Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy.

TRITIUM ACCOUNTANCY IN FUSION SYSTEMS

J. E. Klein[a], E. A. Clark[a], C. D. Harvel[a], D. A. Farmer[a], M. L. Moore[b], L. L. Tovo[a], and A. S. Poore[a]

[a]*Savannah River National Laboratory: Aiken, SC 29808, , james.klein@srnl.doe.gov*
[b]*Savannah River Nuclear Solutions, Aiken, SC USA*

The US Department of Energy (DOE) has clearly defined requirements for nuclear material control and accountability (MC&A) of tritium whereas the International Atomic Energy Agency (IAEA) does not since tritium is not a fissile material. MC&A requirements are expected for tritium fusion machines and will be dictated by the host country or regulatory body where the machine is operated. Material Balance Areas (MBAs) are defined to aid in the tracking and reporting of nuclear material movements and inventories. Material sub-accounts (MSAs) are established along with key measurement points (KMPs) to further subdivide a MBA to localize and minimize uncertainties in the inventory difference (ID) calculations for tritium accountancy.

Fusion systems try to minimize tritium inventory which may require continuous movement of material through the MSAs. The ability of making meaningful measurements of these material transfers is described in terms of establishing the MSA structure to perform and reconcile ID calculations. For fusion machines, changes to the traditional ID equation will be discussed which includes breading, burn-up, and retention of tritium in the fusion device. The concept of "net" tritium quantities consumed or lost in fusion devices is described in terms of inventory taking strategies and how it is used to track the accumulation of tritium in components or fusion machines.

I. INTRODUCTION

Tritium, the radioactive isotope of hydrogen (protium, deuterium, tritium), is of interest for its fusion properties for defense and energy programs, but also for its beta-decay properties (e.g. medical isotope labeling, exit signs, and beta-batteries). Tritium is not a special nuclear material (SNM) such as enriched uranium or plutonium so requirements for nuclear material control and accountability (NMC&A) programs are not defined by the International Atomic Energy Agency (IAEA), but by some other state, governmental, or regulatory authority where the material is to be used. In the United States Department of Energy (US DOE) sites, nuclear material control and accountability (NMC&A) programs are established to maintain control of nuclear materials and similar programs will likely be established for any fusion systems established in the US. Numerous program elements are needed for a complete NMC&A program. This paper discusses key elements of a fusion system tritium NMC&A program and some of the unique challenges to quantify tritium inventory locations in fusion applications.

II. PROGRAM REQUIREMENTS

Minimal program requirements for a tritium NMC&A program include guidance or background documents. These documents describe the facility, how the facility is intended to operate, how the facility will be broken down into smaller sections or areas for the accounting structure, what other nuclear materials are allowed or excluded from the facility, the accounting procedures and systems (records and reports) to be used along with the division of roles are responsibilities of various organizations to independently validate the results of the material inventory process. Other related documents would include material control plans (i.e. physical protection, access control, and other safeguard systems), facility emergency plans, and the procedures to handle incident/anomalies that may occur in the facility related to NMC&A.

In documents describing the facility and intended mode(s) of operations, major processes or unit operations can be described and based on the technology chosen for the process, logical structures may become apparent for defining boundaries for setting an accounting structure to track material flows in and out of the facility. The material balance area (MBA) is the boundary of the material accountancy structure and materials entering or leaving a MBA are to be measured and accounted to form a basis for material inventories. Multiple MBA structures are useful for ensuring custodianship of SNM to better track lost, theft, or diversion and track material form changes of SNM, but a single MBA structure is adequate and more cost-effective to use when only tracking tritium transfers, decay, and breeding.

An MBA is typically broken into material sub-accounts (MSAs) to localize and minimize inventory differences (IDs) between various process operations to better account for tritium in the MBA. Within a MSA, the tritium must be measureable to create a physical inventory (PI) (e.g. gram) values at the end of the PI period while the material entering or leaving the MSA between PI periods must also be measured to support a book inventory (BI) for the accounting process. Material measurements locations of material in, entering, or leaving the MSA are identified as key measurement points (KMPs) and these locations must be described in NMC&A plans.

III. INVENTORY DIFFERENCE (ID) AND LIMIT OF ERROR ON INVENTORY DIFFERENCE (LEID)

Periodically, a PI is performed to measure the tritium inventory and its location within a facility at its KMPs. Many publications in the fusion literature focus on techniques for calculating PI values and associated uncertainties of the measurements.[1] The uncertainty in a value is the standard deviation (σ) of that value and the variance of the value is the square of the standard deviation. Each PI KMP needs a measurement method and a corresponding measurement control program (MCP) to validate the measured or calculated value and the σ obtained for the value.

Between physical inventory taking (PIT) periods, material is transferred in and out of MSAs and the quantity of tritium that crosses a MSA boundary is measured at KMPs of the MSAs. Material transferred into an MSA during a material balance period (MBP) is a "Receipt" and material leaving the MSA is a "Shipment". An inventory difference (ID) is used to determine the difference in nuclear materials inventories between two discrete PI periods and is defined as[2]

$$ID = SI + R - S - EI \qquad (1)$$

where SI is the previous book (physical) inventory (i.e starting inventory), R is the sum-of-Receipts (additions) after the previous book inventory (BI), S is the sum-of-Shipments after the previous book inventory, and EI is the current ending physical inventory.

The statistical uncertainty in the ID, called the Limit of Error on Inventory Difference (LEID), is calculated to determine if the PI value EI at the end of the inventory period exceeds established control limits. The LEID is calculated from the statistical uncertainty from the KMP measurement system σ values. For random measurement errors, the variance (σ^2) of the ID sums the variances of the terms in Eqn. 1 and is given by

$$\sigma_{ID}^2 = \sigma_{SI}^2 + \sigma_R^2 + \sigma_S^2 + \sigma_{EI}^2 \qquad (2)$$

The σ_{EI}^2 term is the summation of all variances for all physical inventory measurements in the facility while the σ_R^2 and σ_S^2 terms are the summation of all variances for Receipts and Shipments, respectively. It is application of Eqn. 1 and Eqn. 2 that makes fusion tritium systems somewhat unique compared to other tritium systems and is focus of the remainder of the paper.

IV. ID AND LEID IMPLICATIONS TO FUSION SYSTEMS MSA DESIGNATIONS

Implicit in Eqn.1 is that within the MBA, the tritium flow or process stops long enough for PI measurements to be performed: the SI and EI terms. The other two terms of Eqn. 1, R and S, are calculated for all material that cross the MSA boundary and their uncertainties must not dominate the uncertainties of the SI and EI terms in Eqn.2 to produce a meaningful ID. Tritium decay in the R and S terms are handled by taking the amount of tritium transferred at a specific time and increasing the transfer value to correspond to the start of the inventory period: material balance period (MBA). Then at the time of the inventory period, the values are decayed so they will correspond with the EI values.

The focus of many tritium fusion systems is to minimize the tritium inventory of the facility. As part of the process design, the tritium not consumed by the fusion process is reprocessed as quickly as possible and reintroduced into the fusion device. Continuous running of the fusion device does not allow the tritium process to be stopped to perform tritium PI measurements to obtain SI and EI terms.

Furthermore, the continuous flow of tritium across a MSA boundary is problematic in calculating the R and S terms in Eqn. 1. The uncertainty in measuring a continuous flow of material (tritium) is proportional to the square-root of time:

$$\sigma(\text{continuous flow measurements}) \propto \sqrt{t} \qquad (3)$$

The point of Eqn. 3 is that for a continuously operating fusion fuel cycle, the uncertainty of the R and S terms for continuous tritium flows will eventually grow with time to the point where the uncertainty in these terms will dominate the measured uncertainties in Eqn. 2. Thus the MSA boundary must be enlarged around the tritium process to the point where material can be physically measured and the flow of material crossing the MSA boundary can be tracked or measured with sufficiently low uncertainties to allow meaningful application of Eqn. 2.

The implication of this section reveals there may be few choices for establishing meaningful MSA boundaries for accounting purposes. The first choice is where tritium from an outside source is shipped to and received by the facility. This material will be measured in a receiving area, or MSA, as part of a shipper-receiver agreement so a starting value entering the MBA. The second MSA would be the fusion process itself where the tritium from the receiving (and possibly also a storage) MSA is measured as it is transferred into the process.

Depending on the design fusion process and its design, there may be other options for designation for MSAs. The criteria for establishing meaningful MSAs, can be interpreted and application of Eqn. 1 and Eqn. 2 where the magnitude of the LEID from Eqn.2 is some fraction of the PI value: possibly on the order of a few or several percent. Another option for establishing a MSA would be a tritiated waste staging area. As material is removed from the process and transferred to the waste staging or storage area, estimates will be made for the tritium content of the material leaving the process MSA (i.e. a Shipment) and the waste area MSA would encounter a Receipt of material. Even if the actual value of the tritium content of the material transferred is initially estimated, the accounting system will allow for adjustment of tritium inventory values for both the process MSA and the waste MSA.

The unfortunate result of limited choices for defining MSAs is that once tritium enters the process MSA, it is effectively in that MSA until is leaves through a process transfer (e.g. stack emission, transfer to waste area) or the process is stopped long enough for PI measurements to be taken. This means that physical control/security measures must be implemented to prevent diversion of material from the process. The impact of limited times to make process measurements and how that impact potential safety basis commitments is discussed in the next section.

V. SAFETY INVENTORY METHODOLOGY

For fusion systems, there may be upper bounds on tritium inventory limits in certain process locations stipulated by safety analysis report (SAR) analyses. Some of these limits can be protected by design of the system (e.g. limited tank sizes and pressures). If there is an inventory limit on the fusion chamber (FC) itself, that poses another interesting application of Eqn. 1 and Eqn. 2. For the MSA containing the FC, Eqn. 1 can be written as

$$ID = SI + (IN + BR) - (BU + LOSS + OUT) - EI \qquad (4)$$

where the previous R terms was modified to include the flow of material into the MSA (IN) PLUS the amount of material produced by breeding (BR), and the S term modified to reflect tritium burn-up (BU), process losses (LOSS), and flows out (OUT) of the MSA. What is proposed for the case where limits exist on the net amount of tritium that is consumed or disappears in the FC is to define the term NET as

$$\begin{aligned} NET &= ID + BU \\ &= SI + (IN + BR) - (LOSS + OUT) - EI \qquad (5) \end{aligned}$$

It is assumed in the application of Eqn. 5 that all tritium that is not measured or accounted for in the other terms of the equation resides in the FC. For now, we will neglect the BR term so the ID in Eqn. 5 now represents the amount of tritium that has entered the FC that is not consumed by the fusion reaction. The remaining terms in Eqn. 5 are

$$NET = SI + (IN) - (LOSS + OUT) - EI \qquad (6)$$

For situations where there is a MBP where PI measurements can be made, the Eqn. 6 terms SI and EI will be calculated and it is assumed that flows in and out of the process and losses from the process can be measured or calculated so the NET amount of tritium that has entered the FC can be calculated. It is assumed that corresponding uncertainties and variances for these terms can also be calculated.

If the amount of tritium in the FC needs to be known (assumed to be equal to the ID) to protect SAR limits, Eqn. 5 can be re-written as

$$ID = NET - BU \qquad (7)$$

In a FC, there will be diagnostic instruments installed as part of the system to monitor the extent of the fusion reaction (e.g. neutron detectors). For these instruments, there will be random errors associated with these measurements and the variance be denoted by $\sigma_{BU\_random}^2$.

Unfortunately, the number of diagnostic instruments and the knowledge of tritium fusion reactions are limited so any FC measurements used to calculate tritium BU will also have systematic uncertainties or biases associated with the measurements. For example, if 10 neutron detectors are positioned in the FC, they will measure a limited region of the fusion reaction. Based on their position and the model used to calculate tritium consumed by the fusion reaction, the calculation of tritium consumed by reaction could be systematically higher or lower than the true value and the systematic variance represented as $\sigma_{BU\_systematic}^2$. The uncertainty in the FC inventory is then obtained from

$$\sigma_{ID}^2 = \sigma_{NET}^2 + \sigma_{BU\_random}^2 + \sigma_{BU\_systematic}^2 \qquad (8)$$

Depending on how the BU values are calculated, the variance for the random contribution to Eqn. 8 will be proportional to the number of cycles or time the FC is operated while the system contribution will be proportional to the square of this same term.

An illustration of how terms like those in Eqn. 8 impact the uncertainty in calculating FC inventories is shown in Figure 1. Figure 1 shows as a percent of some defined SAR inventory limit, the NET amount of tritium introduced into the FC using Eqn. 6: the square symbols in the figure representing random uncertainties. Based on results of FC diagnostic measurements, the amount of tritium burned by the fusion reaction can be calculated and subtracted from the NET amount to produce the ID line shown in the figure.

The random error contribution to the ID uncertainty is shown as square symbols with the dotted lines in Fig. 1 and the systematic error contribution shown as round symbols with the dashed lines.

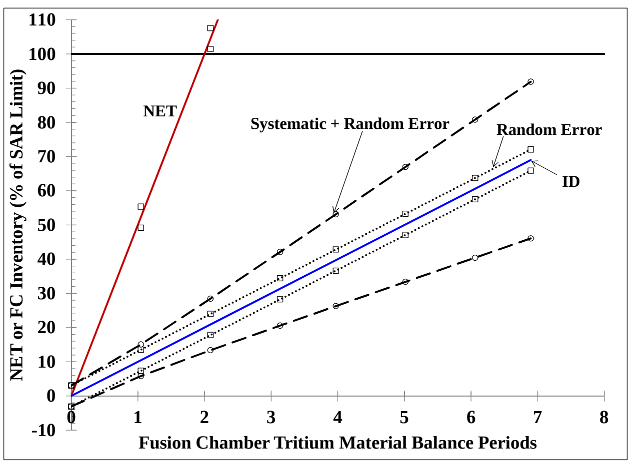

Fig. 1. NET and FC Inventory versus Material Balance Periods

VI. DISCUSSION

The example illustrated in Fig. 1 shows that PI measurements must be made to calculate the NET tritium introduced to the FC. Based on the calculated amount of tritium burned by the fusion reaction, the residual tritium in the FC can be calculated. The figure shows for low cycles or MBPs, the random error dominates the uncertainty of the FC inventory estimate, but as operations continue, the systematic error/bias term in Eqn. 8 dominates the uncertainty in the FC inventory calculation.

One method to improve the calculations in tritium BU, and reduce the magnitude of the systematic bias, is to analyze (destructively assay) the FC to determine its tritium content. By performing this analysis, the uncertainties in the ID calculated for the next FC will be smaller and the ID line illustrated in Fig. 1 better represent the residual tritium content of the FC.

VII. CONCLUSIONS

For fusion systems that are to operate continuously, there are limited options for defining MSAs for NMC&A programs since the material to be measured is not stationary long enough for PIT to be performed. Ultimately, the process will stop and tritium measurements will be made on the process.

Further complicating tritium accountancy in fusion systems is when a SAR based requirement exists were the tritium content of a vessel needs to be limited and the contents of the vessel are not easily measurable. Indirect methods must be used to calculate the maximum possible tritium inventory in the vessel and the uncertainty of this calculated value. Although costly, analysis of a FC after use will yield significant information on the methods used to calculate tritium burn-up and the uncertainty in the residual tritium content of the FC. Additional study is needed on alternate approaches for tritium accountancy in fusion systems.

ACKNOWLEDGMENTS

This manuscript has been authored by Savannah River Nuclear Solutions, LLC under contract No. DEAC09-08SR22470 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting this article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for United States Government purposes.

REFERENCES

1. J. E. Klein, "A Summary of Tritium In-Bed Accountability for 1500 Liter $LaNi_{4.25}Al_{0.75}$ Storage Beds," *Fusion Technol.*, **28**, 1026 (1995).
2. U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research. Chapter 13, Nuclear Material Accounting [book auth.] C. A. Bennett and W.M. Bowen. "Statistical Methods for Nuclear Material Management. s.1.: NUREG/CR-4604, 1988.