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Integration of the SSPM and STAGE with the MPACT Virtual Facility Distributed Test Bed

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Abstract

The Material Protection Accounting and Control Technologies (MPACT) program within DOE NE is working toward a 2020 milestone to demonstrate a Virtual Facility Distributed Test Bed. The goal of the Virtual Test Bed is to link all MPACT modeling tools, technology development, and experimental work to create a Safeguards and Security by Design capability for fuel cycle facilities. The Separation and Safeguards Performance Model (SSPM) forms the core safeguards analysis tool, and the Scenario Toolkit and Generation Environment (STAGE) code forms the core physical security tool. These models are used to design and analyze safeguards and security systems and generate performance metrics. Work over the past year has focused on how these models will integrate with the other capabilities in the MPACT program and specific model changes to enable more streamlined integration in the future. This report describes the model changes and plans for how the models will be used more collaboratively. The Virtual Facility is not designed to integrate all capabilities into one master code, but rather to maintain stand-alone capabilities that communicate results between codes more effectively.

ACKNOWLEDGMENTS

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TABLE OF CONTENTS

FIGURES

TABLES

NOMENCLATURE

ER	Electrorefiner
GUI	Graphical User Interface
MPACT	Material Protection Accounting and Control Technologies
MUF	Material Unaccounted For
NDA	Non Destructive Analysis
SITMUF	Standardized Independent Transformed Material Unaccounted For
SSPM	Separation and Safeguards Performance Model
STAGE	Scenario Toolkit and Generation Environment

1. Introduction

The MPACT program has a 2020 milestone to develop a Virtual Facility Distributed Test Bed [1]. The goal of this milestone is to link all modeling capabilities, development of measurement technologies, and experimental testing together into a Safeguards and Security by Design capability, or a one-stop-shop for complete safeguards and security design for future fuel cycle facilities.

Initially, the milestone will focus on pyroprocessing since much of the work in MPACT has focused on pyroprocessing in the past few years. However, many of the models, technologies, and test beds have also been applied to aqueous processing and other fuel cycle facility types. The capabilities are expected to expand to other facilities, driven by the overall needs in the DOE NE program.

The integration of capabilities is described across the MPACT program as a whole in the Advanced Integration Roadmap [1] and Implementation Plan [2]. These documents describe all the capabilities and how they fit into the larger picture.

The purpose of this report is to discuss two modeling capabilities in more detail. The Separation and Safeguards Performance Model (SSPM) is one of four systems level models that form the core of the Virtual Facility Distributed Test Bed. It is used for safeguards system design and analysis. The Scenario Toolkit and Generation Environment (STAGE) code is another of the systems level models that is used for security design and analysis. Both of these codes are in development and use at Sandia National Laboratories. These tools generate key safeguards and security performance metrics.

The focus of the work from FY17 has been to explore the integration of the SSPM and STAGE within the Virtual Facility Distributed Test Bed in more detail. In addition, the SSPM has undergone model changes to help make it easier to integrate with other capabilities. The following will describe these capabilities in more detail.

2. Background

Both the SSPM and STAGE models have been used for a variety of purposes for safeguards and security design and analysis. The SSPM was developed as part of the MPACT program and was designed specifically for safeguards design and analysis. The STAGE software is a commercial tool that has been tailored for use at Sandia for physical protection analysis. The following sections provide an overview of these two codes. Section 3 and 4 go into more detail about the capabilities and integration in the Virtual Facility Distributed Test Bed.

2.1 SSPM Overview

The SSPM [3,4] is built in the Matlab Simulink environment—a Matlab and Simulink license is required to run the model. Various versions of the model exist including PUREX, UREX+, pyroprocessing, and gas centrifuge enrichment plant models. The base of the model tracks nuclear material and bulk materials through various unit operations in the plant, and a great deal of detail has been spent on correctly modeling flowrates, inventories, separations, and timing sequences. Elements and isotopes are tracked in real time to simulate actual plant conditions from a startup state.

Figure 1 shows an example pyroprocessing model. The base of the model is shown on the right and is set up similar to a plant flow diagram. The grey blocks represent the main unit operations and determine inventories as a function of time and any separations that may be occurring. The algorithms that control each unit operation are contained within the subsystem and not shown in this view. The signals connecting the blocks track the mass flow rate of elements 1-99 as well as the bulk salt flow.

The blue blocks represent measurement points that would be used for accountability. The green blocks represent either process monitoring or confirmatory measurements. A number of bulk measurements are also included but not shown on this level of the model. All of the measurements are used in the Monitoring Subsystem on the left. This is where the material balance calculations and statistical tests are applied.

Scopes are used to monitor the model as it runs, but the model outputs can also be collected as data outputs either as Matlab data blocks in the workspace or as excel outputs. This will be described in more detail in Section 3.

The key safeguards metrics that the model tracks are the overall measurement error (σ_{MUF}), the probability of detection of material loss, and timeliness of detection. Diversion blocks are also included in the model to test the response of the safeguards system to different types of diversion scenarios. The SSPM has been used for safeguards design, analysis of the effect of new measurement technologies, process monitoring integration, and the integration of safeguards and security.

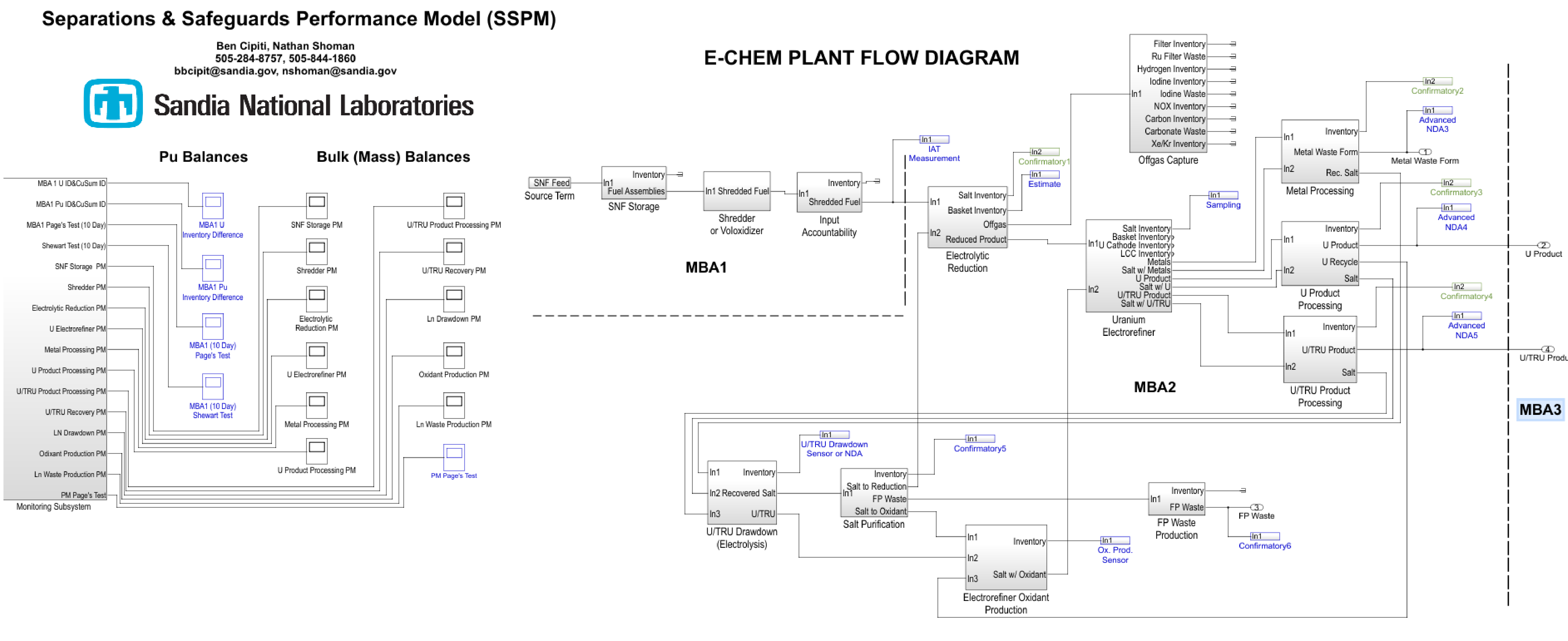

Figure 1: Pyroprocessing SSPM model

2.2 STAGE Overview

The STAGE (Scenario Toolkit and Generation Environment) commercial modeling and simulation software, developed by Presagis, has been used as the core security modeling capability in the MPACT program. Although there are a number of security modeling capabilities available, The STAGE software is more ideally suited to this application. STAGE allows for a single user to perform an analysis and can provide many iterations of a scenario with less time and much lower budget [5]. For this reason, single analyst tools like STAGE have become a first choice for security design analysis. STAGE has the added benefit of being more transparent than other codes, which makes it easier to justify results or show assumptions for a regulator. The current relationship between Sandia and Presagis is good, and small contracts have been set up in the past to request specific capabilities if needed.

STAGE is a 3D, force-on-force, combat simulator. It has a lot of versatility, with scripting support in C++ to program in a variety of features or behaviors. A facility is fully modeled in 3D including all physical security components such as barriers, detection elements, guard forces, etc. Generally, STAGE is used for outsider attack scenarios that may be focused on sabotage or theft, but insider theft or sabotage scenarios have also been examined.

The STAGE software has been used at Sandia for analysis of a variety of nuclear facilities, including reprocessing and small modular reactors. Typically a model is developed for a particular facility, and then assumptions need to be made about the adversary in question and target. The models have probabilities associated with detection and neutralization, so every run will lead to slightly different results. Multiple iterations are used to calculate probabilities of adversary or response force success. These probabilities are the key security metric from STAGE; however, other metrics are tracked. For example, a particular problem might be interested in the timelines for neutralization to help optimize the security design. In theft scenarios, there may be interest in determining the probability that a goal quantity can be removed.

Figure 2 shows an example of a STAGE simulation. The 3D view is shown in the lower left, and the overhead view is shown on the right. The upper left indicates key events by text. This was an example of a generic small modular reactor under an outsider attack to attempt to breach the facility.

Individual runs like these provide a good indication of whether the physical protection design is able to stop the threat, but multiple iterations are used to develop statistics. From there, the designer can either make the design more robust or optimize the design depending on the results. Again, the value of STAGE is the ability to design and analyze a physical security design using a single analyst and without needing to go through expensive table-top exercises. The STAGE results provide justification for a particular security design for a regulator.

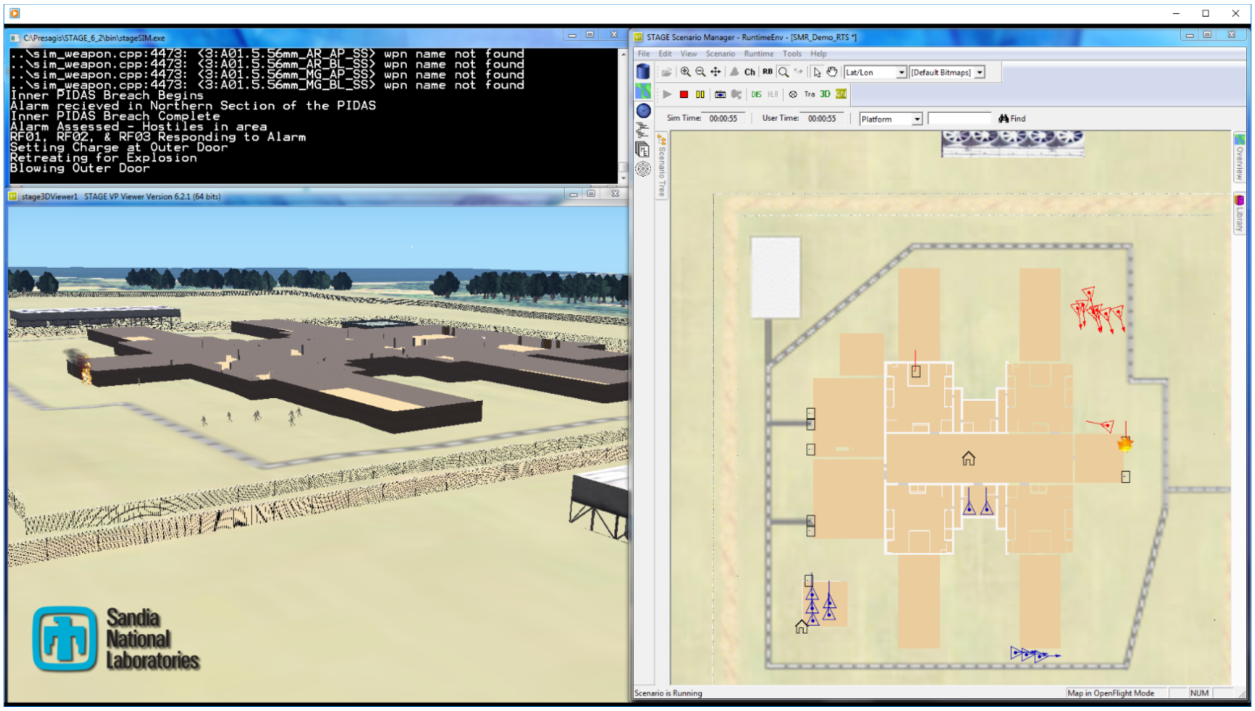

Figure 2: Example STAGE model

3. SSPM Updates

Integration of the SSPM in the Virtual Facility Distributed Test Bed requires a modular, flexible, and integrated modeling and analysis capability. Recent updates to the SSPM increase the modularity and usability of the model. The FY17 updates include improving the source term, adding a GUI for more ease of use, adding isotopic tracking, and standardizing model outputs to make it easier to pass data to others. These updates are described as part of a general overview of the functionality of the model.

3.1 Source Term

The SSPM originally supported nine different fuels that were generated using ORIGEN2 with older ENDF/B-V cross-sections that were processed and read from excel sheets. The SSPM source term has been updated using ORIGEN with ENDF/B-VII cross-section libraries. Additionally, source terms are now stored in an HDF5 database to increase performance and allow for more structured data storage. The database is setup with a standardized format that allows for quickly adding new fuel types or for interfacing with other modeling capabilities.

Along with the updated source terms, the model was modified to allow swapping of the input fuel. Any reprocessing plant will in reality see a range of fuel types and burnups—the fuel swapping option adds variability to the model, which helps to test the robustness of safeguards systems. The table below summarizes the fuels currently available in the database.

Table 1: SSPM source term options

Type	Burnup (GWd/MTU)	Enrichment (wt% u235)	Discharge Options (yr)
Westinghouse 17x17	33	2.6/3.3/4.0	1,5,10,25,50
Westinghouse 17x17	45	3.3/4.0/4.7	1,5,10,25,50
Westinghouse 17x17	60	4.03/4.73/5.43	1,5,10,25,50

3.2 Graphical User Interface (GUI)

The SSPM is now initialized with a GUI to set up all model parameters of interest. The specific plant design and throughput need to be modeled uniquely for each design, so various model versions exist. The GUI is tailored for each version. Figure 3 shows the GUI for the pyroprocessing model.

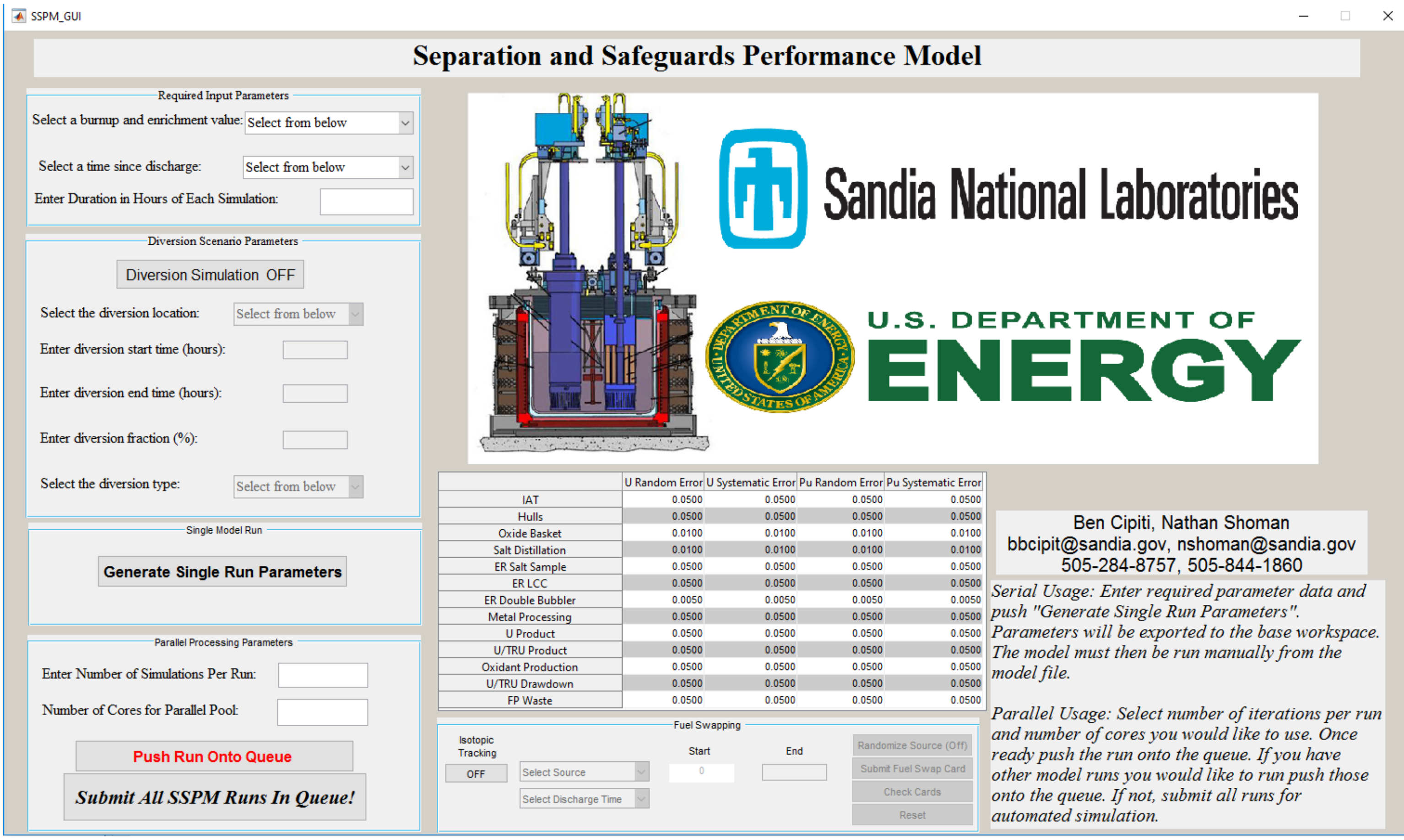

Figure 3: SSPM GUI

The upper left block allows the user to choose the initial source term and set the simulation time (in hours). These are the only options that must be chosen to run the model—all others are options. The user must choose a fuel burnup, initial enrichment, and discharge time.

The next block down has all the parameters required to simulate a diversion scenario. If a normal run is desired, this area is left alone. If a diversion scenario is desired, the button first must be clicked to turn this option on. The rest of the fields allow the user to enter the diversion location, starting time, stopping time, fraction of material diverted, and diversion type (direct material removal or substitution).

The table in the lower center of the GUI allows the user to set measurement uncertainties for the total U and Pu measurement for the key inputs, outputs, and inventory measurements. Most of the bulk measurements are not included, but these can be changed within the model.

Below the uncertainties table is a block that allows the user to turn on isotopic tracking (if desired) and add variability to the source term. By default, the model always tracks elements 1-99, but isotopic tracking adds computational time. For the most part, isotopic tracking is only applicable if the fuel source is changing. (For constant a fuel input, the isotopic ratios of each element would stay the same regardless of location in the model). More detail is given on the isotopic tracking below. The fuel swapping feature allows the user to either set changes in the source term at defined times, or set the source to randomize every fuel assembly.

The model also supports parallel processing which can be configured in the parallel processing block on the lower left. The SSPM can queue multiple runs. For example, a user may want to run 100 runs with a particular set of measurement uncertainties and then another 100 runs with a different set of uncertainties. The SSPM handles this by queueing the jobs. Note that the parallel process toolbox in Matlab is required to use this function.

3.3 Isotopic Tracking

The SSPM has been updated to track 266 isotopes within 57 element groups. ORIGEN tracks approximately 1500 isotopes, but this list was reduced in order to optimize computational time. In general there are many isotopes that are not of interest—the isotope had to meet at least one of the following criteria to be selected:

- Mass greater than 0.1 grams per metric ton
- Activity greater than 10^{-5} curies per metric ton
- Heat generation greater than 10^{-5} watts per metric ton

The isotopics are tracked at 39 different locations in the bulk handling facility. These can then be combined with the elemental mass measurements and passed to other researchers who may need the information to inform measurement models. This isotopic data set can be used to generate gamma or neutron spectra for more detailed NDA measurement simulations.

For processes that only receive and process one batch at a time, isotopic tracking is simplified since it is based on the previous unit operation. Any vessels that have mixing of previous batches require a more detailed calculation. For example, active fission products will go into the oxide reduction salt, so mixing is occurring with each batch processed. The same is true of the electrorefiner salt. When mixing occurs, the model uses the elemental masses along with the different isotopic vectors to calculate the new vector. This is saved for each of the elements for which isotopics are tracked as a function of time.

The end result is that the model can provide a full elemental and isotopic breakdown for any material at any location in the facility. Figure 4 shows an example of the change of the U-235 ratio (within the U element group) in the ER salt due to step changes in the fuel source term. The ratio starts at that of natural uranium which would likely be used for the initial uranium concentration in the salt at startup. The U-235 ratio goes up or down on each batch depending on the U-235 content in the fuel that it being processed.

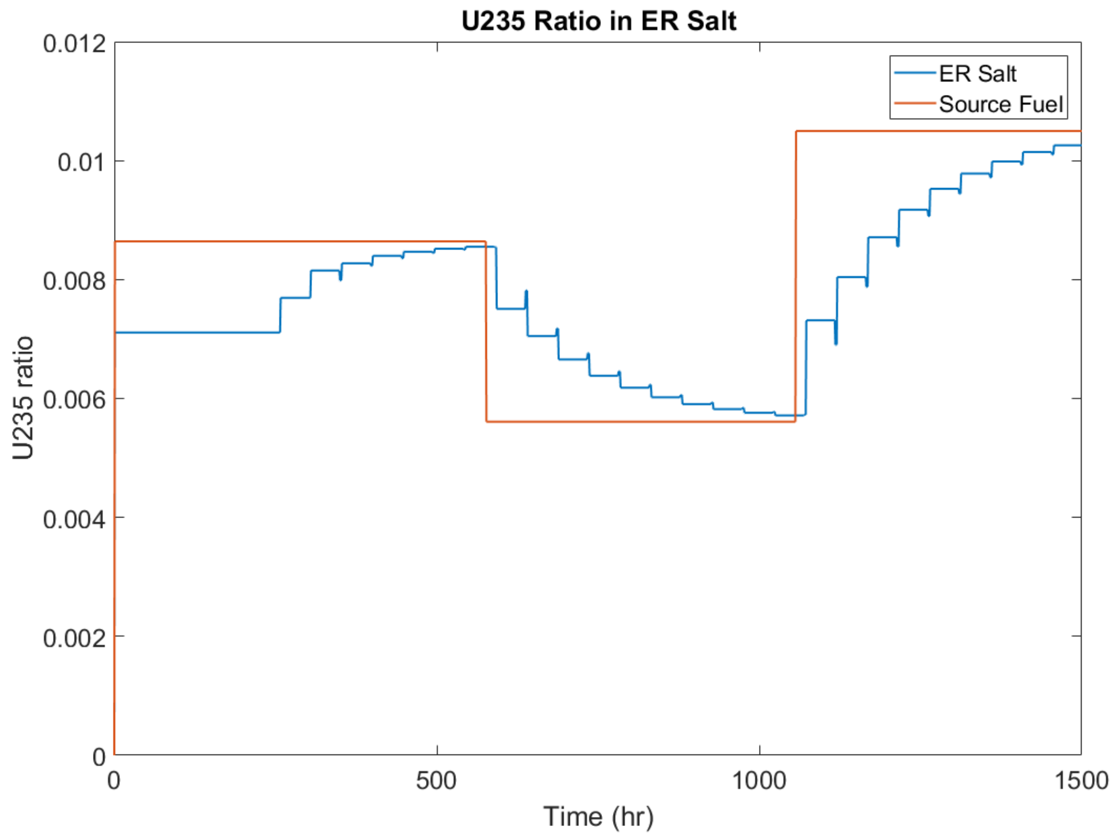

Figure 4: U-235 ratio in the ER salt with step changes in the source fuel

The isotopic changes with time are not always intuitive since the total elemental quantity and ratio can vary with fuel depending on burnup. Figure 5 shows an example of the Cm-244 ratio (within the Cm element group) in the ER salt during similar fuel step changes. In this case, the ratio stays at zero until the first batch of fuel is processed (since there is no Cm in the salt at startup). The ratio immediately starts at the initial fuel source term ratio once the first batch is processed. However, the subsequent step changes in the fuel make much less of an impact on the Cm-244 ratio. In this case, the total Cm content in the first source term was much larger than in subsequent source terms, so the subsequent step changes have less of an effect on the Cm-244 ratio in the salt.

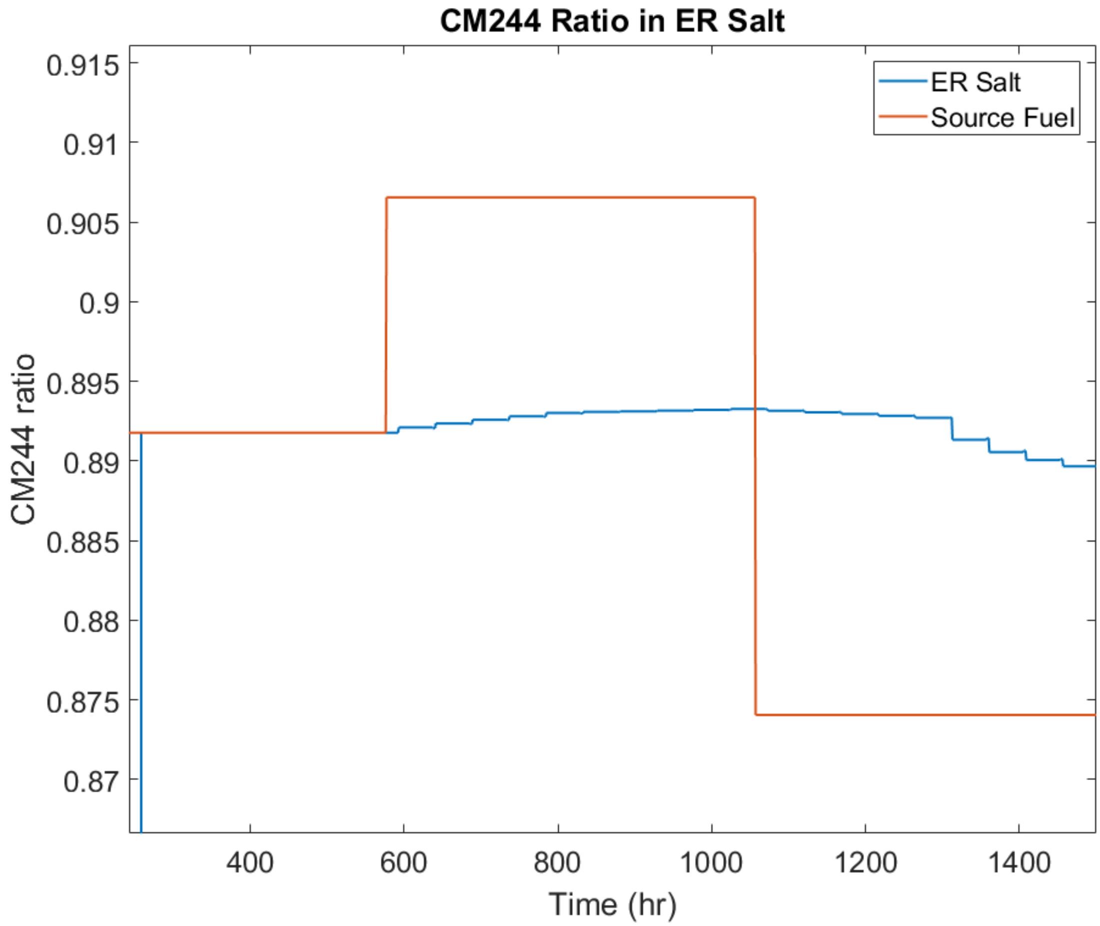

Figure 5: Cm-244 ratio in the ER salt with step changes in the source fuel

The isotopic tracking can be turned on or off from the GUI since it will only need to be used for certain analyses. This helps to cut down on computing time if isotopic tracking is not needed. Isotopic tracking will be most useful for integration of NDA measurements which may simulate gamma or neutron spectra from a particular sample or location in the facility.

3.4 Output Control

The SSPM now includes an output control panel in addition to the GUI (see Figure 6). The panel provides the user with options for what output data should be provided. Options are provided for the type of output, the location, and elements of interest. The panel provides a convenient way for outputting safeguards parameters such as MUF and SITMUF. Elements can be checked for tracking in the SSPM. Elements that are in blue have isotopes tracked. If the excel output option is selected, the elemental and isotopic data is formatted and placed into an excel spreadsheet. This functionality increases the flexibility of SSPM allowing for easier integration with other MPACT modules through a standardized output format.

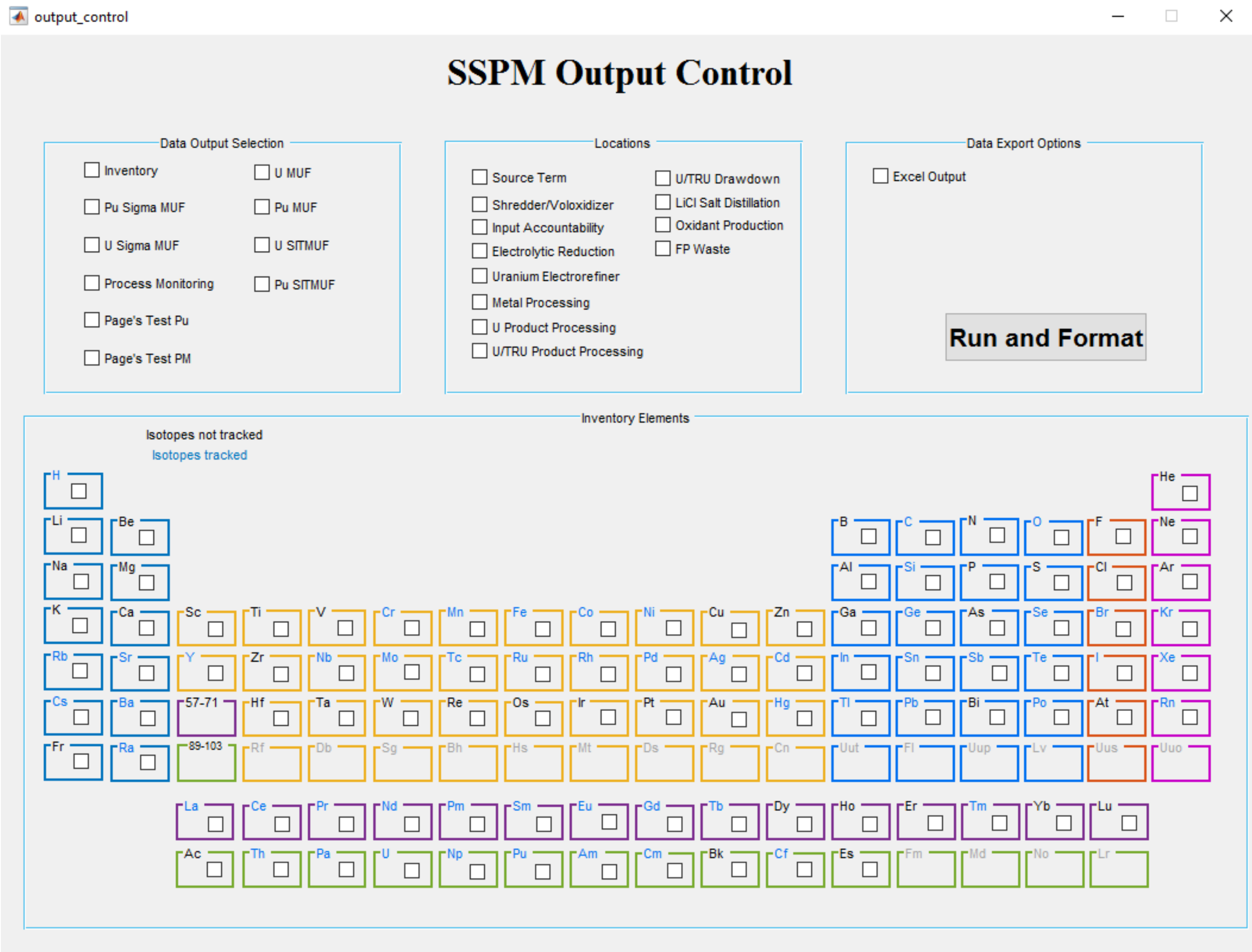

Figure 6: Output control GUI

Table 2 shows an example of the data output from a model run. The various options selected in the upper left of the output GUI will populate the data to different tabs of an excel file if that option is selected. Otherwise, the data is stored in the Matlab workspace. This table shows an example where the U and Pu elemental quantities are tracked in the ER salt as a function of time.

Table 2: Example Excel file data output

	A	B	C	D
1		Element	92	94
2	Time (hr)			
3	0		24	8
4	1		24	8
5	2		24	8
6	3		24	8
7	4		24	8
8	5		24	8
9	6		24	8
10	7		24	8
11	8		24	8
12	9		24	8
13	10		24	8
14	11		24	8
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35	32		24	8

U Sigma MUF | UMUF | USITMUF | ER_INV | FP Waste_INV

4. STAGE Integration

Physical security modeling must be part of the Virtual Facility Distributed Test Bed in order to enable safeguards and security by design. The goal of such modeling is to generate security metrics that are used to determine or prove the efficacy of a physical security design. As described earlier, STAGE has been used for analysis of nuclear fuel cycle facilities, including small modular reactors and reprocessing plants. These analyses have covered both outsider attack and insider diversion and sabotage scenarios.

4.1 STAGE Environment

Past work has developed 3D models using STAGE for generic pyroprocessing facilities to examine insider diversion scenarios. An example of the overall site layout is shown in Figure 7, and Figure 8 shows an example of the model of the main processing building.

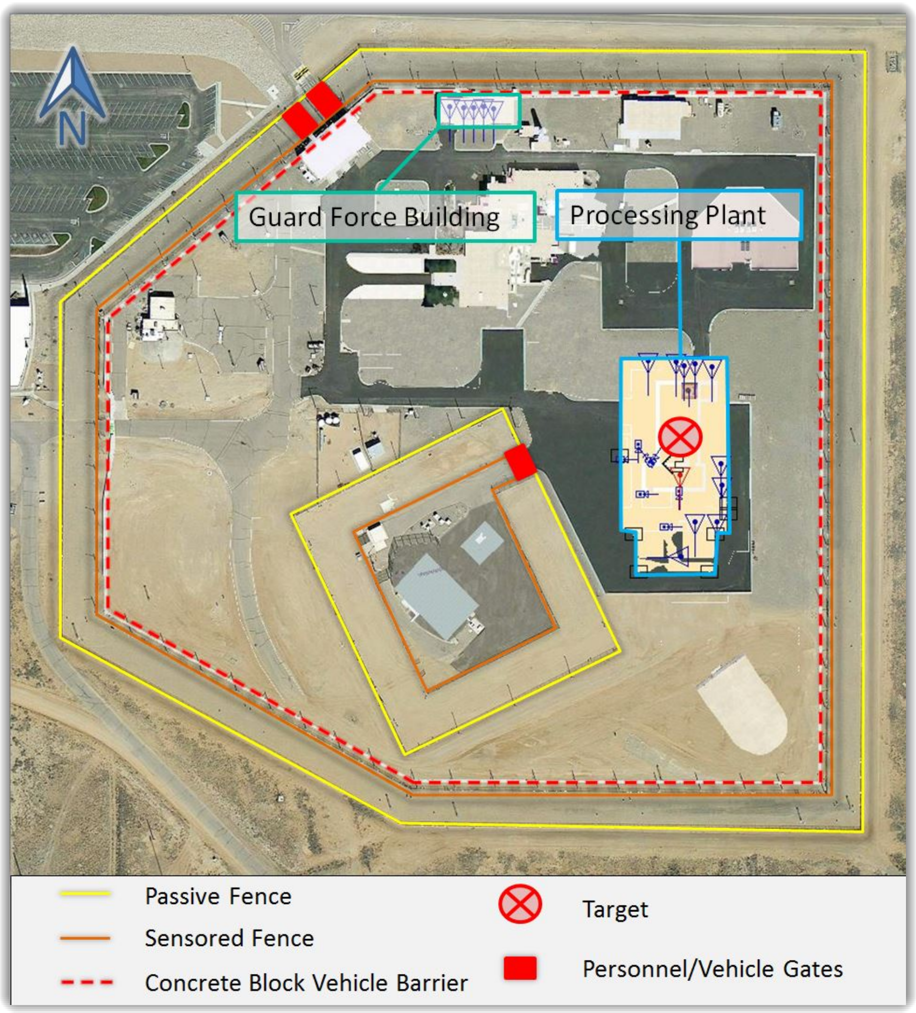

Figure 7: Example site layout in STAGE

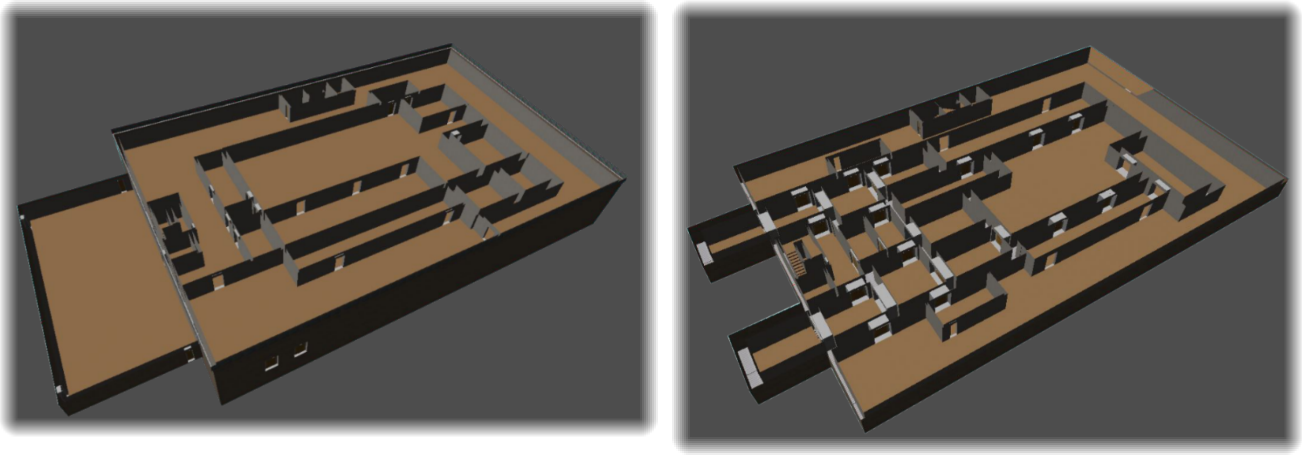

Figure 8: Example processing building models

A lot of detail is included in the models such as barrier information, physical protection elements (cameras, badge swipes, portal monitors, etc.), and guard forces. The models must be capable of analyzing both outsider and insider attack, so it is important to model the internal structures and operations well.

Since STAGE is based on commercial software, there have not been any updates to the models. In addition, STAGE is more useful when preliminary site layout and building designs are available, and this may not occur until slightly later in a design process. The following section examines the integration of STAGE with other capabilities.

4.2 Integration with Other Capabilities

Modeling in STAGE first requires construction of a 3D model using the Creator tool. Import of 3D CAD files is not supported because STAGE (and all other similar tools) needs to be able to program in the physical protection elements, like type of barrier or door. The easiest way to bring information in is to provide drawings of the site layout and floor plans. The drawings can directly be used to build the perimeter, and the analyst will add in the necessary doors, penetrations, and physical security elements as needed. Therefore, direct integration with a plant model is not possible, but also probably not needed since development of the models is a small effort.

In addition, physical security modeling requires a strong amount of experience and background in the physical protection field. All sensors and barriers and guard behaviors need to be programmed in with proper metrics like detection probabilities. Special databases are used. This work cannot be done by just anyone, so integration with a lot of other models will not be effective.

Physical security analyses should take into account safeguards or other plant monitoring data, but complete integration is not desired since compartmentalization is desired for safeguards and security. For example, a worker that routinely accesses materials accountancy systems should not have access to maintenance of physical security elements. Integration is most efficient and effective if only pertinent data is passed between systems, such as an alarm that may indicate that material has been lost or diverted.

It is possible that the scripting support in STAGE could be used to integrate both facility process models and safeguards models. However, this would require re-programming in C++, and would not (in most cases) provide the same capabilities that other models have. This is unlikely to provide any added benefit. Therefore, continuing to provide independent analyses with passing of pertinent data is the most efficient and practical approach to integration of models.

In future work, STAGE will be used to do a complete pyroprocessing facility physical protection analysis for the 2020 milestone. Drawings of plant layouts and data on overall building design will be most useful for building the STAGE model. The analysis can then look at both outsider and insider attack, including both theft and sabotage.

5. Integration in the 2020 Milestone

Figure 9 shows the concept behind the Virtual Facility Distributed Test Bed. The capabilities in the MPACT program can be divided into the four systems level models which can be informed by a number of higher fidelity capabilities. The system level models help tie all the work together, and the SSPM and STAGE models form two of the key systems level models.

The system level models can also inform each other. The flow of information in generally upward or to the right. For example, the flowsheet modeling is used to inform the 3D facility model, and that in turn is used to help build the STAGE model. The SSPM will also produce alarm data that is used to inform the STAGE modeling results. The key metrics generated by STAGE include the probability of success and timeliness information, and that is used along with consequence modeling to consider the overall physical protection design.

The SSPM is informed by the flowsheet model and a number of other higher fidelity capabilities. These may include more detail measurement models, unit operation models, and experimental data for specific measurement technologies. All this information is used to design a safeguards system and generate σ_{MUF}, probability of detection of material loss, and timeliness information.

The 2020 milestone will focus on demonstrating a complete safeguards and security design for a pyroprocessing facility. The milestone will focus on how all the capabilities work together to do Safeguards and Security by Design. The milestone will step through the process, beginning with the flowsheet model and work through plant layout, safeguards, and security models to generate a robust safeguards and security design.

Many of these capabilities also exist for aqueous reprocessing, which may be useful in the future. Future work is also likely to expand capabilities to other nuclear facilities such as fuel fabrication or molten salt reactors. A key goal is to provide capabilities that support the DOE NE mission and help to reduce the burden of safeguards and security to help promote growth in nuclear energy.

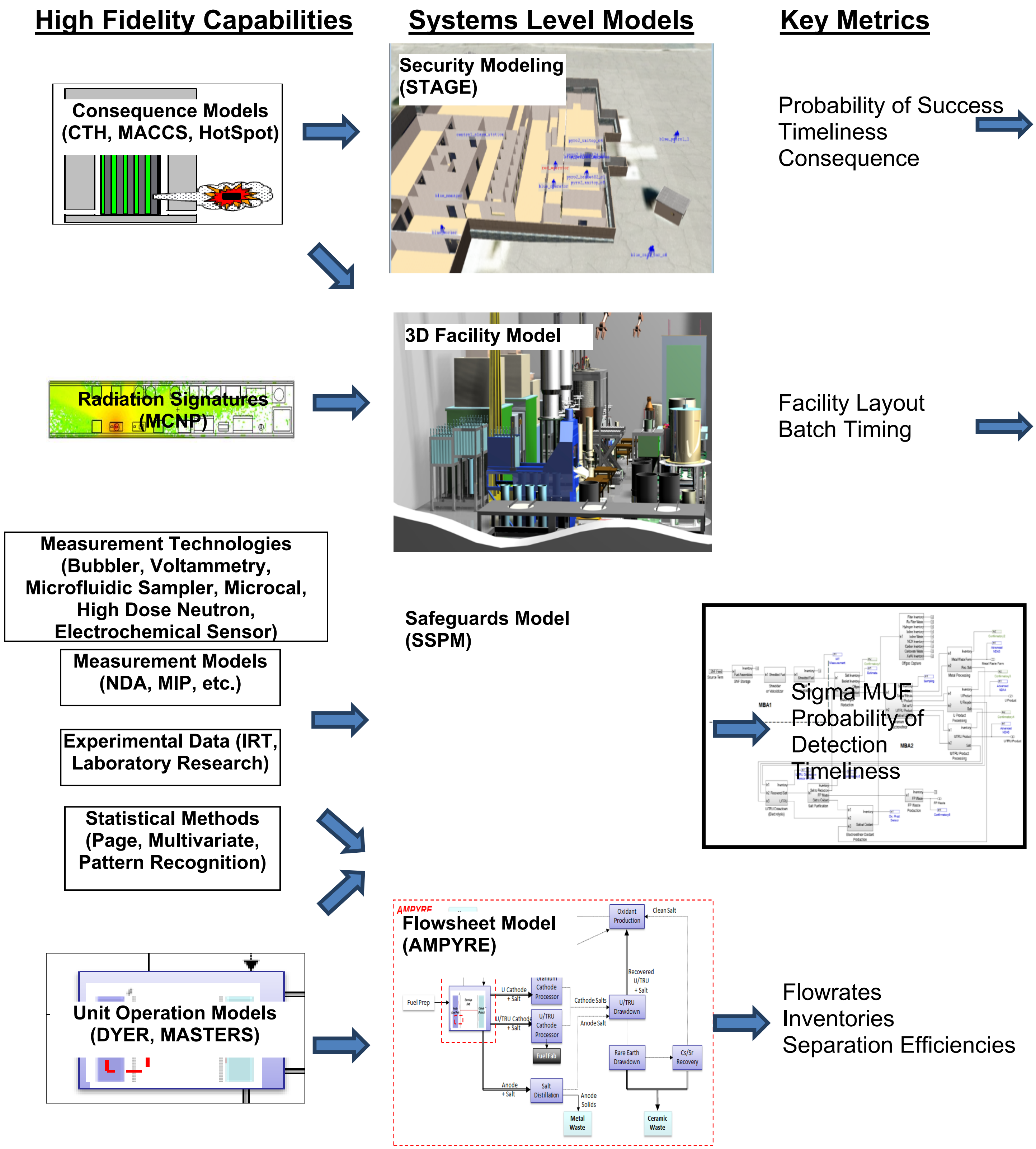

Figure 9: Virtual Facility Distributed Test Bed

6. Summary and Conclusion

Both the SSPM and STAGE models form two of the key systems level models that play a role in the Virtual Facility Distribute Test Bed 2020 Milestone. The goal of the work this year was to examine how the two models will integrate into the milestone and update the models as needed to help support integration.

The SSPM was updated in four key areas. The source term was updated in order to work with more uniform data types that will help with integration in the future. A GUI was added to the model to improve usability and make it easier to set up runs for various purposes. Output control was also added to simply how data in output for other researchers. Finally, isotopic tracking was added to the model to improve the ability to integrate with NDA measurement models. These capabilities should enable better integration within the MPACT program in the future.

The STAGE model was not updated, but rather examined for how best to integrate into the 2020 milestone. Directly integrating data from plant models is not possible, but 2-D drawings can easily be used to generate the STAGE models. The security analyses that STAGE is capable of are best performed by an independent security analyst that can rapidly develop the models and examine threat scenarios. Integration of data will be more limited for STAGE as compared to other capabilities in the Virtual Facility Distributed Test Bed.

Future work will focus on meeting the 2020 milestone for the next three years. A demonstration of complete safeguards and security design for a pyroprocessing facility will be demonstrated by stepping through the various capabilities. Other modeling capabilities should also be considered based on the needs of the DOE NE program.

REFERENCES

1. B.B. Cipiti et al., "Material Protection, Accounting, and Control Technologies (MPACT) Advanced Integration Roadmap," LA-UR-16-27364, Los Alamos National Laboratory (2016).
2. J. Sanders et al., "Implementation Plan," not yet published, Idaho National Laboratory (2017).
3. B.B. Cipiti, "Separations and Safeguards Performance Modeling for Advanced Reprocessing Facility Design," *Journal of Nuclear Materials Management,* 40(3), 6 (2012).
4. B.B. Cipiti et al., "Fully Integrated Safeguards and Security for Reprocessing Plan Monitoring," SAND2011-7292, Sandia National Laboratories (2011).
5. D. Dominguez, M.J. Parks, A.D. Williams, and S. Washburn, "Special Nuclear Material and Critical Infrastructure Modeling and Simulation of Physical Protection Systems," *Proceedings of the 46th International Carnahan Conference on Security Technology,* IEEE (October 2012).

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