

Beyond Byproduct

Rethinking Tritium in Fusion Technologies

By **Taylor Loy**

SUMMARY

- Tritium is an essential component in most nuclear weapons and a significant material bottleneck for stockpile size and sophistication.
- The current “byproduct material” regulatory framework for fusion energy may not adequately address tritium’s role in vertical proliferation.
- The nuclear policy community should ensure that tritium and fusion energy regulations take an even-handed approach with respect to tritium’s dual-use applications.
- Nuclear Weapon States should declassify additional information on their tritium enterprises to increase transparency and promote peaceful-use activities.

1. INTRODUCTION

1.1. Tritium Histories

Hypothesized in the late 1920s, the existence of tritium was first confirmed in Lord Rutherford’s laboratory in 1934 when he, Mark Oliphant, and Paul Harteck bombarded deuterated compounds with deuterons [1]. Additional confirmatory evidence was produced by Tuve, Hafstad, and Dahl around the same time [2]. In 1939, Alvarez and Cornog confirmed tritium’s radioactivity, but its half-life would not be measured with much certainty until Aaron Novick’s analysis at Argonne National Lab in 1947 [3,4,5]. As early as 1942, Manhattan Project scientists had already started designing a so-called “superbomb” that relied heavily on tritium [6]. Even though a “superbomb” as originally conceived was never built, this early research provided the foundations for a new class of powerful hydrogen weapons that would define the global nuclear arms race during the second half of the 20th century.

Tritium is a naturally occurring radioactive isotope of hydrogen with a half-life of ~12.3 years. The dominant cosmogenic and negligible radiogenic production rates of natural tritium are so low that Earth’s global equilibrium is only ~4.5 kg [7]. Because tritium forms the same chemical bonds as other hydrogen isotopes it diffuses rapidly and widely in the environment. Since it decays by emitting a weak beta particle, tritium is also technically challenging to measure. To economically isolate and purify useful amounts of tritium it must be produced either intentionally or incidentally by nuclear technologies.

The largest source of incidental tritium production is heavy water reactors (such as CANDU). The dense population of deuterium in the moderator creates ideal conditions for activation when exposed to the neutron flux of the reactor core. Over time the moderator becomes increasingly tritiated, making it a radiological hazard for workers at the site. Then, the tritiated heavy water is exchanged and stored in tanks as a hold-up volume for decay or for processing at specialized Tritium Removal Facilities (TRF). Only the Republic of Korea and Canada currently operate TRFs, but Romania has recently broken ground on their own facility. The projected total tritium supply available from these three sources has been estimated by Coleman and Kovari to be between 30–40 kg [8].

Most anthropogenic tritium is routinely produced for use in nuclear weapons. This military production is accomplished by intentionally irradiating specially prepared lithium-containing targets inside nuclear reactors. All states possessing nuclear weapons use tritium to varying degrees in the production of sophisticated designs. To maintain a nuclear stockpile, these nations need to produce or procure sufficient tritium to refurbish any lost to decay. In the military context, tritium remains a closely guarded secret of national security. Since the United States offers more transparency into their military tritium enterprise than the other two leading nuclear powers, Russia and China, examples in this essay will focus on U.S. declassified documents and open source intelligence.

To provide a sense of scale, here are some tritium production estimates based on the U.S. case. Thomas Cochran, et al. estimates the total U.S. production at the Savannah River Site (SRS) from 1955–1984 was 139 ± 46 kg [9]. To maintain its nuclear stockpile at current levels, U.S production targets in 2025 are ~ 1.9 kg·yr⁻¹ [10]. If taken as a nominal value for maintaining ~3,700 U.S. warheads the total global nuclear stockpile of ~9,600 might require ~4.9 kg·yr⁻¹

[11]. If this production is only intended to replace decayed tritium ($\sim 5.5\text{-yr}^{-1}$), the global steady state stockpile of military tritium would be ~ 89 kg, or ~ 3 times the peaceful-use supply. This is likely a significant underestimate if only because most nuclear weapon possessing states have been expanding their active nuclear weapon stockpiles in recent years [11].

Tritium is also a pernicious radiological pollutant. Atmospheric nuclear weapons testing remains the largest contributor to environmental tritium levels, which peaked with an estimated inventory of 520–550 kg in 1960 [7]. Due to the ban on atmospheric weapon testing, this legacy contamination has decayed to an inventory of <20 kg and will soon be entirely transformed into stable He-3 [7]. All military and civilian nuclear facilities also release $\sim 78\text{ g-yr}^{-1}$ as waste effluent, which is $\sim 30\%$ of the natural production rate [7].

Even staunch nuclear critics admit that tritium in low doses commonly measured in the environment pose negligible effects on ecological or human health [12]. However, some uncertainty remains with respect to organically bound tritium (OBT) and its environmental impacts [13, 14]. Further research on OBT effects will be prudent before tritium-intensive industries such as fusion energy are widely deployed.

1.2. Fusion Futures

The still nascent fusion energy industry has consistently differentiated its technologies and brands from traditional “nuclear energy” based on fission. On the one hand, these efforts make good sense from technical, business, and public relations perspectives. On the other hand, fusion stakeholders may be obfuscating important overlaps with existing nuclear infrastructures. Fusion does not require the use of Special Nuclear Material (SNM) such as enriched uranium and plutonium, cannot meltdown like a fission core, and does not produce long-lived wastes at the same scale as fission power. However, one of the most promising fuels for fusion, tritium, is an essential component in most nuclear weapon designs and is a significant bottleneck for vertical proliferation. While fusion proponents work to ensure the viability of their technologies, the broader nuclear policy community must maintain a clear-eyed view of how fusion will affect the dual-use nuclear landscape.

The fusion industry has argued before the U.S. Nuclear Regulatory Commission (NRC) that their facilities should be licensed under existing regulations for “byproduct materials” rather than as “utilization facilities” [15]. One alternative to this would be an entirely new regulatory framework for fusion, but industry proponents have a clear preference for complying with existing regulations to assure investors and reduce uncertainty. Additionally, by cementing the fusion difference into law, the “cleaner safer” case can be more credibly made to various publics. In April 2023, the NRC provided a tentative ruling that fusion would be governed under byproduct material regulations, and they reserved the right to revisit this decision once commercial-scale facilities neared operation [16]. Fusion’s regulatory environment appears to be set for the foreseeable future, but the scope of international non-proliferation safeguards regarding tritium is less clear.

In this paper, I argue that tritium policy and regulation for fusion energy should be informed by its history and current role in nuclear weapons. The anticipated scale of the tritium supply chain

needed for a fusion infrastructure far exceeds the small quantities currently used in commercial and scientific applications. Only the defence industries of Nuclear Weapon States (NWS) have produced and managed comparatively large quantities of tritium. However, these infrastructures have remained opaque due to a high level of secrecy related to tritium’s role in nuclear weapons. I secondarily argue that NWS should review and declassify additional information that may be valuable to fusion companies, policymakers, and other stakeholders.

2. TRITIUM’S NUCLEAR WEAPONS LEGACY

Tritium’s primary use by volume has been the testing and deployment of powerful and deliverable nuclear warheads. Daniel Jassby, a retired researcher from Princeton Plasma Physics Lab, suggests that nuclear weapons account for “as much as 90% of the annual demand for tritium” [17]. However, tritium, in much smaller quantities, is also used in scientific research and mundane consumer products. Tritium’s environmental mobility makes it a useful marker for analysing environmental and biological samples. Its radioluminescent properties make it ideal for use in exit signs, remote runway lighting, gun sights, watch faces, and even novelty keychains. Many of these commercial and scientific applications only first became possible when the United States began selling surplus tritium in the early 1960s. Canada—the world’s current supplier of most peaceful-use tritium—did not begin selling tritium until its Darlington TRF started in the 1990s. A 2011 JASON report estimates that Canada sells $\sim 100\text{ g-yr}^{-1}$ [18].

The historical legacy of tritium in the United States can be divided into three distinct but overlapping phases: *Super*, *Special*, and *Byproduct* phases [19]. The *Super* phase (~ 1942 –1960) refers to the wartime and post-WWII efforts to develop a “superbomb” based on the fusion of heavy hydrogen. Proposed “superbomb” designs proved untenable, and U.S. weapons scientists never even possessed enough tritium to experimentally test an actual device. Nonetheless, scientists across the nuclear enterprise advanced production techniques to supply sufficient tritium for successor designs that would later become the backbone of the thermonuclear arsenal.

For the purposes of this paper, tensions between the *Special* and *Byproduct* phases will be the primary focus. Both phases were active from the 1950s until about 1990 and from then until present day the *Byproduct* phase became dominant. The *Special* phase refers to several decades when tritium was treated by weapon designers and war planners as functionally equivalent to SNM. The *Byproduct* phase refers to the characterization of tritium as a comparatively benign but ubiquitous byproduct and radiological pollutant from various nuclear activities in both civilian and military domains. Differentiating factors between these two modes are purity and quantity. While some scientific and commercial uses of tritium require high purity, most are relatively minute quantities. One notable exception is the research and development of fusion energy.

3. TRITIUM’S SPECIALNESS

Tritium has never met the legal definition of SNM as defined by the Atomic Energy Act (AEA) of 1954 as amended [20]. SNM primarily includes plutonium and uranium enriched in fissile isotopes U-233 or U-235. The AEA allows for the NRC to designate other materials

as SNM, but the option to expand this definition has not been exercised. Reviewing many primary source documents dating from ~1960–90—many that have been declassified over subsequent decades—there emerges a clear pattern of referring to and treating tritium as an SNM within the U.S. nuclear weapon complex.

WARHEAD COSTING

• Proper Unit Costs SNM:

Oralloy
Plutonium
Tritium

• Application - Net Warhead Costs.

• Results - Comparison.

FIGURE 1: From the “Proceedings of the Tactical Nuclear Weapons Symposium” (Sept. 3-5, 1969). “Oralloy” is a common term for HEU derived from “Oak Ridge alloy” [21].

In a presentation on “Warhead Costing” from a 1969 nuclear weapons symposium, tritium is listed as an SNM (see figure 1). Within the nuclear weapons infrastructure such a conflation makes perfect sense because highly enriched uranium (HEU), plutonium, and tritium are the three most controlled, costly, and resource-intensive nuclear weapon materials. This conflation is even footnoted in another source, which is taken from a 1980 final report of the DOD/DOE Long Range Resource Planning Group (see figure 2). Because the availability of these three materials “is a major determinant of stockpile size and composition” the authors of this report chose to group them together under the SNM term.

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.

SS2(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.

FIGURE 2: From the “Long Range Nuclear Weapon Planning Analysis for the Final Report of the DOD/DOE Long Range Resource Planning Group” (July 15, 1980) [22].

While NWS certainly have the capability to produce advanced thermonuclear warheads without tritium, the many advantages of its incorporation make it as essential a material as HEU or plutonium. Inserting deuterium and tritium (D-T) gas into

the primary stage of a two-stage thermonuclear weapon can significantly boost the yield. Public estimates suggest that only 1–5 grams of tritium per warhead is needed for boosting yield several times. D-T fusion produces high energy neutrons which causes much more of the fissile and fissionable material to fission. These nuclear weapon designs can produce desired yields while requiring much less SNM than fission-only weapons. This boosting mechanism even allows for so-called “dial-a-yield” functionality which can be adjusted in situ to regulate the amount or timing of the D-T gas injection. In short, tritium allows for more compact, efficient, and flexible warheads than would otherwise be possible.

Some information regarding U.S. tritium production has been declassified. However, details of operations at the SRS—representing at least 90% of total tritium production—remain Restricted Data. The best available data from this period are found in Cochran, et al.’s *Nuclear Weapons Databook*, noted in the introduction, which provides tritium production estimates based on publicly available information on environmental releases and the power capacities of the reactors at SRS [9]. Whereas current tritium production details at the commercial Watts Bar nuclear site were declassified in 2003 and 2004 [23]. Because Watts Bar is a commercial facility operated by the Tennessee Valley Authority (TVA) and regulated by the NRC any knowledgeable observer could readily discern tritium production based on public documents. The reactor targets known as Tritium-Producing Burnable Absorber Rods (TPBARs) are considered “visually unclassified” but specific characteristics of the internal lithium-containing targets remain classified [24].

In the late 1980s and early 1990s, tritium’s specialness began to be deemphasized. While there appears to be no evidence of a distinct moment of paradigm shift, several factors converged during this period that may have brought about the change. First, tritium’s role in nuclear weapons and potential role in disarmament became more broadly known and discussed by informed publics. Second, fusion energy research and development was experiencing a revival. Third, perhaps most importantly, the U.S. shut down its sole remaining military tritium production reactor in 1988. When efforts to replace or refurbish this reactor failed, the ultimate solution of irradiating targets in commercial reactors led to emphatic and official denials of tritium as an SNM.

With the backdrop of the geopolitical sea change of the Soviet Union’s collapse and significant success in quantitative disarmament, vertical proliferation concerns appeared to be on a successful trajectory. In response to the changing nuclear order, world governments placed renewed emphasis on minimizing horizontal proliferation. Rogue states seeking to join the nuclear club did not need tritium; only significant quantities of HEU or weapons grade plutonium were required. The non-proliferation regime focused on reducing stockpiles of these fissile materials and limiting access to the dual-use technologies that could produce them.

Another shift during this era of special/byproduct overlap can be seen in the Dept of Energy (DOE) guidance on nuclear material control and accountancy (MC&A). Tritium was initially regulated similarly to SNM with reportable quantities of 0.01 grams. By 2011, the DOE MC&A order designated tritium as “other accountable nuclear material” and reportable quantities were raised to 1 gram. As of 2023, the active version of this order has even dropped references to the

need of “graded safeguards” for tritium [25].

Tritium had been bureaucratically transformed from primarily a special material necessary for nuclear weapons to a byproduct material with various uses that happen to include thermonuclear weapons. The practical realities of tritium use had changed very little. Additionally, the United States leveraged the newly reasserted boundary between tritium and SNM to justify and legitimate their expedient decision to produce tritium in commercial nuclear reactors.

The final word on tritium’s new status can be traced to an interagency review submitted to the U.S. Congress in July 1998 [26]. While the report acknowledges that the production of weapons materials in a civilian reactor may challenge long-held norms of civil/military separation, its author contends that there are no legal barriers to the practice. The 1983 Hart-Simpson Amendment to the AEA only prohibits the production of SNM for weapons in commercial facilities. Tritium is not an SNM, and other attempts to specifically regulate military tritium production had failed to pass. Tritium’s affirmed status as a byproduct material has allowed weapon-use tritium to be produced in a commercial facility over the past two decades.

The unorthodox practice of producing military tritium in commercial facilities may also offer some positive benefits for the international non-proliferation regime [27]. The secretive military production reactors that have historically produced tritium for weapons are also capable of producing plutonium. When tritium production is moved to commercial facilities, military production reactors can be shut down and decommissioned. This transition eliminates risks posed by continued operation of aging facilities and reduces overall plutonium production capacity. France has also recently signalled that they intend to follow the United States in what appears to be an emerging norm for producing tritium for nuclear stockpile maintenance.

4. TRITIUM REGULATION & FUSION ENERGY SAFEGUARDS

Tritium remains regulated by an international patchwork of agreements and has never been subject to a systematic and unified global framework. In his 2004 book, Martin Kalinowski proposes two complementary and mutually reinforcing policies for separately governing civilian and military tritium infrastructures [28]. Despite Kalinowski’s efforts, little progress has been made in unifying tritium regulations.

In a 2023 essay, Philipp Sauter surveys international law governing nuclear technologies and identifies potential proliferation gaps for fusion and proposes possible solutions [29]. The frameworks most relevant to tritium include The Treaty on the Non-Proliferation of Nuclear Weapons (NPT) Article III.1-2, Comprehensive Safeguards Agreements (CSA), and the Nuclear Suppliers Group (NSG) Trigger and Dual Use Lists [30, 31, 32, 33].

Sauter identifies the categorical limitation of “special fissionable material” in the NPT that parallels and is derived from the SNM exclusion in U.S. law. Since tritium does not qualify as “special,” NPT safeguards are not explicitly required. The NSG Dual Use List does include both tritium and lithium-6 (used to breed tritium), but, as Sauter notes, illicit trade of excess tritium from fusion energy is less of a concern than a state’s direct use of the material for their own vertical proliferation. Furthermore, Sauter determines that the lithium-6 regulation is “too porous and uneven” to affect fusion’s proliferation risks. Ultimately, Sauter concludes, existing legal

frameworks are a useful starting point but insufficient. Possible paths forward include developing a new Additional Protocol to the CSA that will be directly applicable to fusion facilities, and/or the NSG could implement stronger verification and end-use reporting requirements for tritium and lithium-6. The latter would require only a majority vote from the 35-member International Atomic Energy Agency (IAEA) Board of Governors to initiate [29].

Currently, The IAEA takes an ambivalent approach to tritium. First, only NWS produce tritium for nuclear weapons in safeguarded or potentially safeguarded reactors. The legal right of NWS to produce weapon materials is explicitly established in the NPT. Other nuclear weapon possessing states, Israel, Pakistan, India, and North Korea, already operate outside the purview of the IAEA and the broader NPT regime. Second, all tritium produced in non-NWS—most notably Canada and South Korea—has been exclusively dedicated to peaceful use.

As fusion energy development drives demand for more tritium, researchers and stakeholders propose practicable approaches to international tritium safeguards [34]. Rob Goldston, a fusion expert at the Princeton Plasma Physics Lab, along with Alex Glaser and other colleagues have written on safeguards concerns for fusion energy [35]. Goldston and Glaser note that fusion technologies could be leveraged to produce SNM for nuclear weapons, but that these technologies also pose diversion paths for tritium. Even if fusion reactors are designed to prevent the clandestine breeding of weapon-use SNM, tritium will remain an ongoing concern. Strict material accountancy and controls will be required to ensure gram quantities of tritium are not diverted from the anticipated hundreds of kilograms that will be produced, processed, and burned during day-to-day operations.

5. CONCLUSION

For several reasons, tritium should not be designated an SNM. As pointed out above, a rogue state would not need tritium to develop a nuclear weapon. Furthermore, HEU and weapons grade plutonium are durable materials that can be stockpiled, thereby increasing the timelines when they can be stolen, lost, sold, or otherwise put to nefarious use. Tritium, on the other hand, decays at a rate of ~5.5% a year and cannot be easily or cheaply stockpiled in large quantities. To offer long-term nuclear weapon stockpile capability assurances, it is more important to possess credible and sufficient tritium production capacity than material reserves. The dual-use material concerns posed by tritium are not compatible with the concerns posed by HEU or plutonium. Therefore, existing SNM safeguards and regulations would not be fit for purpose.

Furthermore, tritium’s many peaceful use applications would be difficult, if not impossible, to safeguard in the same manner as SNM. In most instances any SNM used or produced in commercial fission reactors is not suitable for weapons use without further enrichment or reprocessing. Tritium is a more inherently ambivalent material, being able to be used in either a nuclear weapon or in a fusion reactor without similarly burdensome processing requirements. In many cases, most notably in D-T fusion reactors, tritium is essential. Novel monitoring and material accountancy methods would need to be applied to effectively safeguard tritium technologies. Given the inter-dependence of these materials in many nuclear weapon designs, SNM and tritium safeguards should be seen as layered and mutually reinforcing non-proliferation tools. Safeguards are not intended to prevent the possibility of diversion for weapons but to ensure that

any such attempts will incur costs sufficient to deter clandestine efforts. Furthermore, if/when deterrence fails, any such efforts will be detected in time to exact additional costs before a first nuclear weapon could be built.

The primary goal of tritium safeguards should be inhibiting the next step of a rogue nuclear state: vertical proliferation, both in quantity and sophistication. The advantages of boosted two-stage thermonuclear weapons can lead to dramatic shifts in warhead delivery capabilities. Smaller and higher yield warheads can be fit on existing delivery vehicles and rapidly expand the threat environment. This is precisely the case in North Korea. Recent concerns with North Korea acquiring nuclear propulsion technology for submarines which could be nuclear armed further emphasize dangers posed by smaller and more powerful warheads. To build and maintain any such weapons, North Korea will need a steady supply of tritium.

Finally, if tritium is indeed going to be treated predominantly as a byproduct material, then legacy research and production within the nuclear weapons complex should be evaluated for further declassification. As fusion industry observers and stakeholders have noted, there will likely be national security implications if the United States or China is the first to make fusion energy work. The United States should not limit the potential of commercial fusion energy either domestically or in closely allied nations because it fails to share valuable information that may no longer need to be classified.

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Taylor holds a postdoc position at Virginia Tech generously funded by a Carnegie Corporation of New York grant to research the civilian/military boundary in nuclear infrastructures. He brings a diverse academic/professional background to the study of civilian and military nuclear technologies. He received his PhD in Science, Technology, & Society (STS) at Virginia Tech, and his dissertation focuses on tritium, a unique and ephemeral radioactive isotope that readily transgresses established boundaries between civilian/military and natural/technological domains.



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