.

[289] Vannevar Bush, "Science the Endless Frontier" (U.S. Government Printing Office, July 1945), https://www.nsf.gov/od/lpa/nsf50/vbush1945.htm.

from 2020 for The Lyncean Group of San Diego[290], tritium is rarely a featured topic. Since I began outing myself as a tritium researcher on social media and at various workshops, I have received several requests to connect with other experts interested in tritium. Many of their stories are similar. They either study or work in the nuclear policy domain, and they devoted some time to the tritium topic before being drawn away to more salient research. Sometimes they tried and failed to engage colleagues on the topic, or they completed a short-term research program and simply moved on. Beyond a few research cohorts focused primarily on tritium science, there are no multi-disciplinary working groups considering the many dimensions of tritium covered in this dissertation.

To meet this perceived need, I intend to establish a Tritium Matters Working Group as part of my postdoctoral research program over the next two years. One of the inaugural tasks of the group will be to establish historical and present-day assessments of tritium capabilities, production rates, and reserves for military use. This effort will complement and be modeled on the excellent work of the International Panel on Fissile Materials (IPFM).[291] Martin Kalinowski provides an excellent starting point for this overview in Table 2.6 in his 2004 book, but a lot has changed in the last 20 years and some of the sources I have reviewed for this dissertation can help further refine his historical account of U.S. tritium production.[292] By consolidating existing data and information on state-level tritium production and inventories into a single source, experts engaged in unclassified research can more easily assess tritium's role in nuclear weapon economies.

Another task I intend to accomplish in collaboration with working group members is to publish an updated edition of *The Tritium Factor* text that recounts and summarizes the workshop's proceedings from 1988.[293] This text is currently difficult to find in print and not easily accessible in digital format. Originally published by the workshop's co-sponsors, Nuclear Control Institute (NCI) and The American Academy of Arts and Sciences (AAAS), the text includes standing permission to reprint material with proper acknowledgment and notifications. I have already contacted representatives from NCI and AAAS to signal my intent to reissue an updated version of the text and have received positive responses from both.

The Tritium Factor workshop represents a unique historical moment when the U.S. had no tritium production capability, and the Soviet Union still represented a looming threat. The discussions held at that time are valuable not only for their assessments of tritium's role in nuclear disarmament but also in better understanding conditions during the final months of the Cold War. Many expert participants are still alive now 35 years later with Robert Kelley actively publishing on the very topic.[294] Part of updating and expanding the text will involve contacting these senior experts for follow-up interviews on this pivotal moment in nuclear history and learning how their thoughts on tritium have possibly changed over the intervening years. How these retrospectives are incorporated into the text will depend on the

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[290] Peter Lobner, "U.S. Tritium Production for the Nuclear Weapons Stockpile – Not Like the Old Days of the Cold War," *The Lyncean Group of San Diego* (blog), January 12, 2020, https://lynceans.org/all-posts/u-s-tritium-production-for-the-nuclear-weapons-stockpile-not-like-the-old-days-of-the-cold-war/.

[291] "International Panel on Fissile Materials," International Panel on Fissile Materials, April 13, 2024, https://fissilematerials.org/.

[292] Kalinowski and Colschen, "International Control of Tritium to Prevent Horizontal Proliferation and to Foster Nuclear Disarmament," 109–11.

[293] Leventhal, *The Tritium Factor*.

[294] Kelley, "Starve Nuclear Weapons to Death with a Tritium Freeze | SIPRI."

breadth and richness of the responses to our requests. The finished product will be made available in a digital and accessible format to ensure that this important text remains available for future researchers.

The core mission of the Tritium Matters Working Group will be to ensure that tritium is no longer an afterthought for nonproliferation and arms control discourse. Furthermore, group members will engage with vanguard fusion research and the further development of regulatory oversight taking into account essential safeguards and novel radiological risks posed by these emerging technologies.

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Appendix A: Tritium Verification and Analytical Techniques

Tritium Production in NWS under the NPT

William Karl Pitts and Alex Misner of PNNL make the case for tritium control in a presentation at the Institute of Nuclear Materials Management (INMM) 52nd Annual Meeting in 2011.[295] They position their control regime in the context of a bilateral agreement between the U.S. and Russia and consider potential inspection technologies based on existing techniques: a calorimetry system developed by Lawrence Berkeley National Laboratory (LBNL) and backward angle neutron scattering evaluated at PNNL. In the first case, measurements of tritium gas canisters can be made without accessing contents, and, in the second case, irradiated TPBARs can be examined on-site before they are moved to an extraction facility.[296] Both techniques are non-destructive and would preserve sensitive information such as TPBAR internals and nuclear weapon designs.

Importantly, they argue, a bilateral tritium control regime could further strengthen New START, commonly seen as the sole remaining bulwark against a new nuclear arms race between the two superpowers. Providing mutual access for independent tritium measurements and analysis would build confidence and potentially limit "breakout and upload scenarios" if the treaty were to lapse or collapse.[297] Since Russia suspended participation in New START in 2023, the window may have closed on strengthening existing agreements. When bilateral dialogue is eventually restored, a tritium control regime should be part of those discussions.

While Pitts and Misner argue that tritium control regimes are well suited for monitoring and verifying larger stockpiles, I further argue that it is also useful for any national nuclear weapon program that has reached stasis, regardless of size. Perhaps the best example of a static stockpile that has entered a phase of maintenance (and potential modernization) is the undeclared but broadly assumed Israeli nuclear weapon program.

Tritium Production in Unsafeguarded Reactors

Recent analysis by Alex Glaser and Julien de Troullioud de Lanversin of the Dimona heavy-water reactor provide a provocative case for monitoring the Israeli nuclear stockpile as a function of tritium production.[298] Historically, the Dimona reactor has produced plutonium and tritium for weapons use. Through open-source data, such as satellite imagery, the operational status of the reactor can reliably be ascertained. What is less clear is its power history. This would be a typical data gap for the operation of any unsafeguarded production reactor.

Using publicly available information, including information shared by the whistleblower Mordechai Vanunu in 1986, Glaser and de Troullioud generate plausible reactor modeling to reconstruct its history and estimate a tritium production rate of 50-60 grams/year. This, they argue, is consistent with maintaining a tritium inventory of 1 kg supplying ~100 warheads (which conservatively exceeds independent estimates of 80-85 weapons).[299] Since the upper bound of their modeling suggests

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[295] William Karl Pitts and Alex Misner, "Advantages of a Tritium Control Regime for Arms Control," INMM 52nd Annual Meeting (Palm Desert, CA: Pacific Northwest National Laboratory, July 12, 2011).
[296] Pitts and Misner, 3–4.
[297] Pitts and Misner, 1.
[298] Glaser and de Lanversin, "Plutonium and Tritium Production in Israel's Dimona Reactor, 1964–2020."
[299] Glaser and de Lanversin, 16.

sufficient plutonium for as many as 150-190 warheads, Glaser and de Troullioud assume that tritium production has likely been prioritized for the past 20-30 years.[300] The shift in production cycles to optimize tritium would consequently produce plutonium in isotopic ratios unusable for weapons.[301]

To briefly summarize, due to the decay of tritium any nuclear weapon program without substantial tritium reserves would necessarily need continuous production to ensure its weapons stockpiles would perform as designed. For a national program that has reached nuclear stockpile stasis, estimated tritium production rates would provide meaningful insight into the number of warheads being maintained. Given the complex infrastructure, high cost, and substantial effort required to produce tritium, it seems unlikely that any nation simply maintaining its stockpile would engage in production-levels beyond the maintenance threshold.

Recent Changes in Tritium Production

Tritium has the dubious honor of being the only essential bomb material routinely and intentionally produced in civilian power reactors. In the United States, this breach of the *firewall* between civilian and military nuclear infrastructures was first announced by Sec. Bill Richardson's Department of Energy (DOE) in 1998 under the Clinton administration.[302] In 2003, the first Tritium-Producing Burnable Absorber Rods (TPBARs) were irradiated during normal power operations at the Tennessee Valley Authority's (TVA) Watts Bar Unit 1 to supply the Department of Energy (DOE) with a reliable supply of tritium for nuclear weapon stockpile stewardship and maintenance. The other major source of global tritium supply comes from the harvesting of *incidental* tritium by-products created in Canada Deuterium-Uranium (CANDU) heavy-water reactors. CANDU-derived tritium can arguably be construed as merely salvaging a high-value *waste* material, whereas U.S. tritium production is inarguably the result of an explicit military intervention into an otherwise "peaceful atom" process.

The DOE argues in the 1999 "Final Environmental Impact Statement for the Production of Tritium in a Commercial Light Water Reactor" (FEIS) that since tritium production is required for the maintenance of stockpiles that have been reduced under international treaties (rather than the development of new warhead designs) it "is not inconsistent with the long-range goal of total nuclear disarmament."[303] Due to the voluntary offer of the U.S., the IAEA is welcomed to inspect its CLWRs, even those irradiating TPBARs, which the IAEA has indicated "would not alter [its] existing Safeguards Program."[304]

Despite having to overcome several technical challenges and regulatory hurdles, TPBAR irradiation has continued at Watts Bar Unit 1 and was recently expanded to the Watts Bar Unit 2 reactor. The most recent License Amendment Requests (LAR) for the Watts Bar facilities were approved on April 15, 2024,

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[300] Glaser and de Lanversin, 16.

[301] An absence of krypton-85 emissions from the site could further corroborate the conclusion that plutonium is no longer being separated from spent fuel. Glaser and de Lanversin, 16; Julien de Troullioud de Lanversin, Malte Göttsche, and Alexander Glaser, "Nuclear Archaeology to Distinguish Plutonium and Tritium Production Modes in Heavy-Water Reactors," *Science & Global Security* 26, no. 2–3 (September 2, 2018): 70–90, https://doi.org/10.1080/08929882.2018.1518693. See the preceding for further reading.

[302] Bergeron, *Tritium on Ice*.

[303] "The Final Environmental Impact Statement for the Production of Tritium in a Commercial Light Water Reactor," S.1.5.4.

[304] "The Final Environmental Impact Statement for the Production of Tritium in a Commercial Light Water Reactor."

and will allow each reactor to irradiate 2,496 TPBARs each fuel cycle, which should allow for meeting the DOE tritium production target of 2,800 grams of tritium every 18 months.[305]

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[305] E.F. Love et al., "Tritium Production Assurance" (Tritium Focus Group, Pacific Northwest National Laboratory (PNNL), May 11, 2017), 8.