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INSIGHTS FROM A JOINT US/INDIA WORKSHOP ON MODELING AND SIMULATION FOR IMPROVED NUCLEAR MATERIAL ACCOUNTANCY

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ABSTRACT

Modeling and simulation (M&S) is an effective tool for nuclear material accountancy (NMA) system optimization. Modeling can be used for measurement system design, NMA performance assessments, process monitoring and control, and exploration of new uses of monitoring data through data fusion. An ongoing collaboration between the National Nuclear Security Agency (NNSA) and the Bhabha Atomic Research Centere (BARC) has investigated the practical implementation of these tools. During the period of January 17-20, 2022, a joint workshop was conducted virtually with NNSA and BARC (under the aegis of Global Centre for Nuclear Energy partnership (GCNEP), India) to create an open dialog between research and development staff and safeguards practitioners on the use of M&S for improving NMA. Rather than strictly providing lecture-style content, this workshop also included interactive exercises based on the open-source Material Accountancy Performance Indicator Toolkit (MAPIT). The modeling tools and methodologies are also being provided to BARC to assist their efforts to develop M&S capabilities for their safeguards practitioners. This paper focuses on lessons learned that can be extended to other virtual events while noting that there is an existing body of literature that discusses the practical uses of M&S for NMA [1, 2, 3, 4, 5].

1 Introduction

All over the world, large throughput bulk handling facilities have faced the challenge of achieving accountancy goals due to process complexity and measurement uncertainties. An ongoing joint effort between the U.S. National Nuclear Security Administration (NNSA) and the Bhabha Atomic Research Center (BARC) is exploring how the use of modeling and simulation (M&S) can improve MC&A for bulk nuclear processing facilities. As a part of Indo-US Technical Exchange, efforts towards the M&S for a Generic Mixed Oxide (MOX) Fuel Fabrication Plant, based on IAEA STR-185, was presented in Nuclear & Radiochemistry Symposium, NUCAR [6]. In January 2022, a joint, virtual workshop was conducted (under the aegis of Global Centre for Nuclear Energy partnership (GCNEP), India) to facilitate open dialog between research and development (R&D) staff, facility operators, and safeguards practitioners on the practical use of M&S for improved facility safeguards.

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2 Background

Safeguards M&S provides a quick and low-cost way to test different MC&A strategies by assessing the impact of different design choices on key safeguards metrics. These metrics include the Material Unaccounted For (MUF) evaluation, the overall uncertainty on MUF (σ_{MUF}), and probability of detection for a material loss. This project incorporates experience from the Separation and Safeguards Performance Model (SSPM)[1, 2] developed at Sandia National Laboratories. This model was developed in MATLAB Simulink and has been used for over a decade to support a variety of safeguards analyses. The SSPM consists of several standalone flowsheets including: UREX+, PUREX, enrichment, fuel fabrication and electrochemical reprocessing. Each of these flowsheets include the same standardized features:

- Source term library informed by reactor physics (if applicable)
- Mass and isotopic tracking through the process
- Customizable measurement points
- Diversion scenario analysis
- Integration with external codes
- Automated calculation of statistical safeguards quantities

Flowsheets in the SSPM are commonly split into multiple material balance areas (MBAs), which are discrete facility areas that have been divided based on process operation, material type and quantity. An example of MBA2 of the SSPM fuel fabrication flowsheet is shown below in Figure 1. The gray blocks in Figure 1 represent unit operations, which contain significant detail to capture accurate timings and mass flow changes. Material inputs and outputs for each unit operation is depicted, and key measurement points are colored in blue. While not shown in Figure 1, the locations of potential diversions are also modeled.

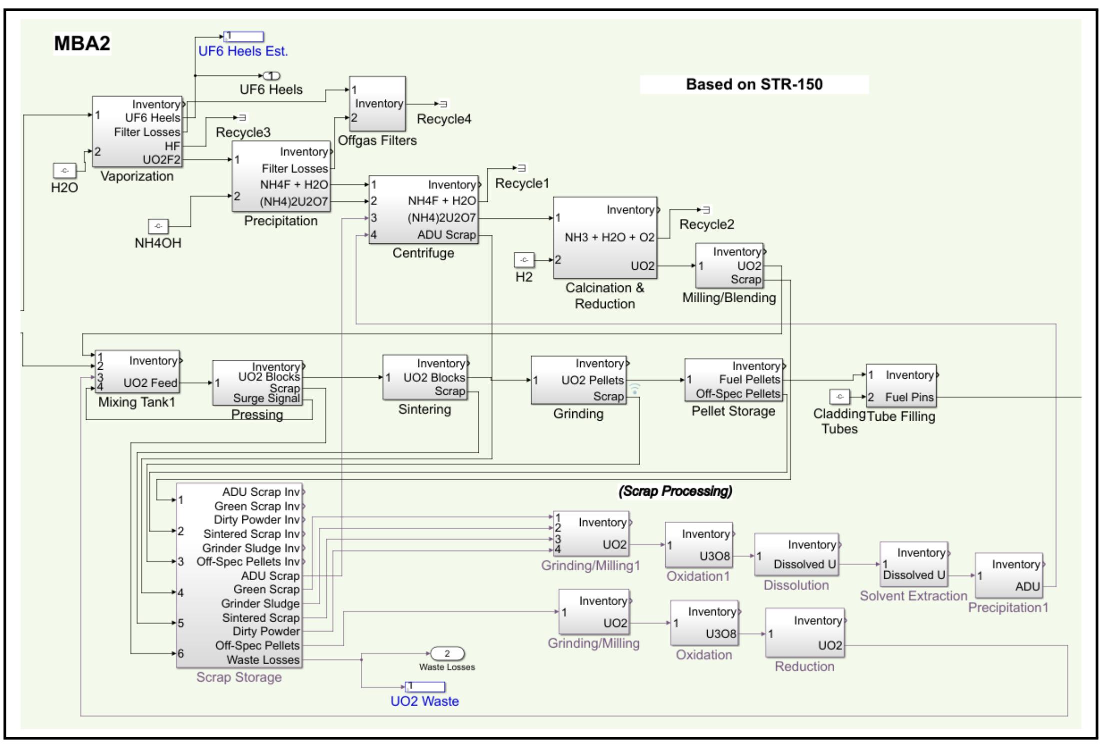


Figure 1: Visual diagram for MBA2 of the SSPM fuel fabrication model.

The SSPM fuel fabrication flowsheet was used to support the workshop in a variety of exercises and use case examples. The model also formed the basis of several examples of best practices for implementing effective M&S strategies.

While the SSPM can be a turn-key solution for MC&A modeling, it is also computationally demanding and challenging to use. As an alternative option, the Material Accountancy Performance Indicator Toolkit (MAPIT) was developed as an analysis tool for calculating safeguards statistics. MAPIT is, to the author's knowledge, the first open-source software for safeguards development and analysis. MAPIT[3] is written in Python with a QT back-end with a GPL 3.0 license. This results in a lightweight, user-friendly tool that can perform tasks such as:

- Automated error propagation
- Automated calculation of common safeguards statistical tests
  - MUF
  - σ_{MUF}
  - SITMUF
  - Page's trend test
- Threshold optimization
- Visualization tools
- Flexible I/O tools

MAPIT utilizes datasets from process models (from the SSPM) and uses a similar approach to generate synthetic safeguards statistics. Because it is built in python and does not perform process modeling, it is much more approachable and less computationally expensive. The analysis area shown in Figure 2 allows a user to vary the parameters of a safeguards plan (such as MBP) and visualizes how minor changes can significantly impact a facility's NMA system.

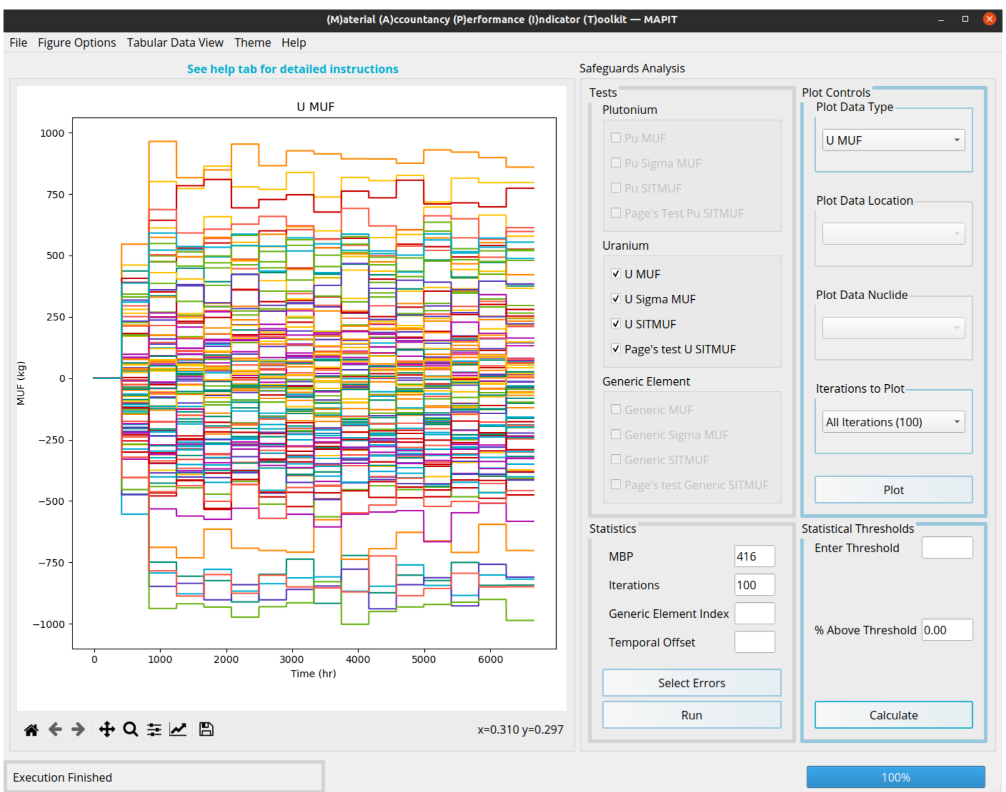


Figure 2: Overview of the MAPIT analysis area.

MAPIT and the SSPM were both used as example M&S tools that can be used in nuclear safeguards. The SSPM was referenced in multiple sessions, and screenshots were used regularly through the workshop to visualize how process models might be constructed. MAPIT was used primarily in the interactive portion of the workshop. As an open-source tool, the software was freely available for all attendees to download and use.

[3]https://github.com/sandialabs/MAPIT

3 Workshop

The collaboration between the NNSA and BARC seeks to improve MC&A at bulk nuclear facilities in India through the use of M&S. The 2022 workshop had two primary objectives: (1) for R&D staff to demonstrate the applicability of computer modeling in safeguards, and (2) for facility/operations staff to provide feedback on M&S tools. The virtual workshop was conducted over 4 days for 4 hours each day for a total of 16 hours. Though the virtual format introduced some challenges, it facilitated the participation of experts from multiple entities throughout the US and India. This ultimately strengthened the workshop by having a wide range of experience and backgrounds represented.

The workshop was comprised of 6 lecture modules (days 1-3) and interactive exercises (day 4). The first four modules provided a thorough and rapid deep-dive into the principles of nuclear material accountancy. Modules 5 and 6 then introduced attendees to foundational M&S concepts and techniques used in the SSPM and provided an overview of a case study to be explored. The workshop concluded with interactive exercises, wherein attendees downloaded, installed, and used the open-source Material Accountancy Indicator Performance Toolkit (MAPIT), a Python-based tool for supporting safeguards analysis and development.

3.1 NMA Sessions

Modules 1-4 involved lecture-style presentations on NMA. The first module, led by BARC, reviewed general statistical concepts and fundamentals of MC&A. Module 2 and 3, led by , discussed more advanced statistical models for safeguards, visualization techniques, and trend tests. Module 4, led by BARC, discussed measurement techniques commonly used in nuclear safeguards (i.e., NDA and DA methods).

Module 1 was entitled Foundations, and reviewed safeguards agreements, key terms in safeguards, and introduced basic statistics for material accountancy. Indias safeguards agreement, INFCIRC/754 involves an item-specific safeguards agreement with both state- and facility-level implementation [7]. The objective of safeguards, as defined in the IAEA glossary[8] and discussed in the workshop, is ... the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities. Subsequently, the definitions for significant quantity (SQ), KMPs, MBAs, and physical inventory verification (PIV) were given, to establish a common foundation for attendees.

Basic statistical concepts were also introduced in the first module. Measurement error was split into two categories: systematic and random. Both types of error are unavoidable, though systematic error can be reduced by effective calibration whereas random error can be minimized through longer or repeated measurements. Figure 3 illustrates the relationship between random and systematic error, and how they impact observation of a target. The distinction between accuracy and precision, and an overview of the normal (Gaussian) distribution were also presented in this module.

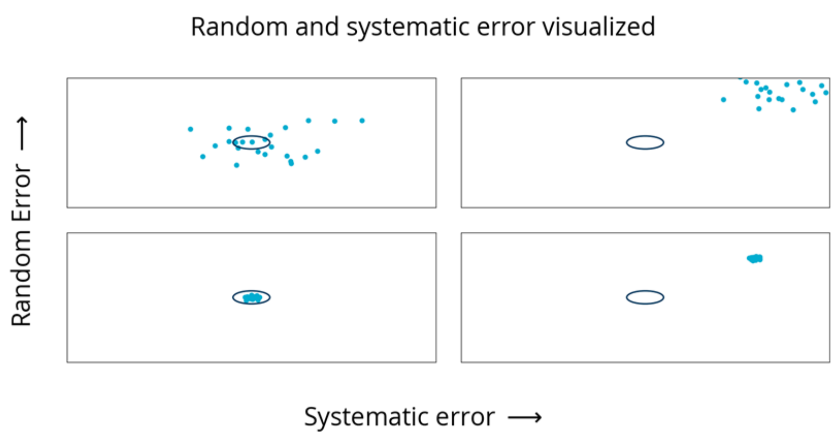


Figure 3: Systematic and random error related to a target value

Module 2, Foundations Review I, continued the review of key concepts for safeguards statistical analysis. Building upon the definitions of systematic and random error from the prior module, this module explored how the propagation of variance impacts MUF and σ_{MUF} for a facility. The instanced equation for MUF at time t is given by Equation 1, where I is an inventory at a given timestep (t or $t-1$) whereas Tin and $Tout$ are in the transfers in and out, respectively. Importantly, MUF is specified at a given time t, which corresponds to a multiple of the material balance period (MBP);

a window of time determined by expert judgment using a number of different factors including operational timings and accountancy goals.

$$\text{MUF}_t = I_{t-1} + Tin_t - Tout_t - I_t \tag{1}$$

In practice, many measurements are required for calculating each term in the MUF equation. Equation 2 illustrates how the MUF calculation can be more complex for a facility with five inventories, two input flows, and three output streams. Keeping in mind that each individual measurement has some error, the MUF_t would be unavoidably nonzero for bulk quantities. The goal then becomes quantification of the uncertainty of MUF (σ_{MUF}), and minimizing it in such a way that the loss of a significant quantity (SQ) of material can be accurately detected in a timely manner.

$$\text{MUF}_t = \sum_{i=1}^{5} I_{i,t-1} + \sum_{i-1}^{2} \int_{t-1}^{t} Tin_{i,t} - \sum_{i=1}^{3} \int_{t-1}^{t} Tout_{i,t} - \sum_{i-1}^{5} I_{i,t} \tag{2}$$

The overall uncertainty on MUF can be written as in Equation 3 provided there is negligible contribution from input and output covariances. Using statistical rules, error propogation, and the MUF definition given by Equation 1, the derivation for the analytical solution of σ_{MUF} was provided, which is described in Equation 4. It is important to note that the exact variance of each measurement term used in Equation 4 is impossible to determine. As such, the IAEA International Target Values (ITV) [9] is used as a reasonable approximation of the true value.

$$\sigma\text{MUF}_t = \sqrt{Var(MUF_t)} \tag{3}$$

$$\begin{aligned} Var(\text{MUF}) = {} & I_t^2(\sigma_{I_t,R}^2 + \sigma_{I_t,S}^2) + Tin_t^2(\sigma_{Tin,R}^2 + \sigma_{Tin,S}^2) + Tout_t^2(\sigma_{Tout,R}^2 + \sigma_{Tout,S}^2) \\ & + I_{t-1}^2(\sigma_{I_{t-1},R}^2 + \sigma_{I_{t-1},S}^2) - 2I_tI_{t-1}\sigma_{I_t,R}^2 \end{aligned} \tag{4}$$

Hand calculations for MUF and σ_{MUF} can become challenging for large-throughput facilities, which may have many individual measurements. Optimization of MC&A approaches at these large facilities could become error prone leading to difficulties when comparing different system designs. Derivations of MUF and σ_{MUF} in module 2 were accompanied by demonstrated use of M&S tools as a more automated and less error prone way to analyze different safeguards systems.

Module 2 concluded with introducing anomaly detection. In nuclear safeguards, it is critical to be able to detect both short-term (i.e., abrupt) and long-term (i.e., protracted) losses at a facility. Control charts are useful tools for visualizing process conditions through time, and enable an analyst or operator to quickly identify off-normal conditions, anomalies, and losses. This topic was more familiar to some attendees, as control charts are used in both process control and safeguards. Shewhart and Cumulative Sum (CUSUM) charts were compared and contrasted, which laid the groundwork for the next module.

Module 3, Foundations Review II, built upon the key concepts from previous modules and applied them directly to nuclear material accountancy. This was achieved by introducing two key concepts: the Standardized Independent Transformed Material Unaccounted For (SITMUF) transformation [10] and Pages trend test [11, 12].

In a previous module, MUF had been discussed in the context of a single instanced value. That is, MUF equations were for a given point in time. Module 3 built on this concept, considering MUF in terms of a sequence, as expressed by Equation 5. This is more reflective of standard practices in NMA, where it is advantageous to consider such values in a sequence to perform trend testing. However, this sequence is comprised of dependent values, rather than independent values. The MUF calculation ignores the correlation between successive values, which translates to a low diagnostic potential.

$$\overrightarrow{\text{MUF}_t} = (\text{MUF}_1, \text{MUF}_2, \text{MUF}_t) \tag{5}$$

SITMUF is more amenable to trend testing than MUF as it is an independent sequence of values. Thresholds for trend testing of SITMUF depend only on the length of the sequence, rather than the form of the covariance matrix. The variance of the SITMUF sequence decreases with time which leads to better performance. In addition, near real-time accountancy (NRTA) can be performed as values arrive, rather than requiring the entire sequence. A thorough explanation and derivation of the SITMUF sequence was performed in this module, to be available to attendees as a reference in the future.

Pages trend test is performed on the SITMUF sequence to identify potential material loss. Multiple trend tests can be applied to the same set of data, with each test tuned for identifying different material loss time frames (e.g., abrupt or protracted). The one-sided Pages test (shown in Equations 6 and 7) on SITMUF is commonly calculated for each balance period. The values of h and k are tuned to achieve a desired sensitivity and false alarm probability (FAP). The alarm condition is reached when $S_i^+ > h$.

$$S_1^+ = SITMUF_1 \tag{6}$$

$$S_i^+ = max(S_{i-1}^+ + SITMUF_i k, 0) \tag{7}$$

The values of h and k are generally chosen for a particular system, and may vary based on MBP, measurement error, and other such factors. The goal is to select h and k such that the FAP is below a facility target or regulatory limit while still achieving a timely detection of anomalous conditions. A smaller k makes the test more sensitive, while a smaller h increases the FAP.

In real world applications, it is recommended to use two tests simultaneously to monitor for both abrupt and protracted material losses [12]. The abrupt-focused test would use a high k value and $h = 0$ (e.g. low sensitivity, higher FAP), while the protracted test would use a lower k and higher h (e.g. higher sensitivity, lower FAP). Tuning h and k is typically performed throughout the lifetime of a facility. However, M&S tools present an opportunity to calculate ideal values of h and k during the design of a facility, and to evaluate different material accountancy strategies.

By applying randomization in process variance and sensor uncertainty, different realizations of a single model will lead to slightly different results. Multiple iterations of a facility model are run to generate synthetic, but informative statistics. This synthetic data can then be used to determine the values of h and k for a given material accountancy strategy while giving due consideration to how real-world measurements vary from case-to-case. This module provided key insights into how quantitative safeguards judgments are made.

Module 4, NDA and DA Foundations, concluded the standard lecture-style presentations on NMA. Accurate measurement of nuclear material at a given point or location is a critical basis for effective MC&A systems. However, there is no “one-size fits all” measurement technique for SNM. Nuclear material can be present in any physical state (i.e., solid, liquid, gas), and in a myriad of physical forms for each state, depending on the stage in the fuel cycle. NMA is complicated by the fact that measurement techniques for one material form may not be appropriate or even feasible for another material form (e.g., powder vs solution).

Nuclear material measurement techniques are broadly categorized as either non-destructive assay (NDA) or destructive assay (DA). NDA techniques are relatively fast compared to DA and the material is recoverable after measurement, though they are typically less precise than DA methods. NDA techniques measure either naturally-occurring or induced radiation of the target source, and produce near-instantaneous estimates of SNM using empirical correlations and relationships. These methods are usually fairly mobile as well, commonly allowing for small form factor sensors that can be hand held. Conversely, DA techniques typically utilize large pieces of relatively static equipment, but measurements can be very precise. Further, DA may require a dedicated analytical laboratory and have a significant delay; results may not be available for days or weeks.

At most fuel cycle facilities, nuclear material exists in multiple forms. An effective safeguards approach requires use of both measurement techniques (both DA and NDA), balancing cost, lag time of results, and required precision at several measurement points through a facility to achieve regulatory goals. This session outlined some of the practical constraints that impact safeguards design for a facility.

3.2 Modeling & Simulation Foundations

The latter half of the workshop transitioned from a conceptual discussion of M&S tools in nuclear safeguards to explicit implementation examples. Module 5 presented an overview of the process modeling and safeguards approach for a specific facility type and outlined how operators might approach material accountancy. Module 6 introduced M&S building blocks used to construct a process model and demonstrated how the calculation of MUF and σ_{MUF} can be automated to support safeguards design.

Module 5, Facility Applications, used a generic fuel fabrication facility as a test case. Information for the reference facility was taken from IAEA STR-150 [13]. Fuel fabrication is broadly split into three process steps: (1) conversion where feed material converted to UO_2; (2) fabrication & assembly which blends, mills, presses, and sinters UO_2 to form pellets, which ultimately form assemblies; and (3) scrap recycle where materials are reprocessed and used in fabrication.

The reference facility is split into three MBAs: (1) the process MBA, which consists of all conversion and fabrication stages, (2) the shipper/receiver MBA, which receives all material from off-site, and (3) the final assembly MBA where rods are cleaned and assembled. A brief overview of each of the process control units was given in the presentation, to illustrate some measurement challenges in a real-world process.

This module concluded with a simplified calculation of MUF and σ_{MUF} for the reference facility. These were calculated using traditional safeguards approaches (e.g., calculation at regular MBPs), though there was some discussion on the potential use of process monitoring to decrease detection timelines and uncertainties. This module built upon the previous material to describe potential real-world safeguards examples and how to apply safeguards statistics.

Module 6, Modeling and Simulation, concluded the lecture-style presentations. This session introduced concepts generally found in M&S tools used for process modeling by using the SSPM as an exemplar. The SSPM was developed in MATLAB Simulink, which is a graphical modeling environment. The SSPM uses Simulink “signals”, which are expressed as arrays and used to define ordinary differential equations, to describe mass flow rates as a function of time. The signals are constructed based on the need for a given facility, and can include thermophysical conditions, slurry conditions, and isotopic or elemental mass.

Process operations of a facility are simulated by manipulating signals. For example, Figure 4 depicts a precipitation unit operation as modeled within Matlab Simulink. Chemical feed (signal 2) is only activated when nuclear material (signal 1) enters the vessel. The feed from both streams is combined, then separated based on the modeled chemical reaction. The inventory of the vessel is tracked over time, and losses due to filtration are modeled as well. Simulink has a wide selection of function blocks available such that a user can simulate most complex processes that are required for realistic process models. This presentation looked at how some process steps for the reference fuel fabrication facility were modeled in Simulink, and how a user can visualize the material inventory at each subsystem to understand the facility process behavior.

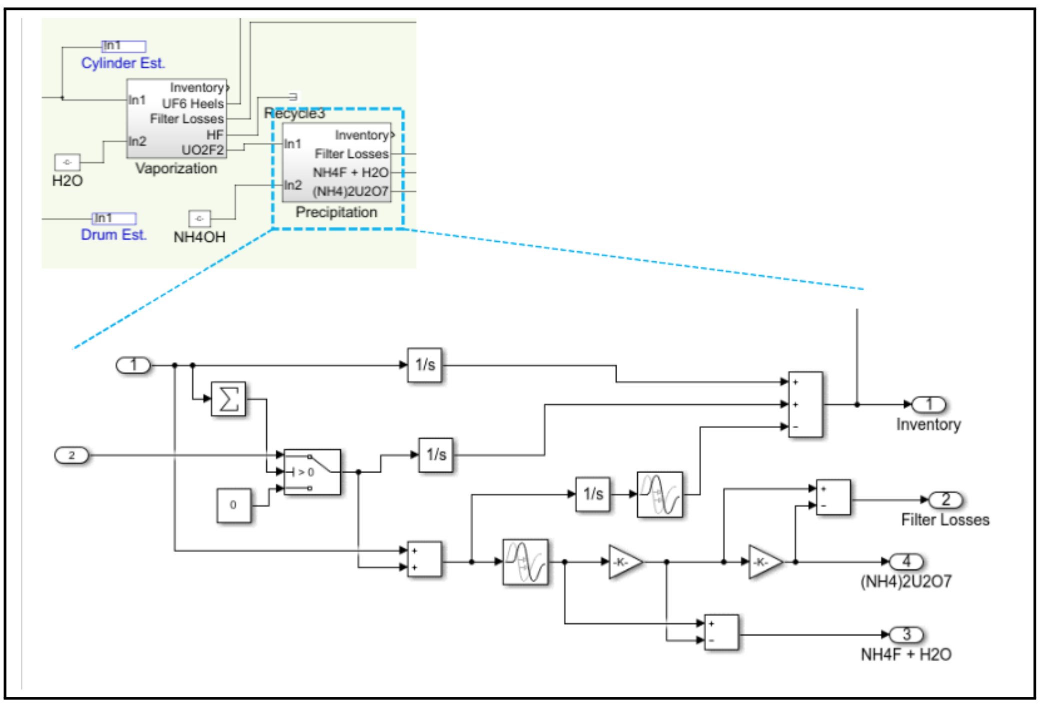


Figure 4: Precipitation model example provided in module 6.

Module 6 also outlined how NMA elements can be coupled to a process model. There are generally two approaches for NMA modeling: (1) measurements and statistical testing can be modeled directly into the process model, or (2) NMA calculations can be de-coupled from the process model and calculated separately. The first approach provides a better intuition of how a plant might operate in practice by showing how measurements might look in “real-time”. However, because multiple iterations of the model are required to generate synthetic statistics, this can be computationally expensive. Alternatively, splitting the NMA and process models into two entities significantly reduces computation time, but might not provide as much insight.

The SSPM utilizes the first approach. Material balances are set up within the model such that MUF and σ_{MUF} are calculated during a simulation run. This allows an analyst to observe how a subtle change in a NMA system (such as increasing the MBP or decreasing measurement uncertainty) might impact overall performance. Module 6 concluded with examples MUF and σ_{MUF} sequences for a single run of the SSPM fuel fabrication model.

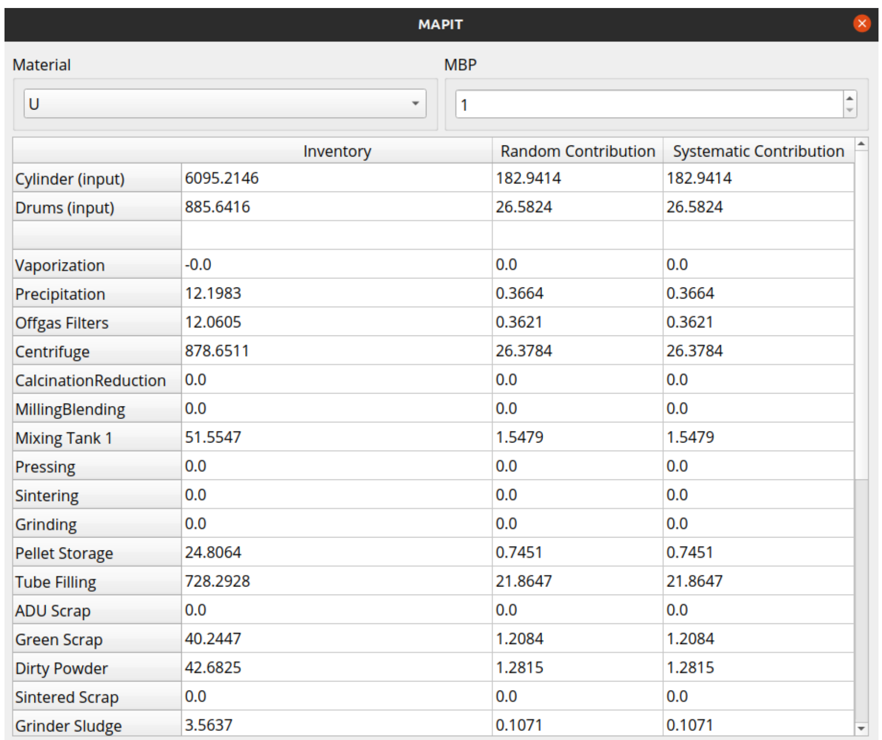
3.3 Interactive exercises

Concepts used to implement MC&A can be difficult to understand in isolation without context. While the lecture sessions provided a some examples to help translate concepts to application, the virtual setting did not encourage the same level of participation as an in-person setting. There was an added challenge in developing content as the background of the attendees was very diverse; ranging from modeling experts with little safeguards experience to seasoned facility operators and experienced safeguards experts. The final sessions were designed with this challenge in mind. The presenters created a series of interactive exercises using MAPIT.

The interactive exercises consisted of four different guided exercises, one challenge exercises, and one help session. The day before the MAPIT exercises, time was dedicated to providing instructions for downloading and installing MAPIT. Approximately an hour before the exercises started, the organizers also hosted a live help session to resolve any problems participants were facing installing the software.

The four guided exercises were conducted live by sharing a screen and following the step by step guide[4]. The first exercise consisted of an introduction to MAPIT that taught participants basic functionality of the toolkit.

The second exercise discussed the impact and contribution of measurement error. This exercise demonstrates how measurement error, and consequently the choice of measurement technology, can impact safeguards metrics. The ability for MAPIT to breakdown error contribution by facility process, as shown in Figure 5, is demonstrated.



	Inventory	Random Contribution	Systematic Contribution
Cylinder (input)	6095.2146	182.9414	182.9414
Drums (input)	885.6416	26.5824	26.5824
Vaporization	-0.0	0.0	0.0
Precipitation	12.1983	0.3664	0.3664
Offgas Filters	12.0605	0.3621	0.3621
Centrifuge	878.6511	26.3784	26.3784
CalcinationReduction	0.0	0.0	0.0
MillingBlending	0.0	0.0	0.0
Mixing Tank 1	51.5547	1.5479	1.5479
Pressing	0.0	0.0	0.0
Sintering	0.0	0.0	0.0
Grinding	0.0	0.0	0.0
Pellet Storage	24.8064	0.7451	0.7451
Tube Filling	728.2928	21.8647	21.8647
ADU Scrap	0.0	0.0	0.0
Green Scrap	40.2447	1.2084	1.2084
Dirty Powder	42.6825	1.2815	1.2815
Sintered Scrap	0.0	0.0	0.0
Grinder Sludge	3.5637	0.1071	0.1071

Figure 5: Breakdown of measurement error contribution by location within MAPIT.

The third exercise explored a notional material loss and the impact on safeguards metrics. While realistic scenarios are not provided, it is nonetheless important for participants to generally understand how different safeguards metrics respond to anomalous conditions.

The final guided exercise explains concepts behind probability of detection and optimization of alarm thresholds. Here, participants optimize alarm thresholds for given false alarm probabilities.

[4] https://sandialabs.github.io/MAPIT/

In addition to the guided exercises, there was an optional exercise for participants to complete on their own. This optional exercise[5] tasks participants to design a MC&A system with a particular set of criteria (e.g., false alarm probability) while minimizing the total cost. This exercise is similar to tasks that might be encountered in real-world facility design. A solution file, which can be imported directly into MAPIT, is provided as a reference.

4 Workshop Feedback & Discussion

Organizers solicited feedback from participants after conclusion of the workshop. The survey asked for a score (1-5) for each session, asked for overall change in knowledge (1-5), and left a space for additional comments. For the purpose of this work, a score of 5 is the best possible for a session and expert-level knowledge of a topic. The average scores per session gathered from respondents (roughly half of the participants) is shown below in Figure 6.

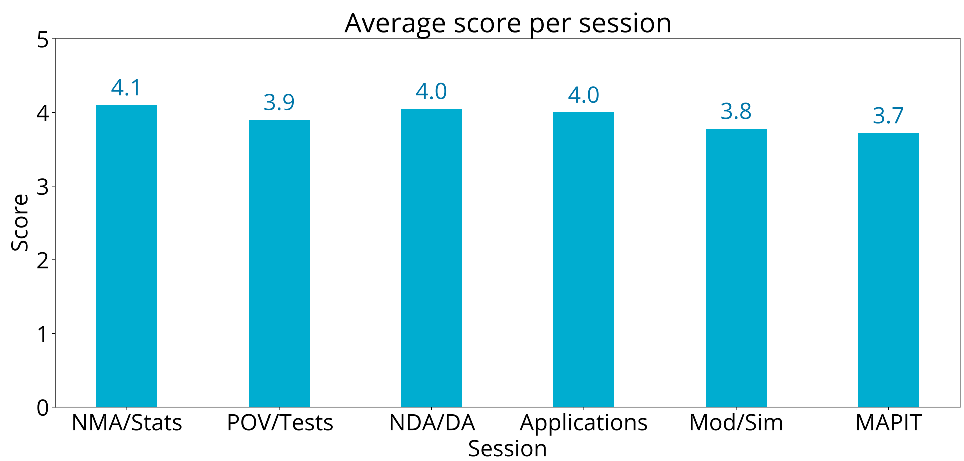


Figure 6: Average score per session topic.

Other feedback provided included:

- Interest in offline modules
- Short class timeline
- Desire for in-person format
- More diverse perspective offered from instructors
- Additional case studies

The workshop feedback showed that the lowest scoring session was MAPIT (i.e., the interactive exercises), but even the MAPIT module scored a slightly above average. This is not unexpected, as there were multiple challenges with software installation for many participants. MAPIT, being an open-source Python-based software, requires several dependencies to run correctly. The original install guide made available to participants assumed some familiarity with programming. This resulted in only roughly 50% of participants being able to install MAPIT and follow along with exercises in real time. Following feedback from attendees, the installation procedure has since been streamlined with the inclusion of simple install scripts.

Modeling and simulation scored slightly lower when compared to other content and almost as low as the interactive exercises. It is hypothesized that, given the audience's general lack of familiarity with the topic, the breadth of material presented may have been too much for the allotted time. Further, this could reinforce the view that safeguards practitioners and facility operators are skeptical of M&S-based approaches. Future engagements will include more detailed surveys to better understand the motivation behind specific session scores.

Lecture-based content, which included the first five modules, generally scored better than the interactive exercises. This suggests that the content presented in those modules were easier for participants to understand. Lectures are also a more familiar medium for workshops than interactive exercises.

[5] `https://sandialabs.github.io/MAPIT/exercise5.html`

The overall knowledge change for participants was rated at 1.45. Specifically, the average knowledge level increased from 2.1 to 3.55. The organizers view the increase in knowledge as an indicator of a successful workshop given the limited total time to present material.

5 Conclusions

The joint US/India workshop on modeling and simulation for improved nuclear material accountancy was an important step in introducing M&S concepts to safeguards practitioners and facility operations in addition supporting overall improved MC&A in India. This workshop facilitated an important information exchange between practitioners and research staff while providing feedback on the inclusion of interactive exercises. Information gathered from this workshop will be used to improve future engagements and reinforce US/India cooperation on safeguards and MC&A.

The initial success of this workshop could form the basis for future workshops. Use of MAPIT, which is open-source and available publicly, encourages a more engaging format for content delivery, which should improve overall usefulness to participants. MAPIT can be customized to support a wide range of safeguards analyses and facility types, which could support multiple workshop objectives.

6 Acknowledgments

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References

[1] B. B. Cipiti and N. Shoman, "Bulk handling facility modeling and simulation for safeguards analysis," *Science and Technology of Nuclear Installations*, vol. 2018, 10 2018.

[2] B. B. Cipiti, "Process monitoring considerations for reprocessing," *Proceedings of the Institute of Nuclear Materials Management*, 2015.

[3] B. B. Cipiti, F. A. Duran, B. R. Key, Y. Liu, I. Lozano, and R. Ward, "Modeling and design of integrated safeguards and security for an electrochemical reprocessing facility.," 10 2012.

[4] B. Cipiti, N. Shoman, and P. Honnold, "Safeguards modeling for advanced nuclear facility design.," *Journal of Nuclear Materials Management*, vol. 49, 11 2020.

[5] T. Burr, M. Hamada, and J. Howell, "Modeling and simulation for nuclear material accounting and process monitoring in nuclear safeguards," *Int. J. Res. Rev. Appl. Sci.*, vol. 8, 01 2011.

[6] International Atomic Energy Agency, "Agreement between the government of india and the international atomic energy agency for the application of safeguards to civilian nuclear facilities," 2009.

[7] A. Rao, N. Shoman, N. Rawat, B. Cipiti, and P. K. Pujari, "Modeling and simulation for numac of a generic mox fuel fabrication facility," in *Proceedings of Nuclear and Radiochemistry Symposium*, 2022.

[8] International Atomic Energy Agency, *IAEA Safeguards Glossary, 2001 Edition*.

[9] K. Zhao, M. Penkin, C. Norman, and S. Balsley, *International Target Values 2010 for Measurement Uncertainties in Safeguarding Nuclear Materials*, December 2012.

[10] B. Jones, "Near real time material accountancy using sitmuf and a joint page's test: comparison with muf and cumuf tests," 1988.

[11] E. S. Page, "Continuous inspection schemes," *Biometrika*, June 1954.

[12] T. Burr and M. S. Hamada, "Revisiting statistical aspects of nuclear material accounting," *Science and Technology of Nuclear Installations*, March 2013.

[13] R. J. Jones, E. V. Weinstock, and W. R. Kane, "Detailed description of an SSAC at the facility level for a low-enriched uranium conversion and fuel fabrication facility," tech. rep., International Atomic Energy Agency (IAEA), 1984.