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# THE ROLE OF MODELING AND SIMULATION IN THE MPACT 2020 MILESTONE*

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## ABSTRACT

The Materials Protection, Accounting, and Control Technologies (MPACT) campaign has a significant milestone due at the end of 2020. The milestone will demonstrate advanced safeguards and security by design for a generic electrochemical reprocessing facility using the Virtual Facility Distributed Test Bed concept. The test bed ties together experimental and modeling capabilities across the laboratory complex to provide a one-stop-shop for advanced safeguards and security by design. Electrochemical facilities were chosen as the demonstration since commercial-scale plants do not exist yet, since there are a number of safeguards challenges, and due to alignment with other DOE programs. System-level models are used to determine the safeguards and security metrics to prove the effectiveness of the designs. The Separation and Safeguards Performance Model (SSPM) is used to determine the key safeguards metrics, and the PathTrace© and Scribe3D© software are used for the security analysis. Experimental data informs the key assumptions in the models and is based on wide variety of current and past research in the MPACT program. The baseline safeguards and security design will be presented along with the design approach. This work represents the contributions of Sandia National Laboratories (SNL) to the 2020 milestone—more complete material will be presented in a special issue of the Journal of Nuclear Materials Management in FY21.

## INTRODUCTION

The MPACT campaign within the Department of Energy, Nuclear Energy program supports domestic safeguards and security challenges for the nuclear fuel cycle. The campaign is working toward a 2020 milestone to demonstrate a Virtual Facility Distributed Test Bed, which will demonstrate the application of Safeguards and Security by Design (SSBD) on a generic electrochemical processing facility [1]. A key goal of SSBD is to consider safeguards and security aspects early in the design process to help optimize facility costs. The Virtual Test Bed ties together experimental work related to safeguards and security, new measurement technology development, and modeling capabilities which are spread across the DOE laboratory and university complex.

The Virtual Facility Distributed Test Bed concept is shown in Figure 1. The "Virtual Facility" aspect means that modeling and simulation is used to develop process, safeguards, and security models to test approaches and generate results. Virtual facility models are informed by laboratory test bed results, development of measurement technologies, and testing of those technologies. The "Distributed Test Bed" aspect encompasses these capabilities from across the laboratories. Figure 1 shows how the various capabilities work together.

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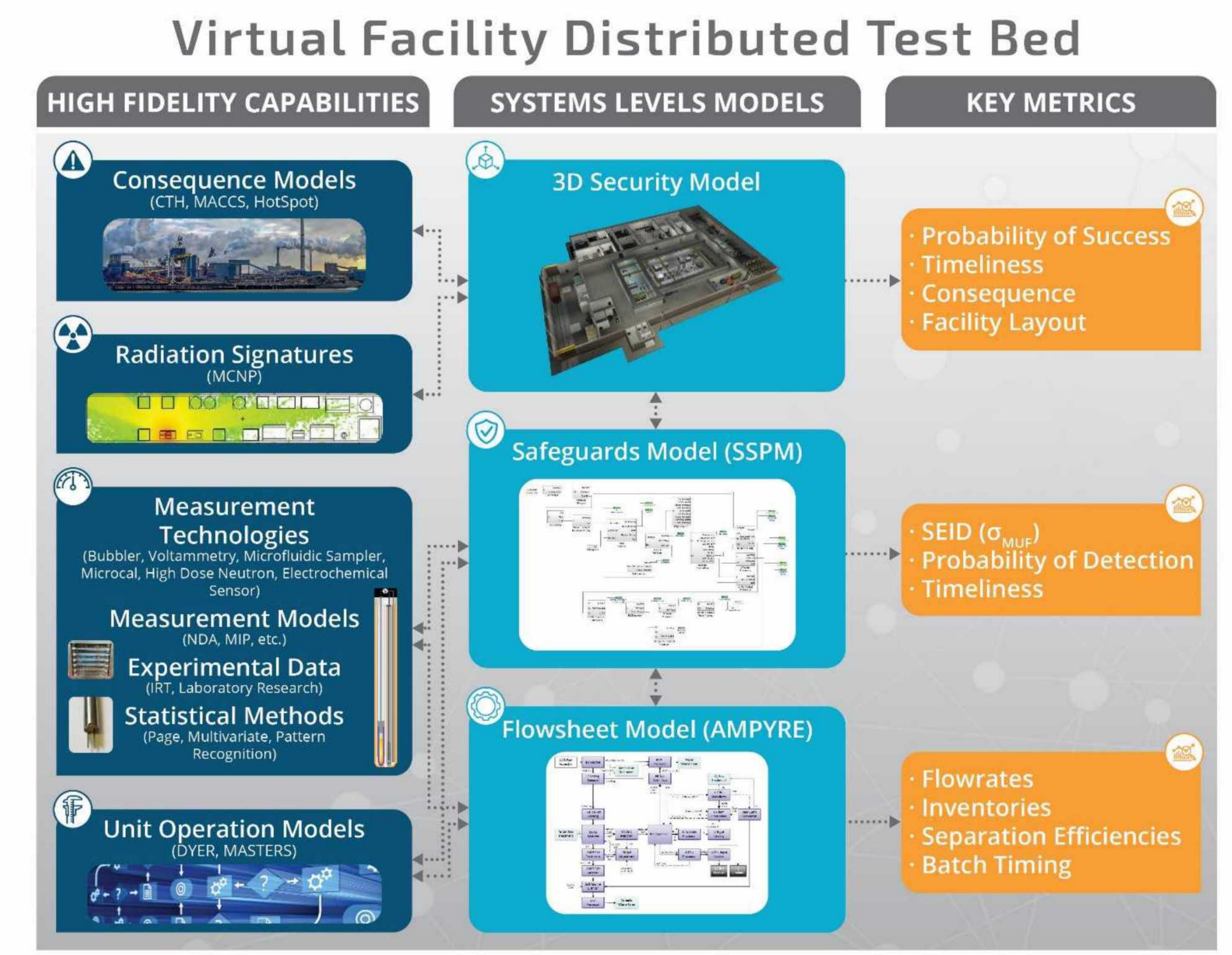

Figure 1. Virtual Facility Distributed Test Bed.

Three systems level modeling capabilities (shown in the center column) are used to calculate key design and performance metrics (shown on the right). Flowsheet modeling is used to set the plant design by establishing flowrates, inventories, and timing of operations among other key parameters. This information is used by safeguards models to set up an appropriate materials control and accountancy design and then calculate safeguards metrics like overall measurement error and detection probability for material loss scenarios. The plant data is also used to setup a layout for physical security modeling, which can analyze the security system design and response to threats. The modeling process is iterative to feedback useful constraints to the facility designers.

The high fidelity capabilities (shown in the left column) include all the detailed experimental work, development of measurement technologies, testing of measurements on surrogates or real materials, and more detailed measurement models or statistical tests. These capabilities and results are pulled into the modeling. For example, testing of sampling and destructive analysis of electrorefiner salt samples and their associated measurement uncertainties will inform the assumption for measurement uncertainty in the safeguards model.

A generic electrochemical reprocessing facility was chosen to demonstrate the concept for a few reasons. First, the MPACT program has supported a significant amount of work on electrochemical safeguards and security work over the past several years. Large scale electrochemical facilities do not yet exist, so it is a good time to apply SSBD while any future designs are still in the conceptual design phase. Lastly, there are a number of identified challenges that need to be resolved, particularly from the materials accountancy perspective.

The following sections delve into more detail on the safeguards and security models that are being used for this work. The safeguards and security design is briefly presented, but detailed results from the analysis will be presented when the milestone is complete at the end of 2020.

## SEPARATION AND SAFEGUARDS PERFORMANCE MODEL (SSPM)

An Electrochemical (Echem) version of the Separation and Safeguards Performance Model (SSPM) has been used for the safeguards analysis and to calculate the key safeguards performance metrics for the 2020 Milestone [2]. The safeguards model is based in MATLAB Simulink and uses the most current flowsheet. Elemental and isotopic material flows are tracked through the various unit operations, and significant detail is included in the timing of operations and correct modeling of vessel inventories as a function of time. 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.

The Echem SSPM model is shown in Figure 2 in the next section. The model is divided into Material Balance Areas (MBAs). MBA 1 includes all head-end operations including fuel assembly receiving, disassembly, decladding, and fuel loading into baskets. All of these operations can occur in an air hot-cell, so the hot cell makes a physical boundary for the MBA. From a safeguards perspective, less research and development focus has been placed on MBA 1 since the front end operations are not much different than traditional aqueous reprocessing plants. Item accountancy, containment, and surveillance are typically utilized for the head-end before precision measurements of the fuel are possible.

Input accountancy is established once the fuel is loaded into the baskets, so this is the first opportunity to take some type of precision measurement of the fuel. MBA 2 starts with the transfer of these fuel baskets into an argon hot cell and includes the bulk of the electrochemical separation processes. MBA 2 ends with the production of the U and U/TRU products as well as the metal and fission product wastes. MBA 2 was the focus of much of the research and development in the MPACT campaign since precision measurements of material are needed in this area.

MBA 3 includes storage of the U product, metal waste, and fission product waste. This is an item accounting area. Due to the lower attractiveness of these materials, storage likely does not need to be contained with as robust physical protection measures. MBA 4 on the other hand, includes the U/TRU storage, which does need to be protected at a high level. A vault-type storage room would be used to meet physical protection requirements.

The current model assumes that the electrochemical facility stops at the production of the U and U/TRU ingots. Some designs could consider co-locating fuel fabrication, but those processes are not included in this generic facility.

The SSPM provides a virtual platform for various applications. Safeguards analyses require a systems-level approach. The uncertainty of measurements used for accountancy along with realistic modeling of flows and inventories is required to determine overall performance. The model has been used for determining the impact of particular measurements, performing diversion scenario analyses, providing virtual plant data, and examining new or novel safeguards approaches.

## SAFEGUARDS APPROACH

The safeguards approach focuses on materials accountancy measurements which are needed to satisfy regulatory requirements. Safeguards aspects such as containment and surveillance, book-keeping procedures, and reporting requirements are not described here because these areas generally are well-established at other facilities and do not require research. Key measurement points have been identified and include measurements of material flows across MBA boundaries and measurement of inventory within the MBA. Figure 2 shows the key measurement points for the generic electrochemical facility design, along with some of the more likely measurement technologies.

The input into MBA 1 are the spent fuel assemblies, and shipper identification is used to estimate quantities of nuclear material. One of the outputs from MBA 1 is the hulls and hardware, which can be characterized with NDA measurements (gamma, neutron, or both). The other is the fuel contained within baskets. Input accountancy of the fuel is assumed through either sampling and destructive analysis or measurement using microcalorimetry [3]. The key challenge here is getting a representative sample since spent fuel varies based on axial position in the assembly. Containment and surveillance would likely be utilized to ensure the inventory of MBA 1.

The two outputs from MBA 1 are also the inputs to MBA 2. One of the values of process modeling is that the material balance period can be chosen at a time when the inventories are minimized in the MBA. In this case, an optimal time to strike a material balance can be found such that all of the unit operations are empty except for the electrorefiner (ER) salt. Precision measurements of the ER salt will be required, but all other areas just need confirmatory measurements to show that they are empty or only contain very small holdup quantities. The measurement technologies being examined for the ER salt include the Bubbler for total salt mass [4], microfluidic sampling [5] for uniform salt samples, destructive analysis, microcalorimetry, and voltammetry [6]. Voltammetry is also being to confirm that no actinides should be present in the OR salt [7].

For the outputs of MBA 2, the two waste forms will likely use NDA measurements (gamma, neutron, or both) for characterization. The High Dose Neutron Detector (HDND) [8] is being examined. The U and U/TRU product may also use the HDND, but sampling and destructive analysis is the fallback. A thermocouple measurement technique [9] is also being considered for the U/TRU measurement, but that may be a less precise process monitoring measurement.

A significant difference with an electrochemical facility as compared to an aqueous facility is that a plant flushout is likely unfeasible. Electrochemical facilities are designed to maintain a certain actinide content in the ER salt for steady-state operation. Flushing out (or drawing down) may not be practical from an operator's standpoint. This means that the plant would need to rely on the ER salt inventory measurement at a yearly or 6-month plant balance. More frequent balances (monthly) may be needed depending on regulatory requirements and plant throughput.

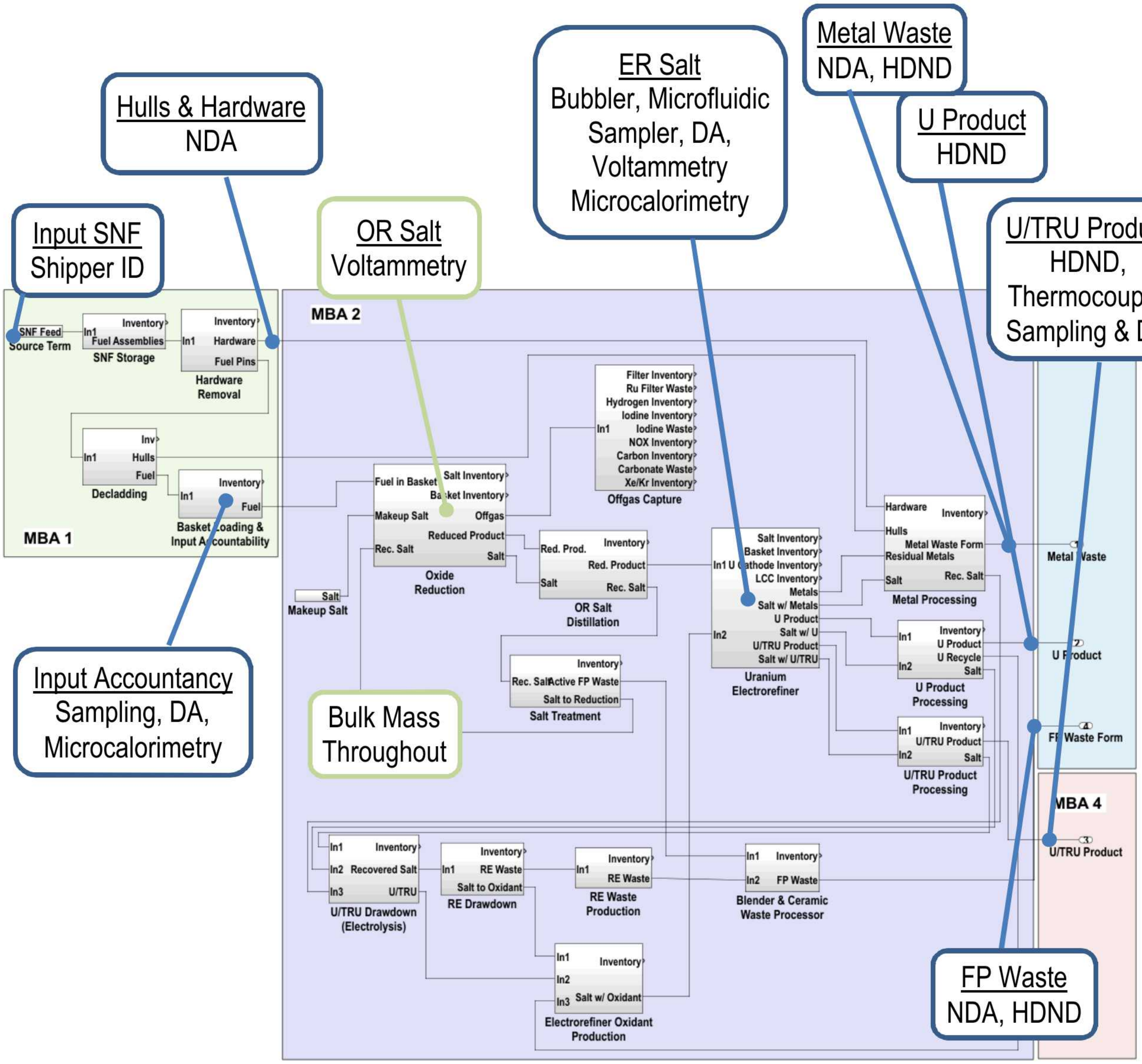

Figure 2. Key Measurement Points for the Safeguards Approach.

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 $\sigma_{MUF}$. 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. The timeliness of the detection is also an important parameter that can be passed to the physical protection system to help augment detection of material loss or abnormal plant operations.

The analysis results are not presented here since the modeling assumptions are not finalized yet. Future work will use the latest measurement uncertainty data from the experimental work in the program to determine the safeguards system effectiveness. This baseline materials accountancy approach will be used for the analysis.

## PHYSICAL PROTECTION SYSTEM DESIGN

The physical protection system (PPS) design approach for the facility was based around the DOE standard Design and Evaluation Process Outline (DEPO) [10]. The process is summarized in Figure 3. Key Steps in the process include:

1. Define system requirements by characterizing the facility, its mission, target materials and operations, and defining and identifying the threat.
2. Design the system based on the concepts of detection, delay and response.
3. Evaluating the system to identify vulnerabilities, propose upgrades, and validate performance.

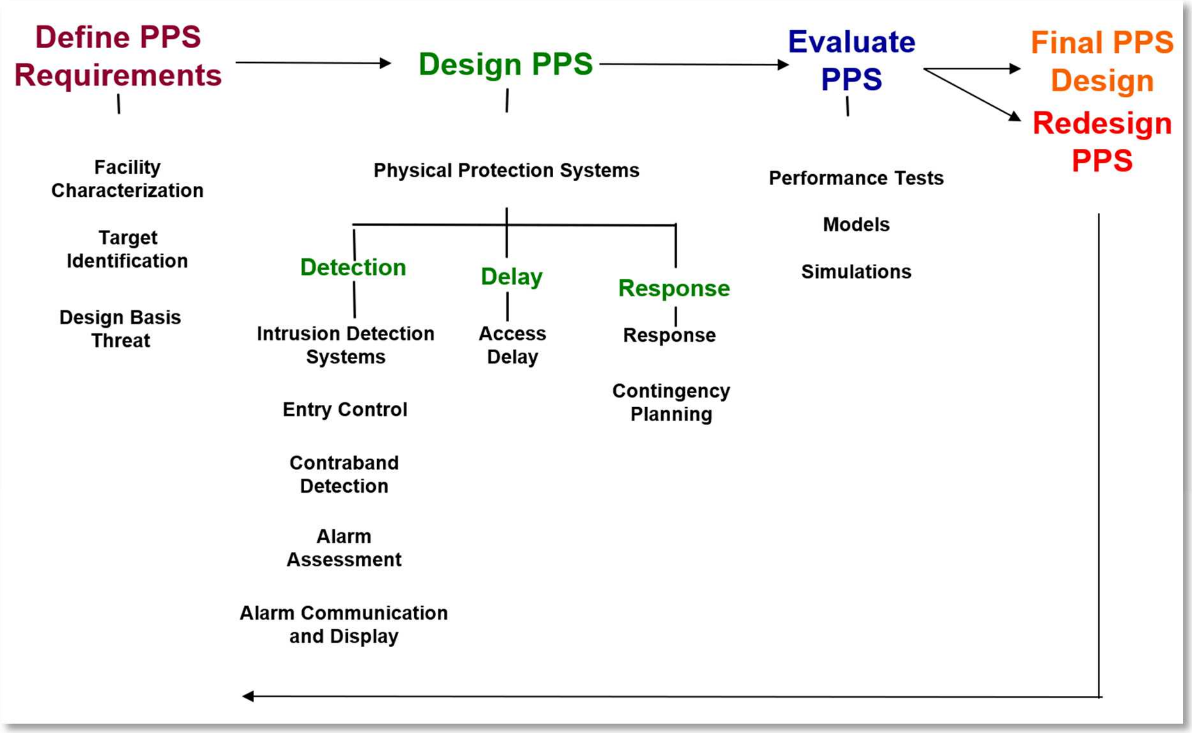

Figure 3. The Design Evaluation Process Outline

This design process has been used by DOE for decades and features the following core design principles:

1. Defense-in-depth – achieved by ensuring the adversary must defeat multiple, diverse barriers on its way to the target.
2. Balanced protection – ensuring that all paths into the facility have the same level of security.

3. High reliability – ensuring that delay and detection elements are complimentary (diverse defeat methods), redundant, and well maintained.

The design of the PPS is based around achieving maximum delay times for theft scenarios due to the underground configuration of the storage vaults. Multiple layers of detection and assessment along the path to the vault ensure that adversaries are detected and positively identified. The goal of this design is to reduce security costs by eliminating costly features such as a Perimeter Intrusion Detection and Assessment System (PIDAS). This system allows onsite guard forces to be minimally staffed, while still maintaining high levels of security performance. The baseline design of the ground floor is captured in Figure 4. From the site layout, one can observe multiple layers of delay and detection along the adversary path to the basement floor. The physical constraints of the basement vault provide a complex breach task and long delay times simply based on underground siting and radiological protection of onsite staff. The two hot cells in the center of this figure would be contained in MBA 1 and 2 as described previously. MBA 3 is not shown but would likely be a separate building. MBA 4, which contains the U/TRU storage vault, is in the basement of this building, below the hot cells.

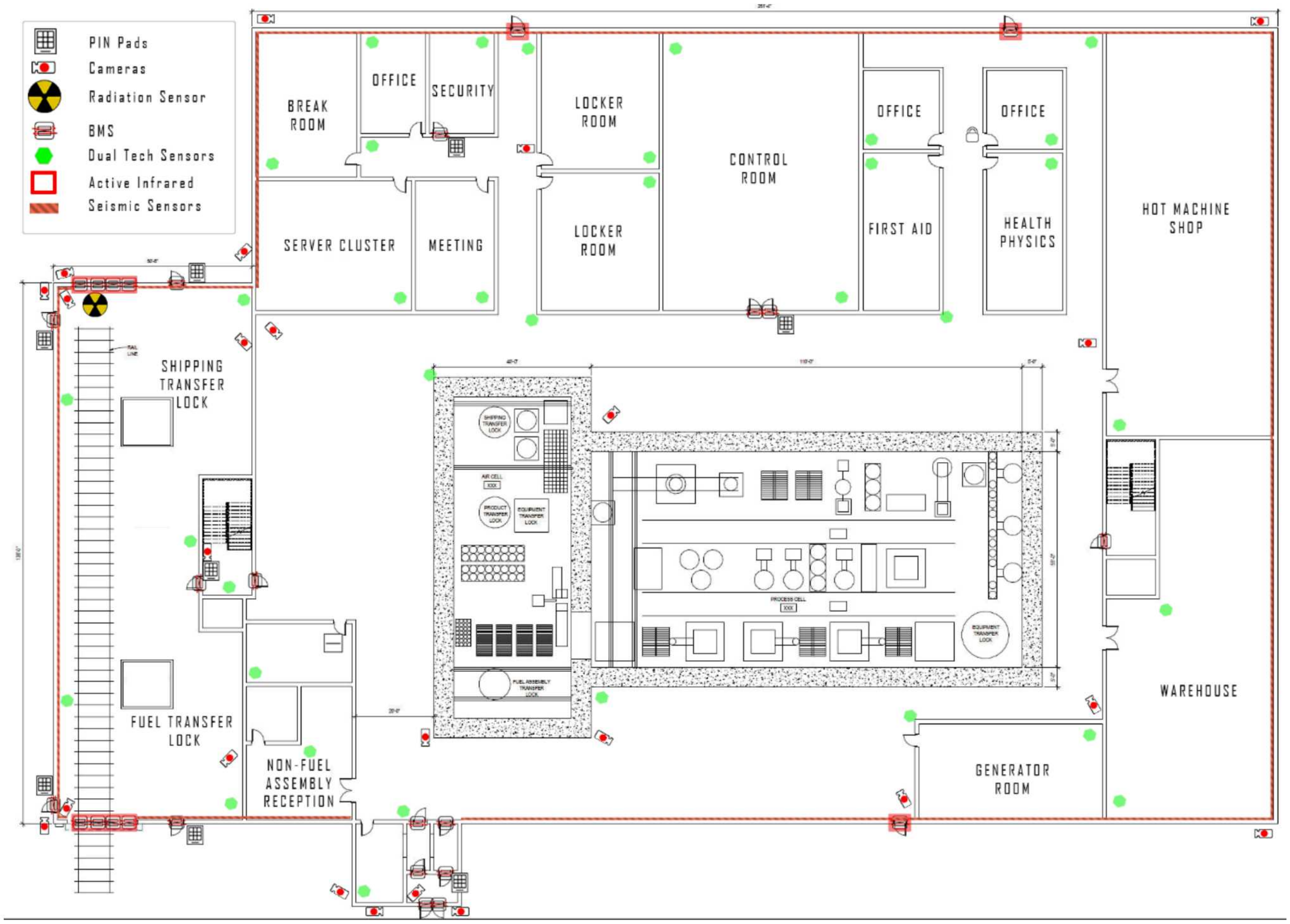

Figure 4. Baseline - Facility PPS for Ground Floor

## PHYSICAL PROTECTION SYSTEM MODELING

In order to understand the performance characteristics (detection, delay, and response) of the physical protection system, detailed modeling is being conducted using SNL-developed modeling and simulation tools. The modeling process is conducted as follows:

1. After the PPS design is complete, PPS elements are characterized and given delay times and probabilities of detection, based on established unclassified elements datasets.
2. Adversary timelines are constructed for both theft and sabotage scenarios and all physical protection elements in the system are identified.
3. Detection and delay values for each protection layer and path element in the Adversary Sequence Diagram are incorporated.
4. The most vulnerable paths (MVPs) are identified using PathTrace by analyzing the effectiveness of detection and delay along each possible path.
5. Scenarios of concern are developed, response timeliness and effectiveness are evaluated using Scribe3D, and system effectiveness is determined.
6. After gleaning PPS performance data, vulnerabilities are identified, and upgrade packages are developed for both theft and sabotage scenarios

After completing the system effectiveness analysis, the vulnerability analysis team examines the paths and scenarios that have lower-than-desired system effectiveness (i.e., high vulnerability). The goal is to identify the system's greatest vulnerabilities to theft and sabotage so that design changes can be proposed to mitigate vulnerabilities and reduce security risk. Modeling and simulation tools allow the analyst to test "what-if" scenarios and consider "next generation" PPS technologies in a controlled setting.

## MODELING AND SIMULATION TOOLS

PathTrace is a tool that allows a user to explore and analyze entry paths in two dimensions. The tool uses widely accepted path analysis drawn from tools like ATLAS and MPVEASI [11]. PathTrace was developed by Sandia National laboratories in the Unity Engine [12] and is available both domestically and abroad. Given an aerial photo or detailed drawings of the facility, the user draws barriers such as walls, fences, windows, doors, and any user created material on top of the image of the facility. The amount of time it would take to breach these barriers is specified as well as the probability that an adversary would be detected in doing so. The tool allows for the drawing of detection areas, which is a distinction between areas of a facility where an adversary may walk slower or be detected more easily due to the nature of existing in that area (sensors, patrols, etc.). Finally, the user may specify the kinds of tools the adversary may be carrying, and its effects on the time to defeat a barrier, as well as their probability of detection. Once the user has mapped out the entire facility, they can then analyze the entry paths into the facility with a variety of methods, given the PPS Response Force Time (RFT) and an adversarial strategy. The user will receive data visually or textually representing the adversarial task time, the total probability of detection, the critical detection point, the time after the critical detection point, the probability of interruption, the probability of detection, delay, and defeat time of every barrier, and detection areas that the adversary has encountered. The final data allows the user to fully explore their facility and any potential vulnerabilities in a simple fashion. Figure 5 shows screenshots from PathTrace for a U/TRU theft of material located in the U/TRU storage vault in the basement.

Figure 5. PathTrace Images of the Echem Security Model

The image on the upper left depicts the ground floor path through the pedestrian door of the highbay and into the stairwell. On the upper right, the basement path from the stairwell into the U/TRU vault is shown. Figure 6 (below) shows the path for a hotcell sabotage scenario, through the emergency exit and directly to the hotcell wall.

Adversary Path Sequence

| | Crossed | PD | Delay | At Time | Tool Used | Dist (m) |
|---|---|---|---|---|---|---|
| 🟩 | Fence No Det | 0.02 | 20.00 | 0.00 | None | 0.48 |
| 🟪 | Random Patrol | 0.02 | 0.97 | 20.00 | None | 0.97 |
| 🟪 | Engage Patrol | 0.10 | 10.00 | 20.97 | None | 0.48 |
| 🟪 | Random Patrol | 0.02 | 34.81 | 30.97 | None | 34.81 |
| 🟥 | Reinforced Door Bms | 0.80 | 30.00 | 65.78 | None | 0.48 |
| 🟪 | Random Patrol | 0.02 | 9.19 | 95.78 | None | 9.19 |
| 🟦 | ArgonCellOuterWall | 0.90 | 122.00 | 104.96 | None | 0.48 |
| 🟩 | ArgonBulk | 0.90 | 124.00 | 226.96 | None | 0.48 |

| Total PD | Total PI | Delay After CDP | Total Delay | Dist (m) |
|---|---|---|---|---|
| 1.00 | 1.00 | 90.00 | 350.96 | 47.86 |

| Response Time | Cumulative PD |
|---|---|
| 30 | 1.00 |
| 600 | 0.00 |

Response Time (s): 90
Run Speed: 1 m/s
Strategy: Denial
Count Dt. Area: Once Cellwise
Clear Path: Clear

Figure 6. PathTrace Images of the Echem Security Model

Scribe3D [13] is a 3D tabletop recording and scenario visualization software, created by Sandia National Laboratories. It was developed using the Unity [12] game engine for use by other National Laboratories, government organizations, and international partners. Unity is a commercial game engine built for developers and non-developers to create a wide variety of games and applications. It features a fully customizable framework and set of development tools. Unity was used to build Scribe3D and many other training and analysis tools within the DOE complex.

Scribe3D is used to create, record, and play back scenarios developed during tabletop exercises or as a planning tool for performance testing, force-on-force, or other security analysis related applications. The tools offered by Scribe3D can help open discussions, capture results, visualize consequences, collect data, record events, and help make decisions while users develop scenarios. Data can be viewed in 2D or 3D and be played back in real-time or at various speeds. Transcript reports are automatically generated from the recorded data. The automated functions of Scribe3D allow for recorded scenarios to be run in a monte carlo fashion to collect large quantities of data for analysis purposes, after initial scenarios are defined in the traditional tabletop exercise. Figure 7 shows screenshots from Scribe3D as the adversary team approaches the facility. Figure 8 shows the site layout of the ground floor (top left), the responders preparing to move to response positions (top right), and the adversaries attempting to breach the hotcell for sabotage (bottom).

Figure 7. Adversaries Approach the Facility (Scribe3D)

Final results for the PPS analysis will be presented in future work. These results will include a discussion of design modifications that were made to increase the robustness of the design as well as SSBD recommendations.

Figure 8. Scribe3D Images of the Echem Security Model

## CONCLUSION

The safeguards and security models are used to explore safeguards and security approaches and generate key performance metrics for the MPACT 2020 milestone. The Virtual Facility Distributed Test Bed ties together this systems-level modeling, new measurement technologies, and experimental testing into a complete capability to demonstrate next generation SSBD. The current use of a generic electrochemical facility is meant to be a demonstration that can be applied to other nuclear fuel cycle facilities. The modeling tools described here have been used for other fuel cycle facilities including aqueous reprocessing, enrichment, fuel fabrication, and advanced reactors. A significant goal of SSBD is cost optimization for future facilities so that safeguards and security requirements do not overly burden a facility.

## ACKNOWLEDGEMENTS

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