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Safeguards and Security Analysis for Fuel Cycle Facilities

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National Academy of Sciences Study: Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors

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U.S. DEPARTMENT OF ENERGY

NNSA

Outline

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- Pyroprocessing
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Safeguards and Security by Design

Terminology

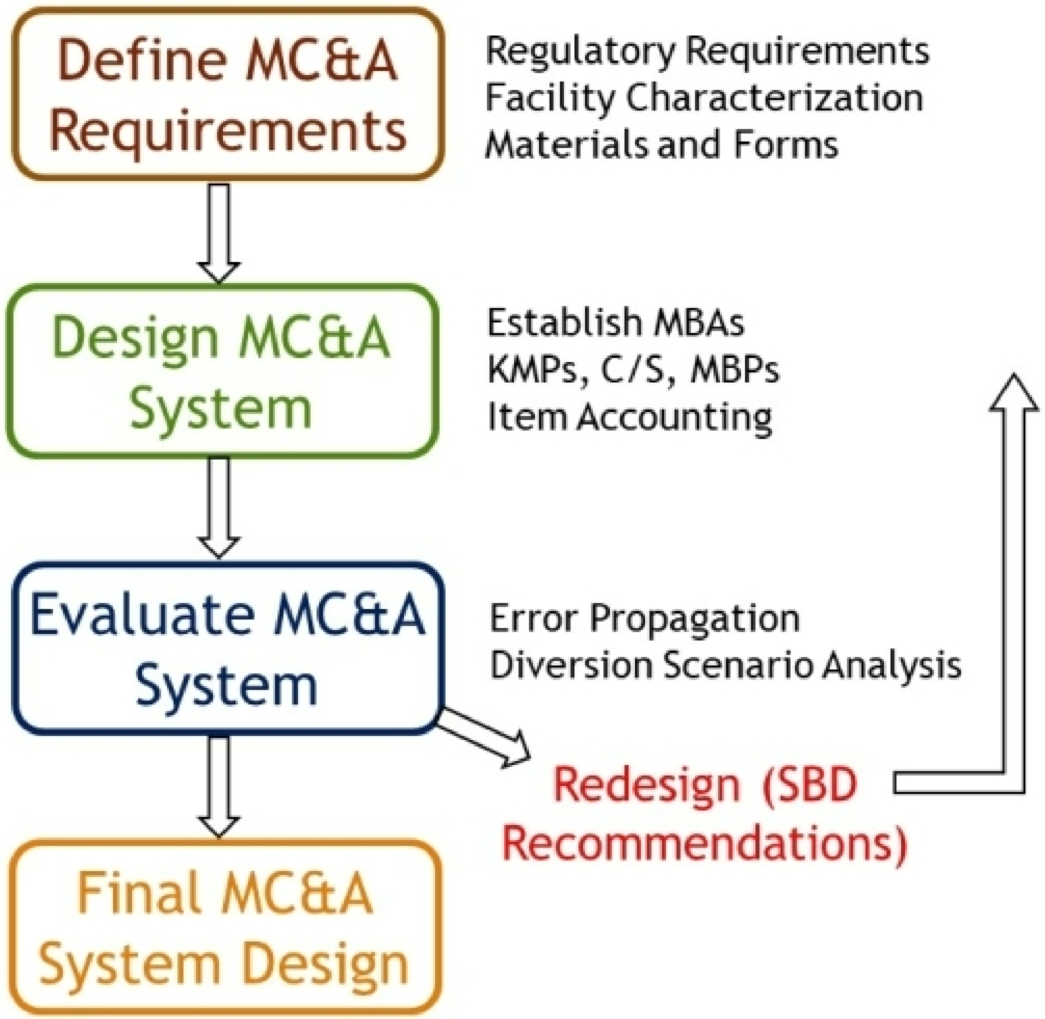
I tend to use the terms **Safeguards** and **Security** is a more general sense, but I'll try to distinguish between domestic and international.

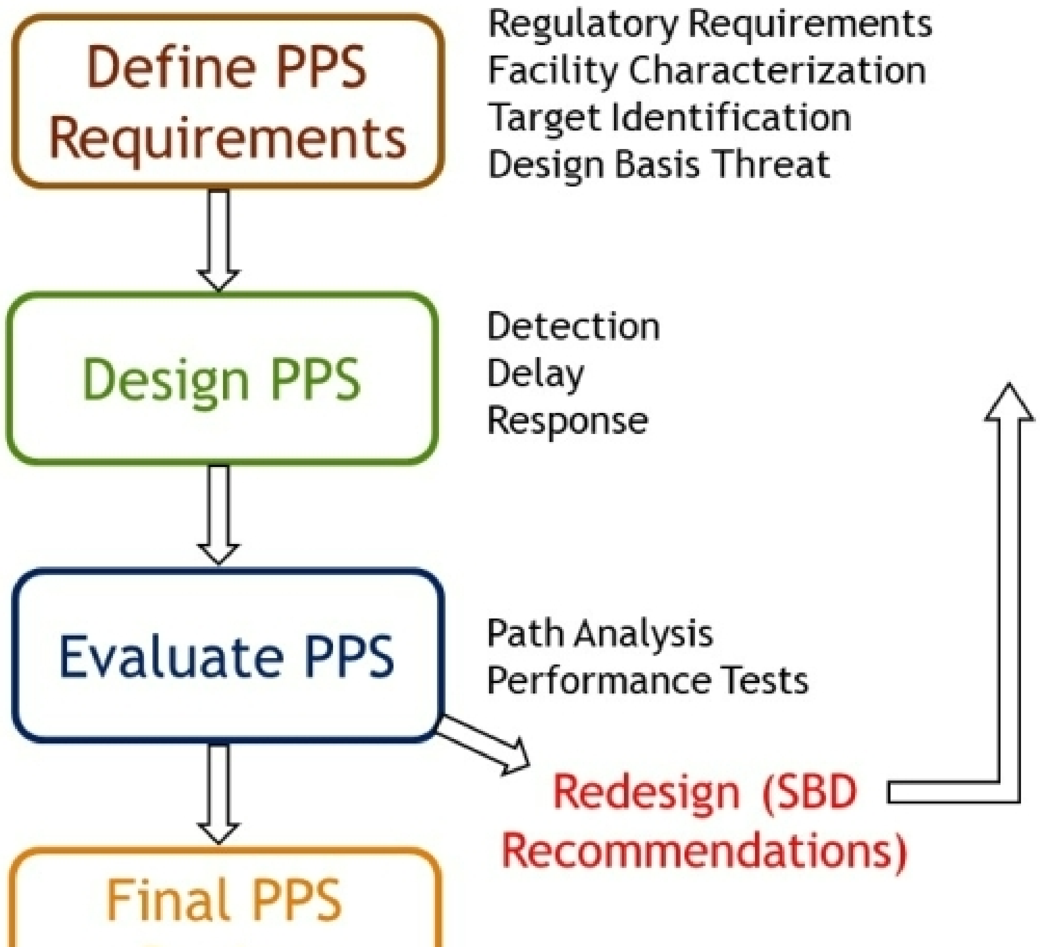
- **Domestic Safeguards:**
  - System designed to meet the state's regulatory requirements for material control and accounting. Nuclear Material Accounting and Control (NMAC) sometimes used.
  - The threat is based on a sub-national group (external or insider).
  - Covered by 10CFR74 in the U.S.
- **International Safeguards:**
  - Refers to international (IAEA) requirements to prevent material diversion or facility misuse by the state.
  - The threat is the host state, goal is to prevent proliferation by the host state.
- **Security:**
  - Mainly in the domain of the state, and operators must meet the state's requirements for physical and cyber protection.
  - Threat is a sub-national group with capabilities defined by a Design Basis Threat.
  - Covered by 10CFR73 in the U.S.

Safeguards and Security by Design

- **Safeguards by Design and Security by Design are not new concepts, but we do need to continue to push these concepts on vendors in order to prevent repeating mistakes of the past.**
  - Expensive retrofits to meet International Safeguards requirements for the Rokkasho Reprocessing Plant in Japan.
  - Overly robust structures and physical protection systems (the PPS should not be a standard design placed around every nuclear facility).
  - Early planning can make materials accountancy measurements and physical security elements more effective.
- **These concepts are not "owned" by any particular community. In general these are best practices for design of systems to meet both domestic and international requirements.**
- **Vendors need to take both requirements into account early in the design process.**

Safeguards and Security System Design Process



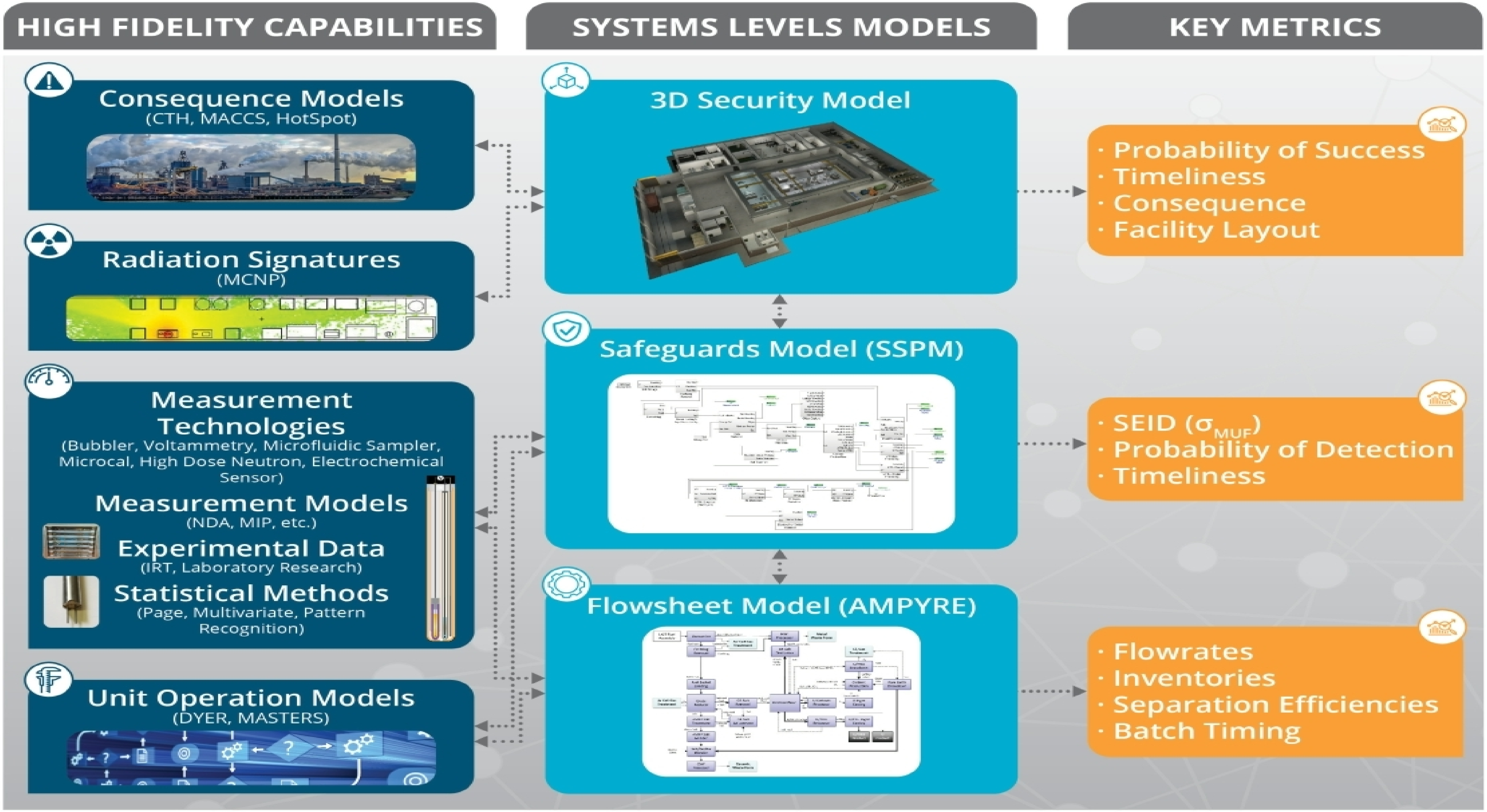


DEPO, ref: M. L. Garcia, "Design and Evaluation of Physical Protection Systems, 2nd edition," Sandia National Laboratories (2008).

MPACT 2020 Milestone

- The Materials Protection Accounting and Control Technologies (MPACT, DOE-NE) working group completed a 2020 Milestone to demonstrate Safeguards and Security by Design for next generation nuclear facilities.
- The milestone is encompassed in a Virtual Facility Distributed Test Bed that incorporates measurement technologies, data from field testing, and mod/sim tools.
- Today we have several single-analyst tools available to help with SSBD. These tools are used to design the system, test against various threats, and refine based on performance metrics.
- The MPACT 2020 Milestone used a conceptual pyroprocessing facility as an example and concluded with a preliminary material control and accountancy (MC&A) and physical protection system (PPS) design, performance metrics, and several SSBD recommendations.

Virtual Facility Distributed Test Bed



Aqueous Reprocessing

Safeguards Requirements

- 10CFR74 covers all aspects of MC&A requirements including reporting, inventory timing, detection goals, item monitoring, alarm resolution, and quality assurance. **Note this regulation specifically excludes large reprocessing facilities.**
  - Cat I facilities report semi-annual inventories.
  - Require statistical test capable of detection 5 formula kilogram quantities with 7 working days (Cat 1b) with 95% detection probability.
  - Standard Error of the Inventory Difference should be less than 0.1% of active inventory
- In the absence of new rulemaking from NRC, IAEA regulations can also be used for reference:
  - Goal to detect the loss of 8 kg of Pu within one month with 95% detection probability (generally for pure materials)
  - Timeliness requirement increases to 3 months for Pu in mixed solutions/materials.

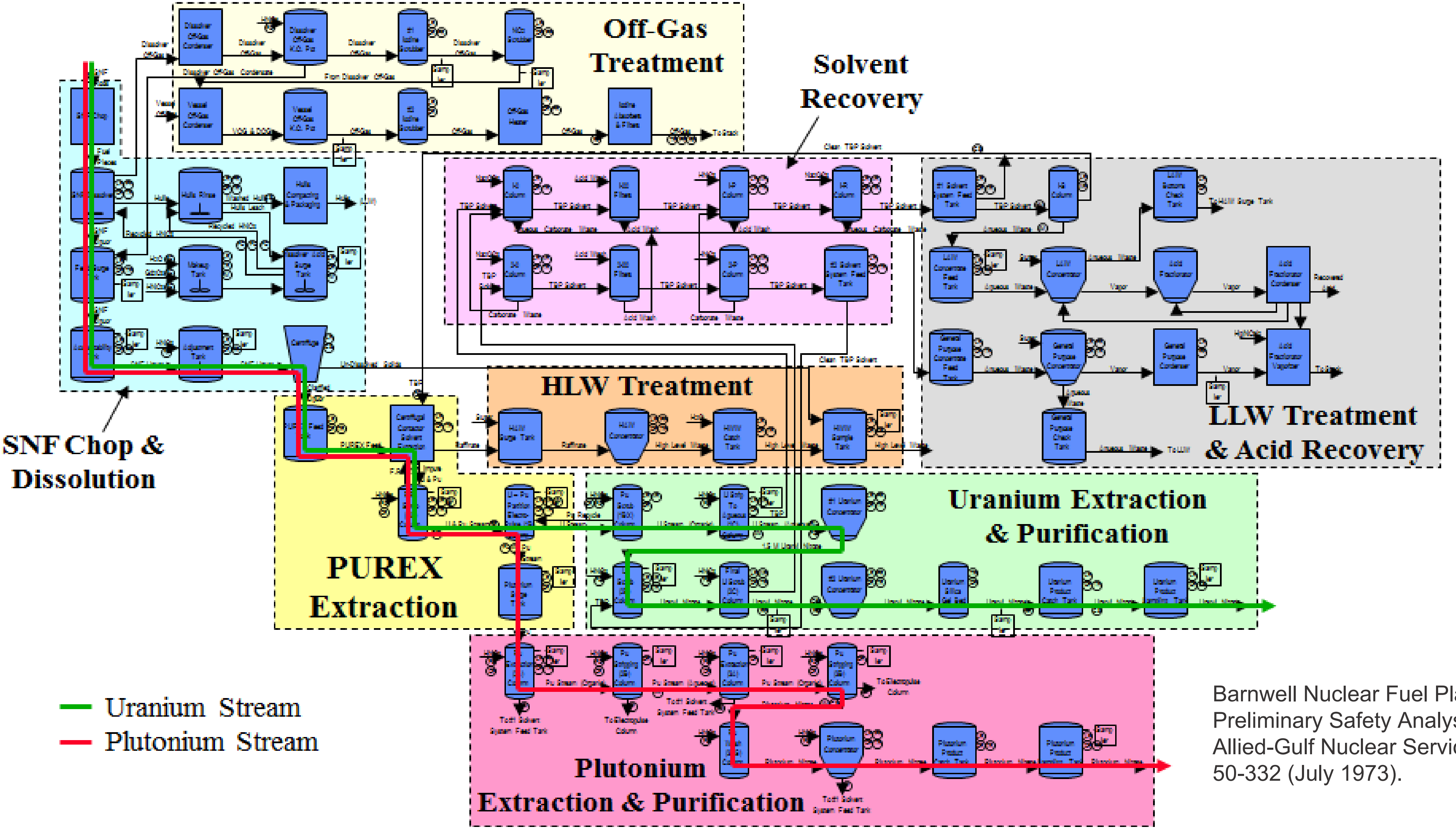
Security Requirements

- 10CFR73 covers the design of the PPS for a Cat I facility:
  - At least one security member on site at all times, but 2 guards at each access control point.
  - Response team of at least 5 members at all times.
  - Perimeter intrusion detection and assessment required around the protected area.
  - At least two barriers for vital areas.
  - **Note that new rulemaking in NRC is leading to changes for advanced reactors that allows them to take advantage of improved safety systems.**
- The design of the PPS is heavily based on the Design Basis Threat (DBT).
  - Defines number of adversaries
  - Capabilities & equipment
  - Outsider vs. insider vs. both

History of Aqueous Work

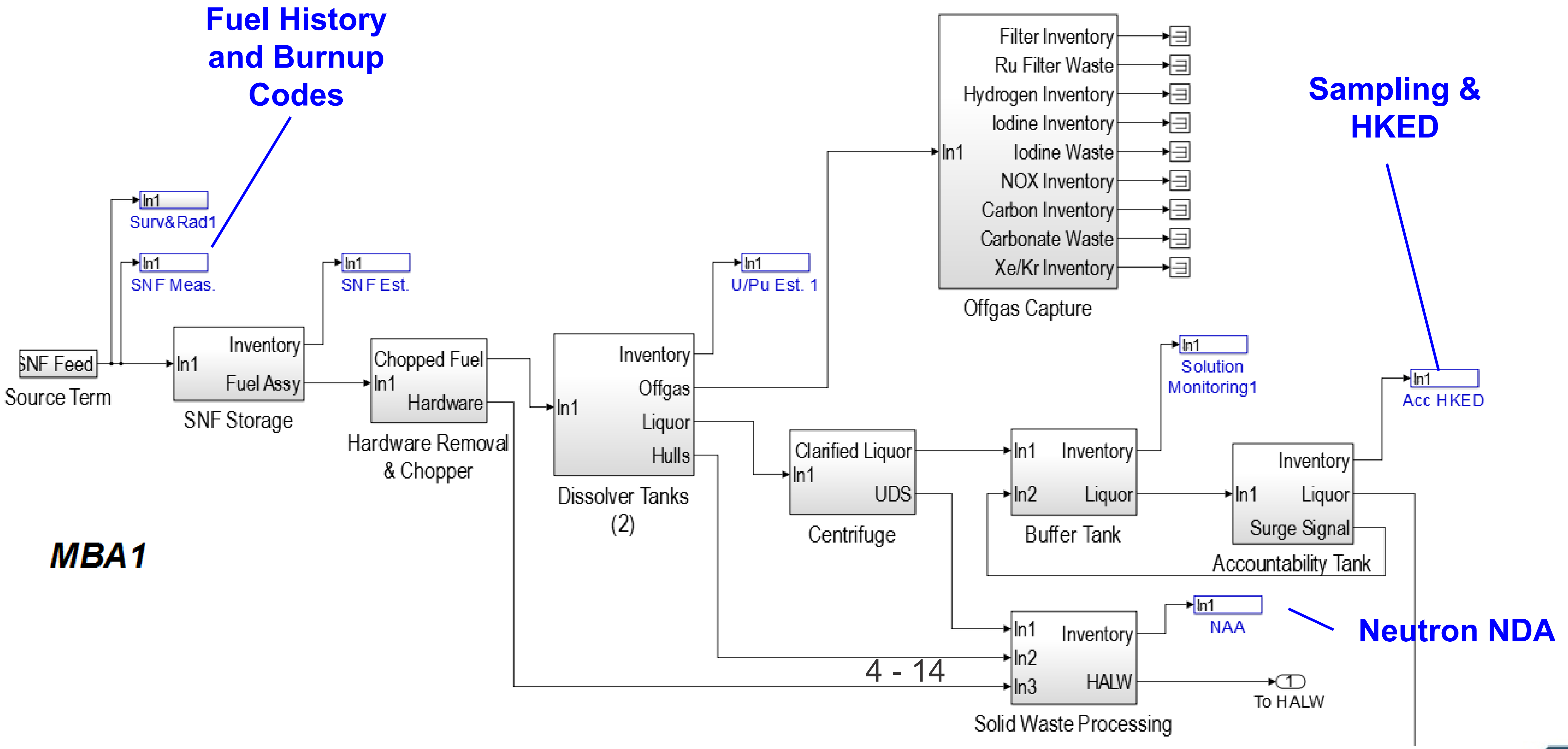
- Process and safeguards modeling work for aqueous reprocessing work ramped up during GNEP, but our domestic work (DOE NE) somewhat ended around 2014.
- The modeling work has continued through NNSA funding to support international safeguards needs. We've maintained the models for some recent work on machine learning applications.
- Aqueous reprocessing traditionally has required very large and costly facilities, and without a clear need for recycling or significant impact on waste reduction, it has been difficult to justify.
- Aqueous reprocessing would likely need to see a revolutionary change in technology improvement to bring down costs.

Barnwell Reprocessing Plant

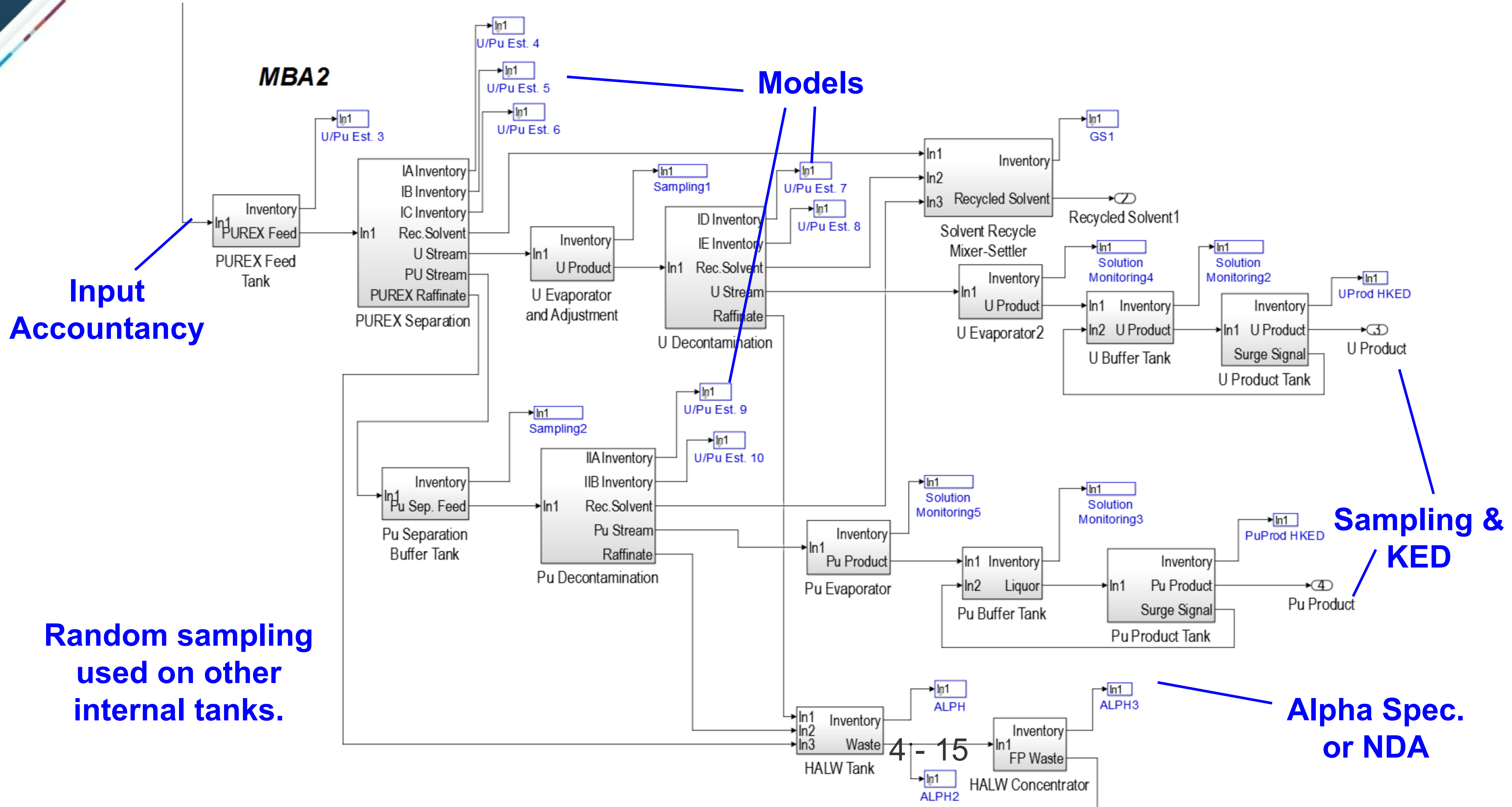


Barnwell Nuclear Fuel Plant, Preliminary Safety Analysis Report, Allied-Gulf Nuclear Services, Docket 50-332 (July 1973).

Material Balance (Front End)



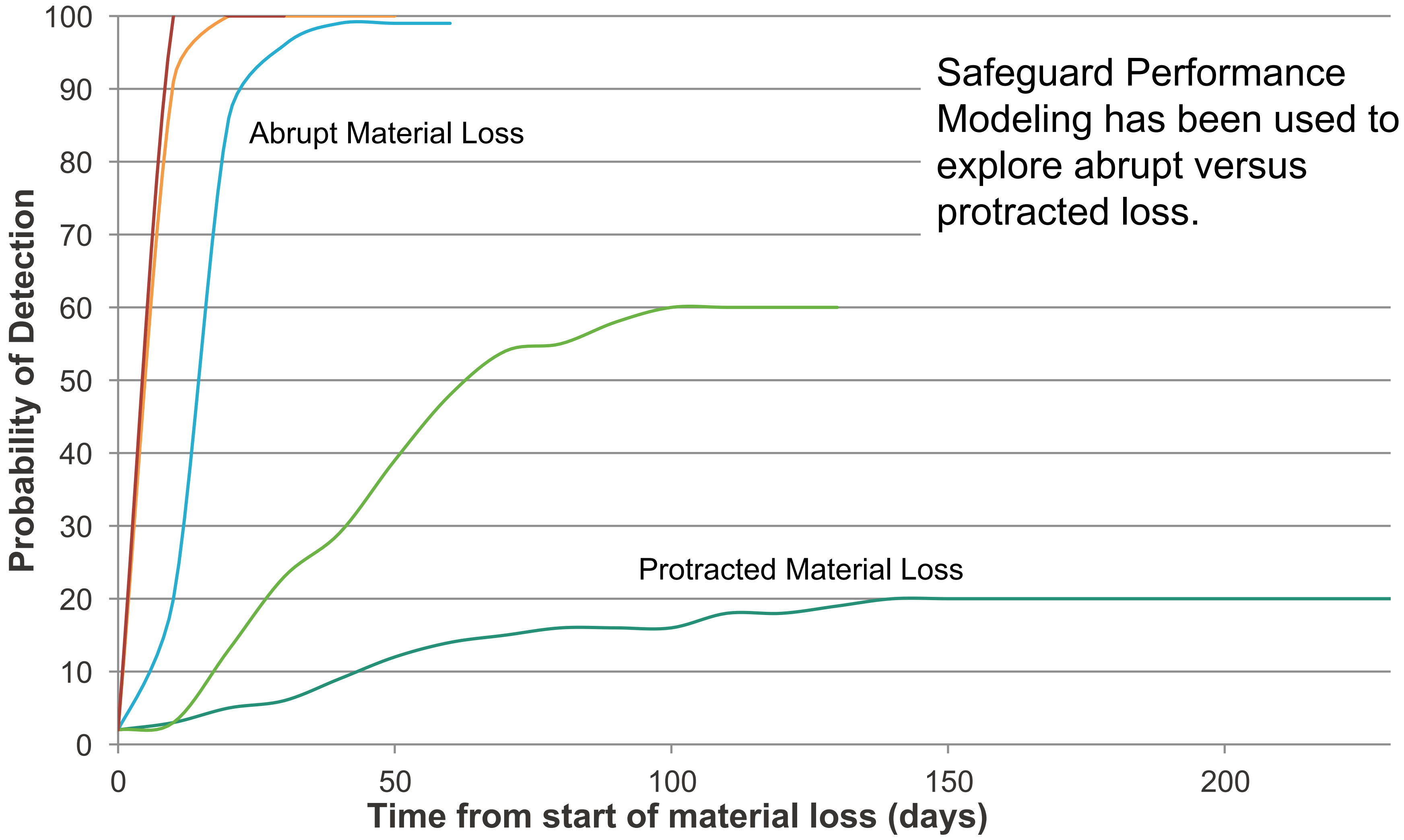
Material Balance (Separations MBA)



Materials Accountancy at Large PUREX Plants

- Materials accountancy measurements for reprocessing are very well established with uncertainties on U and Pu in the 0.2-0.8% range.
- With a 1000 MT/yr facility (processes approximately 10,000-15,000 kg of Pu per year, the measurement uncertainty alone over a year of operation is about 100 kg.
- Since it is difficult to achieve IAEA goals, additional measures are used to provide additional assurance.
- The Interim Inventory Verification (monthly balance) was introduced for the Rokkasho Reprocessing Plant in order to meet the one-month timeliness requirement.
- Impracticalities in getting enough measurements (all at the same time, once per month), led to the design of the Short Inventory Verification (approximately every 10 days).

Probability of Detection Timeliness



- While protracted loss is difficult to detect through the materials accountancy system, there are practical considerations to take into account from the domestic safeguards and security perspective.
- How easy is it for an insider or outsider to remove very small amounts of material over long periods of time?

Materials Accountancy at Large PUREX Plants

	Abrupt Theft 1		
	Baseline	Integration of Pu Balance	Integration of Pu Balance and Bulk Balance
No NMAC Detection	96%	97%	0%
RF Win %	25%	30%	100%
100% of Goal Quantity Removed	79%	79%	0%
	Abrupt Theft 2		
No NMAC Detection	62%	0%	0%
RF Win %	45%	92%	100%
100% of Goal Quantity Removed	48%	3%	0%
	Abrupt Theft 3		
No NMAC Detection	41%	0%	0%
RF Win %	48%	91%	100%
100% of Goal Quantity Removed	40%	2%	0%
	Protracted Theft 1		
No NMAC Detection	15%	0%	0%
RF Win %	57%	80%	100%
100% of Goal Quantity Removed	13%	3%	0%
	Protracted Theft 2		
No NMAC Detection	2%	0%	0%
RF Win %	68%	72%	100%
100% of Goal Quantity Removed	4%	3%	0

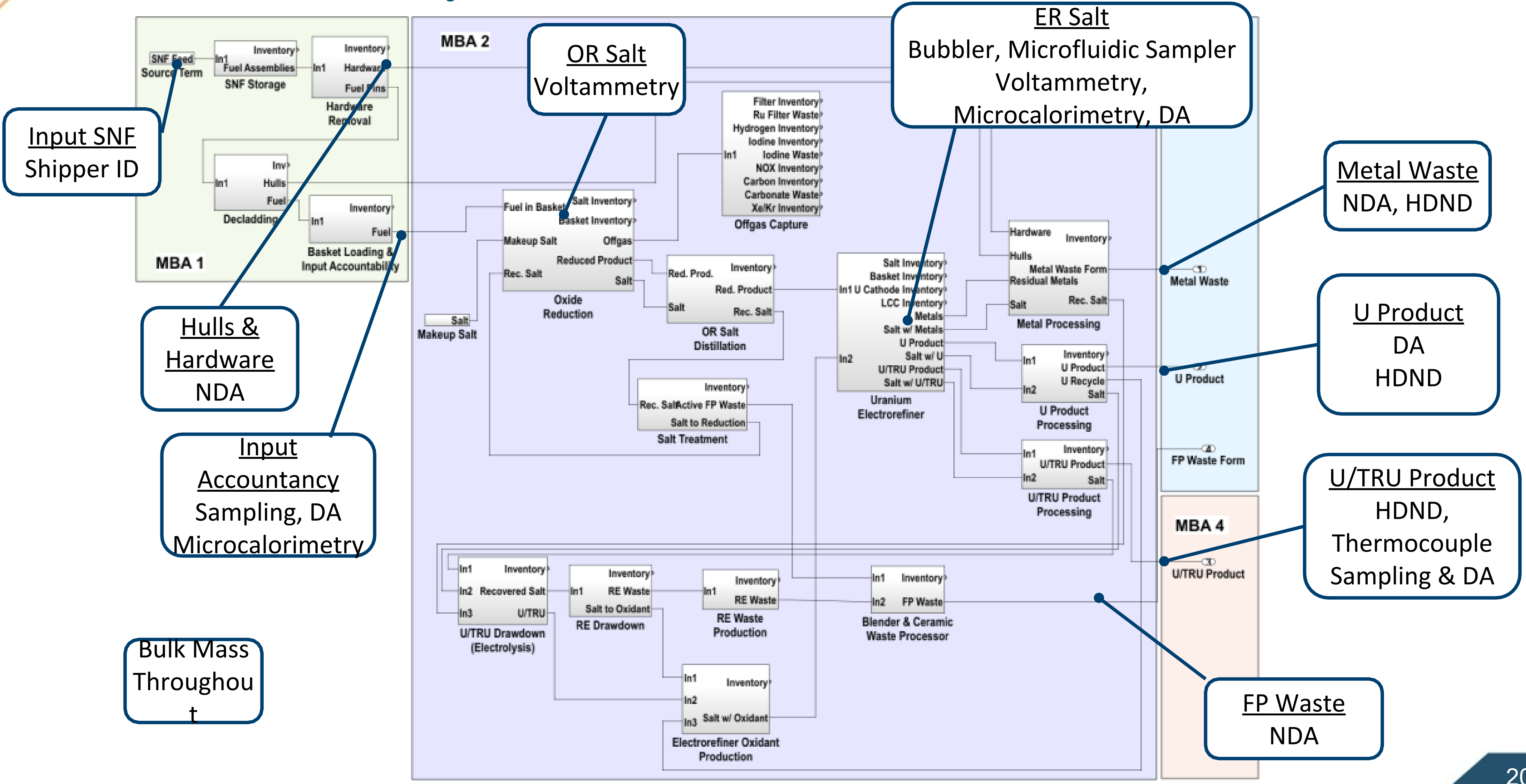
For very abrupt theft scenarios, an insider could potentially remove material before the PPS has a chance to respond. Integration with process monitoring data helps to detect the loss sooner.

For more moderate loss scenarios, the accountancy system can enhance detection and response.

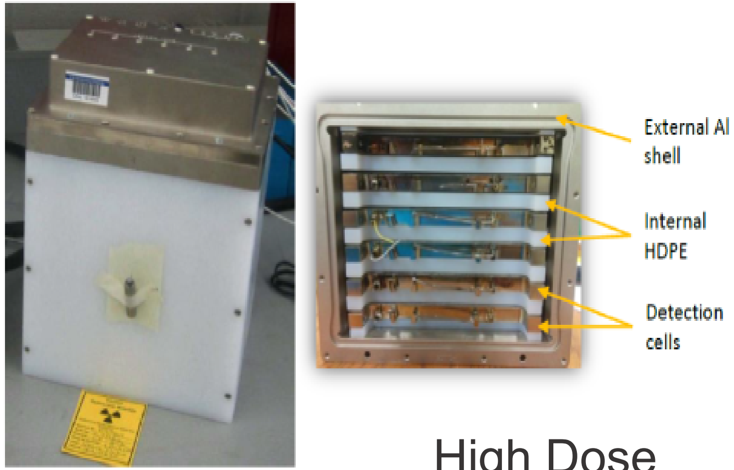
For protracted loss scenarios, the accountancy system doesn’t help much, but the PPS has many more opportunities to detect the activities.

Pyroprocessing

Virtual Facility Distributed Test Bed

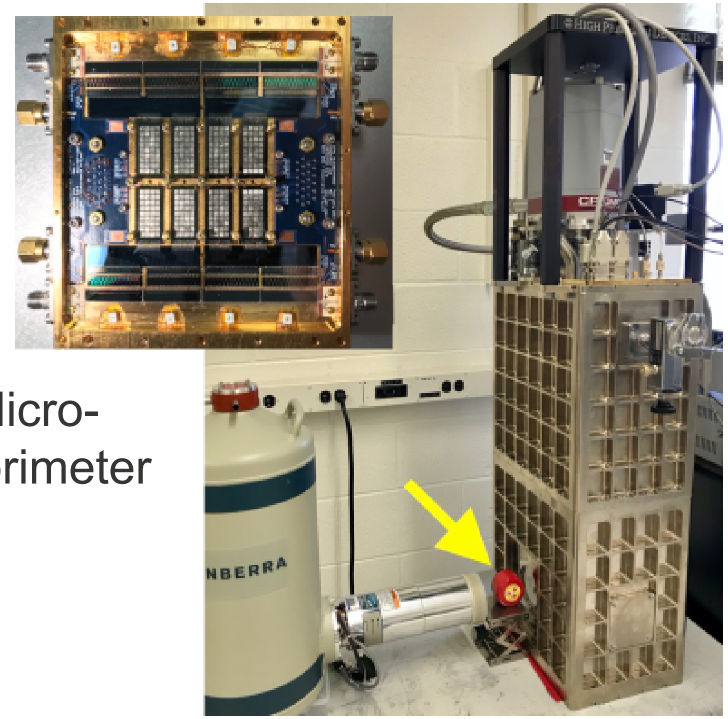


Measurement Technologies to Support MC&A



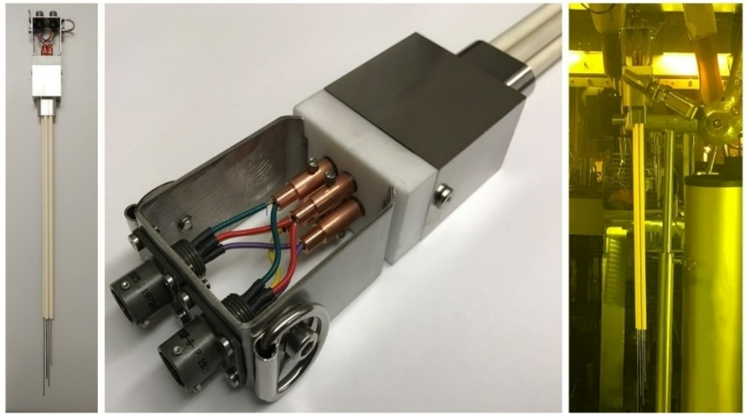
High Dose
Neutron Detector

Triple
Bubbler

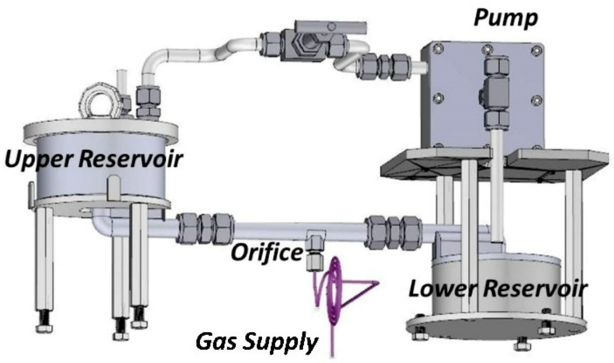


Micro-
calorimeter

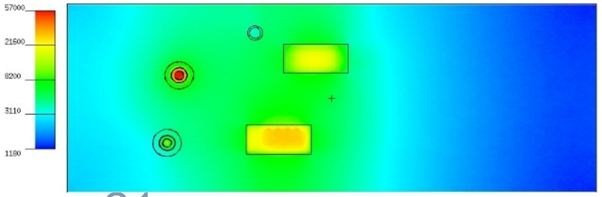
Voltammetry Sensor



Sample Extractor



Hot Cell Flux Mapping



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Safeguards Performance Modeling Results

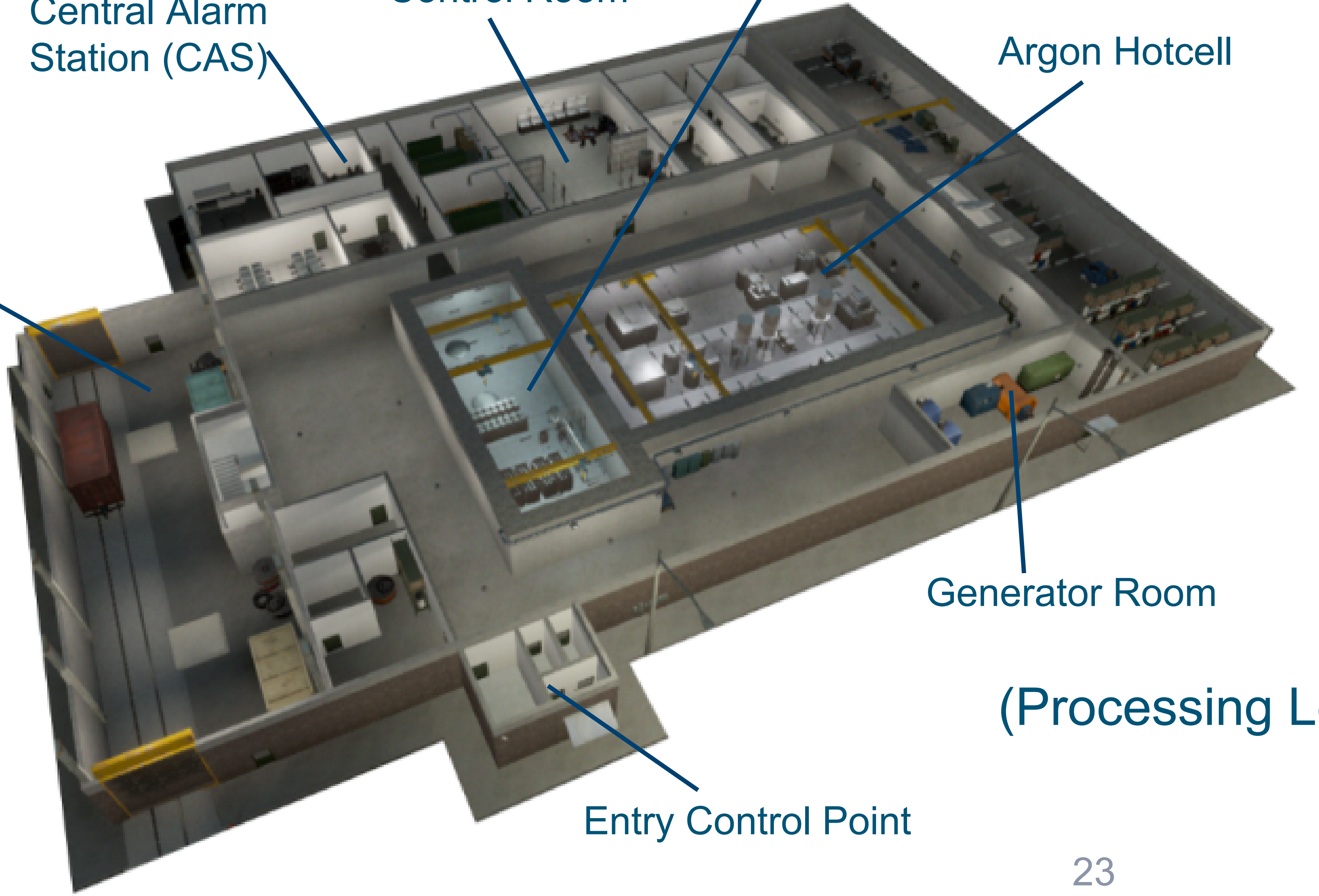
Safeguards Modeling Results Based on IAEA Detection Goal (8 kg Pu in one Month):

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

Safeguards Modeling Results Based on NRC Detection Goal (2 kg Pu 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

PPS Design



(Processing Level)

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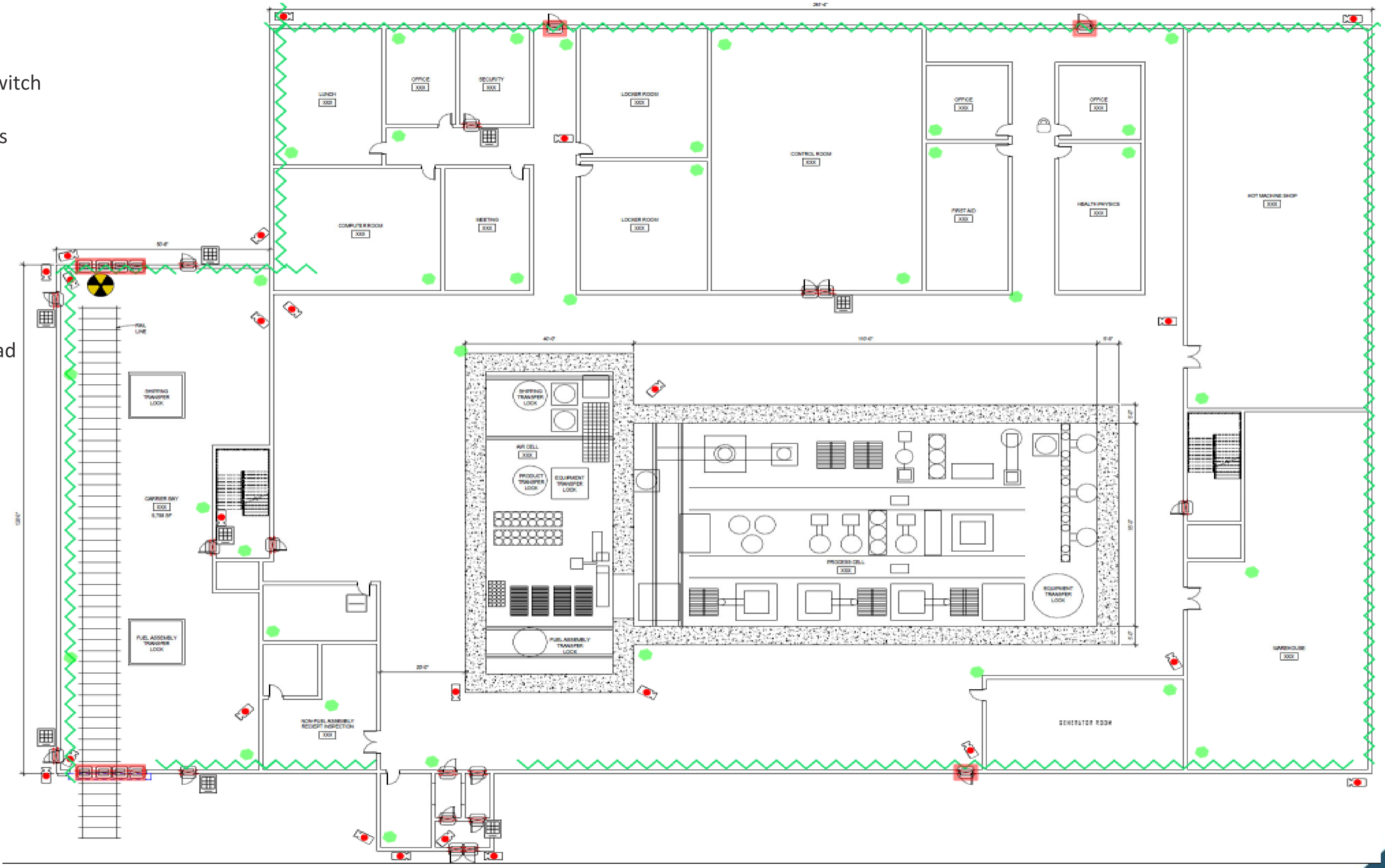
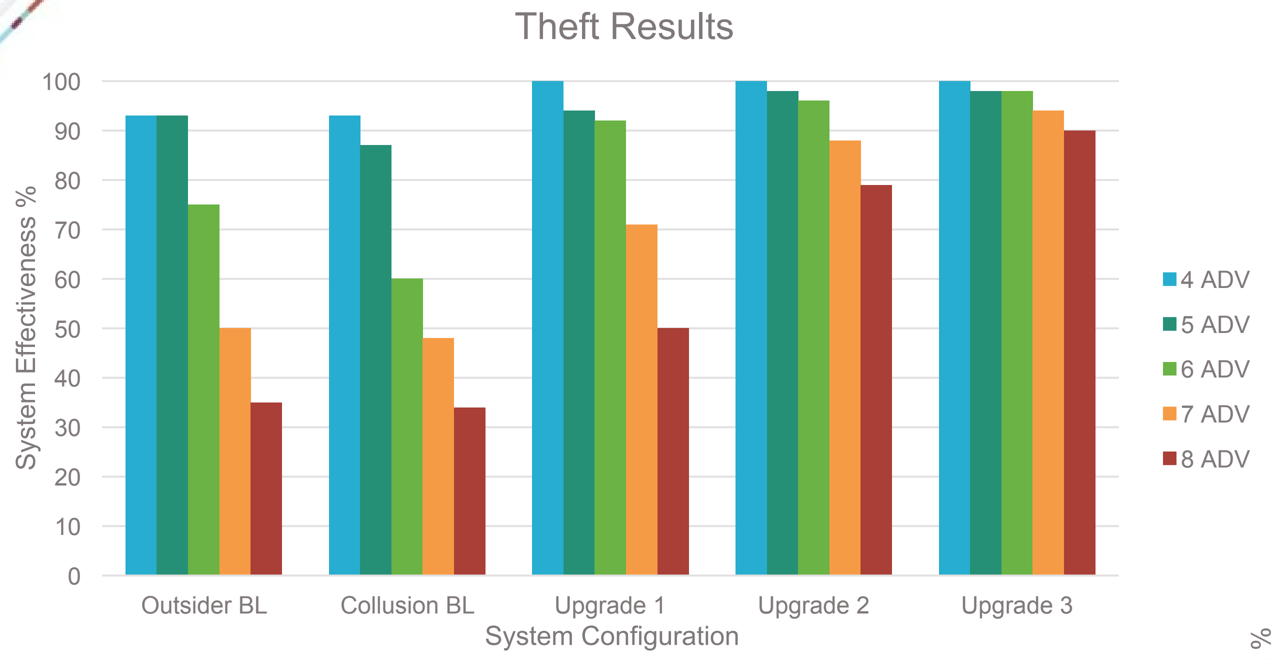
Example PPS Layout

- Balanced Mag. Switch
- Dual Tech Sensors
- Active Infrared
- Cameras
- Card Swipe
- Card Swipe Keypad
- Seismic Sensors
- Rad Sensor

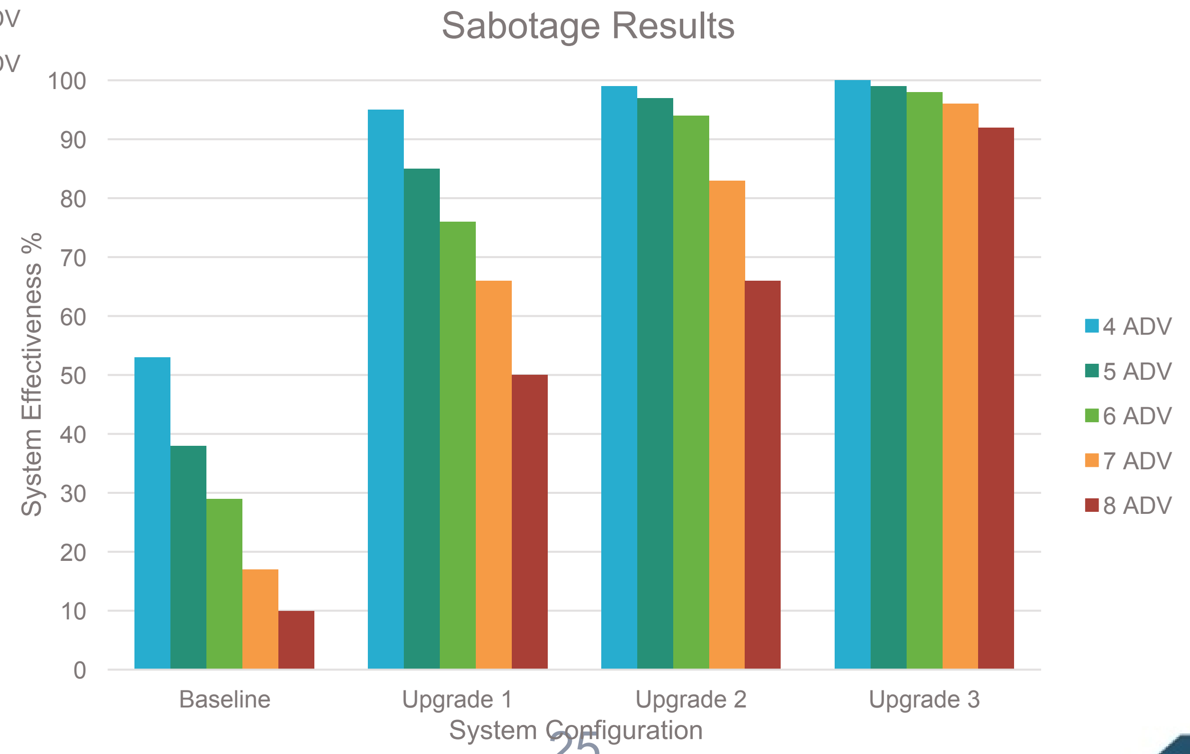


Security Performance Modeling Results



Adversary theft scenario results showing the effect of upgrades

Adversary sabotage scenario results showing the effect of upgrades



Key Safeguards by Design Recommendations

- Input accountancy is a challenge for pyroprocessing since the fuel is measured as particles (instead of a dissolved solution). Recent work has evaluated sampling and homogenization of declad spent fuel, but it requires a lot of effort and destructive analysis.
  - The measurement type needs to be compared to a high-precision DA baseline in order to determine measurement uncertainty. Representative standards will be required to determine systematic errors.
- More work is needed on obtaining representative salt samples. Significant advances were made with the Triple Bubbler, ER Voltammetry, and representative sampling, but the work is still immature.
- Product measurements (on the U and U/TRU products) have been demonstrated using DA, but more work would be required to determine if NDA measurements could be used.

Key Safeguards by Design Recommendations

- Pyroprocessing plants have unique process monitoring signatures (current, voltage), but significantly more work would be required to determine how to use these signals as part of a safeguards approach.
- Advanced data fusion and machine learning approaches were examined, but a more dedicated effort would be needed to advance this work.
- Waste and confirmatory measurements were not completed; though they don't have a significant impact on overall model results, these measurements are a part of the overall safeguards approach.
- Process holdup is difficult to estimate or measure, especially when plant designs are still in a conceptual phase. More work is required on this since holdup can be a challenging problem for any bulk handling facility.
- There is significantly more potential to incorporate SBD by calling for facility design changes that make safeguards measurements or security approaches more effective. One example includes customized hot cell shielding to enable confirmatory measurements

Key Security by Design Recommendations

- The PPS design took advantage of the thick hot cell walls and processing which was localized to one building. An alternative to a PIDAS was used (seismic sensors on building exterior) in order to reduce cost.
- Location of the U/TRU product vault in the basement provide a performance advantage since large explosive breaches would bring the entire building down on an adversary.
- PPS work focused on optimized system design with upgrade options depending on desired performance. Locating responders closer to the target, providing hardened fighting positions, and additional external delays (like ankle breaking surfaces) were considered to improve overall performance.

Conclusions

What is the Goal of Safeguards?

- Ultimately the goal of safeguards is to **provide assurance** to government, policy makers, and the public that facilities are operating as expected.
- We can put as many guns, guards, and gates around a facility as we want, but **we need a materials accountancy system** in place to provide the bookkeeping that shows that material has not been lost.
- Materials accountancy is **limited by achievable measurement uncertainty**, but we can use process monitoring (U.S. domestic) or additional measures (international) to increase confidence.
- Containment, surveillance, and physical protection provide additional barriers to material loss in protecting a plant against a subnational threat (but we can’t depend on physical protection for international safeguards verification).
- **Safeguards by Design** should be promoted to help vendors design facilities that are easier to safeguard.

What is the Goal of Security?

- The purpose of security is to **prevent theft and sabotage** of nuclear facilities which could result in loss of nuclear material, harm to the public, or adverse economic impact on the plant.
- The **materials accountancy system can help augment security** through early detection of material loss or misuse—in particular integration can help prevent insider theft scenarios.
- **Cyber security** is of increasing importance as new facilities increase reliance on digital systems.
- Security costs can be a significant operational cost of nuclear facilities—**Security by Design** is an important philosophy to help vendors design optimized and efficient protection systems.