Assessment of Challenges for Tritium Accountancy and Control in Fusion Energy Systems

R. L. Sindelar[*,†], D.W. Babineau[*], P.W. Gibbs,[**] J.E. Klein[*], and M.L. Moore[***]

[*]*Savannah River National Laboratory*
[**]*Oak Ridge National Laboratory*
[***]*Savannah River Site*
[†]*robert.sindelar@srnl.doe.gov, corresponding author*

INMM & ESARDA Joint Annual Meeting, May 22-26, 2023

Abstract

The D-T fusion reactor energy systems are expected to have large (kg level) inventory of tritium in-process for moderate-to-large (up to 500 MW_{th}) power plants. Accountancy of tritium in these plants is expected be established for several needs including systems efficiencies; radiological safety; safety basis accident scenarios; and environmental release. In addition, because tritium with deuterium can be used to boost the yield of nuclear weapons, the question has arisen as to whether the same or similar safeguards' controls used to manage inventories of special nuclear material (SNM) against theft or diversion should be applied to fusion tritium inventories. Although until 2011 regarded as a SNM by the U.S. Department of Energy (DOE), at present tritium is categorized as an "other nuclear material" for Nuclear Material Control and Accountability (NMC&A) program purposes per DOE-STD-1194-2019 as driven by DOE Order 474.2 for NMC&A. Neither the U.S. Nuclear Regulatory Commission (NRC) nor the International Atomic Energy Agency (IAEA) consider tritium as a SNM. This paper outlines the challenges for tritium accountancy in generic fusion energy systems and discusses the practicality of establishing a regulatory framework for safeguards controls.

1. Introduction

Commercialization of fusion energy using the D-T cycle to provide power globally would result in in-process tritium inventories of several hundred grams up to a kilogram (kg) per fusion power plant. [1]. In addition, once fusion is achieved on a global scale, there could be hundreds to thousands of commercial plants around the world. Also, to make the reaction sustainable additional tritium must be bred on the order of 10 to 20 % above what is burned in the fusion device. This additional 10 – 20% of bred tritium could become a source for diversion of tritium for use other than the specific fusion device at which it is bred.

As tritium is a strategic material used in design of thermonuclear weapons, the would-be abundance of tritium could be at risk for nefarious diversion from the stated purpose of fusion power. At present, prospective fusion energy systems (except for fission/fusion hybrid reactor designs) would not require the use, and therefore the presence of, special fissionable materials and thus would not be subject to safeguards per the IAEA [2]. As such, neither the IAEA or the NRC prescribe requirements for Material Control and Accountability (MC&A) for tritium. However, at DOE/NNSA facilities, tritium is subject to have an NMC&A program by the DOE Order 474.2A [3] with the program in accordance with DOE-STD-1194-2019 [4].

An outcome from the Fusion Energy and Nonproliferation Workshop held at the Princeton Plasma Physics Laboratory in the U.S. in January 2023 [5] was the charge to the fusion system designers to understand required protocols (should they emerge) for nonproliferation as set by regulatory and policy setting agencies (e.g., the NRC and the IAEA) as designers design their fusion systems. As an aspirational goal, the fusion systems could be demonstrated to meet the concept of Safeguards by Design, and in other words for fusion, the concept of "Fusion Nonproliferation by Design."

This paper recaps the major findings on the subject of tritium accountancy from the tritium management panel at the Fusion Energy and Nonproliferation Workshop, and further identifies the status of U.S. domestic and international policy and regulations with regards to tritium control for nonproliferation.

2. Background – Tritium Accountancy for Fusion Energy Systems

2.1. Fusion Energy and Nonproliferation Workshop, Tritium Panel

A *Tritium and Lithium-6 Management* panel with subject matter experts in tritium handling systems, Material Balance Area, Nuclear Material Control & Accountability (NMC&A), and (Nuclear Material) Safeguards for the US DOE/NA-10 Defense Programs (DP) tritium mission and for prospective fusion reactor systems, deliberated tritium management in fusion reactor systems with regards to tritium control for nonproliferation at the Fusion Energy and Nonproliferation Workshop [5]. The questions posed to the expert panel centered around themes such as "if, how, and at what levels of control, should new or modified regulations be established on a U.S. national or international basis for tritium and other fuel and source material inventories?" This question challenged the panel and workshop participants to contemplate tritium accountancy and control for a potentially large worldwide tritium inventory should fusion energy be broadly deployed for global energy production.

The panel expounded on the present methods for tritium accountancy in the systems for recovery and storage of tritium for the U.S. Defense Program mission; for the envisioned continuous use of tritium in D-T fusion; and on the sufficiency of existing regulations related to nonproliferation, including Export Control (EC), for tracking the production and utilization of fusion fuel and fuel-precursor materials.

A major outcome from the panel is the recognition that there are no present U.S. regulations or International Atomic Energy Agency (IAEA) requirements for strict control of tritium since tritium is not regarded as a proliferable, fissile special nuclear material. Rather tritium, its primary production source material, ^{6}Li, and deuterium[1], the other fuel in the fuel cycle for D-T fusion, are already dual-use materials, already subject to U.S. (and other host state) Export Control regulations.

2.2. U.S. Domestic Material Control and Accounting Regulations

Historically, under previous regulations dating back to the 80s, and up until 2011, tritium was treated the same as Category III SNM, and the US did apply some of the graded safeguards' controls used for SNM.

The specific regulations were DOE Order 5633.3A and 5633.3B that contained the following requirement for tritium:

> "Tritium is a nuclear material of strategic importance; therefore, graded safeguards programs for tritium shall be established and followed equivalent to the following categorizations:

[1] Deuterium as heavy water has the potential for use in production of SNM

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."

In 2011, with DOE Order 474.2, tritium was defined as "other nuclear material" for MC&A purposes and changed the minimum reportable quantity from 0.01 grams to 1 gram. However, when the total facility inventory is greater than or equal to 1 gram, all transactions that involve greater than or equal to 0.01 grams must be reported to the Nuclear Material Management Safeguards System (NMMS). Recently, tritium NMC&A requirements have been reduced further in the DOE Order 474.2A, issued February 7, 2023. That is, requirements were removed in 2011 and rewritten as:

"Other Accountable Nuclear Materials must be controlled and accounted for financial and management purposes and be protected in a graded manner consistent with their strategic and monetary importance".

The U.S. NRC does not cover tritium in its MC&A regulations (i.e., tritium is not listed in Title 10 of the U.S. Code of Federal Regulations Part 74, or in Title 10 of the U.S. Code of Federal Regulations Part 75). Therefore, a decision to apply safeguard's level controls to tritium would require the re-establishment of the MC&A regulatory base in the DOE Orders and the establishment of it in the NRC regulations.

3. Tritium Accountancy – Static Systems

As stated, tritium is not a fissile material and thereby not subject to international safeguards controls per IAEA requirements. At present, the U.S. DOE considers tritium to be a category IV other nuclear material required to be managed under an NMC&A program DOE Order 474.2A [3], with program requirement per DOE-STD-1194-2019 [4].

Tritium accountancy is performed on Material Balance Areas (MBAs) where an inventory difference is established. The sensitivity and accuracy of the accountancy method is considered when manifesting an Inventory Difference, the difference between the expected and the measured inventory.

Tritium Accountancy at SRS: An example of implementation of DOE NMC&A for tritium at the Savannah River Site follows.

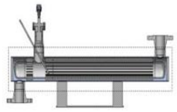
Standard, physical inventory of the in-process bulk tritium inventory and sealed confinement vessel item inventory is conducted once every 2-years to comply with DOE Order 474.2A for NMC&A. The storage systems are: i) conventional tanks; ii) metal hydride beds; iii) molecular sieve beds; and iv) sealed vessels.

INVENTORY MEASUREMENTS

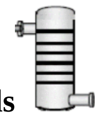
Inventory measurements are with two basic methods: i) pressure-volume-temperature-composition (PVTC); and ii) calorimetric as listed below. These methods are conducted in accordance with DOE-STD-1129-2015 [6].

Conventional Tank: 

- Pressure-Volume-Temperature-Composition (PVTC)

Installed Metal Hydride Beds 

- In-Bed Calorimetric Measurement

Installed Molecular Sieve Beds 

- Calorimetric Measurement Methods

Sealed Confinement Vessels 

- Calorimetric and/or PVTC with Piece-Count

Measurement error uncertainty is quantified for all the individual calibrated volumes and measurement systems (pressure, temperature, composition) used to obtain a best estimate of the physical inventory. It is emphasized that all these systems and accountancy methods are for tritium in a "static," or non-flowing system.

LOSS DETECTION METHODS

Inventory Difference Control Limits

- Statistically Derived Cumulative Uncertainties
    - 95% Confidence Level Warning Limits
    - 99% Confidence Level Alarm Limits

Tamper-Indicating Devices (TIDs)

- TIDs are used on locations (doors/drawers) and ports/valves of containers for sealed storage systems.

Statistical Sampling Plans

- Measurements are made to provide for statistical evaluation, with the defined sample population size of the inventories to be sampled for the physical inventory surveillance.

Account for Production Generation, Losses, & Decay

- Adjustments are made to the in-process bulk inventory and the sealed confinement vessels in remote storage to account for tritium decay losses over time on a monthly basis.

The processes for reconciling nuclear material inventories are described in DOE-STD-1194-2019 [4]. Regarding in-process bulk inventories, reconciliation of the in-process bulk inventory is based on inventory difference control limits (warning, alarm) derived from the cumulative production data between physical inventories. The inventory difference control limits are based on not exceeding 2% of the active throughput inventory between physical inventories. The inventory difference control limits are used to determine if the actual physical inventory difference falls within acceptable limits. The actual inventory difference is determined by subtracting the total inventory determined from measurements taken for the current physical inventory from the book inventory calculated at the beginning of the current physical inventory. The computed value is defined as the book-to-physical inventory difference (BPID) and the value must fall below the warning limit to validate the physical inventory results. If the BPID exceeds the inventory difference control limits, then all measurement data must be investigated to find where errors may have occurred or determine if the physical inventory measurements must be performed over.

For sealed confinement vessels in designated processing and storage locations, reconciliation is based on verifying that the errors identified in the location and serial number of the items are less than 1% of the total items on inventory (e.g., 10 item discrepancies out of 1000 items in storage). That is, this is a “piece count” inventory method.

A lesson learned from the SRS service experience, there are significant “losses” due to tritium permeation and retention in barrier materials.

4. Tritium Accountancy in Fusion Energy Systems

Figure 1 shows a notional design of a generic fusion power plant with potential points in the plant for tritium, Li-6, and also SNM (fissile material) diversion vulnerability. To formally track inventories of nuclear materials, MBA and accountancy methods would be implemented. A topical report on tritium accountancy for fusion systems [7] developed the concepts for tritium accountancy in fusion system where dynamic inventories would be the designed condition vis-à-vis a "static" storage system or a piece count system as described above.

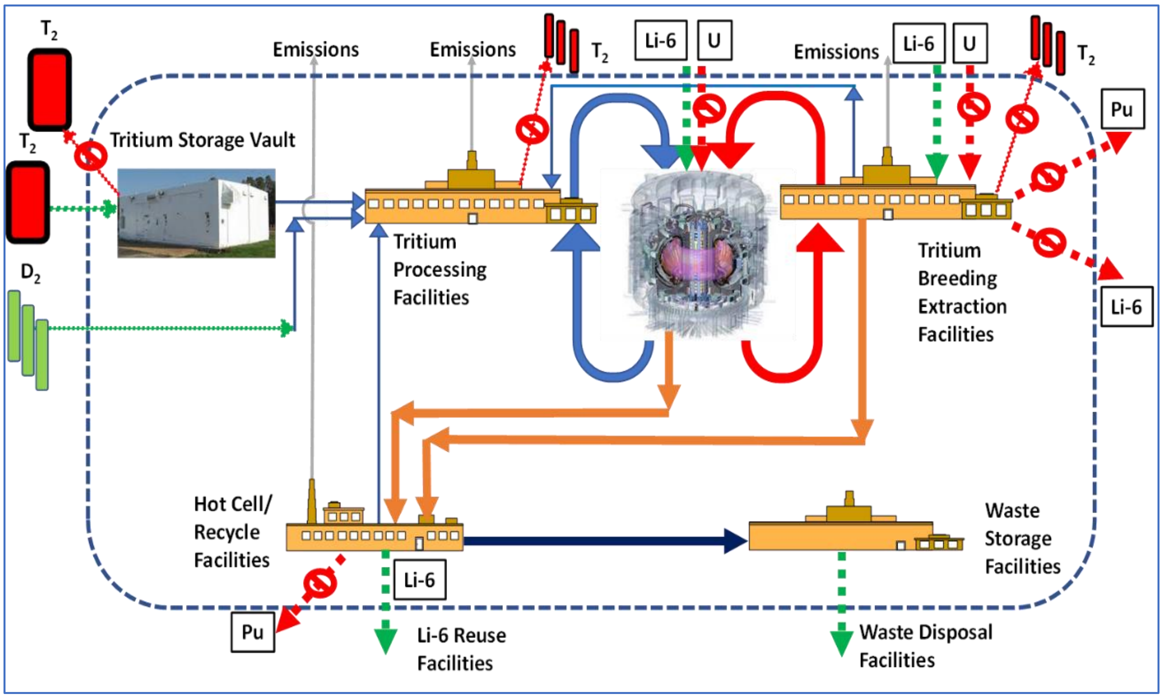


Figure 1. Fusion Power Plant Nuclear Material (T, D, Li-6, and SNM) – Notional Diagram

Reference [8] compiles the various tritium accountancy methods and their cited uncertainties available for fusion systems. Table 1 is a summary of the methods compiled in reference 8. Although in concept, methods for "dynamic" or flowing mass are available, methods to "measure' consumption of tritium in the fusion reaction, and the production in and recovery of tritium from the blanket are not established. A recent paper suggests that Kalman Filter algorithm, applied to a model of the fusion system, has the potential to be a useful technique to reduce uncertainties since tritium accountancy will depend on multiple separate sensor data during the continuous operation of a fusion device [9].

Section 4.1 below lists the challenges for tritium accountancy identified by the tritium panel at the Fusion-Nonproliferation Workshop [5].

Table 1 – Techniques for Tritium Accountancy [from reference 8, Table 1]

Method for Quantification of Tritium Amount	Parameter	Practical Accuracy (uncertainty)
"Static" PVTC (pressure, volume, temperature, concentration)		1 – 5% (integrated)
	Pressure	0.2-0.9%
	Volume	< 0.5%
	Temperature	0.1°C
Tritium Concentration	Measurement Method	
	Ionization Chamber	Few to 10%
	Gas Chromatograph	Few to 5%
	Laser Raman Spectrometer	< 0.5%
	Mass Spectrometer	0.5-5%
	Bremsstrahlung X-ray	A few %
Calorimetric Method		~ 1% (integrated)
"Dynamic" PVTC Accountancy with mass flowing		A few % (integrated)

Notes: 1) Releases to environment are cited to be around 10% accuracy; 2) Measurement methods including indirect methods using neutron flux for tritium consumption by the fusion reaction and for tritium production in the blanket would need to be developed

4.1. Tritium Accountancy Challenges Identified by the Tritium Panel

The findings of the tritium panel below are reproduced from the Fusion-Nonproliferation Workshop report [5]:

- The amount of tritium bred minus the tritium burned (minus other minor losses such as releases and waste) will have to be determined and any excess tritium will then have to be accounted for in plant operation. This excess is where any diverted tritium would have to come from, otherwise, the fusion process will not be sustainable. Furthermore, reaching a "steady-state" operation would not be achieved until tritium permeation and hold-up losses occurred – this would be plant-specific.
- Fusion systems developers are targeting system designs that provide for minimal inventory of tritium with mostly continuous movement of tritium. For example, the total in-process inventory of tritium for the ITER, an experimental facility, is expected to be approximately only 1 kg.
- Accountancy methods would have error spread in the inventory with the evaluation of the flow of tritium in the fusion plant with successive input, burn, output, and breed steps in the tritium fuel cycle.
- The scale of an international staff that would be needed for tritium accountancy monitoring subject to local plant facility and/or international (global) accountancy control enforcement would be substantial.
- Total tritium inventories in the plant would need to be manifested to evaluate safety basis accident scenarios. Radiological release potential is a driver to keep total inventory of tritium at minimum essential.

- The design of any NMC&A program for tritium should be appropriate for the power plant facility, including the scalability of the inventory and time constraint for validation of inventory differences. It was suggested that interface points between shipper/receiver of the fuel and source materials, and at the point of waste manifestation would be logical points for inventory declaration.
- The breakout discussions and panel read-out report stated that tritium in line breaks and loss as either gas or as contaminant in water is a sensitive, real-time detection that an NMC&A program just cannot meet. That is, in a closed flowing system, it is very hard to extract tritium undetected. Operating experience at SRS has shown that environmental monitoring of effluent streams (airborne, liquid pathways) permits real-time detection of tritium releases to allow for mitigation of exposure to receptors and the environment.
- It was suggested that tritium accountancy and MC&A requirements should account for tritium management control in security and safeguards of the fusion power plant facility. It was stated that "proving the negative on diversion" would be very challenging for fusion.

4.2. Additional Notes on Safeguards for Tritium

According to DOE regulations the broad definition of accountable nuclear material refers to all nuclear materials which are to be managed under a facility's Material Control and Accounting (domestic safeguards) program. These materials are divided into two major categories which are Special Nuclear Material (SNM) and other nuclear materials. As noted, tritium is considered "other accountable nuclear material."

Based on perceived risk, different protection strategies are applied using a concept called graded safeguards with those posing the most risk receiving the highest level of protection. SNM, which is considered "direct use" meaning that it can be used directly to make an improvised nuclear device (IND), receives the highest level of protection.

There are two main concepts which are significant quantity and conversion time. While these have been established for SNM, they have not been established for tritium nor has it been determined if they are even applicable as currently defined.

Significant quantity is the approximate amount of nuclear material for which the possibility of manufacturing a nuclear device cannot be excluded. It takes into account unavoidable losses due to conversion and should not be confused with critical masses. SQs are used in establishing the quantity component of the IAEA inspection goals. Conversion time is the time required to convert different forms of nuclear material to the metallic components of a nuclear explosive device.

While tritium can be used to boost a nuclear device, in absence of SNM it cannot be used to create one. Again, as SQ is currently defined, the logic used in establishing SQs values would be difficult to extend to tritium.

5. Conclusions

Tritium in fusion energy systems will have power plant total inventories expected to be at the kg level in post-startup operation for a power plants up to 500 MW_{th}. Fusion energy on a global scale would thus greatly expand the tritium supply that could be at risk for diversion and misuse. The need for safeguards for tritium at such fusion power plants is being deliberated in the U.S.

Although internationally the IAEA never had tritium under safeguards controls, the U.S. DOE did manage tritium similar to a SNM, subject to safeguards controls until 2011. Nevertheless, inventory of tritium is required under DOE NMC&A regulations as an "other accountable material."

Establishment of graded safeguards for tritium similar to SNM would have challenges for tritium accountancy from detection methods and limits, for example, for the continuous consumption and production in-process designs of fusion plants. Tritium accountancy challenges identified by an expert panel at a recent Fusion-Nonproliferation Workshop are listed in this paper.

6. Acknowledgements

This work was funded by the U.S. Department of Energy (DOE) National Nuclear Security Administration (NNSA), Office of Defense Nuclear Nonproliferation and by the DOE Office of Fusion Energy Science. This work was produced by Battelle Savannah River Alliance, LLC under Contract No. 89303321CEM000080 with the U.S. Department of Energy. Publisher acknowledges the U.S. Government license to provide public access under the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

7. References

[1] National Academies of Sciences, Engineering, and Medicine. 2021. "Bringing Fusion to the U.S. Grid". Washington, DC: The National Academies Press.

[2] Statute of the International Atomic Energy Agency, 1956.

[3] DOE O 474.2A, Nuclear Material Control and Accountability, February 7, 2023.

[4] DOE-STD-1194-2019, Nuclear Materials Control and Accountability

[5] "Fusion Energy and Nonproliferation Workshop – Summary Report, Revision 1, April 7, 2023," https://sites.google.com/pppl.gov/nonproliferationworkshop/home

[6] DOE-STD-1129-2015, Tritium Handling and Safe Storage

[7] "Tritium Accountancy in Fusion Systems," J.E. Klein, et. al., in Fusion Science and Technology, 67:2, 420-423, DOI: 10.13182/FST14-T44.

[8] M. Nishi et al. / Fusion Engineering and Design 81 (2006) 745–751

[9] "Investigating the Application of Kalman Filters for Real-time Accountancy in Fusion Fuel Cycles," H.G. Flynn and George Larsen, Fusion Engineering and Design 176 (2022) 113037, https:/ /doi.org/10. l 016/j.fusengdes.2022.113037