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MODELING AND SIMULATION TO SUPPORT THE VIRTUAL FACILITY DISTRIBUTED TEST BED*

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ABSTRACT

The Materials Protection, Accounting, and Control Technologies (MPACT) campaign is developing a Virtual Facility Distributed Test Bed for safeguards and security design for future nuclear fuel cycle facilities. A major milestone is a lab-scale demonstration of an advanced safeguards and security system for electrochemical reprocessing in 2020. The goal of the Virtual Test Bed is to bring together experimental and modeling capabilities across the laboratory complex to provide a one-stop-shop for advanced safeguards and security by design. Experimental testing alone would be too cost prohibitive for safeguards and security design. Modeling and simulation play a key role in developing the Virtual Test Bed by tying together experimental testing, measurement technology development, and models in a way that is a more efficient use of research dollars. The systems-level models are informed by experimental testing and more detailed unit operation models, and they generate key safeguards and security metrics to support the system design choices. This paper provides an overview of the Virtual Test Bed concept and focuses on two of the systems-level models that are used for safeguards and security analyses.

INTRODUCTION

The MPACT campaign is one of several program areas in the Department of Energy, Nuclear Energy program. Part of the MPACT mission is to support domestic safeguards and security challenges for the larger Nuclear Energy program. Historically, the research funded has included the development of new materials accountancy or process monitoring measurement technologies, experimental testing, sabotage and consequence analysis, and system-level studies for safeguards and security design for nuclear fuel cycle facilities. The focus has been on the back end of the nuclear fuel cycle, but varies based on the needs of the program.

The Virtual Facility Distributed Test Bed 2020 milestone focuses on tying together all the MPACT capabilities to demonstrate complete Safeguards and Security by Design [1]. One of the motivations for this work is recognition that a safeguards or security demonstration facility is not

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practical and cost prohibitive. Many of the technologies are developed and tested at various facilities across the national laboratory complex. In addition, a number of systems-level modeling tools are used to develop safeguards and security designs for conceptual or planned fuel cycle facilities. The 2020 milestone ties together the experimental and modeling work. This paper will describe the Virtual Test Bed in more detail and will focus on two of the systems-level modeling capabilities and how they are integrated.

VIRTUAL FACILITY DISTRIBUTED TEST BED

MPACT is working toward a goal of developing and demonstrating the next generation of nuclear materials management for future fuel cycle facilities. This goal includes Safeguards and Security by Design, whereby safeguards and security aspects are considered early in the design process to help optimize facility costs. This goal also recognizes that future facilities will make better use of plant process data and see more integration between safeguards and security systems.

A key component of this goal is the development of the Virtual Facility Distributed Test Bed. Modeling and simulation is relied upon to develop systems-level facility models for design, plant layout, safeguards, and security analyses. A wealth of past work on measurement instrumentation design and 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 metrics of interest.

Figure 1 describes the Virtual Test Bed concept. Information flows generally to the right or up on this figure, but in some cases the information flow is both ways. Higher fidelity capabilities provide much of the needed safeguards and security data. This may include new measurement technologies used for materials accountancy or process monitoring, detailed unit operation models, radiation signatures, consequence modeling, and statistical packages. A significant amount of past work in the MPACT program is pulled on here.

This data is fed into four key systems-level modeling capabilities. The beginning of any safeguards and security design process is to develop a flowsheet model. That feeds into both a safeguards model and 3D facility model. The 3D facility model feeds into a security model. All of the systems-level modeling capabilities generate key metrics. The flowsheet modeling provides key plant parameters like flowrates, inventories, and separation efficiencies. The safeguards model generates overall measurement error (σ_{MUF}), probability of detection of material loss scenarios, and timeliness. The 3D facility modeling provides the facility layout and batch timing. Finally, the security model will examine adversary attack scenarios and determine probability of adversary success, timeliness, and consequence.

The Virtual Test Bed does not pull all modeling capabilities into one over-arching framework—it is recognized that these analyses are best done individually by the subject matter experts in those areas. Rather, the milestone is a framework for linking the various capabilities and formalizing the data inputs and data flow between models, test beds, and experimental data.

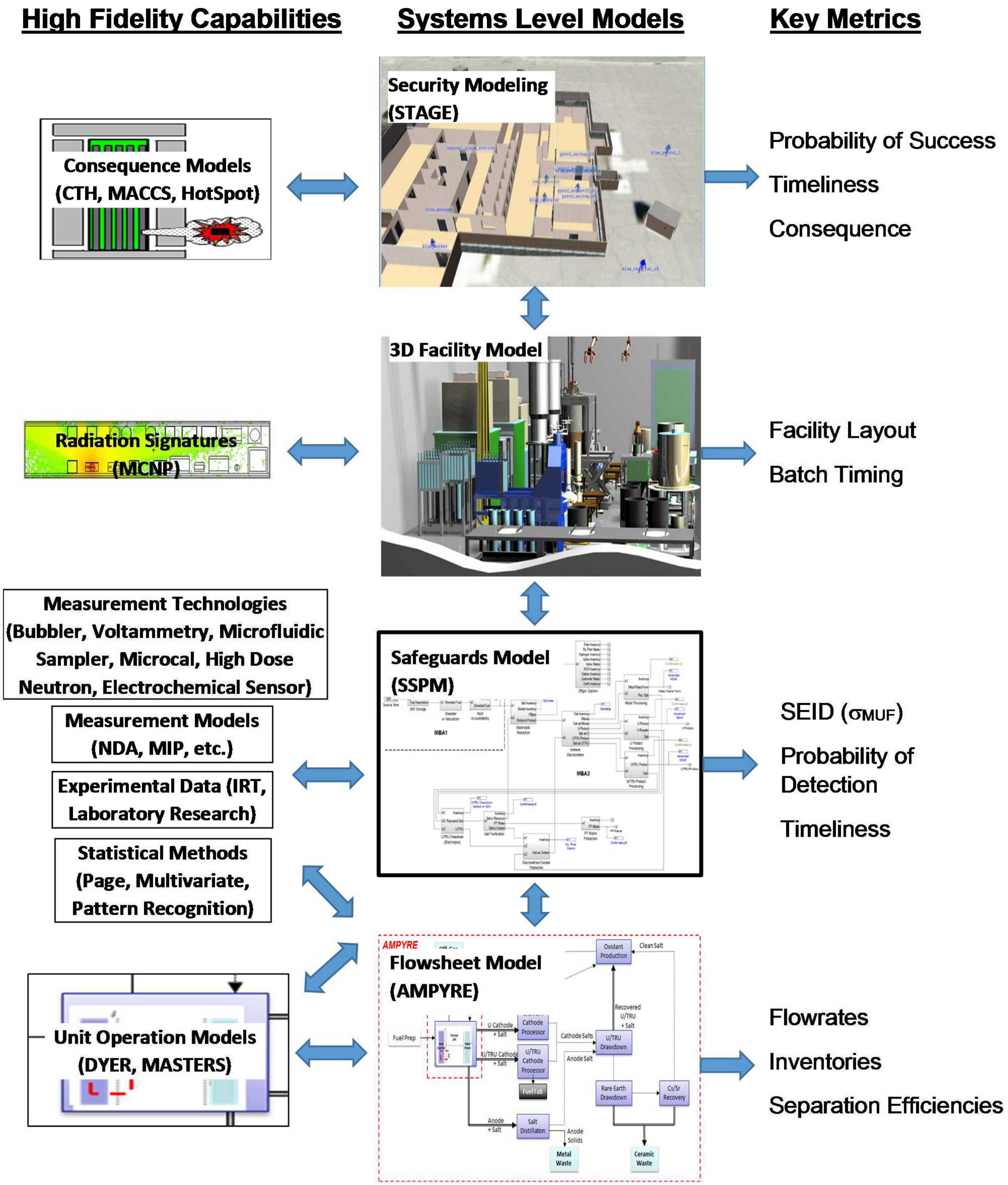


Figure 1. Virtual Facility Distributed Test Bed.

The following sections describe two of the systems-level modeling capabilities in more detail: the safeguards and security models. The models will be described with attention to how they are integrated into the Virtual Test Bed and how safeguards and security can be integrated more in the future.

SEPARATION AND SAFEGUARDS PERFORMANCE MODEL (SSPM)

The Separation and Safeguards Performance Model (SSPM) has been used for the safeguards performance aspects in the Virtual Test Bed [2,3]. Multiple versions of the SSPM exist, including PUREX, UREX+, and Electrochemical reprocessing plant models; fuel fabrication; enrichment; and molten salt reactor models. For the purpose of the 2020 milestone, only the Electrochemical reprocessing model will be described here. These models use Matlab Simulink to track elemental and isotopic material flows through various unit operations in a fuel cycle facility. Measurement blocks are used to simulate materials accountancy and process monitoring data, and these data are fed into an inventory difference calculation. Statistical tests are included for detecting material loss, which can be determined by setting up diversion scenarios to test the effectiveness of a safeguards design.

An SSPM Electrochemical version is shown in Figure 2. The gray blocks represent the processing vessels throughout the plant and contain significant detail about inventories, timing of operations, filling/emptying sequences, etc. The signals connecting the blocks contain the mass flow information of all nuclear material and bulk salt flows. The models need to be self-consistent and as realistic as possible. The blue and green blocks represent measurement points and feed into an overall material balance calculation. All models contain the ability to turn on material diversions from various locations to examine the effect on overall plant safeguards. Capabilities include:

- Spent fuel source term library for user-defined runs
- Mass tracking of elements 1-99, full isotopic tracking, bulk solids/liquids tracking
- Integration with GADRAS (Gamma Detector Response and Analysis Software) [4] to simulate gamma spectra
- Customizable measurement points with user-defined error
- Automated calculation of Material Unaccounted For (MUF) and error in real time
- Statistical tests to set alarm conditions
- Diversion scenario analyses
- Integration with process monitoring data and physical protection systems

The SSPM provides a virtual platform for various applications. Safeguards analyses require a systems-level approach, and only the uncertainty of the measurements is required to determine overall performance. The models have been used for determining the improvement of new instrumentation, examining the integration of new approaches such as more reliance on process monitoring, performing diversion scenario analyses, providing virtual plant data, and providing a platform for training and education.

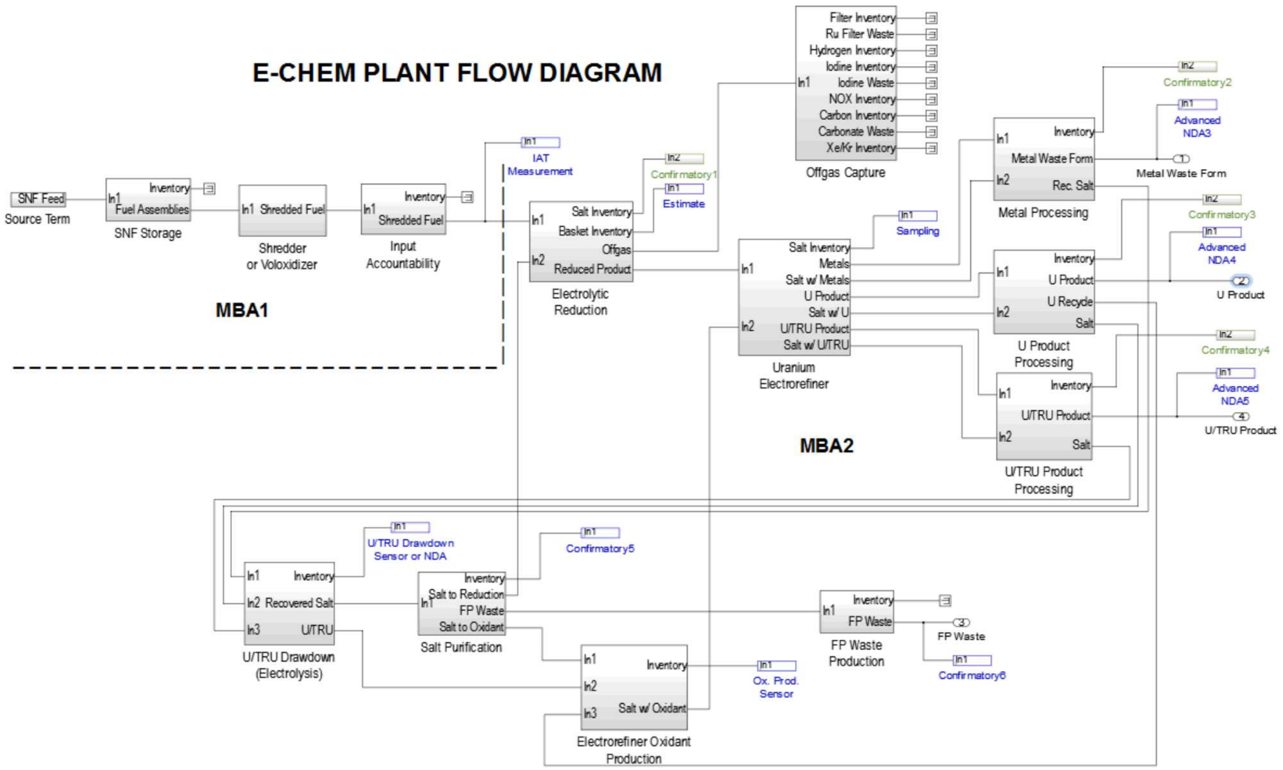


Figure 2. Electrochemical SSPM.

The models are only as good as the data used to build the models. For example, experimental data is used to determine what fraction of species go into certain areas of the plant, like the oxide reduction salt or electrorefiner salt. Small differences can have a significant impact on measurements over time, so it is important to model these separations correctly. The models are informed by flowsheet modeling, which has been in the domain of other national laboratories. The measurements are informed by experimental testing at various laboratories.

The SSPM calculates an overall inventory difference, or Material Unaccounted For (MUF) for the various material balance areas. Of particular attention is the measurement uncertainty for the various technologies. These uncertainties are propagated in the SSPM to determine an overall measurement uncertainty, or σ_{MUF}. The statistical tests in the model use the overall error and the MUF sequences to perform statistical analyses. One of the key safeguards metrics is the detection probability for the loss of significant quantities of nuclear material through various diversion scenarios.

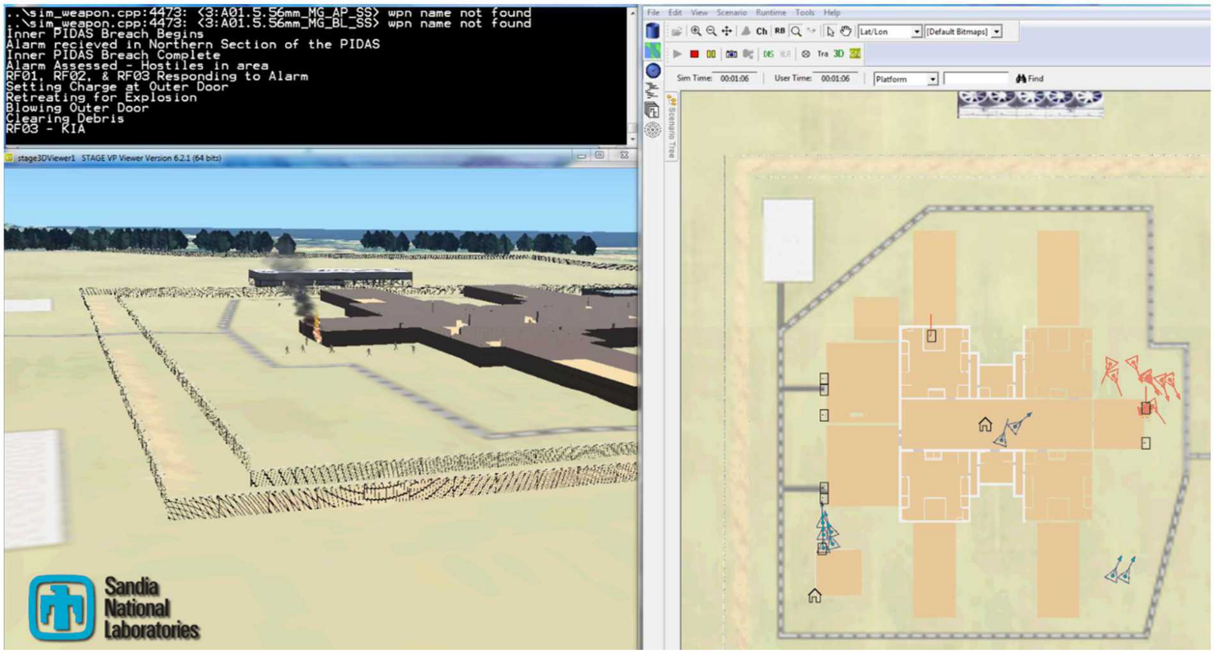
In order the meet the 2020 milestone, the SSPM is being updated with the latest flowsheet and experimental data to both develop a preliminary safeguards system design and calculate safeguards metrics under diversion scenario analysis. These results will feed into the security analysis.

SCENARIO TOOLKIT AND GENERATION ENVIRONMENT (STAGE)

STAGE is commercial software from Presagis that is used for force-on-force simulation of an adversary attack [5]. It has been used for the physical protection modeling because of its versatility in examining both outsider and insider attack, and due to the ability to provide a model and analysis with a limited number of analysts (as opposed to table top exercises). STAGE provides an open-ended 3D platform for modeling all aspects of the physical security design including sensors, operators, and guard forces. It provides the following capabilities:

- Logic based behavior model: Human decision making is modeled based on an "if/then" logic model which takes into account events unfolding in the scenario and is partially controlled by probability analysis.
- Ground navigation: Entities dynamically plan paths both inside and outside the facility. Sensing abilities possessed by the human entities enable visual detection of other humans and objects.
- Event-based entity missions: Help define the primary and secondary responsibilities and strategies of the entities within the scenarios.
- Scripting support/Federation: Provides the ability to integrate materials accountancy or process monitoring data from other codes such as the SSPM.
- 2D/3D environment: Provides visual representation of the scenarios.

Figure 3 shows an example of a STAGE model during an example outsider attack. The window in the upper left is a text print out of the current event. The 3D view of the facility is shown in the lower left, and an overhead view of the facility is shown on the right. The red triangles represent the adversary forces, and the blue represent the responders. Multiple iterations of STAGE are typically run to develop statistics for a particular scenario since the probabilities lead to slightly different results on every run.



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..\sim_weapon.cpp:4473: <3:A01.5.56mm_MG_AP_SS> wpn name not found
..\sim_weapon.cpp:4473: <3:A01.5.56mm_MG_BL_SS> wpn name not found
Inner PIDAS Breach Begins
Alarm recieved in Northern Section of the PIDAS
Inner PIDAS Breach Complete
Alarm Assessed - Hostiles in area
RF01, RF02, & RF03 Responding to Alarm
Setting Charge at Outer Door
Retreating for Explosion
Blowing Outer Door
Clearing Debris
RF03 - KIA
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Sim Time: 00:01:06
User Time: 00:01:06

Figure 3. STAGE Model.

For the Virtual Test Bed, a generic electrochemical reprocessing facility design will be modeled in STAGE. From there, a preliminary physical protection system will be developed and added to the model. Various outsider and insider sabotage and theft scenarios will be modeled to examine the response of the physical protection system. From there, the process is iterative to make changes as needed or suggest facility design changes.

INTEGRATION OF MODELING CAPABILITIES

The SSPM and STAGE models calculate the key safeguards and security metrics that are used to prove safeguards and security designs. These metrics must meet regulatory requirements or be shown to meet the spirit of the regulations in some other way. For example, safeguards requirements usually require a material balance and statistical analysis to detect the loss of some significant quantity of nuclear material with a 95% detection probability. Security analyses need to show the ability of the responders to successfully thwart a variety of adversary attacks with a high probability.

These calculations need to ultimately tie back to the extensive experimental work that is used in the models. Therefore, part of the goal of the model development is transparency so that all assumptions used in the models either tie back to an experimental result or reference.

Another key theme of the modeling work is to examine Safeguards and Security by Design, or the consideration of safeguards and security requirements early in the design process. The experience of the past has shown that adding safeguards or security after the fact leads to expensive re-design or retrofits. Costs can be optimized when the requirements are considered up front. The entire plant design process should be iterative, and these modeling tools allow for that to happen.

The interface between safeguards and security is also considered. Traditionally, safeguards and security systems have been separate, in part due to the need for compartmentalization and to reduce the possibility of insider sabotage or attack. However, safeguards information could be better utilized by the physical protection system to increase the timeliness of detection, and thus increase the probability of responder success against adversary attack. Past work has shown examples of how this is possible [6].

CONCLUSION

The Virtual Facility Distributed Test Bed ties together systems-level modeling, new measurement technologies, and experimental testing into a complete ability to demonstrate next generation Safeguards and Security by Design. The Virtual Test Bed concept will be demonstrated as part of an MPACT 2020 milestone focusing on electrochemical processing facilities. However, the concept of tying together the various capabilities holds for other facility types. Extensive work has been done in the past on aqueous processing, and various other capabilities exist for other fuel cycle facilities. The SSPM and STAGE models form part of the backbone of the Virtual Test Bed and provide versatility for safeguards and security analysis. Particular attention is focused on integration and cost optimization for future facilities so that safeguards and security requirements do not overly burden a facility.

ACKNOWLEDGEMENTS

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