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Low Enriched Fuel Fabrication Safeguards Modeling

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ABSTRACT

The Material Protection, Accounting, and Control Technologies (MPACT) program utilizes modeling and simulation to assess Material Control and Accountability (MC&A) concerns for a variety of nuclear facilities. Single analyst tools allow for rapid design and evaluation of advanced approaches for new and existing nuclear facilities. A low enriched uranium (LEU) fuel conversion and fabrication facility simulator has been developed to assist with MC&A for existing LEU fuel fabrication for light water reactors. Simulated measurement blocks were added to the model (consistent with current best practices). Material balance calculations and statistical tests have also been added to the model.

ACKNOWLEDGEMENTS

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
ADU	ammonium diurnate
AHA	acetohydroxamic acid
FHA	formohydroxamic acid
FP	fission product
HNO_3	nitric acid
ID	inventory difference
KMP	key measurement point
LEU	low enriched uranium
LWR	light water reactor
MBA	material balance area
MBP	material balance period
MC&A	material control & accountability
MPACT	material protection, accounting, and control technologies
MUF	material unaccounted for
PUREX	plutonium uranium extraction
R&D	research and development
SEID	standard error of inventory difference
SSBD	safeguards and security by design
SSPM	separation and safeguards performance model
TBP	tributyl phosphate
UF_6	uranium hexafluoride
UO_2	uranium dioxide

1. INTRODUCTION

The Material Protection, Accounting, and Control Technologies (MPACT) campaign conducts Research and Development (R&D) to support safeguards and security challenges for the U.S. nuclear energy program. Specifically, activities on the front- and back-end of the nuclear fuel cycle are of recent interest to the MPACT campaign. The work presented here focused on updating the low enriched uranium (LEU) fuel fabrication model and running key statistical tests on the flow of material throughout the facility.

There are presently three LEU fuel fabrication plants licensed for operation in the U.S: Westinghouse, in Columbia, South Carolina; Global Nuclear Fuel-Americas in Wilmington, North Carolina; and Framatome in Richland, Washington. These sites each perform a similar task: convert solid, enriched uranium hexafluoride (UF_6) into fuel assemblies that are usable by commercial power reactors (pressurized water reactors and boiling water reactors). The Westinghouse and Global Nuclear-Fuel Americas sites can process 1500 t/yr of uranium. The Framatome facility is capable of processing 1200 t/yr of material [1].

In large-throughput facilities, like a fuel fabrication plant, small measurement errors can correspond to large quantities of material unaccounted for (MUF). Holdup, which is a source of measurement uncertainty, is a current concern that can require many man-hours to resolve as part of the plant's Material Control and Accountability (MC&A) system. Modeling and simulation provide a way to simulate and address gaps in MC&A approaches to help with current challenges facing fuel fabrication plants, such as holdup. Further, simulation can help determine locations where material is most likely to be lost, which can inform both inspections and ongoing research.

The MPACT campaign has developed a generic systems-level model of a fuel fabrication facility. This model is developed upon the framework of the Separation and Safeguards Performance Model (SSPM) [2] [3] [4], which is a systems-level facility simulator that has been applied toward a variety of fuel cycle facilities. The SSPM combines process variance, measurement uncertainty, and statistical tests with the standard operation cycle for a target facility. The model is used to determine if a facility can meet regulatory goals for a given array of sensors. This report provides background on the SSPM and details the modifications made to the fuel fabrication facility model and presents the MC&A assessments performed.

2. BACKGROUND

The MPACT program is focused on developing and demonstrating technologies and practices for management of nuclear material for civilian fuel cycle facilities. One goal of MPACT is implementation of Safeguards and Security by Design (SSBD) practices, whereby safeguards and security constraints are considered early in a facility's design process, to minimize operator costs while providing the same level of performance against regulatory requirements. Opportunities for SSBD utilization are highlighted in advanced or in-development facilities, but the same techniques can be applied towards existing facilities as well.

2.1. Virtual Facility Distributed Test Bed

The capabilities of the MPACT program have been summarized in a Virtual Facility Distributed Test Bed [5]. Figure 1 depicts how the various MPACT technologies and capabilities work together to create the Virtual Test Bed (shown for pyroprocessing as an example). Systems-level facility models for flowsheet design, safeguards, and security analyses are used to analyze facilities and generate key performance metrics. Sensor performance obtained from testing along with high fidelity modeling capabilities are fed into the systems-level models. Ultimately, the systems-level models generate key plant design, safeguards, and security performance metrics of interest.

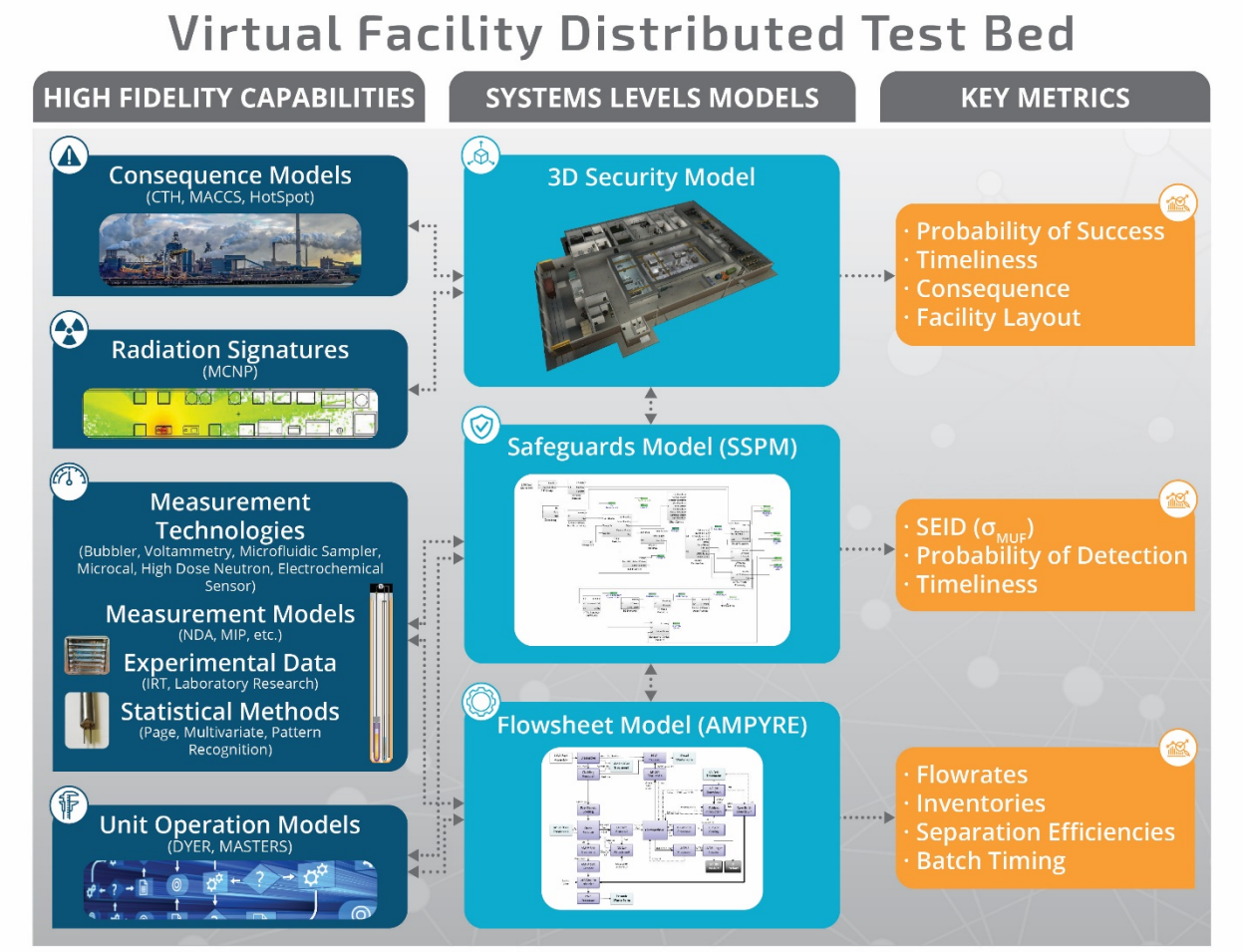

Figure 1: Virtual Facility Distributed Test Bed

This report focuses on the development of a safeguards model for a fuel fabrication facility. Key Measurement Points (KMPs), Inventory Difference (ID), and statistical tests have been implemented in the fuel fabrication model. A key aspect of the Virtual Facility Distributed Test Bed is that the capabilities can be deployed to different facilities for different safeguards and security challenges in the nuclear fuel cycle.

2.2. Separation & Safeguards Performance Model

A significant component of the Virtual Facility Distributed Test Bed is the Separation & Safeguards Performance Model (SSPM). The SSPM framework has been used to model a variety of fuel cycle facilities including enrichment, fuel fabrication, and reprocessing. The SSPM enables low-risk and non-intrusive design and testing of MC&A systems for a given facility. The SSPM was developed on the MATLAB Simulink platform, which is a graphical programming environment that utilizes the full suite of MATLAB toolboxes. Simulink is traditionally used to design, test, and implement control systems. The SSPM uses this infrastructure by adapting the parallel signal architecture to model flow rates of bulk materials of interest. Mathematical operations are used to model tank activities (emptying, filling, reactions) and the realistic timing of process unit operations [5].

Bulk and elemental measurements are simulated on the "true" values, incorporating user-defined measurement uncertainty. Error propagation and statistical tests (such as Page's trend test) are used to determine if material losses can be detected and if MUF values exceed regulatory requirements.

The SSPM splits activities into multiple mass balance areas (MBAs), like what would be observed at a real facility. Multiple unit operations are nested within a single MBA, with the MBA boundaries based either on physical constraints (different buildings) or logical boundaries (multiple operations in the same material form). Both direct and substitution material loss can be modeled within the SSPM, at various points throughout the given process, to test the performance of the MC&A system.

This framework provides many capabilities for safeguards analysis. The utilization of user-input uncertainty integrated with diversion simulation enables new techniques and instruments to be modeled prior to field application. False alarm probabilities can also all be modeled and varied by the user. This allows the user to calculate detection probabilities for a given sensor array and material loss scenarios.

3. FUEL FABRICATION FACILITY

A LEU conversion and fuel fabrication facility is modeled using the SSPM infrastructure. The facility is based on STR-150, a guidance document from the International Atomic Energy Agency (IAEA) [6]. The virtual facility has an annual throughput of 300 tons of UO_2, with a nominal enrichment of 3.0 wt% ^{235}U. The UO_2 delivered to this theorized facility is recovered scrap material to be recycled in this facility. UF_6 and UO_2 drums are modeled entering the facility, and the uranium material is converted to light water reactor (LWR) fuel assemblies.

The facility is separated into three distinct MBAs based on STR-150 [6], shown in Figure 2. The first MBA (MBA1, the purple shaded region) monitors the UF_6 cylinders and UO_2 drums entering the facility. The second MBA (MBA2, the green shaded region) monitors the conversion processing of UF_6 to UO_2, conversion of UO_2 powder to fuel rods, and tracks scrap material from each of these processes. The third MBA (MBA3, the orange shaded region) encompasses the construction of fuel assemblies from the fuel rods entering from MBA2.

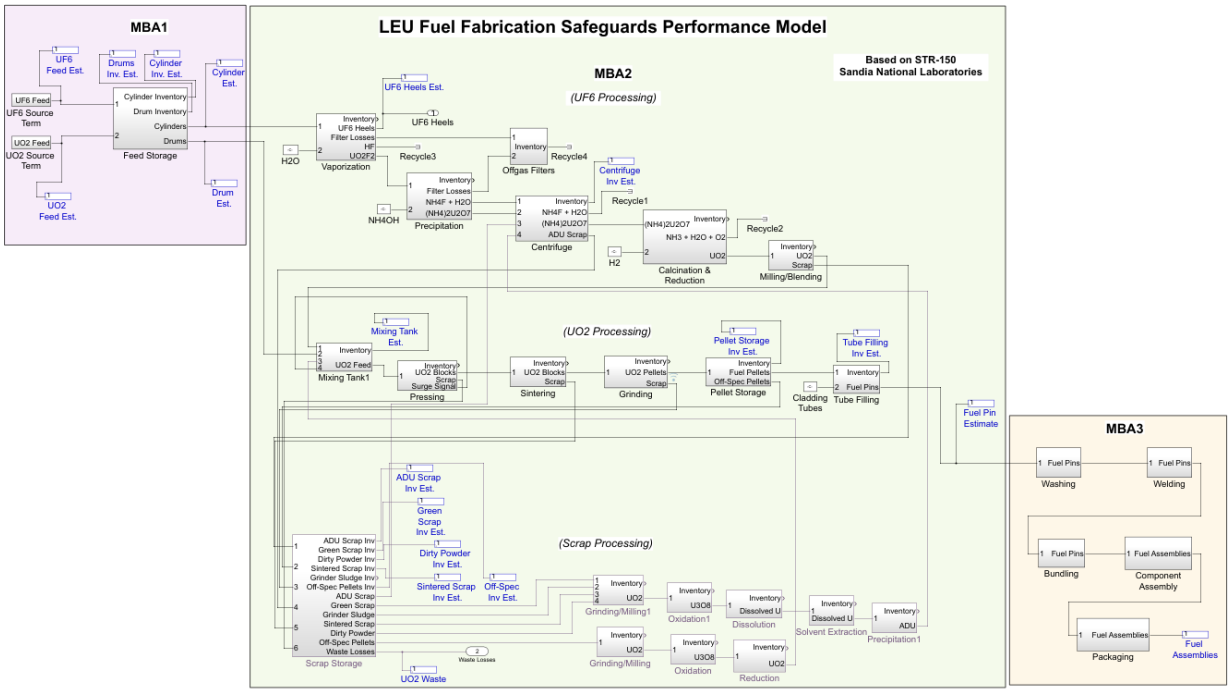

Figure 2. Simulink Model of Uranium Conversion & Fuel Fabrication Facility

Blue labels in Figure 2 indicate KMPs, where measurements are taken to track material. These measurements, in conjunction with statistical analysis, are used to track uranium. Equation 1 shows the basic relation for ID and is the generic equation used to track uranium within the LEU fabrication facility [6].

$$ID = \sum inputs - \Delta inventory - \sum outputs \quad (1)$$

3.1. MBA1: Shipping/Receiving Area

Uranium is introduced to the facility through UF_6 cylinders and UO_2 drums, as depicted by Figure 3 as the UF_6 and UO_2 source terms. The source terms are modeled as pulses, where new cylinders and drums enter the facility every 32 hours. The mass ratio of UF_6 to UO_2 entering the facility is 3:1. The second block in MBA1 simulates storage of feed material at the front end. A delay is implemented to ensure that 28 tons of UF_6 and 2 tons of UO_2 are stored prior to starting the reprocessing and fabrication process in MBA2. Six measurements are made across MBA1 to calculate the ID. Table 1 summarizes these KMPs.

Table 1. KMPs Associated with MBA1

KMP	Material Involved & Description
Material Entering MBA1	UF_6 cylinders entering facility UO_2 drums entering facility
Inventory Measurements in MBA1	UF_6 cylinder in storage UO_2 drum in storage
Material Leaving MBA1	UF_6 cylinders exiting MBA1 (to MBA2) UO_2 drums exiting MBA1 (to MBA2)

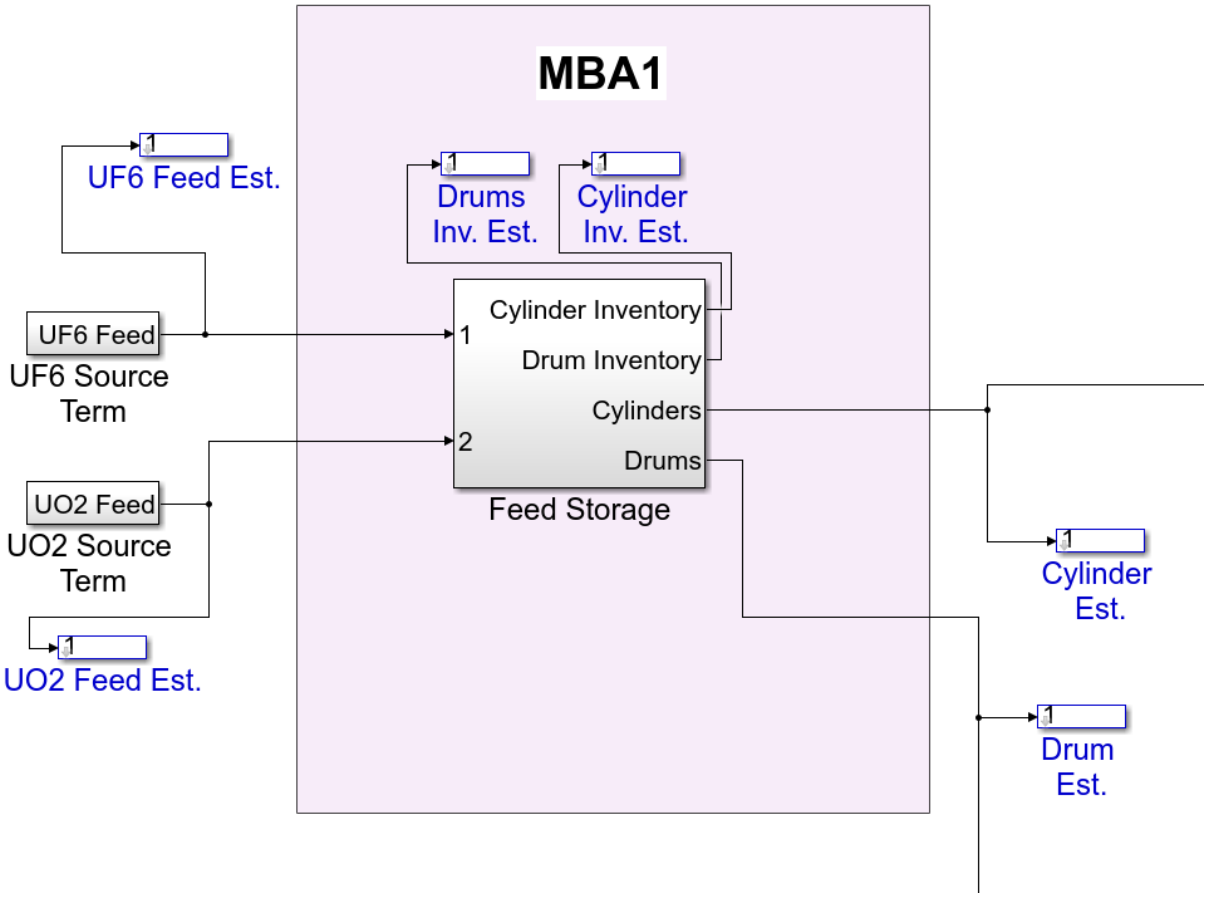

Figure 3. MBA1: Shipping/Receiving Area

Figure 4 shows the nominal behavior for the inputs, inventories, and outputs for MBA1. Material enters the facility every 32 hours, and once the front-end storage reaches a preset maximum value, material starts exiting MBA1 to enter MBA2.

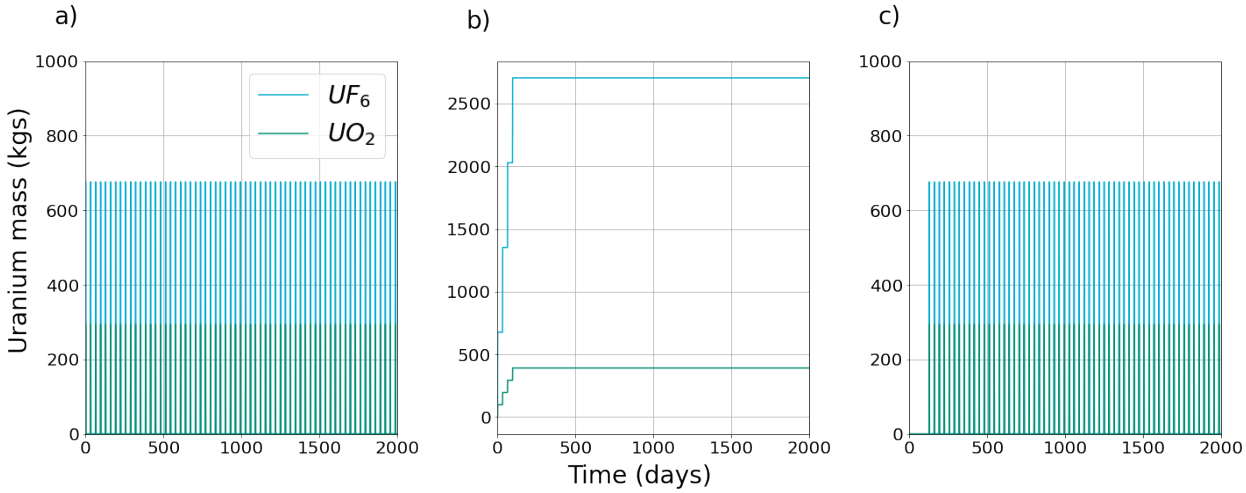

Figure 4. Plots showing a section of the run for the uranium mass entering, exiting, and stored within MBA1. a) UF_6 cylinders and UO_2 drums entering MBA1, b) UF_6 cylinders and UO_2 drums stored in MBA1, and c) UF_6 cylinders and UO_2 drums exiting MBA1.

3.2. MBA2: Fuel Conversion & Fabrication Processes

MBA2 has three major material processes: conversion of solid UF_6 to powdered UO_2, conversion of powdered UO_2 to UO_2 fuel rods, and conversion of waste products to powdered UO_2 or ammonium diurnate (ADU) [7]. This is illustrated in Figure 5. UF_6 can be converted to UO_2 by the following process: [5, 7].

1. The vaporization block models the sublimation and vaporization of the UF_6 to uranyl fluoride (UO_2F_2)
2. The precipitation block models the precipitation of uranyl fluoride to ADU.
3. The centrifuge block models the separation of ADU crystals from the precipitation liquid.
4. The calcination and reduction block models ADU crystals being converted to a UO_2 powder.
5. The milling/grinding block models the formation of a fine UO_2 powder.
6. The UO_2 powder leaves the milling/grinding block to join the UO_2 powder from the drums in the mixing tank to begin the pelletizing process.

The UO_2 powder undergoes the pelletizing process:

1. The mixing tank block models the UO_2 powder entering from the UO_2 drums, UF_6 conversion process, and the UO_2 from the scrap processing.
2. The pressing block models the pressing of the UO_2 powder.
3. The sintering block models sintering of pressed UO_2 powder to be prepared for pelletizing.
4. The grinding UO_2 block models the grinding of the sintered UO_2 block to form UO_2 pellets.
5. The pellet storage block models the storage and verification of fuel pellets for preparation into being made into fuel rods.
6. The tube filling block models the formation of fuel pins to exit MBA2.

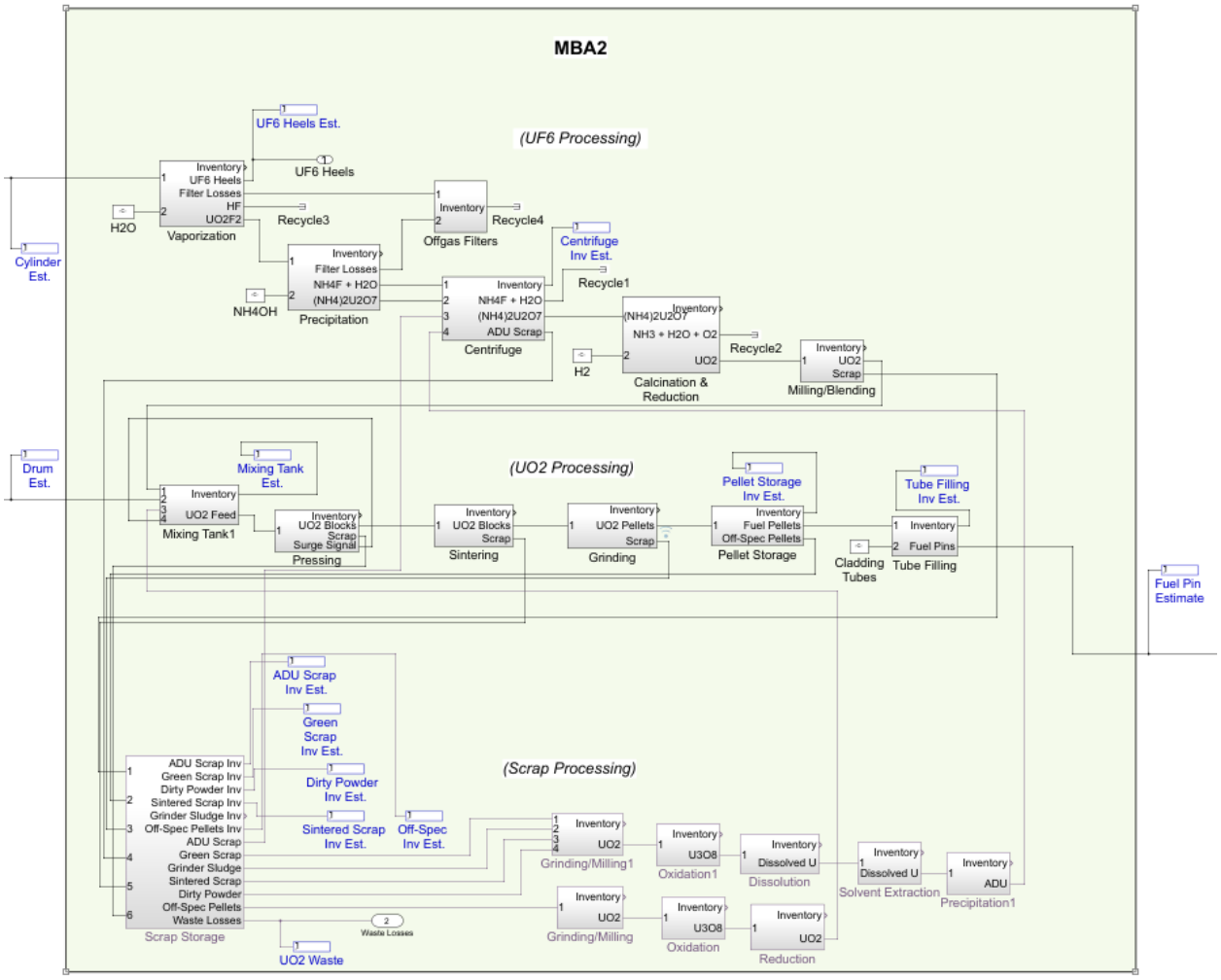

Figure 5. MBA2 - UO_2 Conversion and Fuel Fabrication

Scrap material throughout the conversion and fuel fabrication procedures is sent to scrap storage. Most of the scrap material is converted to ADU and renters the UF_6 conversion process within the centrifuge process. Off-spec pellets are converted back to UO_2 powder and recycled to the mixing tank to be formed into UO_2 pellets.

MBA2 is the most complex MBA in the fuel fabrication facility. Fourteen measurements are made across MBA2 to determine ID, as shown in Table 2. The following subsections describe the unit operations in more detail.

Table 2. KMPs Associated with MBA2

KMP	Material Involved & Description
Material Entering MBA2	UF_6 cylinders entering MBA2 UO_2 drums entering MBA2
Inventory Measurements in MBA2	ADU crystals inventory during the centrifuge process Mixing tank inventory during the UO_2 pellitization process Pellet storage inventory during the UO_2 pellitization process Fuel rods inventory during the UO_2 pellitization process ADU scrap inventory in the scrap storage Off-Spec fuel pellets inventory in the scrap storage Sintering scrap inventory in the scrap storage Green inventory in the scrap reprocessing Dissolution inventory in the scrap reprocessing
Material Leaving MBA2	UF_6 heels exiting MBA2 Waste from processing and pellitization exiting MBA2 UO_2 fuel rods exiting MBA2

3.2.1. UF_6 Processes

UF_6 is a standard material form in enrichment but requires conversion before fuel fabrication. UF_6 is stored and transported as a solid, typically in 30B cylinders. The first processing step is to convert the UF_6 from solid to gas. Figure 5. MBA2 - UO_2 Conversion and Fuel Fabrication**Error! Reference source not found.** shows the vaporization block, which perform the sublimination of UF_6 and hydrolysis to convert the UF_6 to uranyl fluoride (UO_2F_2). UF_6 is heated to approximately 135 °F at atmospheric pressure, which causes solid UF_6 to subliminate directly to the gas state. The gaseous UF_6 then reacts with deionized water to form uranyl fluoride and hydrofluoric acid, as shown by Equation 2. There are two KMPs at this stage—the uranyl fluoride inventory and UF_6 heels remaining in the 30B cylinder are both measured [7].

$$UF_6 + 2H_2O \rightarrow UO_2F_2 + 4HF \quad (2)$$

The uranyl fluoride solution flows to the precipitation block. The solution is mixed with ammonium hydroxide (NH_4OH), to produce ADU crystals. This reaction is shown by Equation 3. The ADU crystals are sent to a centrifuge for further processing, and scrap ADU is sent to the scrap storage. A KMP for MBA2 measures ADU crystal inventory during the precipitation process [7].

$$UO_2F_2 + 6NH_4OH \rightarrow (NH_4)_2U_2O_7 + 12NH_4F \quad (3)$$

A centrifuge separates the ADU crystals from the liquid solution, to prepare the ADU for calcination and reduction. The rotational forces of the centrifuge push the ADU crystals outward to a receiver tank, and the liquid is recycled to previous stages in the process. Some ADU scrap is sent to the scrap storage. The ADU crystals separated during the centrifuge process are measured.

Calcination and reduction are performed to convert ADU to UO_2. The calcination process involves heating the ADU, in the presence of steam and hydrogen, to approximately 700 °F, to generate U_3O_8, shown in equation 4. The U_3O_8 then undergoes reduction in a hydrogen-rich environment, between 700 °F and 930 °F to generate UO_2. This reaction is shown in Equation 5. Scrap material is routed to scrap storage, and UO_2 is sent to the next stage. The final step in the UF_6 conversion process is milling; milling is used to pulverize the UO_2 clumps into a fine powder.

$$3(NH_4)_2U_2O_7 \rightarrow 2U_3O_8 + 6NH_3 + 3H_2O + O_2 \quad (4)$$

$$2U_3O_8 + 4H_2 \rightarrow 6UO_2 + 4H_2O \quad (5)$$

Figure 6 shows the nominal conditions for the processing steps required to convert UF_6 to UO_2 powder. The large spikes starting in the centrifuge are based on a new method for modeling the scrap materials prior to entering processing and will be discussed later in this section.

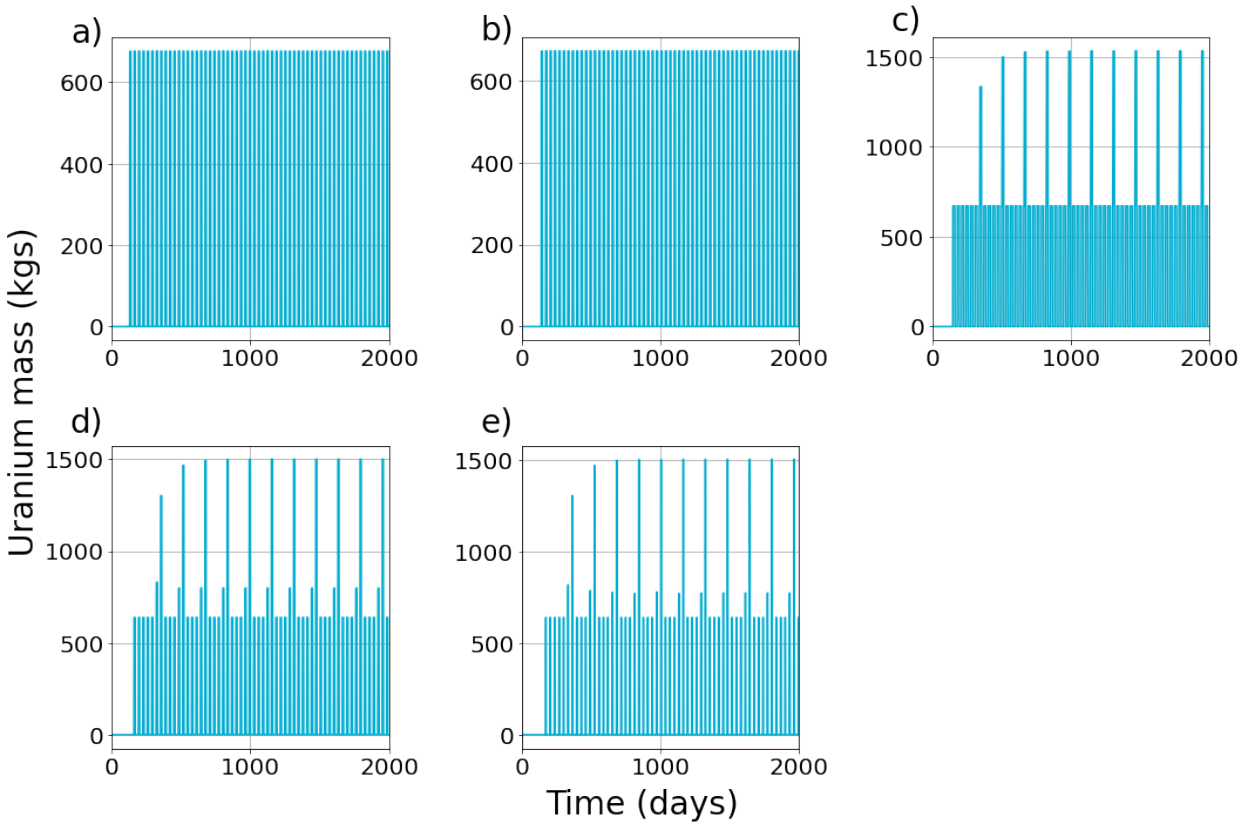

Figure 6. The nominal inventories for the UF_6 conversion to UO_2. a) Vaporization, b) Precipitation, c) Centrifuge, d) Calcination and Reduction, and e) Milling and Blending

3.2.2. UO_2 Pelletization

The UO_2 pelletization process first mixes UO_2 from the various sources (UO_2 drums from MBA1, UO_2 converted from UF_6, and UO_2 recycled from scrap material) in a mixing tank. This mixing tank is a KMP, where the stored UO_2 inventory can be measured prior to forming UO_2 fuel pellets.

After leaving the mixing tank, the UO_2 powder is first pressed at approximately 10,000 psi to densify the UO_2 powder. The UO_2 powder is then sintered and grinded into UO_2 pellets. Following the sintering and grinding, the fuel pellets are then placed in a fuel pellet storage area; the pellet storage area is another KMP, wherein the pellet inventory is tracked. UO_2 pellets taken from the pellet storage area are clad and stored in fuel rods. The inventory and count of fuel rods leaving MBA2 are the final two KMPs in the UO_2 pelletization process [7]. Figure 7 plots the nominal inventories for the pellitization process. The mixing tank, pellet storage, and tube filling processes have a non-zero

inventory once material enters these processes. Similar to the UF_6 conversion, this is based on the increased amount of material due to scrap material leaving the scrap storage area and being processed back into the UF_6 and UO_2 processes.

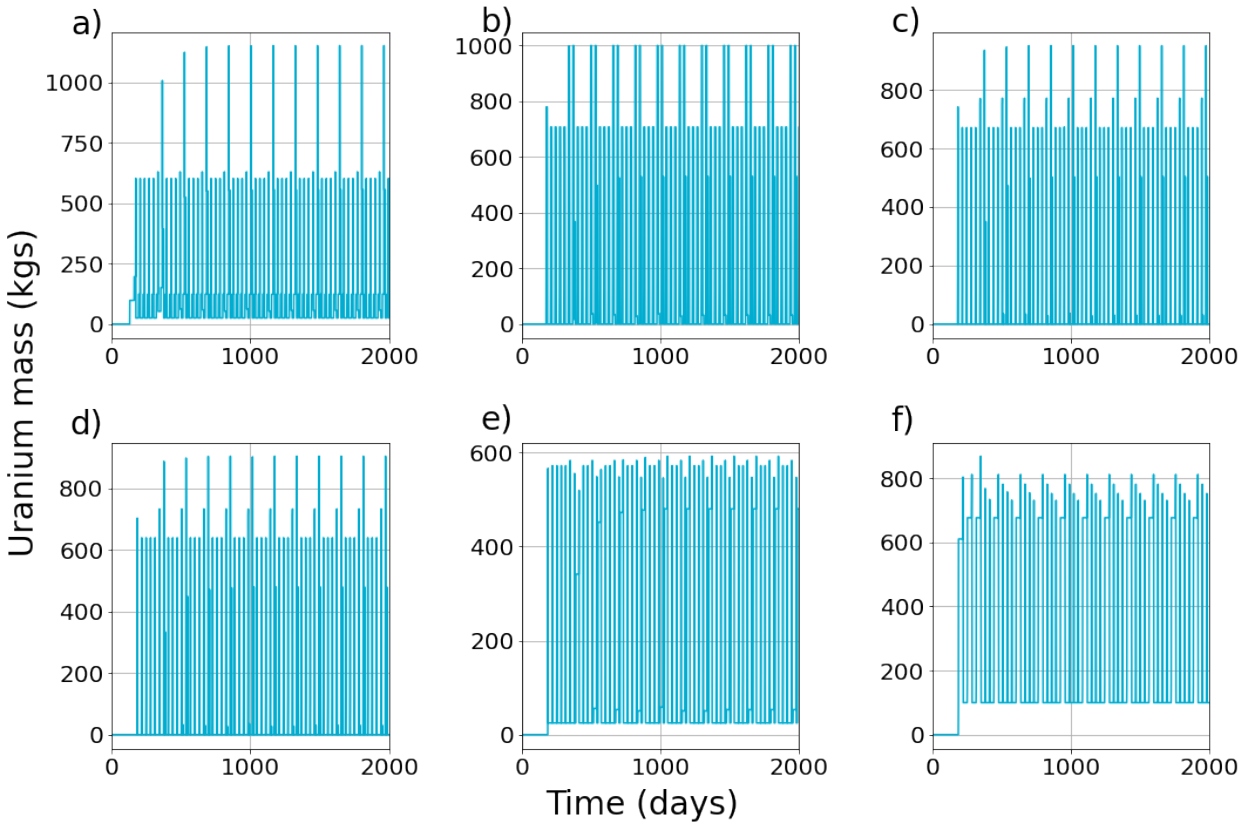

Figure 7. The nominal inventories for the UO_2 pelletization process. a) Mixing Tank, b) Pressing, c) Sintering, d) Grinding, e) Pellet Storage, and f) Tube Filling.

3.2.3. Scrap Storage

Scrap material from the UF_6 conversion and UO_2 fabrication all enters a single scrap storage area within MBA2. Time delays within the scrap storage block allow material to build up before chemical reprocessing occurs. Most scrap material is converted to ADU and is sent to the centrifuge during UF_6 processing to be converted into UO_2 powder. Off-spec UO_2 fuel pellets are re-ground to a fine powder and recirculated to the mixing tank at the start of the pelletization process. Figure 8 shows the storage of scrap material within the scrap storage. This is a major change made to the fuel fabrication model to better emulate a real facility, rather than scrap material being in the ADU reprocessing first entails grinding or milling to a fine powder. UO_2 undergoes oxidation to be converted to U_3O_8, which is more easily dissolved. Dissolution occurs by mixing the U_3O_8 in a nitric acid solution. Equation 6 shows the chemical equation that manages the conversion of U_3O_8 to $UO_2(NO_3)_2$. The $UO_2(NO_3)_2$ is then filtered and processed by solvent extraction to generate a product more suitable for recycling back through the facility.

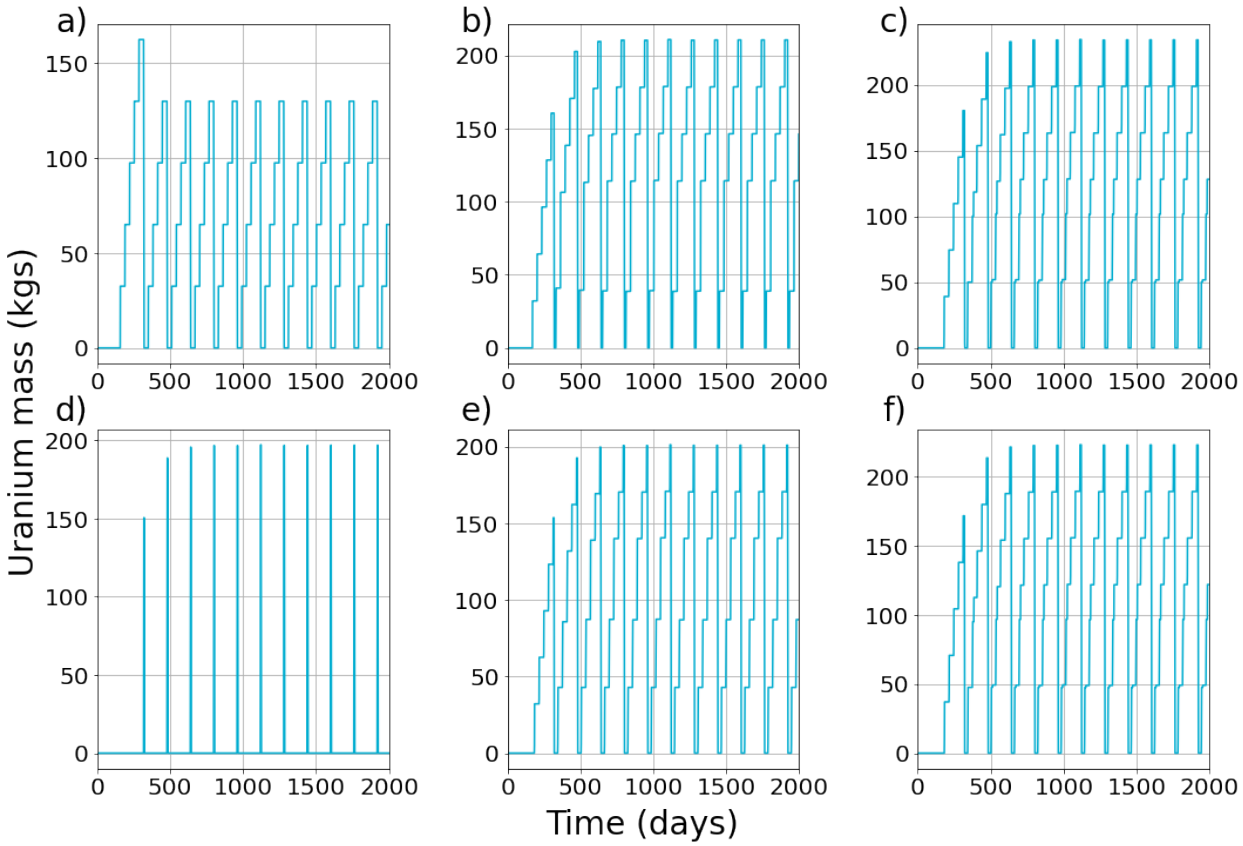

Figure 8. Nominal Conditions for the storage of scrap material from the UO_2 and UF_6 processing steps. a) ADU scrap, b) Dirty Powder, c) Green Scrap, d) Grinder Sludge, e) Off-Spec Pellets, and f) Sintered Scrap

$$U_3O_8 + 8HNO_3 \rightarrow 3UO_2(NO_3)_2 + 2NO_2 + 4H_2O \quad (6)$$

$UO_2(NO_3)_2$ is extracted from byproducts for further refining and precipitated back to ADU to re-enter the UF_6 reprocessing steps.

There are six KMPs within the scrap storage processes. In the storage area, the off-spec pellets, grinder sludge, sinter scrap material, and waste losses are all separately measured. In the ADU processing, milling and dissolution steps are both KMPs to track material within the production of ADU.

3.3. MBA3: Fuel Assembly Fabrication

MBA3 focuses on fuel assembly construction; fuel pins entering MBA3 are converted into fuel assemblies. MBA3 has 5 KMPs: fuel rods entering, fuel assemblies leaving, fuel pin inventory after washing, fuel pin inventory after welding, and fuel bundles after initial assembly. Figure 9 depicts MBA3.

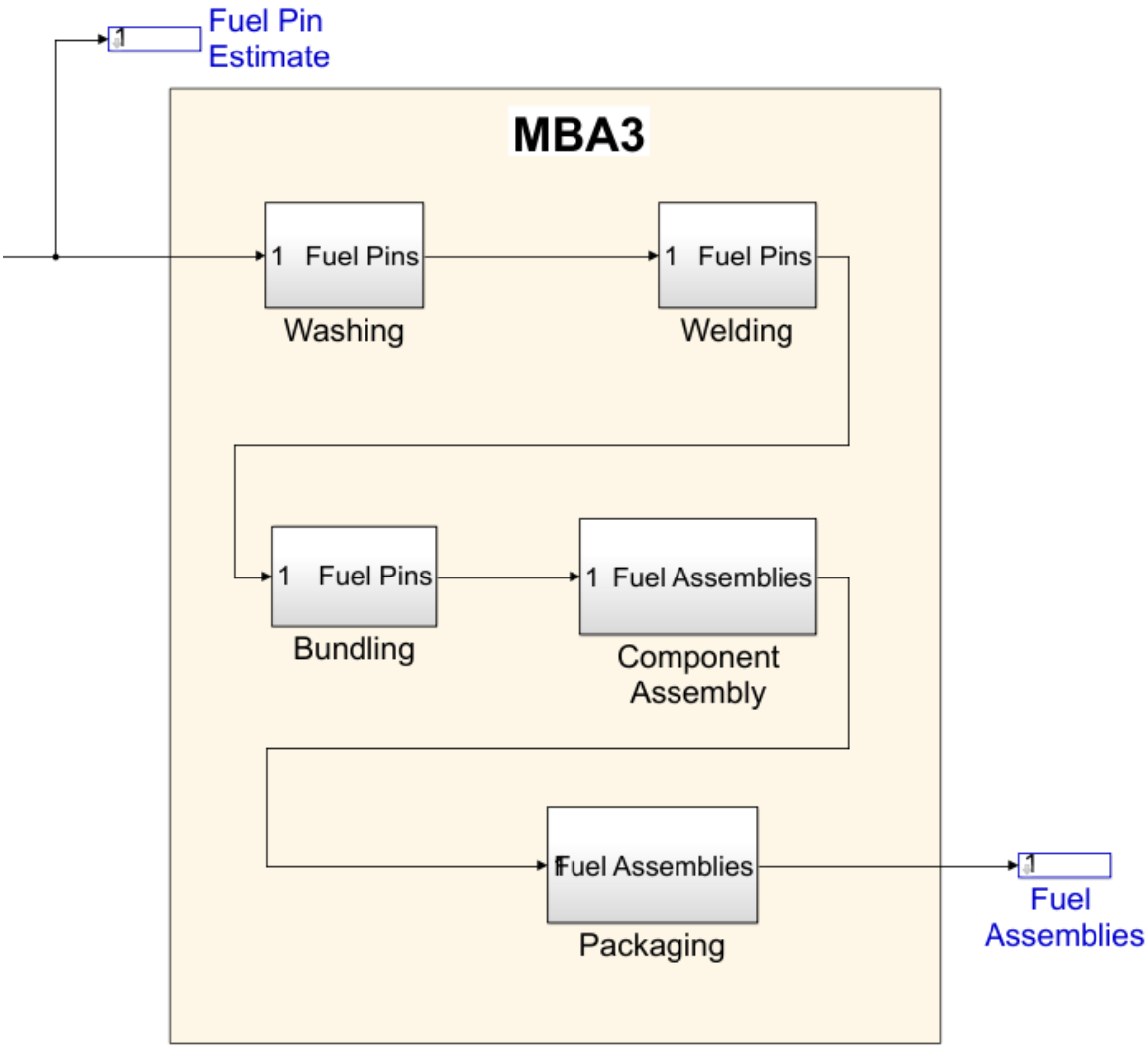

Figure 9. Fuel Pin Conversion to Fuel Assemblies

The MBA3 processes are simple compared to those for MBA2. A major change occurs at the interface between MBA2 and MBA3. Rather than viewing the material as individual fuel rods entering into MBA3, a set of fuel rods associated with a single fuel assembly entering MBA3 are tracked. The previous method of having individual fuel rods entering MBA3 created problems with the integrator in Simulink—the new method better simulates batch processing that would more likely be used in a real fuel fabrication facility (see Figure 10). The first step involves washing of fuel pins with either water or air, to remove excess scrap. The fuel pins are then closed and sealed by welding and prepared to be placed in fuel assemblies. The welded pins are placed within assemblies, which are processed and prepared for shipment. The Material Balance Period (MBP) is optimized such that MBA3 requires only 2 KMPs, the material entering and the material leaving MBA3, as shown below in Table 3.

Table 3. KMPs Associated with MBA3

KMP	Material Involved & Description
Material Entering MBA3	UO_2 fuel pins entering MBA3
Material Leaving MBA3	Fuel assemblies leaving MBA3

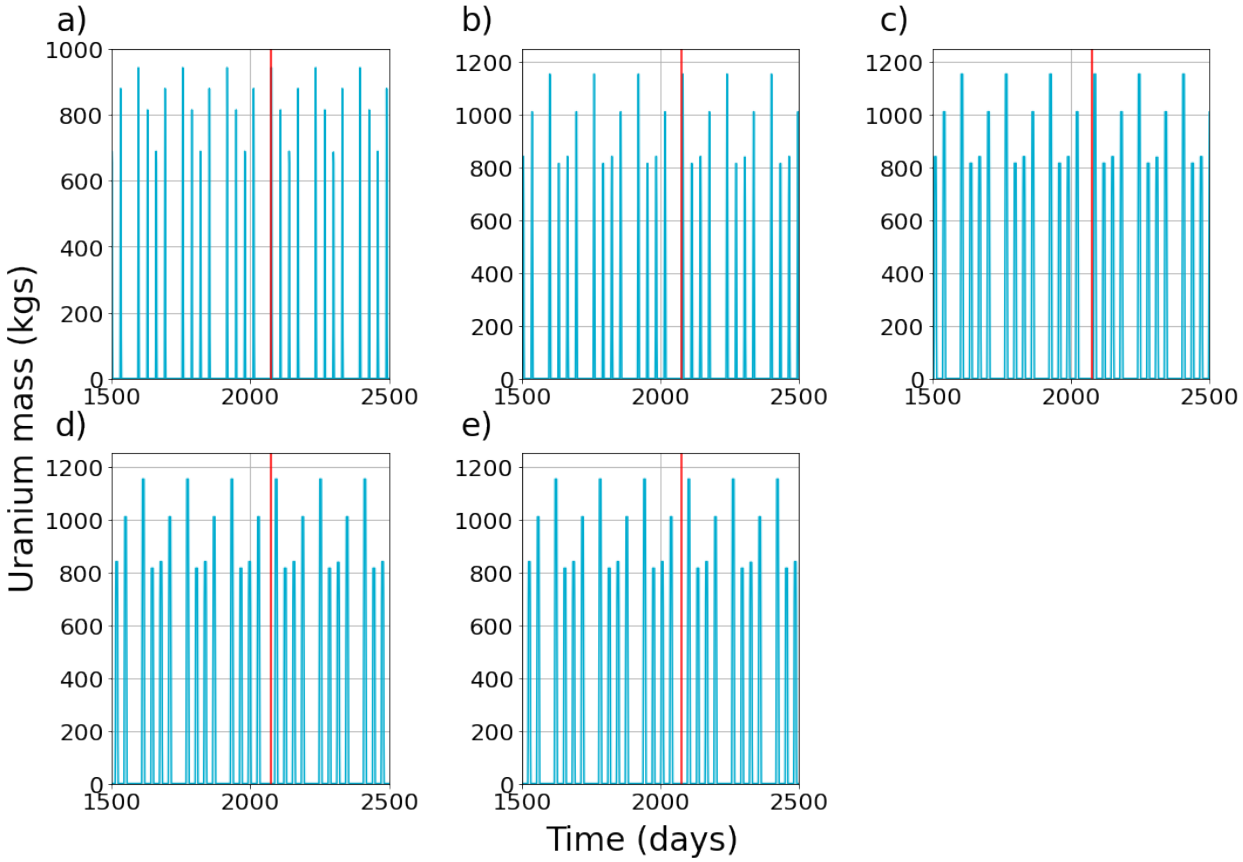

Figure 10. Nominal conditions for MBA3, where the red line indicates where a MB measurement occurs. a) Washing, b) Welding, c) Bundling, d) Component Assembly, and e) Packaging.

3.4. Statistical Tests

Detection of material loss (either diversion or holdup) is a critical aspect of nuclear safeguards. In principle, a site should account for all material, such that the ID is zero. However, measurement uncertainty makes such a goal practically unachievable. The utilization of statistical analyses helps mitigate the impact of measurement uncertainty and are widely accepted tools in the realm of safeguards.

Two key calculations are ID and Page's trend test. ID is a statistical test used to measure the difference in material inventories based on the MBA and the MBP. The general equation for ID is shown in Equation 1. Equations 7 and 8 are specific applications to MBA1 and MBA2, incorporating the inputs, outputs, and inventories from Tables 1-3.

$$ID = \sum_{i=0}^{2} input_i - \sum_{i=0}^{2} \Delta inventory_i - \sum_{i=0}^{2} output_i \quad (7)$$

$$ID = \sum_{i=0}^{2} input_i - \sum_{i=0}^{10} \Delta inventory_i - \sum_{i=0}^{3} output_i \quad (8)$$

The standard Page's test assumes statistical independence of each value in a series of ID measurements. However, ID measurements are correlated, as the beginning of one inventory measurement is equal to the ending inventory of another measurement. This lack of statistical independence demands adjustment. To utilize ID measurements for Page's test, the ID is converted into a standardized independent transformed ID (SITMUF). The ID measurements for a facility can be considered as a series of ID measurements shown by Equation 9 [9-11].

$$\overrightarrow{ID} = [ID_1 ID_2 ID_3 ...] \quad (9)$$

The ID series shown in Equation 9 has a variance/covariance matrix

$$\begin{matrix} V_{11} C_{12} C_{13} \\ \lfloor C_{21} V_{22} C_{23} \rfloor \ldots \\ C_{31} C_{32} V_{33} \end{matrix}$$

There exists a lower triangular matrix [T] and a diagonal matrix [U] such that:

$$[T][V][T]^T = [U] \quad (10)$$

The ITMUF [I] is calculated as

$$\overrightarrow{ID} = [T] \times \overrightarrow{ID} = \vec{I} \quad (11)$$

And SITMUF is calculated as:

$$\overrightarrow{SITMUF} = \frac{\vec{I}^T}{[U]} \quad (12)$$

Page's trend test is then applied to the SITMUF series. Page's test uses a chosen *h* and *k* values to achieve a desired false alarm probability. The *k* value changes the sensitivity and the *h* value is the threshold condition to signal an alarm. Currently *k*=0.5 is used as a sensitivity variable for this model and h was dependent on the statistics of the MBA. The one-sided Page's trend test is calculated at each MBP as:

$$\begin{matrix} S_i^{+\overrightarrow{SITMUF}} \\ S_i^{+max} \end{matrix} \quad (13)$$

An alarm condition is reached when S_i^{+h}.

3.5. Material Balance Periods

A key consideration for ID measurements is the proper configuration of MBPs. Different MBPs can be set for each individual MBA. MBPs should be based on expected timeframes for materials entering and leaving the MBA. It is ideal for measurements to be taken when transfers are not occurring and when material is concentrated in fewer vessels, to minimize the impact of uncertainty propagation. A run time of 6480 hours was used to emulate a working year at a fuel fabrication facility.

An algorithm was developed to aid the selection of MBPs for each of the MBAs. The algorithm first finds the times where inputs and outputs are not entering or exiting the MBA. The algorithm then investigates the inventories to determine the optimal time to take a measurement to minimize the amount of inventory during the MBA calculation. In some cases, like MBA 1, it is trivial to use this algorithm, where there are only two inventories. However, when there are multiple processes within a MBA (MBA2) or material is entering and exiting a MBA on different periods (MBA3), the algorithm aids the selection of MBP.

3.5.1. MBP for MBA1

Figure 11 shows where the measurements will be made for MBA1, indicated as green dots on the inventory measurement. Figure 11 shows the total inventory for MBA1, and in this case, the equilibrium inventory is reached and maintained throughout the run. UO_2 drums and UF_6 cylinders enter and exit regularly on a 32-hour period. For this work, a 2-month (1600 hour) MBP was used, as this value lined up well with the MBPs in MBA2 and MBA3.

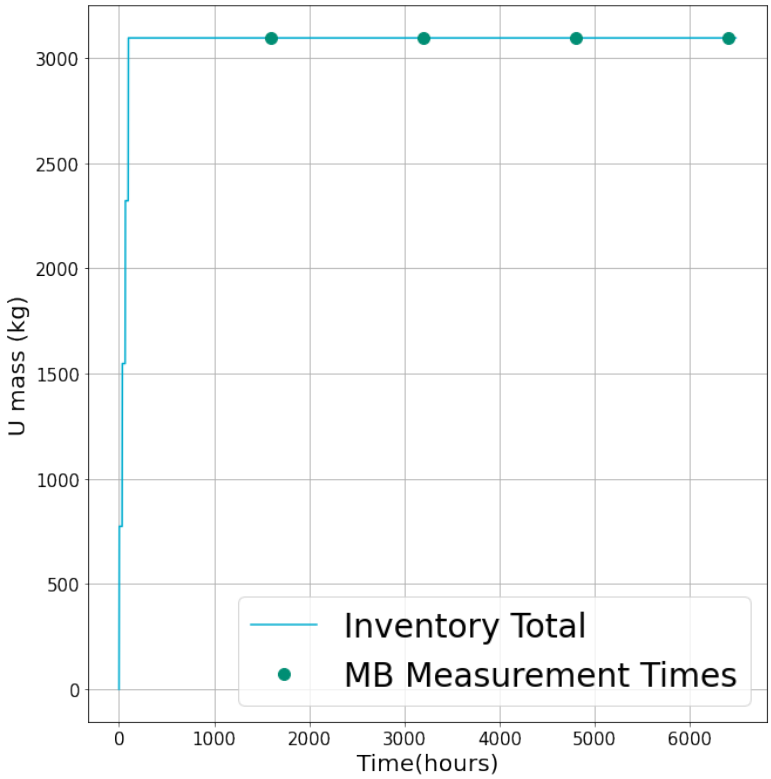

Figure 11. Total Inventory as a function of time in MBA1.

3.5.2. MBP for MBA2

Like MBA1, material enters and exits MBA2 on a 32-hour period; however, the material in MBA2 goes through significantly more processes to convert to the desired fuel form of UO_2. The time period for MBA2 changes as the LEU moves through MBA2 until it reaches an equilibrium period of around 34 hours. Changes were made to the scrap storage rather than the material being directly sent for processing—the material is stored for approximately one week. Following storage, the material begins the processing to be reintroduced into the UF_6 and UO_2 processes. The selection of the MBP greatly benefited from the use of the algorithm, identifying the time where there was a

minimal amount of LEU within MBA2. Figure 12 shows the total inventory within MBA2 as a function of time.

A key difference is the level of processing and changes to the uranium form compared to MBA1 and MBA2. As discussed previously, MBA2 involves conversion of UF_6 to UO_2, then changes the physical form from powdered UO_2 to UO_2 fuel rods. Tracking uranium through each of these processes (as well as scrap storage and reprocessing) requires care in selecting a MBP to minimize the number of required measurements in MBA2. A 1536-hour MBP is implemented to ensure measurements are not made during the transfer of material.

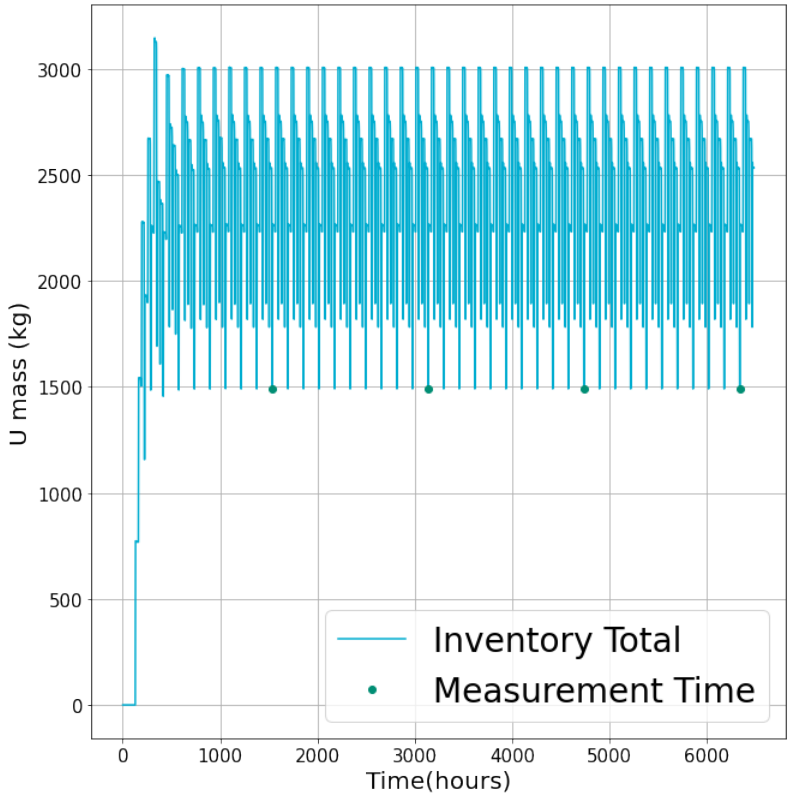

Figure 12. The total inventory measurement as a function of time in MBA2.

There are 25 potential KMPs in MBA2. Implementing a one-hour delay, only 10 of the KMPs have a non-zero inventory; the other 15 processes would be empty at the time of the measurement. This minimizes the effort required to quantify uranium in MBA2.

3.5.3. MBP for MBA3

MBA3 is the last stage in the fuel fabrication facility, and involves washing, preparation, and packaging of final products. Fuel pins enter MBA3 on a 32-hour time period, and packaged fuel assemblies exit on a time period that is based on the flow of material into the MBA. Initially the period is similar to a 38-hour time period, however over time the time decreases to a 34-hour period. This difference in time period necessitates a different approach in setting up the MBP for MBA3. The algorithm helped identify times where material enters and exit in such a way that no material is

entering the facility and the material is minimized during the processes. A MBP of 2073 hours was selected as no material processing occurs during those times (shown in Figure 13).

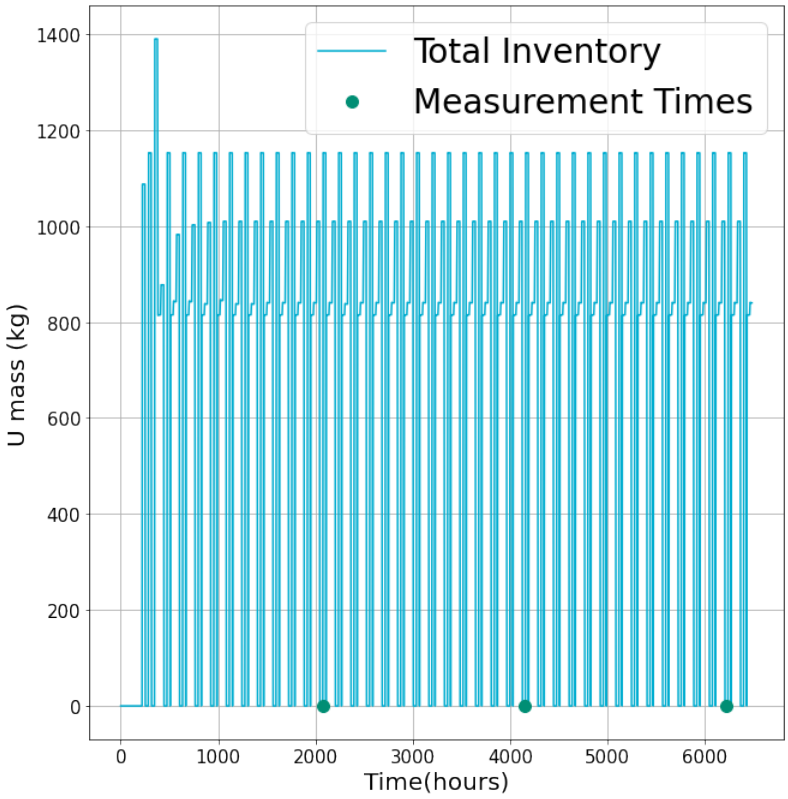

Figure 13. Total Inventory as a function of time for MBA3.

3.6. Inventory Difference Calculation

After defining the MBP for each of the MBAs, the fuel fabrication model was used to determine the ID and standard error of the inventory difference (SEID) throughout the facility. Systematic error is defined for all measurements at the beginning of a simulation run. The value of the random error changes with each measurement, as taken from a normal population based on the user-defined uncertainty. Each measurement is assumed to have a multiplicative error model, as shown by Equation 13.

$$M_{i,t} = G_{i,t}(1 + S_i + R_{i,t})$$
where
$$S_i N(0, \delta_S^2)$$
$$R_{i,t} N(0, \delta_S^2) \quad (14)$$

- $M_{i,t}$ = Measured value at location *i* and time *t*
- $G_{i,t}$ = Ground truth value at location *i* and time *t*
- S_i = Systematic error random variate at location *i*
- $R_{i,t}$ = Random error random variate at location *i* and time *t*

- δ_S^2 = Systematic relative variance
- δ_R^2 = Random relative variance

Figure 14 illustrates the average ID and average SEID for a hundred simulated runs of the fuel fabrication model through MBA1, MBA2, and MBA3. The random and systematic errors are based on the published values in the International Target Values [8]. Primarily, 3% random and 2% systematic were used for the UO_2 and the UF_6 processes primarily used 5% random and 2% systematic. A key difference between the three MBAs is the number of inventories measured in each MBA, with MBA2 having the most (ten) and MBA3 having zero required inventory measurements. It is noteworthy that, since a LEU fuel fabrication facility is a bulk handling facility and throughput dominated, the impact of the measurements within the MBA is minor compared to the large amount of material entering and exiting each MBA.

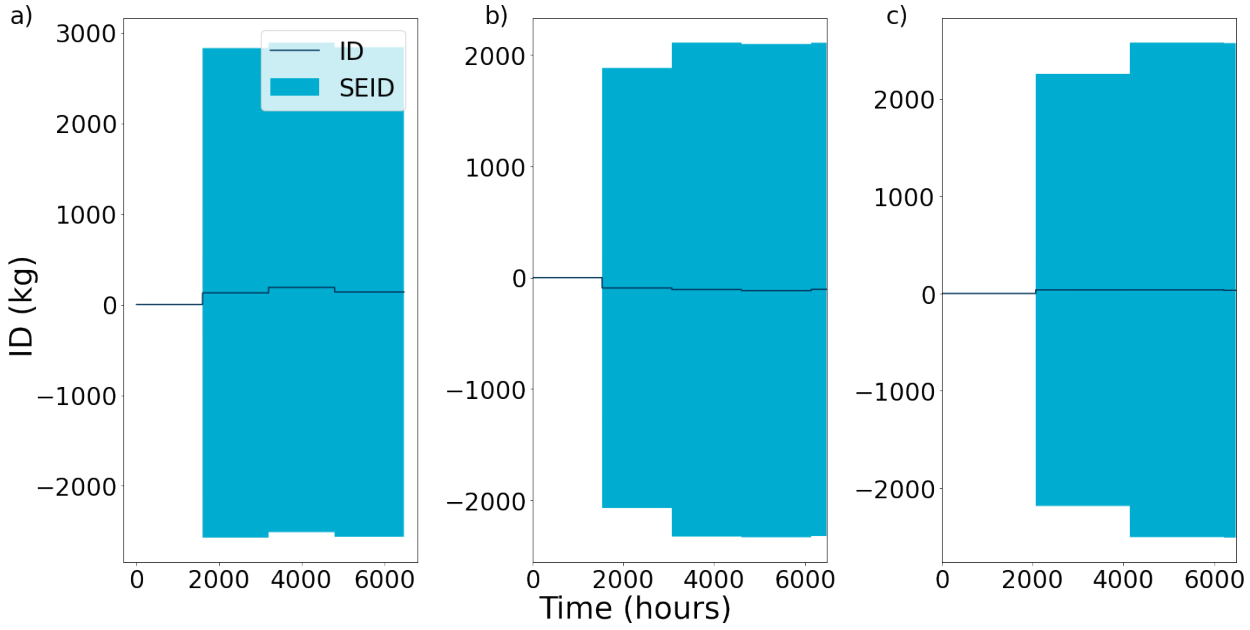

Figure 14. Uranium ID and SEID for a) MBA1, b) MBA2, and c) MBA3.

As MBA2 is the most complicated MBA within the LEU fuel fabrication model, MBA2 was tested with two different material loss scenarios. Both material loss scenarios were protracted losses, looking at lost material over longer periods of time. For material loss scenario 1, more material was removed over a shorter period of time as compared to material loss scenario 2. The ID and variance related to each measurement were converted to SITMUF to utilize Page's trend test. The SITMUF values for MBA2 are plotted in Figure 15 The k-value was chosen to be 0.5 ($k = 0.5$), and the S_i-value was chosen to be 0.6 ($S_i = 0.6$), the value where 5% of the SITMUF values are above that value during nominal conditions. Both material loss scenarios had very high probabilities of detection.

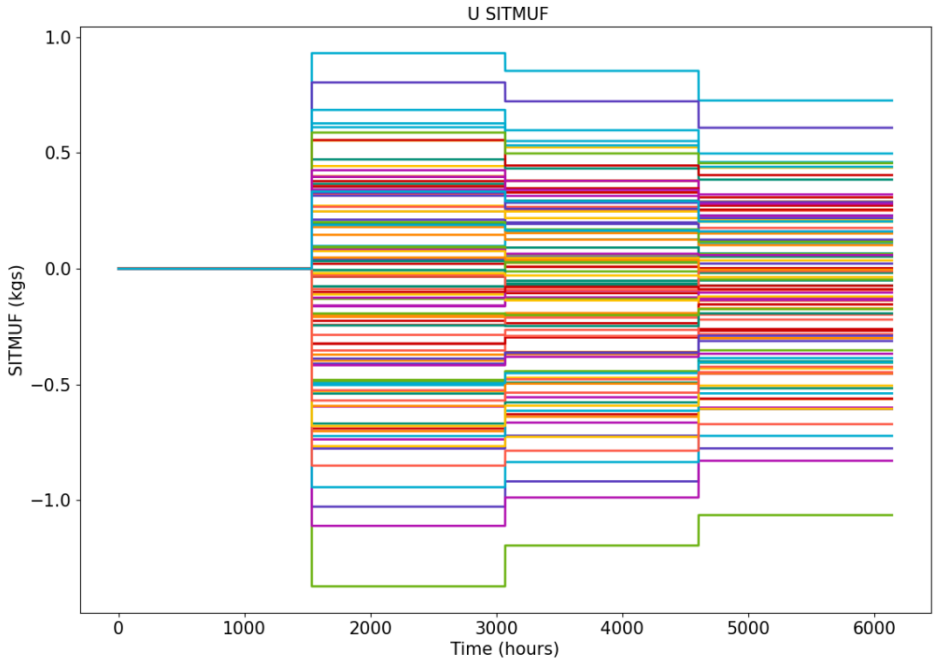

Figure 15. SITMUF for MBA2

3.7. Summary

The LEU fuel fabrication model has been updated to include the identification of KMPs and the implementation of statistical tests to better track the uranium material transferring throughout the facility. The facility was broken into three MBAs based on STR-150: MBA1 (Shipping/Receiving Area), MBA2 (Fuel conversion and fabrication), and MBA3 (Fuel Bundle Assembly). The development of an algorithm to identify the optimal KMPs was developed to improve the ability to find the lowest amount of material within the system.

Within MBA1, 6 KMPs have been identified to perform ID measurements and perform Page's trend test: UF_6 cylinders entering the facility, UO_2 drums entering the facility, UF_6 cylinders inventoried in MBA1, UO_2 drums inventoried in MBA1, UF_6 cylinders exiting MBA1, and UO_2 drums exiting MBA1. The implementation of ID and Page's trend test indicates the expected results for nominal conditions of a LEU fuel fabrication facility.

MBA2 is the most intricate MBA within the facility, covering the UF_6 conversion into UO_2 powder and UO_2 powder converted to UO_2 fuel rods. The MBA2 inventory is monitored with 15 KMPs to identify the uranium material within the MBA.

MBA3 covers the assembly and packaging of fuel assemblies for LWRs. Due to the difference in material entering and exiting, the algorithm developed successfully identified key measurement periods to identify the best time to make statistical safeguards measurements, when there is no material in the assembly and packaging area.

Material loss scenarios, although only shown for MBA2, were able to be performed in all 3 MBAs. A key aspect of a LEU fuel fabrication facility is that large amounts of uranium need to be diverted to acquire significant quantities of material. Although the SEID is large, the measurement system was still able to detect material loss scenarios with high probability of detection.

4. CONCLUSIONS

This work described the development of a LEU fuel fabrication facility model. The intent for this activity is to support MC&A analysis and to enable a virtual test bed for advanced instrumentation to be incorporated into a facility-wide MC&A system prior to field tests.

Final results for the fuel fabrication model are presented, based on an assumed MBP of 60 days for MBA1 and MBA2. Page's trend test and ID calculations are performed, assuming using systematic and random errors based on the international target values published by the IAEA. Due to the large throughput of the facility, this resulted in a wide band of SEID. Additional work will look to develop a new fuel fabrication model based on this to emulate fuel fabrication for advanced reactors. The use of high-assay LEU introduces a unique problem where the high SEID bands will no longer be tolerable and optimizing the MBAs and MBPs will be more important.

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