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Breaking Down Complexity to Accelerate Commercialisation

Tritium and the Regulatory Blind Spots Shaping Fusion's Future

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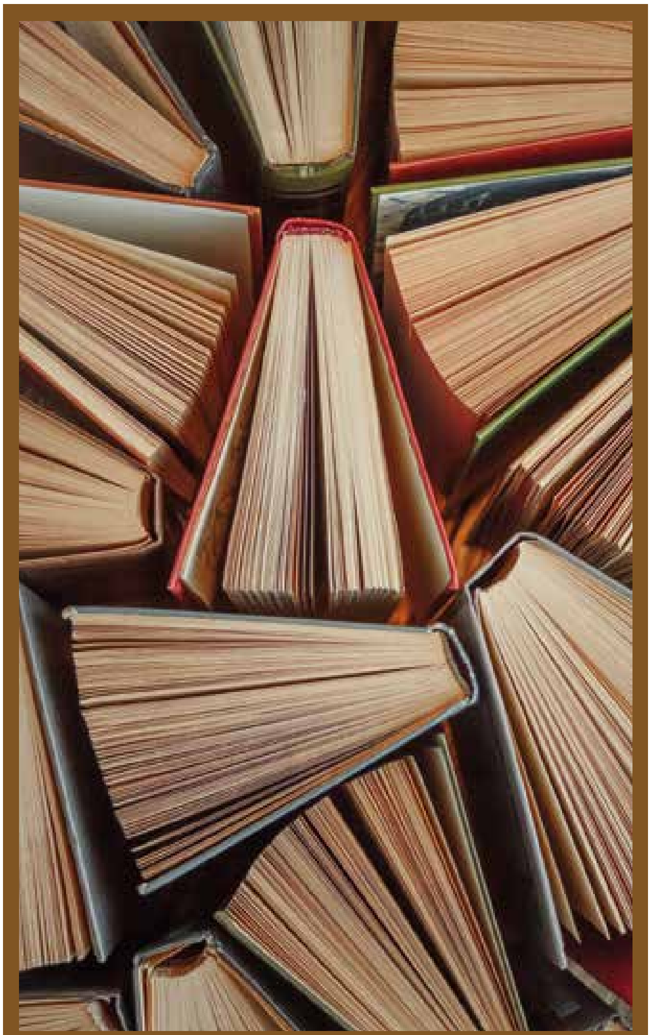

Artificial Intelligence as a Catalyst for Fusion Energy

By **Alex F. Savin**, **Harry Westhead**[1], **Philip Horton**[1], and **Richard A. Johnson**[1]

SUMMARY

- AI models, such as digital twins and surrogate models, offer significant potential to speed up and improve the design and optimisation of fusion reactors, but must be applied in targeted areas where sufficient high-quality data exists to ensure trustworthy results.
- The scarcity of experimental data in fusion presents challenges for AI implementation; thus, a problem-specific approach is recommended, focusing on well-benchmarked aspects like transport phenomena and adaptive reactor control.
- A symbiotic relationship between the AI and fusion sectors could accelerate innovation in both fields—fusion provides sustainable energy for AI's growing demands, while AI delivers the advanced modelling and control needed to realise commercial fusion energy.

1. INTRODUCTION

Nuclear fusion – often heralded as always being "30 years away" [1] – is now, finally closer than ever with groundbreaking scientific milestones being passed on a regular basis [2, 3]. In addition to scientific breakthroughs, the commercial fusion sector is expanding with impressive momentum, with the sector attracting over $2.6 billion USD in 2024/2025, taking total investment in private sector fusion companies to over $9.7 billion USD [4]. Beyond the 'core' fusion companies, the supply chain is also developing at pace with companies in Europe, Asia, North America and Australia all contributing to building a supply chain from a near-standing start [5].

Over and above merely attracting investment, many of these fusion companies are also reporting remarkable progress on their route towards the commercialisation of fusion [6-13], with the overwhelming majority of fusion companies self-reporting a target of delivering power to the grid between 2030 and 2035 [4].

However, while progress to date is impressive, it is equally clear that there are significant scientific and engineering challenges to overcome in the quest to commercialise fusion. While the trajectory for many of the plethora of fusion approaches is undoubtedly positive, it remains the case, as can be seen from Figure 1, that only the National Ignition Facility at the Lawrence Livermore Laboratory has reported experimental success of attaining ignition [3, 14, 15]. Even then, ignition is only a first hurdle to overcome. Strictly speaking 'ignition' (also referred to as scientific breakeven), only compares the amount of energy put into the fuel with the amount of energy obtained from the fusion reaction. In order to be commercially viable, fusion needs to go one step further and obtain more energy from the fusion reactions than is put into the entire reactor system overall. This level of yield is, as of yet, unattained.

Addressing these challenges will require the development and implementation of a whole suite of new technologies, ranging from high-temperature superconductor (HTS) magnets [16], laser amplifiers [17] and diodes [18], and improvements in fuel cycle systems [19]. These new technologies, coupled with the inherent stochasticity of high-temperature, high-pressure plasma physics [20] makes it incredibly challenging to model the performance of fusion reactors and, consequently, improve and iterate the designs of these reactors.

In the nuclear fission, or 'nuclear' sector, it is already appreciated [21, 22] that AI will be a valuable tool for achieving systems integration in nuclear reactors. The same is true for fusion. However, where conventional nuclear reactors are well-understood systems that can provide an abundance of training data for the development of optimisation algorithms [23], and surrogate models [24], this is not the case for nuclear's cousin fusion.

This article therefore outlines a measured and limited approach to implementing AI models in a manner that incrementally improves the understanding of fusion reactor physics and engineering to ensure that the outputs of AI models can be trusted to improve reactor design. By producing reliable outputs, we assert that the burgeoning fusion supply chain will benefit from an instilled confidence in the projections put forward by the fusion sector. This confidence is vital for facilitating the development and growth of a global commercial fusion sector

After specifically considering the potential for the use of digital twins [25] to enhance fusion reactor design, we briefly discuss the

[1] Mewburn Ellis LLP, Aurora Building, Counterslip, Bristol, BS1 6BX

potential symbiosis between the AI industry and the fusion sector, as well as the nuclear industry more widely, to highlight the mutual benefit for both industries if they each support the successes of the other.

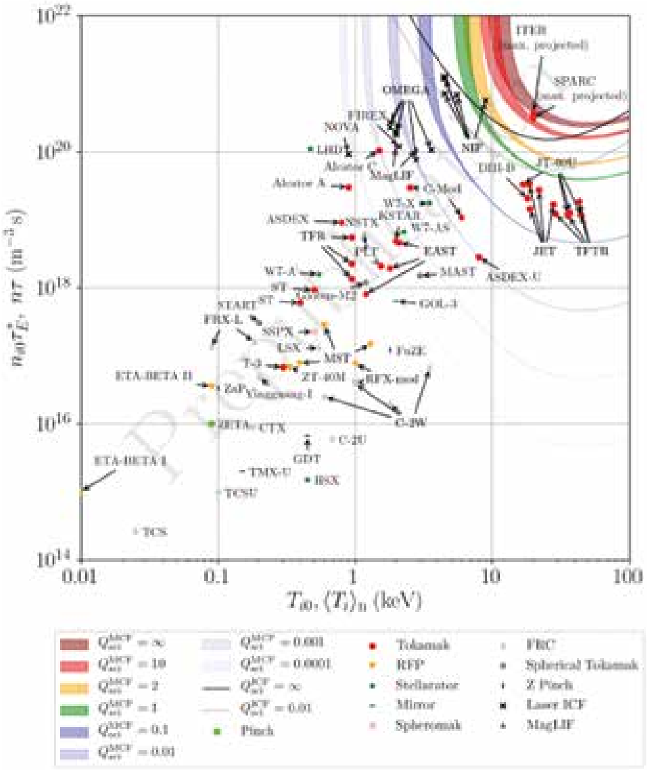

FIGURE 1: Obtained from Wurzel & Hsu [15]. A graph depicting the experimentally inferred Lawson parameters of fusion experiments. To date only NIF has successfully demonstrated ignition conditions (top right corner).

2. DIGITAL TWINS FOR FUSION

Historical approaches to computationally model physical systems has involved running codes to solve the governing physical equations (e.g., Maxwell's equations of electromagnetism, Newton's laws of motion, laws of conservation, equations governing fluid mechanics, and the like) to predict, numerically, the performance of physical systems. This is, in part, because many of the equations governing physical phenomena are only solvable numerically. For example, the stochastic elements arising from turbulence in fluid dynamics make it impossible to find an exact solution to the Navier-Stokes equations in such circumstances. As these systems become evermore complex, the costs, in terms of processing power and time, associated with these numerical approaches also escalates. There is, therefore, a continuing need to adopt more efficient approaches to computational analysis and prediction.

Digital twins, and surrogate models more widely, are examples of these more efficient computational tools, and have already been deployed across a range of industries with great success [26]. For example, models have been proposed to integrate surrogate modelling capabilities into the control systems of nuclear plants to improve the automation of analysis and control [21]. Instead of methodically and painstakingly solving governing physical equations to precisely model the performance of a system, digital twins are trained, using real obtained experimental data, to emulate real systems to predict a likely outcome for a given set of input parameters. That is, the models are trained to infer, based on a compilation of historic experimental results, the most likely physical outcome for a system operating with a given set of parameters. As digital twins are trained to infer their emulated predictions using a data-based approach, they are not constrained by the costs associated with a thorough and detailed calculation of the governing physical equations.

However, the successful deployment of such models requires high-quality training to build trust between the models and their end-users. In the vast majority of cases, this data is available as actual real measurements of the performance of an entire system being digitally twinned (e.g., there is a plethora of data about the performance of nuclear reactors).

In the case of fusion, there is – as yet – only one facility achieving ignition (although as noted above, even ignition is not sufficient for commercialisation) [3, 14, 15], and so real data indicative of whole-reactor performance for fusion reactors capable of achieving ignition or higher yields is much more limited. As such, there is significantly less whole-reactor data available for training surrogate models and digital twins. As the old adage goes, "Garbage In, Garbage Out" [27], so how can AI models which, inherently, require training on high-quality data be used to support R&D in the fusion space?

The solution, we posit, is to deploy digital twins in a specific and limited manner, targeted towards modelling specific aspects of a fusion reactor to answer well-defined and well-understood problems. This approach is, in fact, already in the early stages of adoption at the HL-3 tokamak in China, where a digital twin system is being developed and deployed to model just the temperature distribution within the vacuum chamber of HL-3 [28].

Over and above modelling temperature distributions, we suggest that fusion reactor design could also benefit from the targeted application of digital twins to the modelling of transport phenomena in fusion plasmas. Heat transport [29-31] and particle transport [32, 33] within fusion plasmas are already known to be critically important processes requiring precise control to optimise the performance of fusion reactors.

While the physics governing fluid transport is well-understood, solving the governing equations in the presence of turbulence generally requires a probabilistic approach. In particular transport phenomena in fusion plasmas are subject to the stochastic impacts of turbulence [34], and an abundant range of system-specific plasma instabilities [35, 36]. This makes it difficult, if not impossible to analytically determine the impact of transport effects without the use of large-scale models such as Vlasov-Fokker-Planck codes which have been developed and iterated upon for decades [37, 38]. These models can take several hours, even days, to numerically calculate the distribution functions for a given plasma, and, as such, consume significant computing resources.

However, transport phenomena are readily measurable using experimental techniques [39-44]. This makes digital twinning an ideal candidate for reducing the processing costs associated with optimising solutions to transport problems. As digital twins are simplified models that are data-driven, as opposed to physics-based, a digital twin is capable of solving problems much faster than a physics-based model [45]. This is readily extensible to fusion reactors. Provided the application of the digital twin is limited to modelling phenomena for which sufficient amounts of high-quality data is available, such as transport, digital twins offer an exciting route for improving the efficiency of reactor design and optimisation.

We propose that surrogate models such as digital twins could and should be applied in a piecewise fashion to the overarching problem of reactor design, with each model being trained to optimise the parameters for a specific and targeted problem for reactor design for which experimental data is available in both high quantity and high quality. For example, inertial confinement fusion approaches, as schematically illustrated in Figure 2 could implement a series of surrogate models to optimise: (i) laser beam profiles, (ii) target geometries, (iii) transport phenomena, (iv) target-loading configurations, and/or (v) diagnostic set-ups. Meanwhile, magnetic confinement fusion approaches could implement a series of surrogate models to optimise: (i) HTS magnet arrangements, (ii) magnetic field patterns and strengths, (iii) fuel injection procedures, (iv) shielding material performance, (v) plasma transport phenomena, and/or (vi) diagnostic set-ups, as is depicted similarly in Figure 3. As the reader will no doubt appreciate, these lists are not exhaustive but rather exemplary of the broad potential applicability of surrogate models to fusion reactor design and optimisation. What is important is that models are applied in a deliberately targeted fashion, with a piecewise layering of models – each of which can be independently validated with real experimental data, to build trust in the overall optimisation procedures. Moreover, above and beyond the application of surrogate models to reactor design, it may also be feasible and even desirable to apply these piecewise models to sensitivity analysis [46] to build an understanding of which parameters are most impactful on reactor performance.

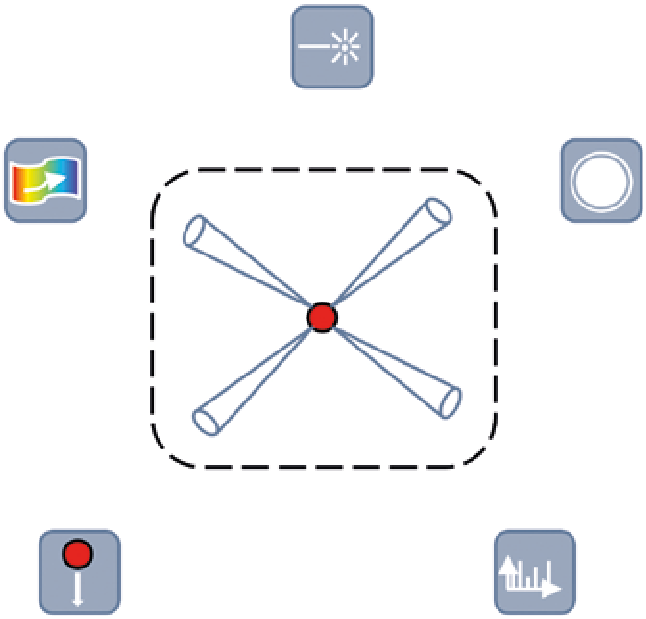

FIGURE 2: Schematic illustrating the potential applicability of discrete surrogate models/digital twins (peripheral objects) to the development of an inertial fusion energy reactor. Digital twins could be suitably and separately applied to one or more of (clockwise from top): (i) laser beam profiles, (ii) target geometries, (iii) diagnostic set-ups and measurements phenomena, (iv) target-loading configurations, and/or (v) transport phenomena.

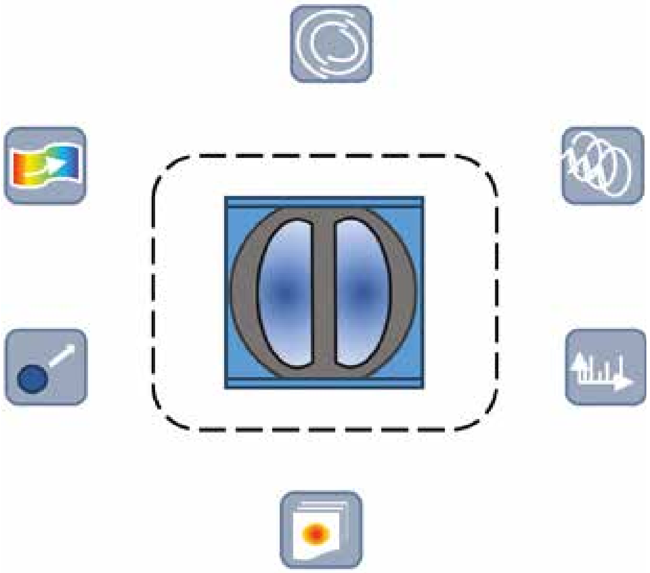

FIGURE 3: Schematic illustrating the potential applicability of discrete surrogate models/digital twins (peripheral objects) to the development of a magnetic fusion energy reactor. Digital twins could be suitably and separately applied to one or more of (clockwise from top): (i) HTS magnet arrangements, (ii) magnetic field patterns and strengths, (iii) diagnostic set-ups and measurements, (iv) shielding material performance, (v) fuel injection procedures, and/or (vi) transport phenomena.

3. FURTHER OPPORTUNITIES FOR THE APPLICATION OF AI

Beyond surrogate models, AI has the potential to shape other elements of reactor design and control in the fusion sector. AI-controllers for adaptively controlling actuators based on prediction from deep reinforcement (DRL) models have already been demonstrated on the DIII-D National Fusion Facility [47]. There, researchers demonstrated that their DRL models are able to adaptively respond to detected fluctuations within a few tens of milliseconds, thereby limiting the development of parasitic instabilities that could disrupt the confinement of the plasma. Such rapid, adaptive, control of operational parameters is far superior to anything achievable by manual control by a human operator.

Meanwhile, in inertial fusion research, generative AI is being used to optimize target design [48], a critical problem that must be solved to successfully commercialise laser-driven fusion. More broadly, the use of AI has been flagged by the Clean Air Task Force as being a critically important tool for building a fusion materials database to assist with materials selection [49].

Fusion would also stand to take inspiration from its more experienced cousin, the traditional nuclear industry. From robotics software [50] to wider systems control [21], from data analysis [51] to reporting that complies with regulatory requirements [52], the nuclear industry has already begun to see the successful adoption of AI to improve systems and processes across the organisational workflow. Fusion should take heed of this experience and adapt it to their needs.

4. MUTUAL BENEFIT

It's not just fusion that stands to benefit from AI, AI also stands to benefit from the nuclear and fusion revolutions.

When the development of a commercial fusion reactor is successful, Big Data will be offered the prospect of harnessing an inexhaustible source of clean energy. With the ever-booming growth of AI, there is already a huge demand for sustainable energy source to power AI-data centres [53]. Indeed, it is commonly and publicly highlighted by leaders in the AI industry that an energy breakthrough is necessary to support the growth of AI [54].

Large data centres will be vital to support the widespread use of AI and cloud-based computing applications. According to the International Energy Agency, overall capital investment by Amazon, Google, and Microsoft in new data centres contributed to 0.5% of US GDP in 2023 [55]. The power demand for data centres in the US alone is projected to increase to up to 12% of the total US electricity consumption by 2030 [56]. With many countries announcing pledges to achieve net zero emissions within the next few decades, there is a desire to meet these demands without the use of fossil fuels. Enter both fission and fusion.

Beyond being an energy supply, the high-performance computing requirements associated with achieving fusion also provide a bedrock for building a skilled AI workforce to deliver the next-generation developments in AI and high-performance computing more generally [57]. No doubt, it is this combination of benefits that has driven, and will likely continue to drive, the biggest tech companies in the world to invest significantly in the success of fusion companies, as recently evidenced by Google's recent power purchase agreement with US fusion company Commonwealth Fusion Systems [58], and OpenAI CEO Altman's multi-million investment in Helion Energy [59].

It is clear the AI industry seeks to benefit from the advancement of nuclear fusion, and that nuclear fusion stands to flourish by exploiting the capabilities of new and developing AI algorithms. Recognition of the synergies between these two industries is extending beyond the private sector, as governments also begin to see the potential symbiotic benefits. For example, the UK government announced earlier this year that it will deliver the first AI Growth Zone at the headquarters of the UK Atomic Energy Authority [60]. This public sector initiative aims not only to invest in AI infrastructure in the UK but also to advance fusion energy research, a clear demonstration of the strategic convergence of AI and fusion.

With a clear trajectory across academia, the public sector, and the private sector of a growing closeness between the fusion and AI sectors, it is clear that the futures and interests of both industries are set to become ever more closely aligned.

5. CONCLUSIONS OR CONCLUDING REMARKS

Many of the physics and engineering challenges impeding the successful commercialisation of fusion energy stand to benefit from the judicious application of AI models to make the optimisation of reactor design and control more accurate, reliable and efficient. However, as discussed above, it is important to note that a model is only as good as the data used to train it and, given the relative scarcity of fusion reactor data when compared with more established physical systems (such as conventional nuclear systems), any approaches to implementing AI solutions in the fusion sector require careful adaptation so that each model deployed is applied only to situations against which the model's veracity can be fully tested and benchmarked. This leads to the conclusion that models such as surrogate models and digital twins can still be implemented to assist fusion R&D, but must be deployed in a piecewise fashion to iteratively construct an overall reactor model, instead of adopting the more conventional approach of training a digital twin to treat an entire reactor system holistically.

Through the careful and targeted application of AI to fusion engineering, the progress of commercialisation could be significantly accelerated, thereby bringing the ambition of a commercial fusion reactor closer to fruition. Conversely, as a potentially significant source of carbon-free energy and a breeding ground for an engaged high-skill workforce, it is in the interest of Big Tech companies to support the development of fusion so that this emerging industry can contribute to the continued development of the new AI data centre paradigm.

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RICHARD A. JOHNSON

Chairperson, Partner, Patent Attorney

Richard develops and manages IP portfolios for clients in the UK and abroad, contributing to and assisting in the formulation and execution of IP strategies. Richard also handles patent prosecution at the European Patent Office and the UK Intellectual Property Office for a wide range of clients including on advanced nuclear technologies. His clients are primarily based in the UK, US, and China, spread across a range of diverse technical sectors including precision health, technical fabrics, telecommunications, affective computing and nuclear fusion and fission technologies. As chairperson at the firm, Richard is responsible for all Partnership business as well as being a member of the firm's Management Board. He holds an MPhys in physics from the University of Oxford.

HARRY WESTHEAD

Associate, Patent Attorney

Harry is a patent attorney in the firm's engineering and ICT team. His specialisms include power generation, nuclear reactor safety systems, image processing, radar systems, optical systems, cryptography, and medical devices including wearables, laryngoscopes, and surgical endoscopes. He works with a variety of different clients including UK-based start-ups, universities, and SMEs as well as multinational companies and international attorneys in Japan and USA. He holds an MPhys degree with a professional placement at a nuclear power plant from the University of Bath.

ALEX F. SAVIN

Patent Attorney

Alex works across all stages of the patent life cycle from invention capture and drafting, through prosecution, to opposition proceedings at the EPO. He is experienced in helping start-up companies and SMEs build and manage their patent portfolios and has particular expertise in the nuclear sector, including fusion and power generation, and in the field of optics & photonics. He has an MPhys degree in Physics and a DPhil in Atomic & Laser Physics, both from the University of Oxford. His research focussed on designing and implementing high-power laser experiments exploring inertial confinement approaches to nuclear fusion at major international laboratories dedicated to laser-driven fusion in the US, UK and Europe including the Lawrence Livermore National Laboratory, and the Central Laser Facility.

PHILIP HORTON

Patent Technical Assistant

Philip is a trainee patent attorney working in the engineering practice group. He has an MEng in Chemical Engineering from the University of Cambridge. He worked as a process engineer at a MOF-focused startup, where he led the scale up of their manufacturing process and worked on the development of MOF-based adsorptive systems including hydrogen storage, carbon capture, and air purification.

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 (~5.5%·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 ~78 g·yr^{-1} as waste effluent, which is ~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

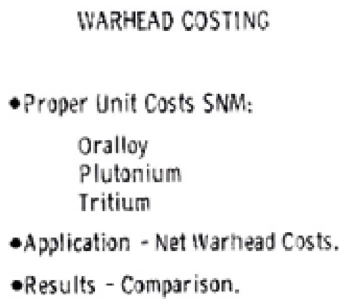
Tritium's primary use by volume has been the testing and deployment of powerful and deliverable nuclear warheads. Daniel Jassby, a retired researcher from Princeton Plasma Physics Lab, suggests that nuclear weapons account for "as much as 90% of the annual demand for tritium" [17]. However, tritium, 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 began selling tritium until its Darlington TRF started in the 1990s. A 2011 JASON report estimates that Canada sells ~100 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.

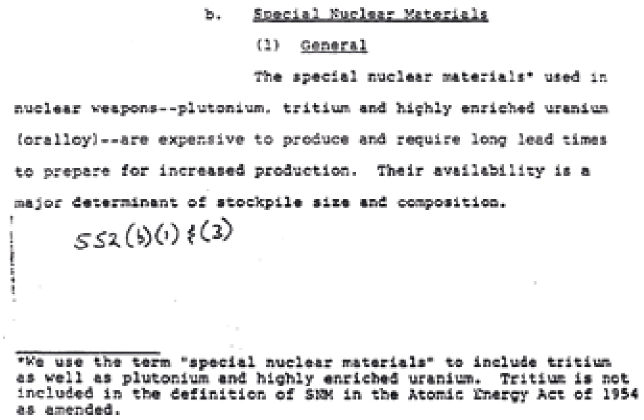


WARHEAD COSTING

- 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.

552(b)(1) & (3)

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*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 brough 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.

TAYLOR LOY

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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