SAFEGUARDS MODELING OF TRISO FUEL FABRICATION FACILITIES

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ABSTRACT

Sustained global interest in advanced reactors has necessitated the development of safeguards systems and models for their associated fuel fabrication facilities. High temperature gas reactors (HTGRs) are planning on utilizing high-assay low enriched uranium (HALEU) Tri-structural ISOtropic (TRISO) particle fuel. A TRISO fuel fabrication facility converts a HALEU starting material to TRISO fuel through a variety of physical and chemical processes. The presence of HALEU in comparison to low enriched uranium (LEU) impacts safeguards performance and requires deeper analysis. A TRISO fuel fabrication facility model is built within the Separation and Safeguards Performance Model (SSPM), to investigate the impact HALEU has on meeting safeguards requirements. Page's trend test on SITMUF shows the lower throughput aids the facilities ability to meet safeguards requirements; however, with increasing throughput, material balance period, and uranium enrichment, safeguards by design is required to ensure safeguards limits are met.

1 Introduction

Advanced nuclear reactor vendors are investigating new and different approaches to clean energy, utilizing new fuel types, and higher fuel enrichment. The current nuclear fleet is primarily fueled with low enriched uranium (LEU), U^{235} enriched between 2-5%; however, new vendors are proposing higher enriched fuel, high-assay low enriched uranium (HALEU), U^{235} enriched between 10-20% [1]. A popular reactor design, being proposed at various scales, is the high temperature gas reactor (HTGR), which utilizes TRi-structural ISOtropic particle fuel (TRISO fuel) to power the design [2, 3]. Safeguards strategies need to be developed to ensure that international safeguards requirements are being met for this new class of fuel. New fuel fabrication facilities, at higher enrichment at different throughput, are coming online and an investigation into the ability to meet international safeguards requirements is needed. Material control and accountancy (MC&A) is a notable part of regulatory requirements for fuel fabrication facilities that may require new insights with the higher enrichment levels of HALEU.

There are several features within MC&A that impact a fuel fabrication facilities' ability to meet international safeguards requirements:

- The material balance areas (MBAs)
- The material balance periods (MBPs)
- The throughput of the facility
- The U^{235} enrichment of the material

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MBAs, MBPs, throughput, and enrichment impact the statistical calculations associated with MC&A: Material unaccounted for (MUF), σ_{MUF}, standardized independent transform MUF (SITMUF), and Page's trend test on SITMUF [4–8]. The fuel fabrication facilities of light water reactors (LWRs) and HTGRs have several commonalities in terms of safeguards; however, key differences (throughput and uranium enrichment) may play a role in meeting safeguards requirements.

The structure of the MBAs will likely remain the same with a facility being composed of two shipping-receiving areas and one processing area [9, 10]. The shipping-receiving areas are where feed material and final fuel forms entering and exiting the facility are stored, and the processing area is where the feed material is converted to the fuel form. The statistical tests for a TRISO fuel fabrication facility are the same as the LWR facility. The key difference between these two facilities, is the throughput and the enrichment level. TRISO fuel fabrication facilities are planning to have significantly lower throughput, decreasing from the 1000 metric ton throughput, with enrichment levels between 3-5%, to the order of 10-100 metric ton throughput for TRISO fuel fabrication facilities, with proposed enrichment levels between 10-20% U^{235} [11].

Past work has developed models of LEU fuel fabrication facilities to perform statistical analysis based on STR-150, which showed that facilities are able to meet international safeguards requirements for LEU at larger throughputs, approximately 300 metric tons per year [9, 12]. MC&A will continue to be a powerful tool for advanced fuel fabrication facilities to ensure that no material is lost during nominal operation. A scalable TRISO fuel fabrication model is developed to perform statistical analysis at varying levels of HALEU enrichment and the preliminary results quantifying the impact MBP and enrichment have on identifying material loss scenarios is shown.

The goal of this work is to quantify the impact HALEU enrichment has on meeting safeguards requirements. A TRISO fuel fabrication facility model is created to calculate and quantify the flow of material through the facility and calculate statistical tests used in international safeguards. This preliminary work is focusing on the impact fuel enrichment has on meeting international safeguards requirements and detecting material loss scenarios. There are two key focuses of this work:

- **Development of SSPM model (Section 3.1):** Existing models within SSPM [13], have simulated the flow of material for reprocessing facilities and LEU fuel fabrication facilities. This model is the first foray into fuel fabrication facilities for advanced reactors. This model is developed with modern facilities in mind, the model is scalable to different throughput and different fuel enrichment.
- **Analysis of safeguards metrics (Section 4):** After the development of the model, the MAPIT API [14] is used to perform statistical analysis to quantify MUF, σ_{MUF}, SITMUF, and Page's Trend Test. The impact enrichment has on these statistical tests is the focus.

2 Related Work

The development of TRISO fuel and HTGRs started in the late 1950s, with demonstration reactors built in the late 1960s and 1970s [15, 16]. In recent years, HTGRs have been proposed by many vendors, with commercialization requiring fuel fabrication facilities, safeguards analysis is required for TRISO fuel fabrication facilities. Figure 1 shows the process of converting U_3O_8 to a UCO (a mixture of UO_2 and UC_2) kernel [17]. The conversion process has two major steps, the first is the creation of the broth, where chemicals are mixed together and the second is the internal gelation process, where silicon oil is used to create and shape the TRISO particles. Following the gelation processes the TRISO particles are washed and dried prior to the standard ceramic fuel processing: calcination, reducing, and sintering [10, 16, 17]. With the move from demonstration reactors to power reactors, the throughput of TRISO fuel fabrication facilities will need to increase to meet the demand.

Statistical tests play a key role in safeguards. The majority of literature focuses on the development and application of "near-real-time" accounting wherein statistical evaluations are made in regular intervals throughout the year rather than a single yearly evaluation [6, 7, 18]. The most common approach to material accountancy for bulk facilities involves the calculation of MUF [7, 19] and the associated uncertainty (σ_{MUF}). Larger facilities often employ more complex statistical tests such as a combination of the standardized independent transformed material unaccounted for (SITMUF) [8], Page's trend on SITMUF test [5, 6].

Overviews of key safeguards approaches for TRISO fuel fabrication facilities is a new field with limited resources [10]. The overviews have identified material balance areas (MBAs) and key measurement points (KMPs) throughout the facility.

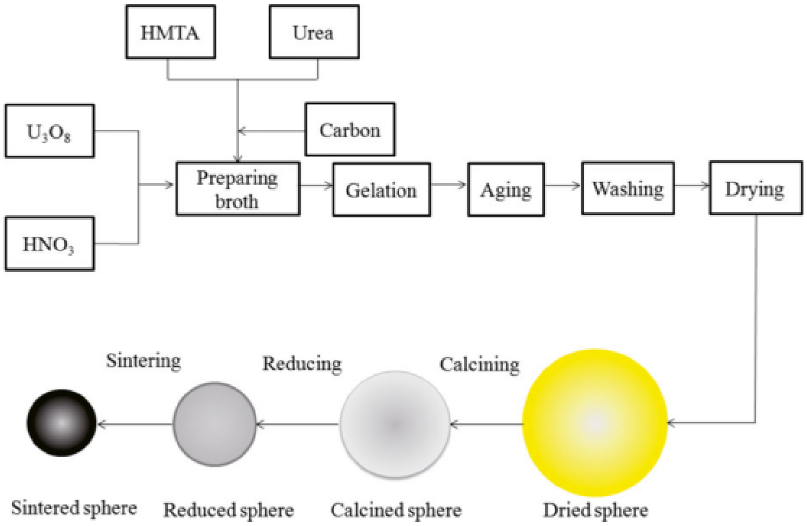

Figure 1: UCO kernal production [17].

The proposed structure is similar to the MBA structure of the LEU fuel fabrication facility within STR-150 [9], where the facility is broken into three MBAs:

- Shipping-Receiving Area (feed material entering the facility)
- Processing Area (feed material converted to the TRISO fuel form)
- Shipping-Receiving Area (TRISO fuel being prepared for shipment)

Analysis presented in this work is motivated by the need to understand the impact HALEU fuel has on meeting safeguards requirements. Separations and safeguards performance modeling (SSPM) is a key methodology in quantifying the material transferring throughout the facility and developing datasets for further analysis [13]. Previous work within SSPM has been used to develop models emulating LEU fuel fabrication facilities, based on STR-150 [12]. The LEU model simulates the UF_6 to UO_2 conversion process and the UO_2 pelletization process to generate datasets for safeguards statistical analysis. The material accountancy performance indicator toolkit (MAPIT), an open-source material accountancy toolkit, is designed to calculate common statistical tests utilized by the International Atomic Energy Agency (IAEA) [14]. MAPIT is used to calculate MUF, σ_{MUF}, SITMUF, and Page's trend test on SITMUF for the datasets created within SSPM.

Literature focused on material accountancy strategy for TRISO fuel fabrications dates back to 2022 and is relatively small [10]. Initial work has been focused on identify MBAs and KMPs for these facilities, identifying measurement technologies for the different material processes within the facility, and identifying key safeguards requirements that TRISO fuel fabrications need to meet. The work presented here builds on the previous work with the development of an SSPM model of a TRISO fuel fabrication facility to calculate safeguards statistical tests.

3 Methodology

This work considered the quantity of material transferring through a TRISO fuel pebble fabrication facility, based on information from the US AGR program [20]. A TRISO pebble facility was chosen as it is the more prevalent design, and changes needed to simulate a prismatic bed facility would not significantly impact the statistical calculations. The goal is to quantify the material entering the facility, being chemically and physically converted to TRISO fuel, and material exiting the facility to calculate key statistical results and understand how the higher enriched fuel impacts safeguards.

The TRISO fuel pebble fabrication facility is modeled as a part of the SSPM. This model, based in MATLAB SIMULINK [21], is designed to be scalable in various ways to simulate different characteristics associated with TRISO fuel fabricaiton facilities. The scalable nature of the model aids safeguards by design as changes in the fuel and throughput can easily quantify the material and statistical tests for TRISO fuel fabrication facilities. The model features a scalable throughput, enrichment level of the fuel, and individual processes can be further modified to better simulate different aspects of the TRISO fuel fabrication process. The dataset generated from the SSPM model are then fed into MAPIT to calculate the statistical tests of interest.

3.1 Model

In this work, a TRISO model has been developed to quantify the flow of material throughout the facility. Figure 2 shows the MBA structure and key processing steps for the conversion of UO_2 to UCO within TRISO pebbles. The model's MBA structure is based on STR-150 [9], where there are three MBAs: two shipping/receiving areas and one processing area. MBA1 simulates HALEU UO_2 entering the facility. MBA1 has the singular function of taking in UO_2, storing the material, and sending the material to be processed within MBA2. MBA2 models the chemical and physical conversion of the UO_2 to UCO TRISO pebbles. The conversion process is broken into three major parts: internal gelation, kernel densification, and pebble formation. The gelation process first prepares the broth a mixture of uranyl nitrate, urea, HMTA, and carbon. The broth then goes through the internal gelation process, where silicon oil is used to form the TRISO kernels. Following the gelation process, the kernels are washed, aged, and dried. Following the gelation process, densification of the kernels is the next step; calcination, reducing, and sintering are performed to get the UCO kernel to the ideal density and radius. Following sintering, the TRISO kernels are then coated with C and SiC to create the TRISO pebbles. MBA3 simulates the transfer of TRISO pebbles into the final shipping and receiving area within the facility. TRISO pebbles are placed in drums and sent out of the facility for use in power reactors. Key aspects of the TRISO fuel fabrication facility are summarized in Table 1. This analysis explores a hypothetical facility with a notional throughput of 22 MTU per year; this value is chosen arbitrarily and does not reflect any vendor plans. Two U^{235} enrichment levels are investigated in this work: Enrichment_a, 10 % U^{235} and Enrichment_b, 19.9 % U^{235}, are used to understand the impact HALEU enrichment has on safeguards tests.

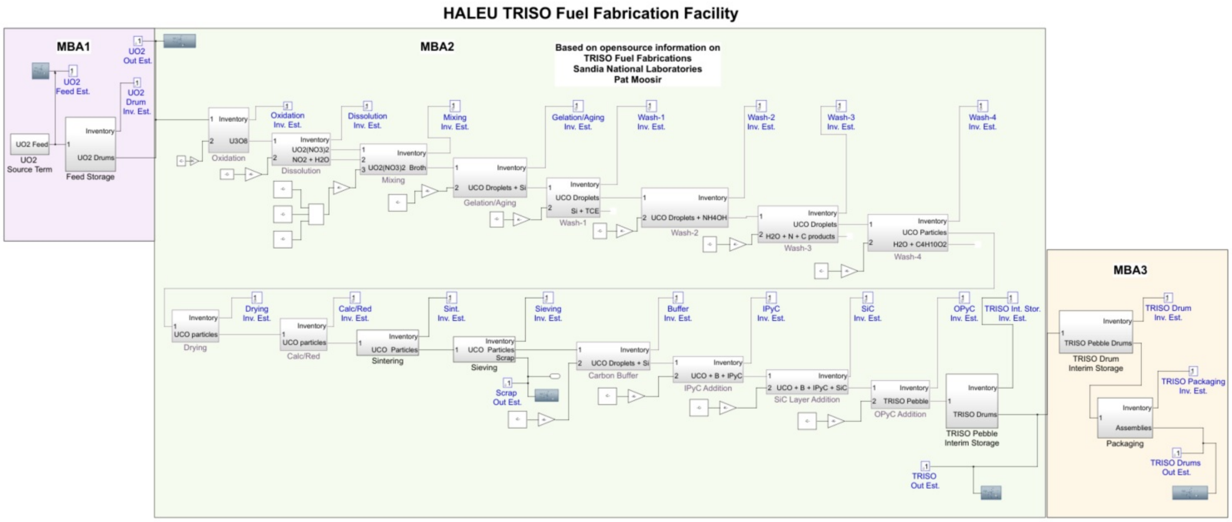

Figure 2: MBA Structure of the TRISO SSPM Model

Characteristic	Quantity
Notional Throughput	22 Metric Tons U/year
Starting Fuel Form	Powdered UO_2
End Fuel Form	UCO TRISO Fuel Pebbles
Enrichment_a	10% U^{235}
Enrichment_b	19.9% U^{235}
MBP_1	1400 hours (2 months)
MBP_2	2800 hours (4 months)

Table 1: Summary of dataset characteristics.

Scenario	**Enrichment**	**MBP**	**Initiation Time**	**Material Loss Amount**	**Duration (MBPs)**
1	a	MBP$_1$	0	0	0
2	a	MBP$_2$	0	0	0
3	b	MBP$_1$	0	0	0
4	b	MBP$_2$	0	0	0
5	a	MBP$_1$	3MBP$_1$	1SQ	MBP$_1$
6	a	MBP$_1$	3MBP$_1$	1SQ	2MBP$_1$
7	b	MBP$_1$	3MBP$_1$	1SQ	MBP$_1$
8	b	MBP$_1$	3MBP$_1$	1SQ	2MBP$_1$
9	a	MBP$_2$	3MBP$_2$	1SQ	MBP$_2$
10	a	MBP$_2$	3MBP$_2$	1SQ	2MBP$_2$
11	b	MBP$_2$	3MBP$_2$	1SQ	MBP$_2$
12	b	MBP$_2$	3MBP$_2$	1SQ	2MBP$_2$

Table 2: Summary of datasets.

3.2 Data

Twelve datasets are generated to determine the impact HALEU has on detecting material loss scenarios for a TRISO fuel fabrication facility. The six datasets, associated with MBP$_1$, are over 1 operational year, with a MBP of 1400 hours, approximately 2 months, The six datasets are as follows: two datasets for nominal operation, two datasets for an abrupt material loss scenario, and two datasets for a protracted material loss scenario. the remaining six datasets, associated with MBP$_2$, are over 2 operational years, with a MBP of 2800 hours, approximately 4 months, the six datasets are as follows: two datasets for nominal operation, two datasets for an abrupt material loss scenario, and two datasets for a protracted material loss scenario. The two datasets cover the two enrichment's of interest: Enrichment$_a$ and Enrichment$_b$. Table 2 summarizes the twelve datasets developed for this work. Both the initiation time and loss duration are expressed in terms of the MBPs utilized in both sets of datasets. All of the material loss scenarios modeled simulate a 1 significant quantity (SQ), 75 kg U^{235}, loss. Figure 3 plots the nominal condition for datasets 1 and 2, over the three MBAs within the TRISO fuel fabrication facility.

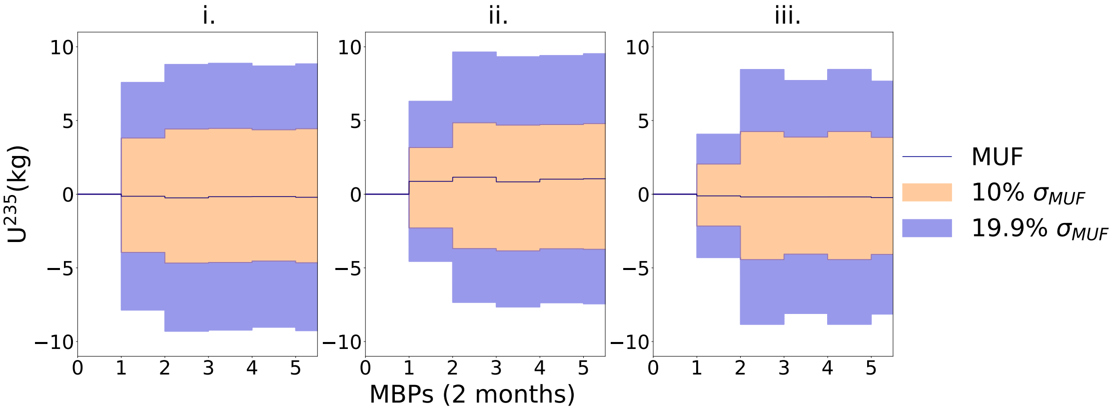

Figure 3: MUF and σ_{MUF} for the three MBAs. i.) MBA1, ii.) MBA2, and iii.) MBA3.

4 Results

The results are divided into two major sections: **Section 4.1** shows the results based on the nominal operation of the facility, and **Section 4.2** shows the results based on the material loss scenarios.

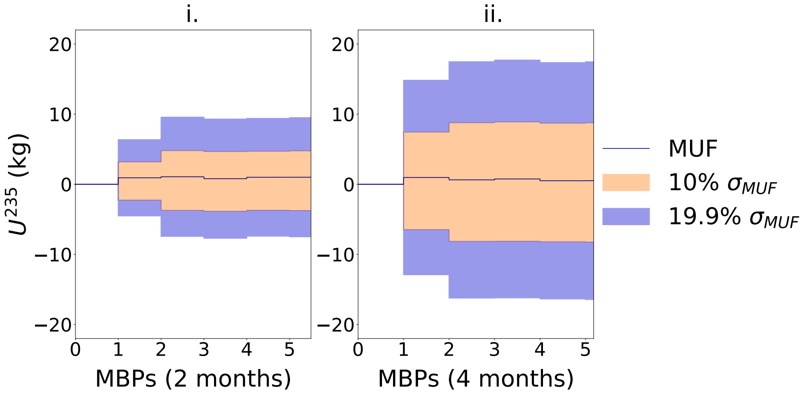

Figure 4: MUF and σ_{MUF} of MBA2 for different MBPs. i.) MBP_1, ii.) MBP_2

4.1 Nominal Operation

The nominal MUF and σ_{MUF} of MBA2 for both MBPs are plotted in Figure 4. Figure 4 is plotted with a 0.5% measurement uncertainty assumed for each key measurement point. The σ_{MUF} of the 19.9% enriched fuel is higher due to the increased amount of U^{235} within the fuel. With a 0.5% measurement uncertainty held constant between the calculations, the impact of MBP is clear. The σ_{MUF} associated with the 2 month MBP is roughly half the σ_{MUF} of the 4 month MBP. The enrichment of the fuel also plays a key role in the σ_{MUF} of the MBP; the 19.9% HALEU nearly doubles the σ_{MUF} of the 10% σ_{MUF}.

Figure 5 plots the impact MBP has on the σ_{MUF} as a function of enrichment, MBP, and measurement uncertainty. The MBPs are varied from 2 months to 9 months to quantify σ_{MUF} as the MBP increases. As expected, with increasing MBP the σ_{MUF} increases. Even with precise measurement uncertainty, the 19.9% enriched HALEU fuel approaches the 1SQ, indicating a material loss scenario may be difficult to detect.

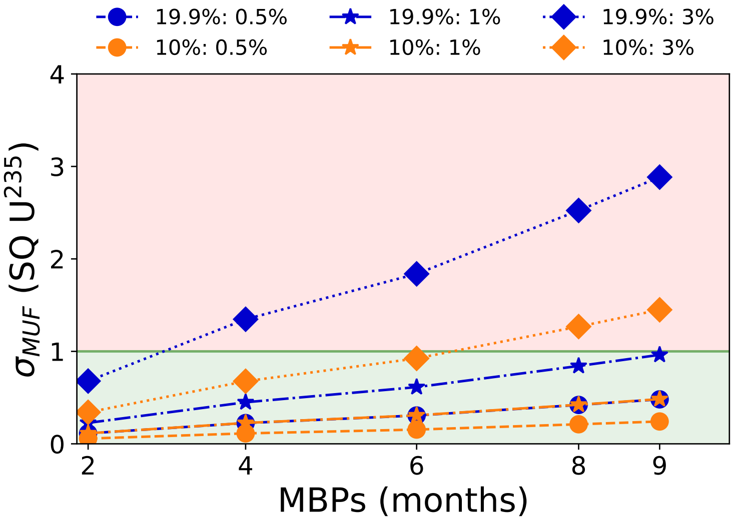

Figure 5: σ_{MUF} for MBA2 with different MBPs and measurement uncertainties.

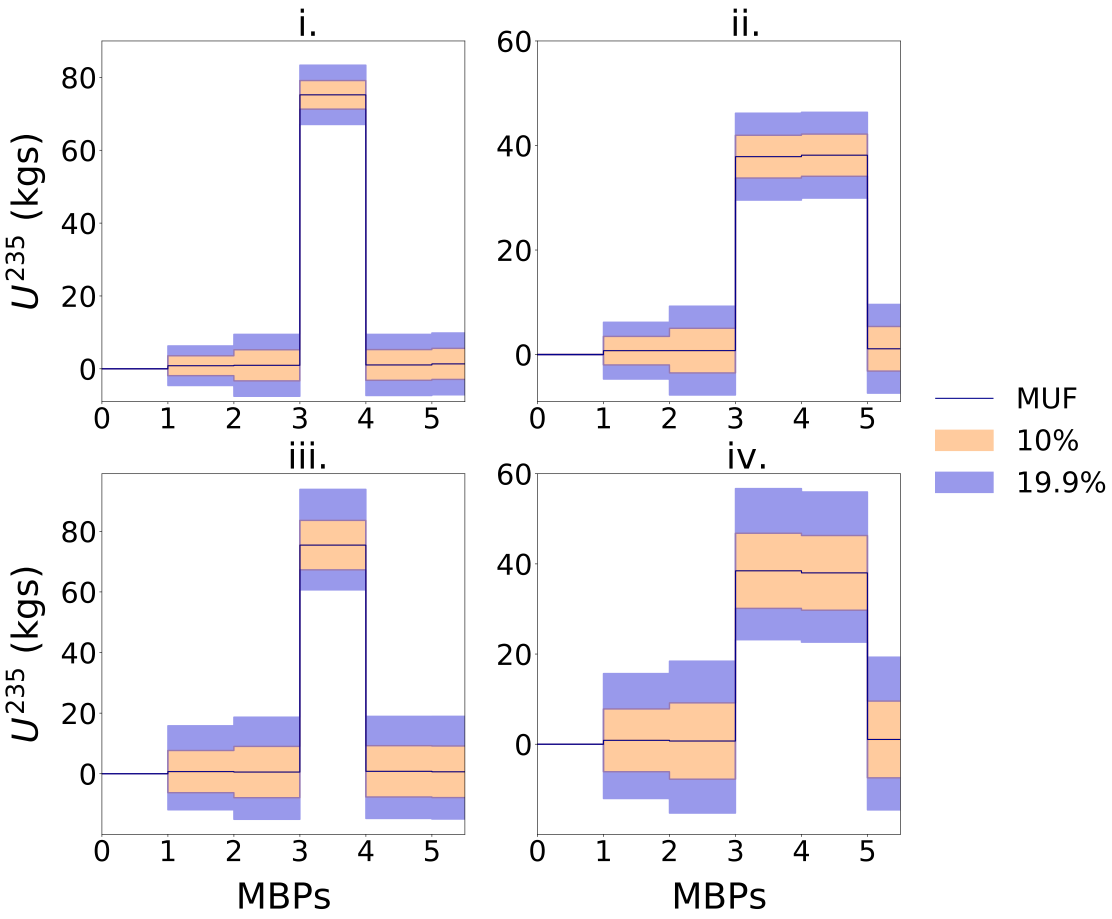

Figure 6: MUF and σ_{MUF} for the material loss scenarios. i.) Abrupt, MBP_1, ii.) Protracted, MBP_1, iii.) Abrupt MBP_2, and iv.) Protracted MBP_2.

4.2 Material Loss Scenarios

Two styles of material loss scenarios are investigated: abrupt loss (material lost over a single MBP) and protracted loss (material lost over several MBPs). Figure 6 plots the MUF and σ_{MUF} for the two types of material loss scenarios at the different MBPs (MBP_1 and MBP_2) investigated in this study, similar to Figure 4 these plots are using 0.5% measurement uncertainty to generate this data.

SITMUF and Page's trend test are used to quantify the probability of detecting a material loss scenario. The nominal condition is used to identify the h,k, the threshold and the precision, of the dataset. The h,k variables are fine-tuned to a 5% false alarm probability on the nominal dataset. Table 3 summarizes the results of Page's trend test, with measurement uncertainties less than 1% detecting identifying most, if not all, of the material loss scenarios. Two variables are controlled in this analysis: the MBP and the enrichment of the fuel. The larger MBP and the higher enrichment impacted Page's trend test greatly. The performance of Page's trend test noticeably started to drop at the 1% measurement uncertainty case with MBP_2 with the 19.9% enriched fuel, whereas the performance for the 10% facility did not drop until the 3% abrupt case with MBP_2. Higher enrichment and longer MBPs cause increases to σ_{MUF} leading to lower probabilities of detection.

5 Discussion

An SSPM TRISO fuel fabrication model was developed and preliminary statistical analysis has been performed. For LEU fuel fabrication facilities, it is more common, to include the conversion of UF_6 to UO_2 within the facility. Whereas with the move to HALEU, vendors are planning on separating the conversion and fuel fabrication process into two facilities. There are two major benefits in regards to safeguards in splitting the conversion and fabrication into different

Scenario	**Detection Probability and σ_{MUF} as a function of Measurement Uncertainty**					
	Enrichment ($\%U^{235}$)	**MBP**	**All 0.5%**	**All 1%**	**All 3%**	**All 5%**
Abrupt	10%	MBP_1	100%	100%	91.4%	61.4%
	10%	MBP_2	100%	100%	33.6%	17.8%
	19.9%	MBP_1	100%	98.8%	54.2%	30.0%
	19.9%	MBP_2	100%	64.4%	13.8%	8.0%
Protracted	10%	MBP_1	100%	100%	87%	43%
	10%	MBP_2	100%	99.4%	24.2%	7.6%
	19.9%	MBP_1	100%	95.0%	32.4%	15.8%
	19.9%	MBP_2	100%	55.2%	6.6%	5%

Table 3: A summary of the Page's trend test results.

facilities: the first is that each facility now has less key measurement points within the processing MBA, and the second is the decrease in the number of waste streams. Less measurement points will leads to lower σ_{MUF} and waste streams tend to have the highest measurement uncertainty, so having fewer waste streams benefits σ_{MUF} as well.

This preliminary analysis is based on the notional 22 throughput HALEU TRISO fuel fabrication facility. Two MBPs are shown, a MBP of 2 months and a MBP of 4 months, to quantify the statistical tests associated with MC&A for TRISO fuel fabrication facilities and identify how longer MBPs impact the probability of detecting material loss scenarios. Figure 5 showed an initial look into what occurs when the MBP is increased. With the notional throughput of 22 metric ton throughput U, the enrichment of the HALEU fuel greatly impacts the σ_{MUF} at longer MBPs. However, with several pilot TRISO fuel fabrication facilities being planned at the 5-15 metric ton scale, these results are very promising and suggest that with an achievable measurement precision a MBP of 9 months is possible. At higher throughputs HALEU may require additional analysis and safeguards by design is needed when selecting a MBP; with more highly enriched HALEU likely requiring shorter MBPs to maintain similar performance to LEU or more lowly enriched HALEU.

Figures 3-6 and Table 3 quantify the impact HALEU enrichment has on MC&A statistical analysis. The enrichment of the HALEU fuel greatly impacts the σ_{MUF}. A 19.9% HALEU fuel is going to have double the σ_{MUF} of a 10% HALEU fuel and four times the σ_{MUF} of a 5% LEU fuel. The enrichment of the fuel causes the probability of a 19.9% material loss scenario to be lower in comparison to the 10% facility. The decrease in probability is due to the amount of material lost; the SQ condition for a 19.9% facility is half of a 10% facility. The increase in σ_{MUF} with increasing fuel enrichment requires more thought to be placed into the MC&A plan, with facilities wanting to maintain longer MBPs. Table 3 clearly shows the impact enrichment has on detecting material loss scenarios, with the 10% TRISO pebbles outperforming the 19.9% TRISO pebbles in every dataset analyzed. More highly enriched HALEU fuel will likely require additional thought and analysis within the MC&A plan.

6 Conclusion

This work provides a preliminary analysis of the MC&A safeguards analysis for a TRISO fuel fabrication facility. Protracted and more highly enriched HALEU material losses resulted in lower detection probabilities. Measurement uncertainty and enrichment play a major role in Page's trend test identifying material loss scenarios. With measurement uncertainties below 1% most material loss scenarios are able to be detected, which is a promising sign for the current HTGR vendors planning on low throughput facilities. Future work will continue to improve the model and develop datasets to investigate the following scenarios:

1. Add additional functionality to the SSPM model, add recycling pathways for the uranium material during the gelation process.
2. Investigate the impact throughput has on detecting material loss scenarios.
3. Investigate the TRISO fuel fabrication facilities safeguards ability to meet MC&A requirements by the U.S. Nuclear Regulatory Commission (NRC).

Overall, the decreased throughput of TRISO fuel fabrication facilities greatly aids the probability of detecting a material loss scenario. Measurement uncertainties, for TRISO fuel fabrication facilities, are likely to be below 1%, this indicates that material loss scenarios, for low throughput facilities, are likely to be detected with high precision. However, with longer MBPs (shown in Figure 5) and higher throughput, the higher enrichment of TRISO fuel will require additional analysis and MC&A optimization to ensure material losses can be detected; large throughput HALEU facilities will require safeguards by design early in the development to account for the higher U^{235} enrichment's impact on safeguards.

7 Acknowledgements

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