The MPACT 2020 Milestone: Safeguards and Security by Design of Future Nuclear Fuel Cycle Facilities

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Abstract
The Materials Protection, Accounting, and Control Technologies (MPACT) campaign, within the U.S. Department of Energy Office of Nuclear Energy, has developed a Virtual Facility Distributed Test Bed for safeguards and security design for future nuclear fuel cycle facilities. The purpose of the Virtual Test Bed is to bring together experimental and modeling capabilities across the U.S. national laboratory and university complex to provide a one-stop-shop for advanced Safeguards and Security by Design (SSBD). Experimental testing alone of safeguards and security technologies would be cost prohibitive, but testbeds and laboratory processing facilities with safeguards measurement opportunities, coupled with modeling and simulation, provide the ability to generate modern, efficient safeguards and security systems for new facilities. This Virtual Test Bed concept has been demonstrated using a generic electrochemical reprocessing facility as an example, but the concept can be extended to other facilities. While much of the recent work in the MPACT program has focused on electrochemical safeguards and security technologies, the laboratory capabilities have been applied to other facilities in the past (including aqueous reprocessing, fuel fabrication, and molten salt reactors as examples). This paper provides an overview of the Virtual Test Bed concept, a description of the design process, and a baseline safeguards and security design for the example facility. Parallel papers in this issue go into more detail on the various technologies, experimental testing, modeling capabilities, and performance testing.

Introduction
The U.S. Department of Energy, Office of Nuclear Energy supports nuclear energy research across the full scope of the fuel cycle. The MPACT campaign conducts R&D to support U.S. domestic safeguards and security challenges for the larger Nuclear Energy program. Historically, the research funded has included the development of new material 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. Work

has focused on the back end of the nuclear fuel cycle but varies based on the needs of the program.

The MPACT program and work presented here is focused on U.S. domestic safeguards and security, which includes the operator's Material Control and Accountancy (MC&A) system and Physical Protection System (PPS). The purpose of these systems is to provide assurance that nuclear material is adequately protected and detect and respond to theft or sabotage by sub-national groups. International safeguards measurements and verification are not the subject of this work, but many of the measurement technologies and analyses presented here can also be applied for international safeguards.

The Virtual Facility Distributed Test Bed was developed as part of a 2020 milestone to tie together all the MPACT capabilities to demonstrate complete SSBD for future nuclear fuel cycle facilities.[1,2,3] The "Virtual Facility" aspect involves the use of modeling and simulation to develop process, safeguards, and security models to test approaches and run analyses for a particular facility. However, the models are only as good as the data fed into them. Much of the modeling work has been informed by laboratory test bed results, development of measurement technologies, and testing of those technologies. The "Distributed Test Bed" aspect encompasses these capabilities across the laboratories. One of the motivations for this work is recognition that a safeguards or security demonstration facility is impractical and cost prohibitive. The national laboratories and universities have several smaller, distributed test beds where individual testing and evaluation of technologies can be performed. The Virtual Facility Distributed Test Bed provides a template for how advanced SSBD may be realized, using a generic electrochemical reprocessing facility as an example. Many of these same technologies, test beds, and modeling capabilities can be applied to other facility types as well.

The goal of SSBD is to include safeguards and security considerations from the initial phases of new facility design. Dealing with safeguards and security requirements after a plant design has been finalized can lead to higher costs and poorer performance due to retrofits and unoptimized monitoring systems. In the nuclear field, safety has long been fully integrated into plant designs, but safeguards and security often has been examined later in the design process. SSBD also recognizes that future facilities will make better use of plant process data and see more integration between safeguards and security systems.

This paper provides an overview of the SSBD approach and presents a preliminary MC&A and PPS design for a notional electrochemical reprocessing facility. Accompanying this special issue are several more detailed articles that describe measurement technologies, test results, modeling, and analysis to support the SSBD approach. Throughout this paper, these accompanying articles are referenced.

Virtual Facility Distributed Test Bed

Figure 1 describes the Virtual Facility Distributed Test Bed concept. Starting from the right, the key performance metrics for a new nuclear facility are those parameters that prove that the design meets safeguards and security requirements. While the focus of this effort is on U.S. domestic requirements, the process can also be applied to international safeguards and security requirements as well. Initially, facility flowrates, inventories, separation efficiencies, and timing of unit operations are defined for the facility of interest. Safeguards analyses determine the Standard Error of the Inventory Difference (SEID), probability of detection of loss or misuse, and timeliness. Security analyses determine probability of success against adversary attack, timeliness, and consequence.

The key metrics are generated from systems-level models. Flowsheet modeling is used initially to define the facility, but the design of the flowsheet is iterative as safeguards and security concerns are taken into account. The safeguards models consider inventories, flowrates, and the design of measurement systems for accountancy. Both the flowsheet and safeguards models inform 3D layout and physical protection models which are used to simulate adversary attacks on the facility.

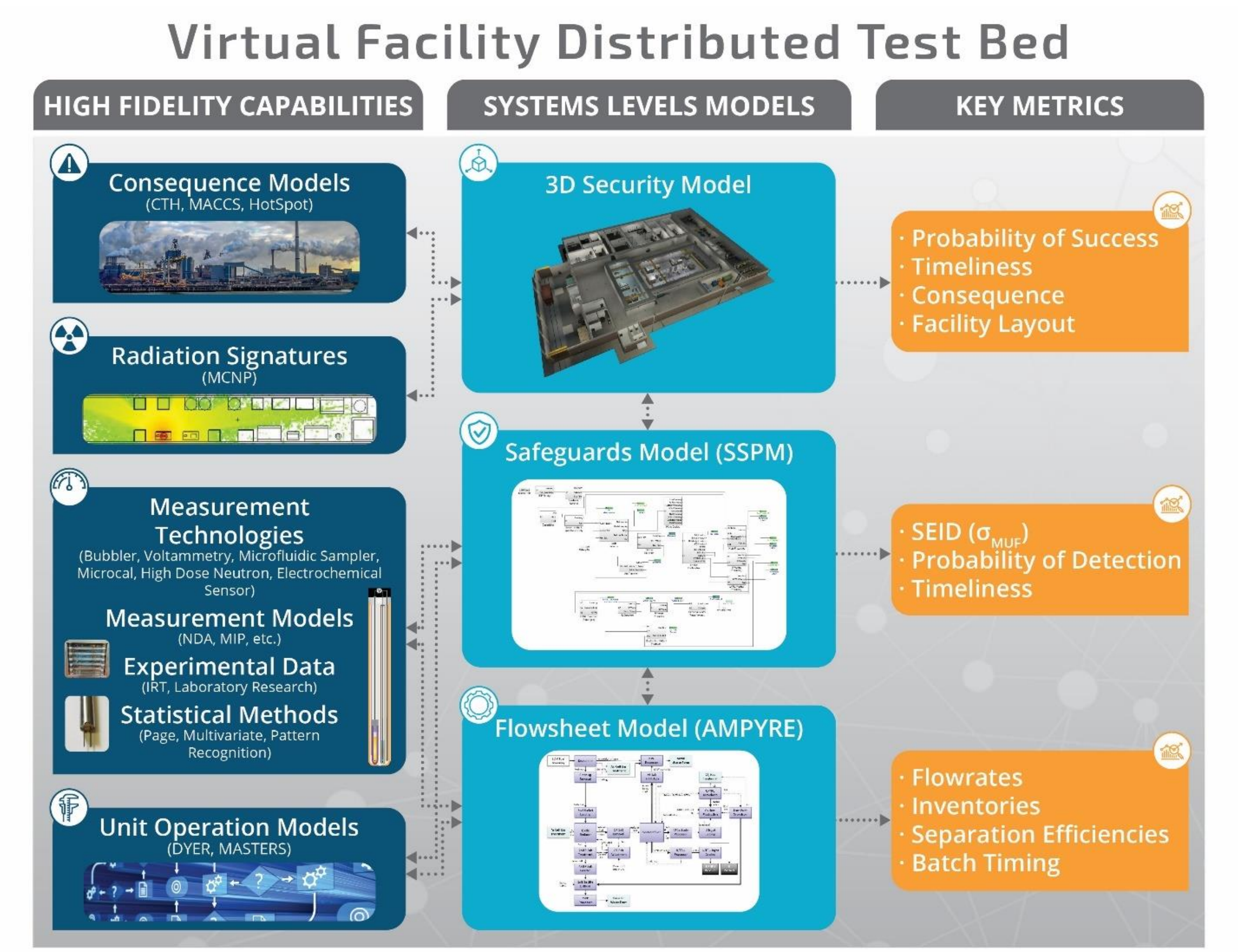

Figure 1. Virtual Facility Distributed Test Bed

Electrochemical process experts help inform the design by defining operational goals and constraints. It is important to understand the operational needs of the facility so that safeguards or security recommendations are not at odds with operational goals. Process experts also provide a check on assumptions used in the modeling efforts.

A significant focus of the MPACT program has been on the development of high-fidelity capabilities which include new measurement technologies, testing in facilities around the U.S. laboratory complex, more detailed measurement or consequence models, unit operation models, and statistical techniques. These technologies and capabilities inform the systems level models and form the base of much of the expertise on SSBD around the complex. The overall analysis is only as good as the data used to inform the models.

Detailed unit operation models can be used to improve the fidelity of the flowsheet or safeguards models. Research on new accountancy or process monitoring measurements is used to inform the assumptions of measurement uncertainties used in the safeguards model. In some cases, more detailed measurement models can be used instead. Radiation signatures modeling, which may include both modeling gamma and neutron emissions, is helpful for both safeguards and security modeling. Consequence modeling may be used to explore sabotage targets in greater detail.

The Virtual Facility Distributed Test Bed is essentially a distribution of capabilities across the laboratory complex, and the number of capabilities utilized is flexible based on the needs of the user. It is intended that facility designers will employ these capabilities in future work to help optimize their designs, operation, and cost of materials accountancy and physical protection systems.

Electrochemical Facility SSBD Demonstration

A generic electrochemical reprocessing facility was chosen as the demonstration of the concept due to potential applications supporting advanced reactor designs and a strong U.S. domestic R&D effort. With a resurgence of interest in small and advanced reactor designs (driven by the U.S. nuclear industry) and advanced fuel types, electrochemical reprocessing may be a consideration for future nuclear fuel cycles.[4] However, since commercial-scale facilities do not yet exist, there are several engineering challenges with developing safeguards and security approaches. It is worthwhile to consider SSBD for these facilities now while any potential plant designs are still at an early stage in the conceptual design process. The SSBD process includes feedback to developers that will result in a facility design that incorporates safeguards and security concepts and can alter the process to facilitate both.

Electrochemical Reprocessing Background

Electrochemical reprocessing facilities use molten salts and electrochemical operations to separate actinides from spent nuclear fuel (SNF). The technology was originally designed in the U.S. for processing metallic fuels but can also be used for oxide fuels. Variation in the flowsheet design, beyond what is used as the basis for this work, is certainly possible and depends somewhat on operator/country needs, engineering issues, and any safeguards or security considerations. An accompanying article[5] provides more detail on flowsheet options and describes the AMPYRE (Argonne Model for Pyrochemical Recycling) and DyER (Dynamic Electrorefiner) models. Additional information on electrochemical flowsheets can be found in references 6 and 7, but a brief description is provided here.

The flowsheet is based on a 100 metric ton per year (MT/yr) throughput of SNF. Fuel assemblies are initially disassembled in a hot cell, and the fuel rods are de-clad to liberate the fuel. The SNF is chopped into small particle sizes and loaded into porous metal baskets for processing.

Oxide fuel first goes through an oxide reduction (OR) step to convert most of the fuel to a metallic form while liberating oxygen and some of the gases in the SNF. This is accomplished by lowering the baskets into a molten salt and applying a potential across the basket and an anode. As current is passed, the oxide fuel reduces to metallic form, and the oxide ions are released into the molten salt and transported to the cathode where they are oxidized to produce oxygen gas.

The metallic fuel in the baskets then gets transferred to an electrorefiner (ER) vessel, where the baskets are lowered into another molten salt. An electric potential is applied between the basket and a cathode—this potential drives fuel into the salt phase and extracts actinides in the salt onto the cathode. Separate cathodes are used for uranium (U) recovery and uranium/transuranics (U/TRU) recovery. The products are ultimately purified and consolidated into an ingot form for storage and/or future use for fuel fabrication.

Separate fission product recovery processes are used to remove active metals from the OR salt and rare earth fission products from the ER salt. Residual noble metals stay in the ER basket and are recovered and placed into a metal waste form along with cladding and assembly hardware.

Safeguards Challenges

Several safeguards challenges have been identified for electrochemical reprocessing, and most of them relate to the unique environment, material forms present, and lack of large-scale operational experience. Since large-scale aqueous reprocessing plants exist, their safeguards systems can be used as a basis.

- Plant Flushouts – In aqueous reprocessing plants, processing solutions are typically drained to select vessels for interim inventory measurements or completely flushed from all vessels and pipes every 6 or 12 months to facilitate a physical inventory. By contrast, completely flushing out an electrochemical facility is not as feasible since the process is designed to maintain a steady-state actinide content in the ER salt. Actinide concentrations in the salt can be reduced through a drawdown process, but materials accountancy approaches generally need to consider interim measurements of the salts.
- Input Accountability – Aqueous plants establish input accountancy by dissolving fuel and taking samples of well-mixed liquid samples. This input accountability tank allows the operator to take precision measurements due to the homogeneity of the solution. Electrochemical plants face a difficult challenge in establishing input accountancy of the oxide fuel, which is inhomogeneous.
- Representative Salt Samples – ER salts may be difficult to measure accurately since they can include metal fines throughout the salt, dross or scum in a layer on top of the salt, and/or solid debris on the bottom of the ER vessel. Obtaining replicable samples can be challenging and may require unique engineering approaches.
- Accountability of Metallic Products – The U and U/TRU metallic products require measurement approaches that differ from output accountancy measurements for aqueous plants. Sampling and destructive analysis (DA) of melts is possible but may be difficult

and costly for routine measurements. Non-destructive assay (NDA) measurements can also be considered, but there are challenges with measuring large metal products.

- Holdup – Every bulk handling facility needs to identify both process and residual holdup locations. Electrochemical plants are no exception; operators will need to determine how to account for material held up in these locations.
- Confirmatory Measurements – Due to the need for greater reliance on interim inventory measurements in electrochemical plants compared to aqueous plants, confirmatory measurements (of empty vessels, or those with low quantities of actinides) are needed to fully close out a material balance. However, confirmatory measurements would need to be performed in a hot cell using NDA techniques, and such measurements can be particularly challenging due to the high radiation environment.
- Process Monitoring – Electrochemical facilities have unique processing signals which can be used for monitoring the process. Current, voltage, or voltammetry measurements can be used for overall process control and/or safeguards, but these measurements need to be understood better.

Security Challenges

The security aspects of electrochemical facilities are not significantly different than at any other nuclear facility, and in some cases the nature of the process provides opportunities that provide a benefit to the PPS. Theft targets can include the U/TRU ingots or any of the intermediate forms (like dendrites or molten salts), but many of these forms would be difficult to work with or remove from the facility. Sabotage targets can include sources of radioactive material that may be dispersed or plant systems that keep operations maintained.

The threat is defined in a Design Basis Threat (DBT), which contains sensitive information about the adversary force that the PPS should be designed to protect against. The DBT includes information like number of attackers and attacker capabilities. One of the challenges nuclear facilities face is in designing the PPS to be robust against the DBT while trying to minimize the number of on-site responders needed.

The thick walls of the hot cell canyon, along with the argon gas environment, provide barriers to access, and this is taken into account in the design of the PPS. MC&A measurements, which are needed in the hot cell, do provide some challenges to security since these instruments will require maintenance. The U/TRU ingots produced by the process are the most attractive target for theft, so protection of this material needs to be a central part of the security design. Security analyses are usually done on a case-by-case basis—identification of vulnerabilities and mitigations are part of any analysis and design.

Safeguards and Security by Design Process

The process for designing a safeguards and security system for a new facility begins with regulatory requirements. In the U.S., physical protection of plants and materials is outlined in the Code of Federal Regulations (CFR)[8] 10 CFR Part 73, and material control and accounting of special nuclear material is outlined in 10 CFR Part 74. However, Part 74 specifically excludes reprocessing, so it can only be used as a rough guide. For this work, IAEA safeguards regulations have also been used since they were developed for large throughput reprocessing facilities. Once the regulatory requirements are established, the design of the systems can begin.

MC&A System Design

The overall MC&A design includes nuclear materials accountancy, process monitoring, and containment & surveillance (C/S). The MC&A design process is outlined in an accompanying article.[9] A first step is a definition of the MC&A goals. Since NRC goals are not really written for large scale reprocessing facilities, both NRC and IAEA goals were used in this work. The NRC goal is to detect 2 kg of Pu within 7 days with 95% detection probability and 5% false alarm probability.[8] The IAEA timeliness goal is to detect the loss of 8 kg of Pu within 1 month (for direct use material) with 95% detection probability and 5% false alarm probability.[10]

The second step is to define material balance areas (MBAs). The MBAs are logical boundaries placed around a processing area in which inputs, outputs, and the change of inventory is tracked. MBAs are often chosen to coincide with physical boundaries, such as all within the same hot cell or within the same building. They may also be chosen based on grouping material of similar attractiveness as well as ease of measurement. For example, most aqueous reprocessing facilities set MBA 1 to include fuel receipt and all front-end operations (disassembly and fuel chopping) up until the accountability tank. The front end is difficult to measure until the accountability tank, so the MC&A system relies more on item accounting and C/S. MBA 2 typically goes from the accountability tank through product processing since the bulk material can be sampled and measured throughout this area. The switch back to item accounting on the back end usually means another MBA will be defined.

The MBA structure for the example electrochemical plant is shown in Figure 2. MBA 1 covers front end operations which occur within an air hot cell. The front end includes fuel receipt and storage, disassembly of the fuel assemblies, decladding, and chopping of the fuel. The plant design assumes that some type of (undefined) sampling or NDA measurement is used to establish input accountancy for the fuel either before or within the fuel baskets, just before the baskets are transferred to the argon hot cell.

MBA 2 covers all operations which occur in the argon hot cell. These operations include oxide reduction, electrorefining, distillation steps, cathode processing, drawdown, and active fission product removal steps. The outputs of MBA 2 are the U and U/TRU products, active metal and rare earth fission product waste, and metallic waste form.

MBAs 3 and 4 are item accounting MBAs. MBA 3 includes storage of the U product and waste forms. MBA 4 includes the U/TRU vault, which stores the U/TRU ingot products more securely until they are shipped out. MBA 3 is likely in a different building than the other three MBAs since the material attractiveness is lower.

The definition of the MBA structure identifies the key measurement points, which include both flow and inventory measurements. Flow measurement points are used when material transfers into or out of the MBA. Inventory measurements are used for periodic interim or physical inventory taking. A significant portion of the MPACT campaign has focused on the development of measurement technologies that can be used for these various key measurement points. The overall goal of these measurements is to provide material tracking for reporting to a regulatory body, and ultimately to provide assurance that material has not been removed.

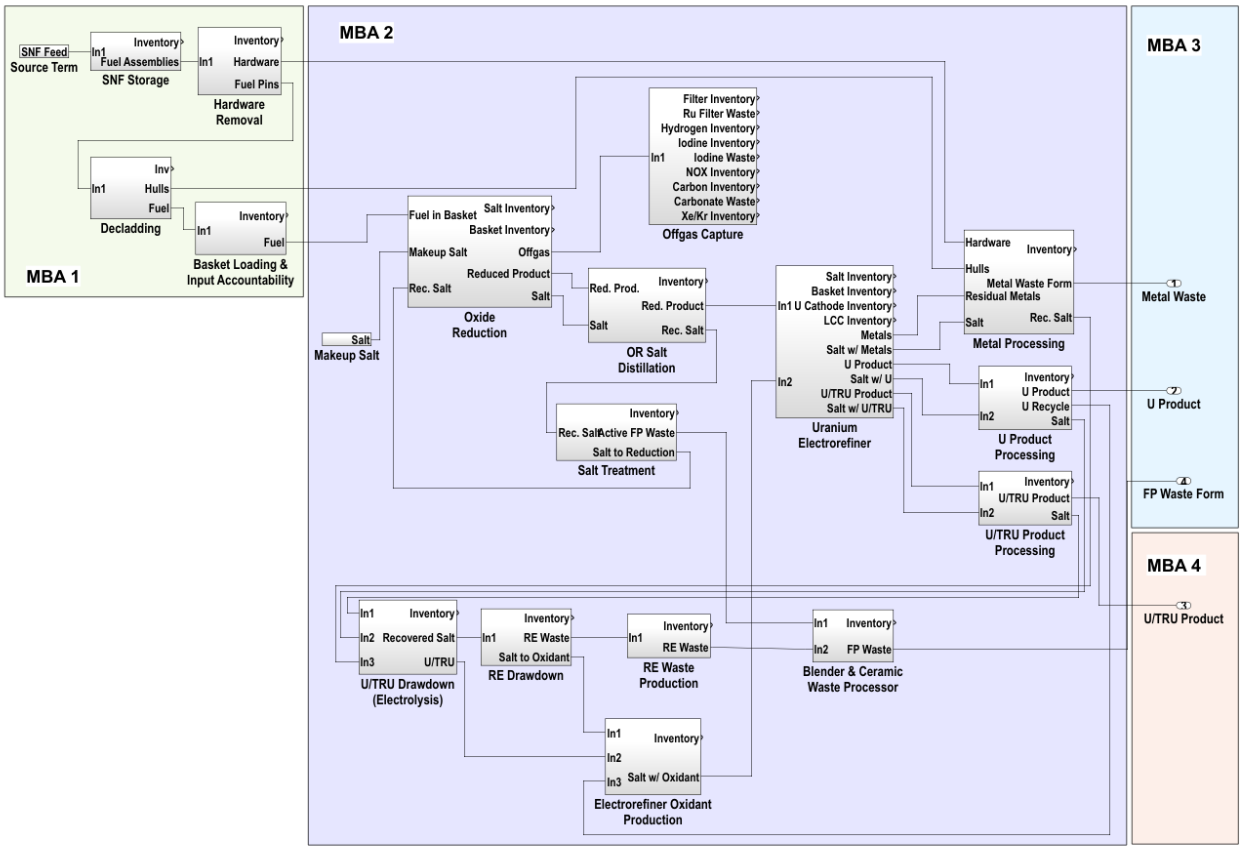

Figure 2. MBA structure for the generic electrochemical facility

Process monitoring may also be used to help the operator account for the nuclear material in their facility. Process monitoring is defined in a U.S. DOE Standard[11] as “a methodology to ensure that special nuclear material (SNM) is in its authorized location and when effectively implemented, it is a useful tool to detect anomalous process conditions and indicate losses of SNM well before the scheduled physical inventory.” Process monitoring is particularly useful to the operator who has a large amount of facility data to utilize. Electrochemical facilities contain different types of process monitoring data and technologies (compared to other fuel cycle facilities) such as current, voltage, and temperature which can be used to monitor the process.

Machine learning is a relatively new data analysis approach that is beginning to be evaluated for application to MC&A. The wide variety of plant process data (such as bulk mass, current, voltage, etc.) could be tied into the safeguards approach along with NDA measurements to detect material loss of other misuse scenarios with high probability. More details on this potential research area are provided in accompanying articles.[9,12]

C/S are also a significant part of the overall safeguards system, but because many of the C/S technologies exist already, less R&D is needed. For an electrochemical facility, many of the C/S technologies that are used for existing aqueous reprocessing plants can be applied. These include surveillance cameras, entry control, locks on hatches to the hot cell, tags, and seals. C/S also crosses over into the PPS design, which is described next.

PPS Design

Security system design, even in a SSBD concept, starts slightly later than the safeguards system design because a preliminary building layout is needed. That being said, the building design should remain fluid during this stage so that security considerations can affect the layout.

A vulnerability assessment (VA) estimates the PPS effectiveness against theft or sabotage against a range of threats.[13] The beginning of a VA is to identify metrics and assumptions, which are defined in the regulatory basis. The facility and processes are then characterized to identify high-consequence targets and characterize existing or baseline PPS elements and strategies used to protect those targets at the site. Threats would be defined in a DBT as described earlier.

For a new design, typical PPS elements will be added to the preliminary building layout including: entry control points, access controls, badge swipes, cameras, portal monitors, and switches for doors and hatches to the hot cell. The location of the central alarm station, secondary alarm station, and guard forces will also be identified.

Next, pathway analysis identifies the easiest/quickest path to a particular target and determines the timeline required for an adversary to reach their goal. A full physical protection analysis may use table-top exercises or single analyst tools to run red team-blue team (adversary-defender) simulations to determine if the PPS is able to successfully stop the adversary. Any weaknesses or vulnerabilities are identified. System effectiveness is reported as the probability of neutralization—generally values less than 80% would be considered low or moderate, and so improvements will be made to the design to increase the effectiveness to above 80%. The process is inherently iterative until an acceptable PPS design is developed.

Electrochemical Facility Safeguards and Security System Design

The following section provides a baseline approach for the design of a safeguards and security system for a generic electrochemical reprocessing facility. This design can be used as a starting point for future facilities. A number of SSBD recommendations are included. This section contains several references to articles accompanying this special issue.

Electrochemical Facility MC&A Approach

The focus of the safeguards design work in the MPACT program has been on the MC&A measurements. Reporting requirements to the NRC are also an important part of the overall safeguards system, but these approaches are administrative and outside of the purview of this work. Figure 3 provides an overview of the measurement technologies that were examined in the MPACT program for accountancy and process monitoring.

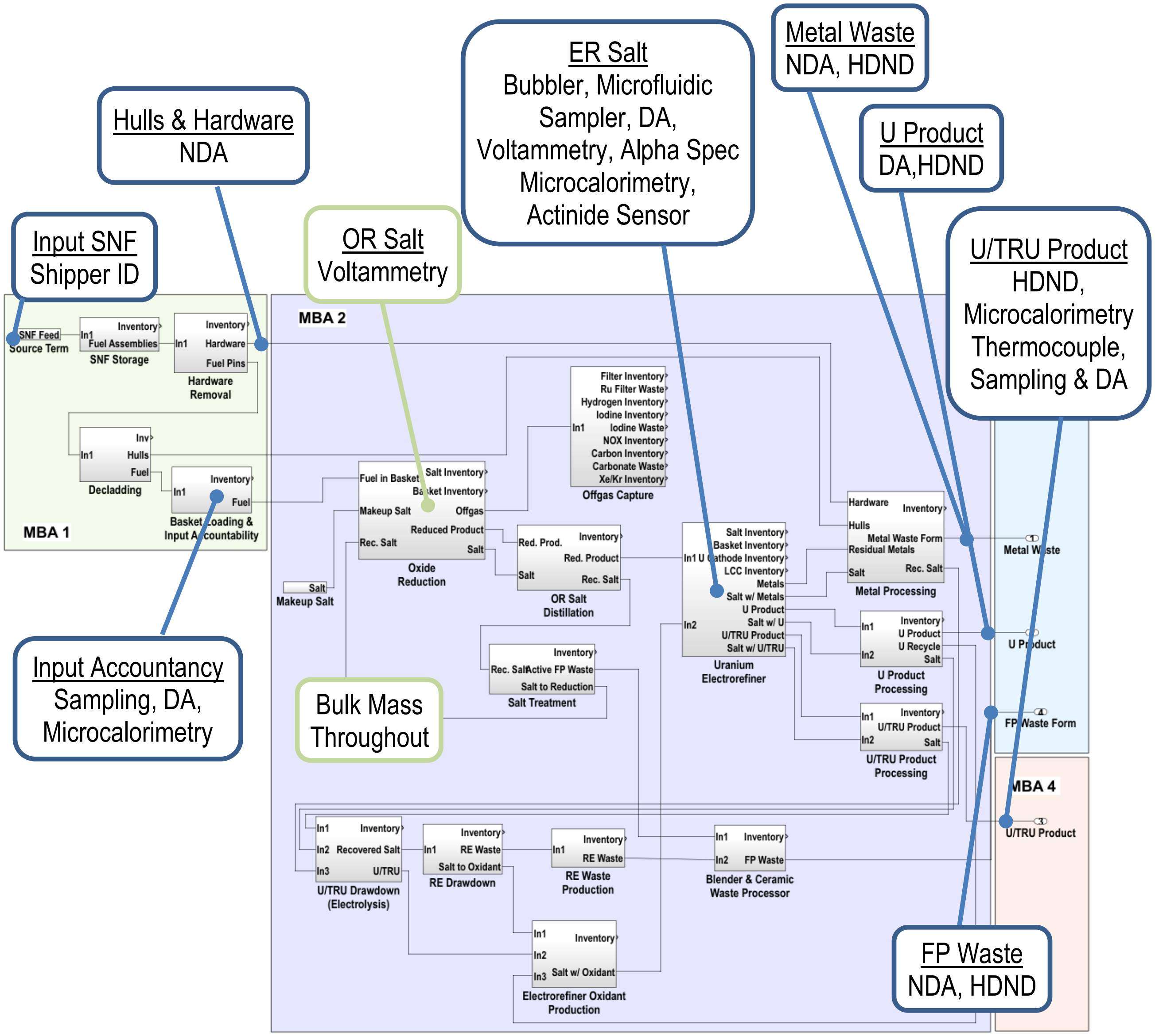

Figure 3. MC&A approach

In MBA 1, MC&A is primarily accomplished by tracking items (fuel assemblies) entering the facility and using shipper declarations of initial enrichment, burnup, and cooling time. Typically, the uncertainties are high (5-10%) based on estimates from burnup codes, but C/S is also used to ensure material is not removed. A more precise measurement of the spent fuel is achieved at input accountability, which serves as the output of MBA 1 and input to MBA 2. The modeling work and safeguards analysis did not focus on MBA 1.

A vast majority of the MPACT work on new measurement technologies applies to MBA 2. The key measurement points in addition to input accountancy include: the ER salt, the U product, and the U/TRU product. These areas contain the bulk of the actinides and so require precision measurements. Other inventory measurements may be needed, such as the inventory of actinides in the drawdown vessel, but the quantities are low enough that precision measurements are not required. Confirmatory measurements are also required—confirming no or trace actinide quantities in the OR salt is one example. Waste streams also need to be characterized, but the actinide content is low enough that measurements with high uncertainty are acceptable.

MBAs 3 and 4, are both item accounting areas. These areas contain the U and U/TRU product ingots as well as waste forms which are all measured in MBA 2. Each discreet item will be tracked based on their original compositions as measured through DA or NDA measurements.

Input accountability was identified as a key challenge area and is still a somewhat unresolved measurement point. Homogenization mixing of the solid fuel (after voloxidation) has been proposed in past work,[14] and the sampling uncertainty could range from 1-3% depending on several variables. NDA measurements using microcalorimetry were evaluated for a potential input accountancy measurement. Microcalorimetry is an ultra-high resolution gamma spectroscopy nondestructive method of detecting changes in concentration of key isotopes throughout the process. The SOFIA (Spectrometer Optimized for Facility Integrated Applications) microcalorimeter instrument was used to measure spent fuel samples from real-world facilities and purified U and Pu reference materials. The enhanced energy resolution of microcalorimetry as compared to germanium detectors was found to improve NDA capabilities by increasing the peak-to-background ratio and the ability to resolve closely-spaced gamma ray energy peaks. SOPHIA was demonstrated to be capable of measuring certain actinide and fission product peaks with 1% counting statistics in a period of hours.[15] For example, a measurement of a high-burnup spent fuel sample indicated that key resolved gamma ray peaks from the $^{243}Am/^{239}Np$ parent/daughter and ^{155}Eu could be quantified to 1% statistical precision in 4.6 hours and 1 hour respectively. Compared with destructive analysis, a relatively larger number of rapid nondestructive microcalorimeter measurements could be completed in order to reduce the effect of sampling error. However, translating these peak measurements into a determination of U/Pu content for high throughput facilities will require more research.

Microcalorimetry was also used to evaluate ER salt samples.[15] Gamma rays from $^{243}Am/^{239}Np$ and ^{155}Eu were determined to be most useful for detecting changes in salt composition. For the sampled range of ER salt compositions, SOFIA was demonstrated to be capable of quantifying these gamma ray peaks to 1% statistical precision in 1.6-24.4 hours. This is a good match for daily measurements of salt composition; however, there are other sources of error which must be considered in future work including sampling and calibration.

As an alternative to sampling and DA/NDA, voltammetry has also been examined for more routine measurements of the ER salt. Voltammetry may play a significant role in the operator's process monitoring system. ER Voltammetry has demonstrated an ability to make repeated in-situ measurements of actinide and lanthanide concentrations over long durations with a relative standard deviation (RSD) of less than 1%.[16] These sensors have been assessed during a 100-day testing campaign and have survived salt immersions lasting greater than a year and a half with no degradation in performance.

A microfluidic sampler was developed for generation of uniform salt samples for analysis.[16,17] Acquiring representative salt samples was identified as a key challenge area for electrochemical safeguards, and this technology serves to fulfill that need. In addition, commercial scale plants will benefit from an automated way to collect samples. The microfluidic salt sampler has demonstrated capabilities for high-throughput sample generation with coupled analysis.

The ER salt measurement requires a precision salt level measurement to determine total bulk mass. The Triple Bubbler is an in-situ probe that determines salt level for routine operator use or for materials accountancy declarations. The Triple Bubbler has demonstrated a 1.2% RSD for total salt mass.[18]

Additional technologies that were examined for the ER salt measurement include the actinide sensor,[18] alpha spectroscopy,[12] and Hybrid K-Edge Densitometry.[12] At the current time, these technologies are slightly less developed and have higher measurement uncertainties. Although Hybrid K-Edge Densitometry performs well in aqueous solutions, more research will be required to optimize its performance on molten salts.

The U product measurement would most likely be performed using NDA with occasional confirmation using DA on melt samples. Data from the International Target Values reference[19] shows that U-235 abundance can be determined using DA to 0.2% RSD (random and systematic) for U with U-235 enrichment from 0.3% to 1% (typical of SNF). NDA can achieve RSDs around 10% random and 3% systematic using NaI detectors. However, even small amounts of impurities from minor actinides or fission products can change the effectiveness of gamma measurements. Microcalorimetry has the potential to improve the precision of U-235 enrichment measurements and to lower detection limits for actinide and fission product impurities in a uranium product. Measurements of uranium oxide enrichment standards indicate that the improved energy resolution of microcalorimetry relative to HPGe and NaI detectors translates to a direct improvement in the ability to resolve peaks from U-235 and U-238 in the 100 keV region. Further work is planned to evaluate performance for U metal products from electrochemical reprocessing.

Modeling work was carried out using the High Dose Neutron Detector (HDND) to determine detection of small amounts of TRU in the U ingot in the case of off-normal operation.[20,21] The calculations found that a 0.005% weight contamination of Pu in the U ingot would be detectable with greater than 95% detection probability using the HDND with a counting time as low as 10 minutes. This then would provide a promising way to confirm normal operation of the process. Note that the modeling assumes optimum HDND operating settings, which are expected to be tuned to the measurement environment (background conditions and gamma emissions rates from an item).

Both NDA and DA have been considered for the U/TRU product measurement as well. Since the U/TRU product contains the majority of the Pu, precision measurements of this product are needed for accountancy. DA of melt samples is possible, but routine use may put significant burden on the analytical laboratory—especially since larger facilities may generate one U/TRU ingot per day. NDA has been examined using the HDND.[15,22] Testing on surrogates was performed at Idaho National Laboratory and focused on the capability of HDND to measure multiplication using correlated counting. Measurement of multiplication can be used to extract information on Pu content. Uncertainty of correlated counting is tightly connected to neutron detection efficiency and characteristics of nuclear material (^{240}Pu and ^{244}Cm content for U/TRU ingot). The available surrogates did not include ^{244}Cm and measurements could only be performed in reduced HDND configuration with less than half detection cells (i.e. reduced efficiency), which impacted the full uncertainty quantification. However, the testing confirmed the capability of HDND to perform multiplication measurements even in the reduced configuration with an overall measurement uncertainty of <5% on the doubles to singles (D/S) ratio in 1000s.

An alternative technology for the U/TRU measurement is an in-situ measurement of Pu content using a thermocouple and knowledge of phase diagrams during ingot melting/casting. Testing using U/TRU alloys found that this technique could determine total Pu content with 5-10% RSD.[18] More work would be required to determine if improved techniques can reduce the error, but a key advantage is that this measurement is done in-situ for ease of routine use.

Microcalorimetry was also evaluated for the U/TRU product by combining measured spectra from pure uranium and plutonium reference materials in a ratio that corresponds to a material with equal mass fractions of U and Pu. SOFIA was demonstrated to be capable of quantifying the ^{235}U/^{239}Pu ratio to a 1-sigma statistical precision of 1.0% in 24 hours.[15] The improved resolution of the microcalorimeter spectrum relative to HPGe significantly reduces the potential for bias resulting from peak overlaps or interferences in the complex U/TRU spectrum, therefore improving confidence in results and reducing the need for complementary destructive analysis.

Beyond the key measurement points, confirmatory measurements will be needed by the operator to establish that vessels are empty or contain low actinide content at the time of the material balance. Voltammetry can be used to confirm normal OR operation and ensure that actinides are not going into the OR salt. Low levels of actinide content should be easily detectable on voltammetry traces, but threshold values have not been quantified yet. Recent work has resolved materials issues to prevent corrosion or deposition on the probes.[18]

Neutron and gamma flux profiles have been developed for the key unit operations.[20] There are a couple of useful results of this work. The first is to determine if the HDND could measure a U/TRU ingot within the hot cell. The modeling work showed (as expected) that performing the measurement away from the ER and OR provided the greatest difference between a measured value and background (roughly a factor of 2-15 difference depending on location). This work can be used to design the hot cell with shielding to facilitate such a measurement. This work provides insight about how well the HDND could measure holdup or misuse within the hot cell. Accumulations of fuel being processed by unit operations (such as fuel baskets in the ER) or ingot deposits being processed in the U and U/TRU cathode processors could be distinguished from normal background. This is more of a gross confirmatory measurement.

Waste measurements are also needed to show low actinide quantities going into the waste forms as well as to characterize the waste for disposal or storage. NDA measurements, which may be a combination of gamma and neutron measurements, can be used. The HDND and microcalorimeter could also be used for these measurements, but simpler gamma and neutron measurements may also be worthwhile since high precision is not needed.

Several process monitoring measurements could be tied into the overall safeguards approach as well. Current and voltage monitoring would be routinely used by the operator to ensure the extraction processes in the ER vessel are operating as expected. The DyER modeling tool was developed to predict ER operation, and recent analysis of the tool in comparison to a large variety of past experimental work showed very good agreement comparing modeled data with experimental results.[5] University work has also explored the use of ER models.[12] An operator would likely use an ER model for process monitoring. Off-gas monitoring, either of the OR vessel or the entire hot cell is also useful for monitoring the process and ensuring no unusual reactions are taking place. This was not specifically evaluated as part of the MPACT program but will be a routine operator measurement. Finally, bulk mass measurements will be used throughout the process to track bulk transfers of material. This includes baskets, cathodes, salt return, etc. using a variety of instruments including the Bubbler, scales, and load cells.

Holdup is a concern for any reprocessing facility, but more work will be required to determine holdup in actual facilities. Since the material balance is designed with many of the vessels empty at the time of the balance, proper hot cell design and placement of shielding could facilitate the use of confirmatory measurements that ensure material is not present. These same measurements could be used for holdup estimates.

Based on this MC&A approach, and the measurement uncertainties that were demonstrated at the various test beds across the complex, safeguards modeling was used to determine the overall performance of the system. Several material loss scenarios were modeled at various points in MBA 2 to examine the ability of the system to meet both NRC and IAEA detection goals. The following section describes the modeling results.

Safeguards Modeling Results

The safeguards modeling work examined the response of the potential accountancy measurements to various material loss scenarios. Based on the accountancy measurements listed above, and performance of those technologies as described in the accompanying journal articles, a material balance was set up in the Separation and Safeguards Performance Model (SSPM) to evaluate various loss scenarios.[9] The SSPM has incorporated a great deal of past work in the MPACT program related to the design of the material balance and statistical tests used to determine detection probabilities.

Two material balance periods were designed for the analysis. An 8-day balance period was used to examine the ability to meet the NRC detection and timeliness goal. (Although the timeliness goal is 7 days, 8 days was chosen in order to be consistent with the plant’s roughly 4-day cycle time—multiples of 4 days provide a more optimal balance timing.) A 30-day balance period was used to examine the ability to meet the IAEA detection and timeliness goal.

The analysis used a range of relative standard deviation (RSD) assumptions (1%-3%-5%) for the critical measurements, and only the Pu balance over MBA 2 was examined. The less important measurements, for either confirmatory measurements or waste streams with very low actinide content, had very little impact on the overall safeguards performance, so these RSDs were set to 5% for all scenarios. The total mass measurements were set to 1% in all cases to be consistent with the bubbler performance, although measurements using scales can likely perform better. The parametric study only examined changing the input accountancy, ER salt inventory, and U/TRU product RSDs, again focusing on the Pu balance. In all cases, the 1%-3%-5% assumption was used for both the random and systematic RSDs.

The 1% RSD assumes the best case and includes the use of microcalorimetry on the input spent fuel, voltammetry on the ER salt, and microcalorimetry on the U/TRU product, which appeared to perform the best of all the measurement technologies tested. The analysis also assumes that several of the other technologies are used for confirmatory measurements. While not specifically part of the material balance calculations, these confirmatory measurements are just as important for the overall safeguards approach. A 3% RSD assumption was examined since it is possible that the technologies will have worse performance in an actual facility (and due to challenges with obtaining representative samples). 5% was also examined to represent potential use of less precise NDA measurements.

Starting with the NRC goals, Table 1 shows a conceptual loss scenario of fuel from MBA 2. For these scenarios, 2 kg of Pu were removed in both abrupt and protracted loss scenarios. The RSD assumptions are shown by the column labels, and the table results show the detection probabilities. The bottom row shows the overall measurement error (SEID) in kg of Pu. At the 1% RSD assumption, only the abrupt loss case could be detected above the detection goal of 95%. An increase in the RSD leads to a rapid drop off in the ability to detect the loss. The SEID values provide insight. With the critical measurements at 1% RSD, the SEID (per balance period) was 1.2 kg of Pu, which is below the material loss amount. However, at 3% RSD, the SEID was 3.0 kg of Pu, which means that a 2 kg loss is hidden in the measurement uncertainty.

Table 1. Conceptual fuel loss scenario results based on NRC goal (2 kg loss in 7 days)

Loss Scenario	**Measurement Uncertainty (RSD)**		
	All 1%	All 3%	All 5%
Abrupt Loss	97%	14%	7%
Protracted Loss	83%	7%	5%
SEID (kg Pu)	1.2	3.0	4.9

These results show the difficulty of achieving the NRC goal. The material balance would also require weekly inventory measurements which could be burdensome for the analytical laboratory. As described earlier, since the NRC regulations were not written for large reprocessing facilities, these results should be taken into account if future rule-making is considered.

Table 2 shows an example of the loss scenarios that focus on the IAEA detection goal. These results include the detection probability as a function of measurement uncertainty for the loss of 8 kg of Pu (an IAEA significant quantity) within 30 days for loss of the U/TRU product. A high detection probability was seen in all loss scenarios at the 1% RSD assumption and for the first two scenarios at the 3% RSD assumption. These results show that if the technologies examined as part of the MPACT program are able to reach 3% RSD, the MC&A system will still do reasonably well detecting material loss. The results are all notional for a 100 MT/yr facility, and different facility sizes will have different requirements in order to reach the goal. Table 2 also shows the SEID for each assumption. The SEID by itself is not always a good indicator of performance, but as the SEID gets closer to the loss amount, the detection probability drops off more.

Table 2. Conceptual fuel loss scenario results based on IAEA goal (8 kg loss of Pu in 30 days)

Loss Scenario	**Detection Probabilities and SEID as a Function of Measurement Uncertainty (RSD)**		
	All 1%	All 3%	All 5%
Abrupt Loss	100%	99%	63%
Protracted Loss 1	100%	93%	31%
Protracted Loss 2	100%	66%	13%
SEID (kg Pu)	1.9	5.5	9.1

Other material loss scenarios based on the IAEA detection goal were examined for MBA 2, and the results were similar to Table 2. This is expected since material loss of the same quantity within the same MBA should have similar detection probabilities.

To summarize the safeguards modeling results, the MPACT measurement technologies described in the previous section suggest that 1% random and systematic RSDs for Pu accountability are likely best-case assumptions for the most critical measurement points. However, RSDs as high as 3% could still meet IAEA detection goals unless material loss is protracted over very long periods. NRC detection goals are more challenging to meet for all but abrupt material loss, and this fact should be taken into account should future rule-making be considered in this area.

Electrochemical Facility PPS Approach

The baseline plant layout that was used for the PPS design was loosely pulled from an open reference from work at Argonne National Laboratory to design an electrochemical facility.[7] The design was modified to provide more realism for spacing of rooms, entries, and for inclusion of PPS elements.[13,22] Figure 4 shows a 3D view of the operating floor in the main processing building with some of the key material handling areas and security-related areas called out.

In the baseline facility design, SNF is received in the high bay, and material is transferred underground and through hatches to the processing cells. The air hot cell stores SNF and includes the front end operations in MBA 1. The argon hot cell contains the remainder of the electrorefining operations in MBA 2. U product and waste storage (MBA 3) will be in a different building outside of the main processing building, and the U/TRU vault (MBA 4) is contained in the basement of the main processing building (both are not shown in the figure). Much more detail on the assumed plant layout and PPS design can be found in an accompanying article.[13]

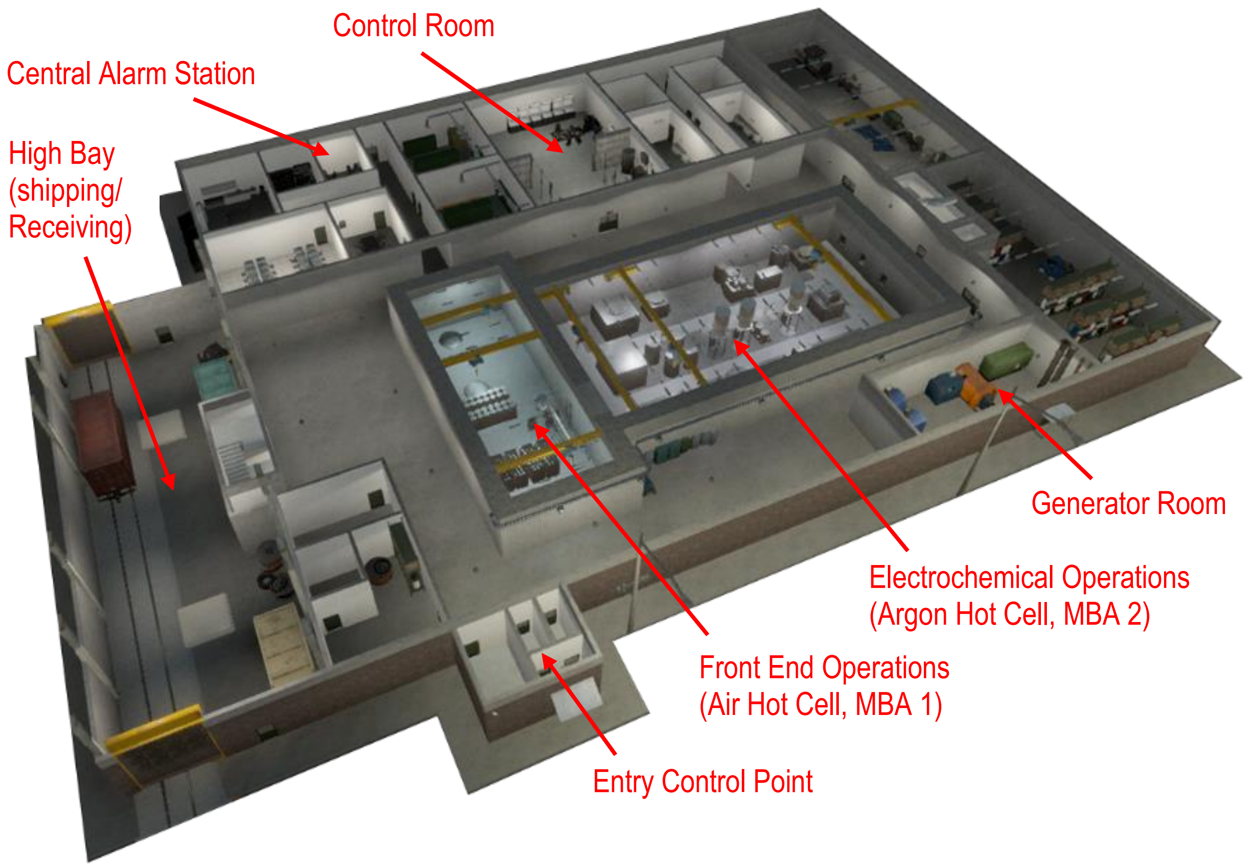

Figure 4. 3D model of the conceptual electrochemical reprocessing facility for the security analysis

A target set was identified based on potential theft or sabotage targets in the facility. A fairly complete list was developed even though some targets are more attractive than others. The key theft targets include SNF, ER salts, and U/TRU products. The key sabotage targets include the OR and ER salts, wastes, and the backup generator.

The placement of PPS elements for the baseline design was based on current best practices for nuclear facility security. Figure 5 shows PPS elements for the main processing floor. One of the Security by Design recommendations from this work is to reduce costs by eliminating an external Perimeter Intrusion Detection and Assessment System (PIDAS) and instead equipping the facility walls with seismic sensors to serve as intrusion detection. Exterior cameras are also used to assess alarms. Exterior doors are equipped with balanced magnetic switches to detect unauthorized entry. A single passive fence around the site is utilized to limit public access. The entry control point follows standard designs with a mantrap for personnel passage, balanced magnetic switches (BMS) on the exterior doors, a proximity card reader, and personal identification number (PIN) pad for entry and exit. A personal portal monitor is included to detect metal items or radioactive substances.

Interior PPS features include surveillance cameras, dual technology sensors in hallways and vault areas, BMS's, PIN pad entry for room access, and radiation detectors. A vault type door is used for the U/TRU vault in the basement. The baseline PPS design shown in Figure 5 was modified as a result of the security analysis, which is described in the next section.

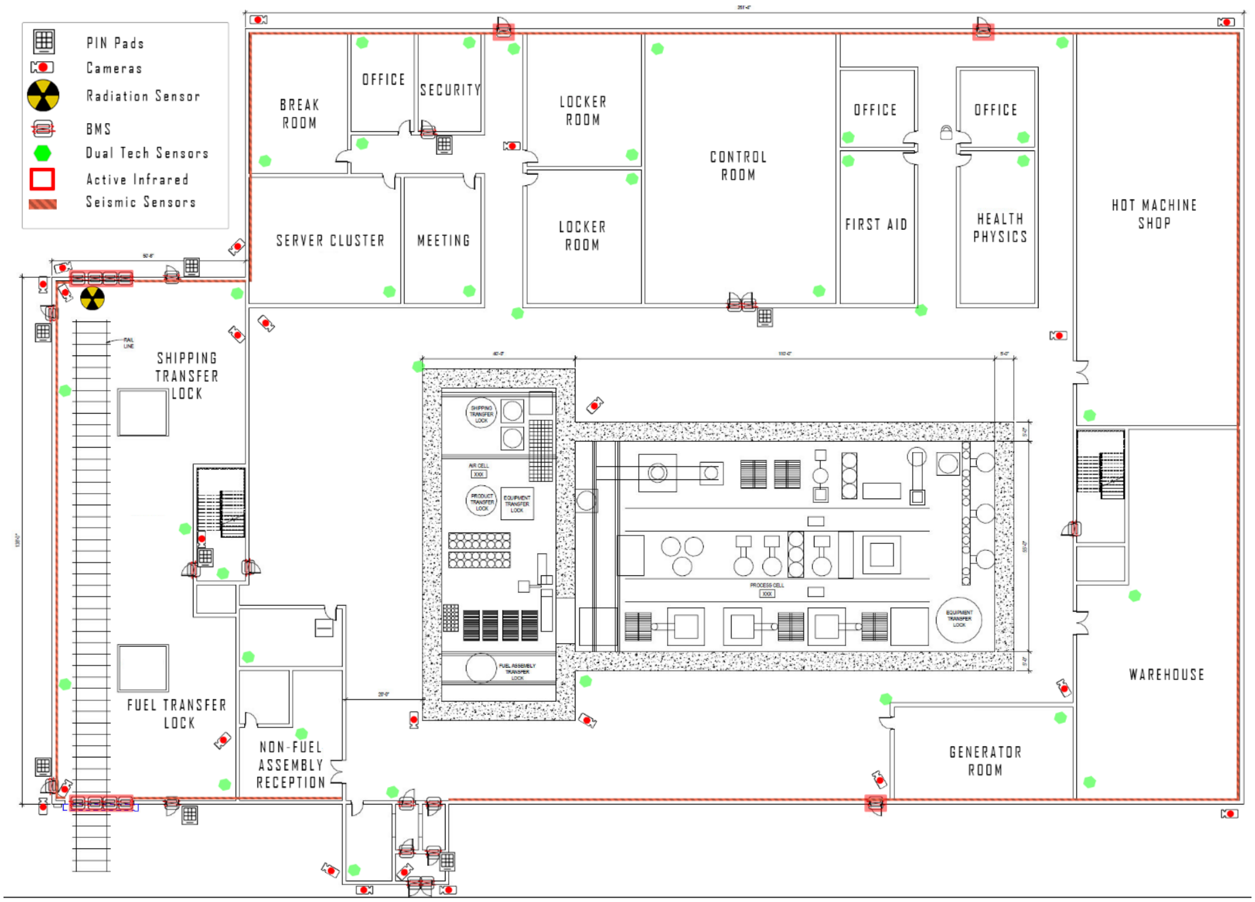

Figure 5. Conceptual PPS design for the operating floor level

The response force was assumed to consist of 10 responders onsite and reliance on 2 offsite local law enforcement officers which arrive 10 minutes into an event. More details on the on-site responders as well as the adversary threat are provided in the accompanying journal article.[13]

Security Modeling Results

Using single analyst tools, the baseline PPS design was tested against a wide variety of adversary attack scenarios.[13] A range of adversary numbers (4-8) were considered to approach the problem from a more parametric perspective. Scenarios covered outsider and insider attack as well as theft and sabotage scenarios. Based on the results, the PPS design was optimized to provide more robustness where needed and to reduce the system cost where appropriate. Examples of the scenarios are presented here.

A brute force outsider theft scenario was examined to test the robustness of the building design against theft of U/TRU ingots. Path analysis showed that theft from the U/TRU vault had a shorter timeline than theft from the hot cell, but the timeline was still long at around 16 minutes. The long timeline was due to the number of successive explosive breaches to enter the facility and access the U/TRU storage vault. This provided ample time for on-site responders to set up containment of the threat and prevent theft. The probability of neutralization was 93%, 93%, 75%, 50%, and 31% for 4 through 8 attackers respectively, which indicates a fairly robust security design. The location of the U/TRU storage vault in the basement, with very thick shield walls around it and above it limited the size of explosives the adversaries could use without bringing the entire building down—this led to long timelines for access and should be maintained in any future building designs.

A theft scenario with insider collusion was also examined, and the system effectiveness was similar to the outside only theft scenario. Despite good results for 4-5 adversaries, upgrades were considered to improve the overall system effectiveness. Upgrade 1 included mantraps on all exterior doors to increase delay for adversaries entering the facility. Upgrade 2 included mantraps plus shifting the exterior patrol to the interior of the building. Upgrade 3 included extended detection around the facility utilizing a Fused Radar and Video Motion Detection using the Deliberate Motion Algorithm, ankle-breaking anti-transit landscaping, and hardened fighting positions in the building. Figure 6 shows the results of the neutralization analysis for the two baseline theft cases along with the results for the collusion scenario after the upgrades are applied. The upgrades progressively provide more robust protections for the plant and provide options to create an extremely well-secured design. A facility designer can use this information to determine an optimal design based on upgrade cost and the size of the threat.

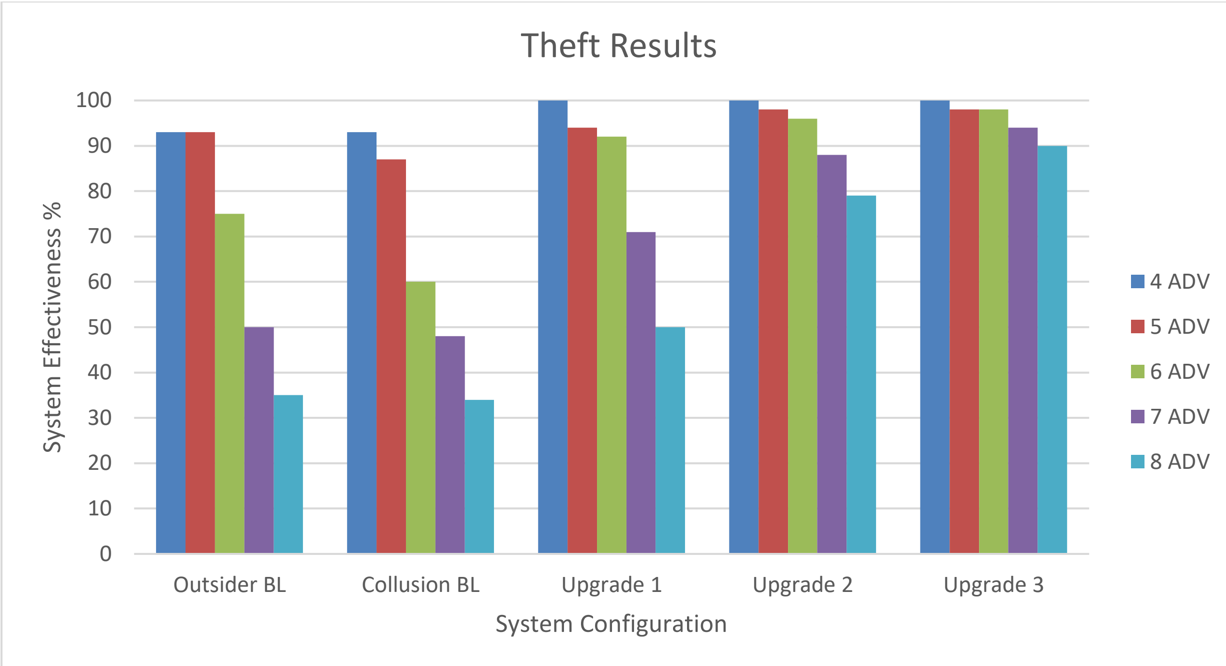

Figure 6. Probability of neutralization - outsider theft scenarios with upgrades

A hot cell sabotage scenario was also examined wherein an outside adversary group attempted to breach the facility, breach the hot cell, and plant an explosive to cause a release on-site. In this case, the attack timeline was more rapid at just under 6 minutes. The adversaries were able to access the building quickly through emergency exits and gain access to the outer hotcell wall quickly. The probability of neutralization was poor ranging from 53% for 4 adversaries down to 10% for 8 adversaries.

As a result of the poor performance against the sabotage scenario, upgrades were once again considered. Upgrade 1 included mantraps on all exterior doors and response force changes to tactics inside the building. Upgrade 2 included mantraps plus shifting the exterior patrol to the interior of the building. Upgrade 3 included extended detection around the facility utilizing a Fused Radar and Video Motion Detection using the Deliberate Motion Algorithm, ankle-breaking anti-transit landscaping, and hardened fighting positions in the building. Figure 7 shows the results of the neutralization analysis for the baseline sabotage case along with the results after the upgrades are applied. Again, the upgrades progressively provide more robust protections for the plant, and a facility designer can use this information to determine an optimal design.

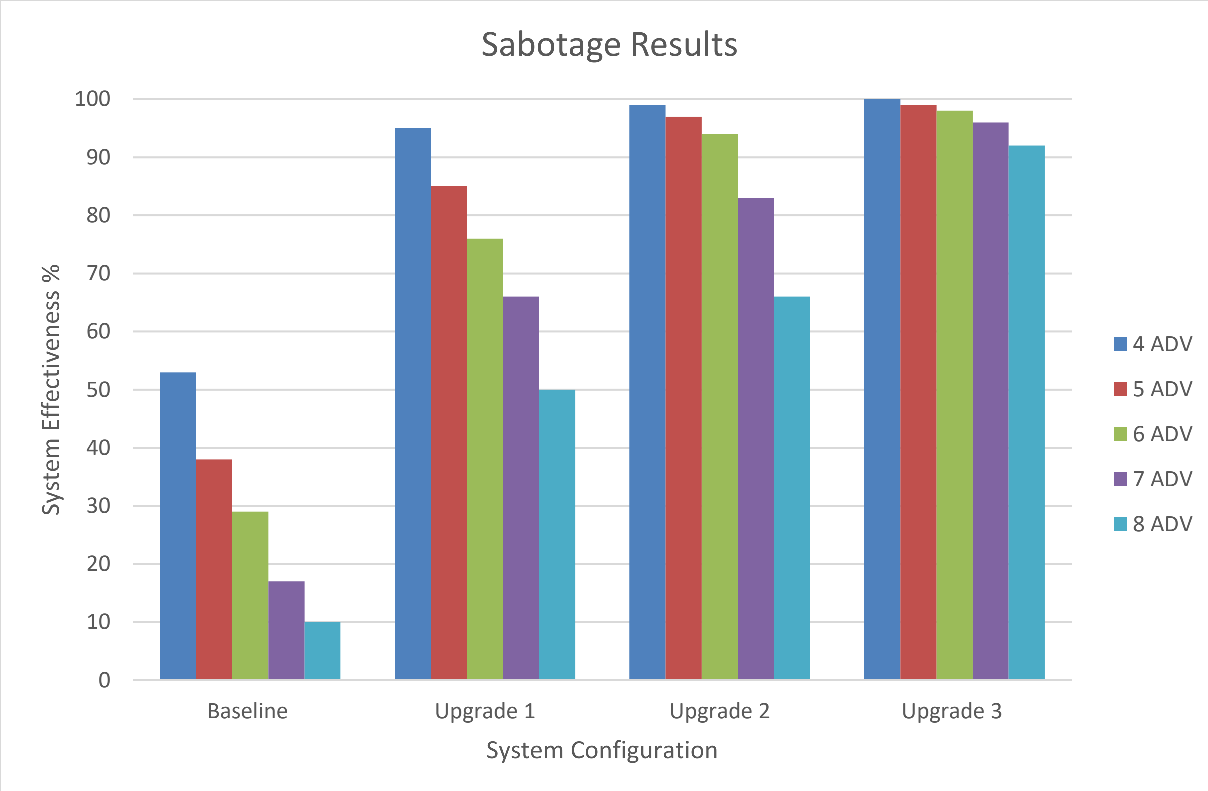

Figure 7. Baseline and upgrade results for the conceptual sabotage scenario.

Security Discussion

Based on security analysis, the PPS design and response force tactics were modified as needed to improve results. The PPS performance metrics and iteration provide confidence that the PPS design is robust against a range of threats. That being said, a future real plant design will need a full analysis since sometimes small changes in designs or tactics can make significant changes on overall performance. The use of thick shield walls and the argon hot cell provide barriers to access that are taken advantage of in the PPS design. Replacement of a PIDAS with Fused Radar and Video Motion Detection provided advanced detection of outsider incursion. Small changes, such as the need for mantraps at emergency exits, were required to add more delay in certain attack scenarios. Response force tactics were also found to be important and tended to rely on containment strategies during specific attacks.

Safeguards and Security by Design Recommendations

A safeguards system on the front end of an electrochemical reprocessing facility will likely rely mainly on C/S like other reprocessing facilities. It makes sense to make the MBA 1 boundary the same as the physical boundary for the air hot cell. MC&A is established with item accounting of spent fuel assemblies entering the facility, C/S of head end operations, and the input accountancy measurement as well as NDA measurements of hulls and hardware.

The boundary of MBA 2 aligns with the boundary of the argon hot cell, which contains most of the electrorefining and cathode processing operations. For MBA 2, flushout of the facility may not be realistic depending on the flowsheet design. However, the material balance can be performed when most of the actinides are located in only one or two vessels. Plant balances require measurements of inputs and outputs, along with a precision measurement on the ER vessel only. Other locations can utilize less precise NDA or process monitoring measurements to quantify small actinide quantities or to verify only trace amounts.

Input accountancy continues to be a challenge area for electrochemical facilities. Future plants should consider modifications to front end operations to facilitate an input accountancy measurement. Other research suggests that homogenization and sampling will be able to achieve measurement uncertainty goals, but the potential need for DA measurements for each assembly would require turning around daily analytical results. The use of microcalorimetry appears promising, but still relies on reduction of sampling error. It may be possible to conduct more independent measurements with nondestructive microcalorimetry than with DA in order to reduce the effect of sampling error.

For the ER salt, the Triple Bubbler was able to achieve an RSD near 1% for total mass. ER voltammetry appears to be promising for an in-situ measurement of actinides and other properties of the salt with an RSD less than 1%. Other technologies have been examined and may serve as fallbacks. Getting representative salt samples still requires more work, but on-line sampling shows promise. Fortunately, salt measurements for accountancy are only needed at the time of the material balance, which may be required weekly or monthly depending on regulatory requirements.

For the U product measurement, a combination of NDA and periodic DA measurements would likely be utilized. Modeling work found that 0.02% contamination of Pu could be detected with the HDND with high detection probability. Thus, the HDND is a good confirmation for the operator that the process is operating as expected. Microcalorimetry has the potential to improve quantification of U product composition based on measurements of U oxide reference materials.

For the U/TRU product measurement, melt sampling would likely be used to measure every product which will be needed for both accountancy and process control. Microcalorimetry and the HDND also showed promise in this location for the accountancy measurement, but more experimental work is necessary. The thermocouple measurements had higher measurement uncertainties but might be considered for process monitoring.

Waste measurements were not specifically performed as part of the MPACT work, but it is expected that NDA technologies already developed for aqueous reprocessing can be used for electrochemical waste streams as well.

Electrochemical plants do present the potential to utilize unique process monitoring technologies. OR voltammetry has proven to be successful in detecting actinide presence in the OR salt. Current and voltage monitoring, along with detailed ER models, such as the DyER model, can be used by the operator to estimate inventories and operation of the facility. Bulk mass measurements throughout would also be used by an operator for bulk material tracking. More

R&D is needed to explore data analytics and machine learning approaches for incorporating the variety of operator data into safeguards or process monitoring systems. Challenges include the amount of require training data and how to make the underlying algorithms more transparent.

Gamma and neutron flux mapping was used to determine how well an in-cell HDND could detect actinides. Future plants should consider hot cell designs that shield other processing vessels from the OR and ER. This would facilitate confirmatory or holdup measurements.

For the physical security design, depending on the operator's goals, a PIDAS could be replaced with either seismic sensors on the building surface or Fused Radar and Video Motion Detection, which can save considerable up-front PPS costs. The location of the U/TRU vault in the basement provides a significant PPS advantage since there is a considerable delay time required to access the vault without bringing the entire building down on top of the attackers. Man traps on all emergency exits were needed in order to provide more delay against one of the sabotage scenarios. Response force tactics also play a critical role in overall effectiveness.

Conclusion

The MPACT 2020 milestone demonstrates how technology development, experimental testing across the U.S. national laboratory complex, and modeling tools work together to apply SSBD for new nuclear fuel cycle facilities. These capabilities can be utilized by vendors for optimizing safeguards and security designs for future facilities. Optimization is a driving principle in this work since one of the goals is to allow future facilities to meet regulatory requirements with cost-effective materials accountancy and physical protection systems. Many aspects of this effort have investigated new technologies or approaches that reduce burden to the operator.

The Virtual Facility Distributed Test Bed was demonstrated using an electrochemical reprocessing facility as an example. The materials accountancy design, using the best-case measurement uncertainty performance, was able to meet IAEA detection goals for abrupt loss scenarios in MBA 2. NRC requirements could not be met, but those requirements were not written for large reprocessing facilities. The PPS design was able to meet regulatory requirements after some iteration on the design, and cost-saving efforts were included. These baseline system designs are available to use as a starting point for future developers of this type of reprocessing facility.

Many of the capabilities used as part of the Virtual Facility Distribute Test Bed can be or have been applied to other fuel cycle facility types. SSBD helps stakeholder to consider MC&A and PPS challenges early in the design process in order to develop robust systems with optimized cost. Stakeholders should consider these capabilities in future design and licensing efforts.

Keywords

Electrochemical; Safeguards; Security; Safeguards and Security by Design; Pyroprocessing;

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