ADVANCED REACTOR SAFEGUARDS & SECURITY

Material Control and Accounting (MC&A) for Liquid-Fueled Molten Salt Reactors: MSR Control Boundary Analysis and Holdup Measurements

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Presentation Overview

- Motivation
- Impact of uncertainties in code predictions and measurements on physical inventory
- High-level MC&A Concept
- Material Balance Area (MBA) Structure Options
- SNM Holdup Monitoring and Measurement Strategies
- Reporting Nuclear Material Management and Safeguards System (NMMSS)
- Summary

Motivation

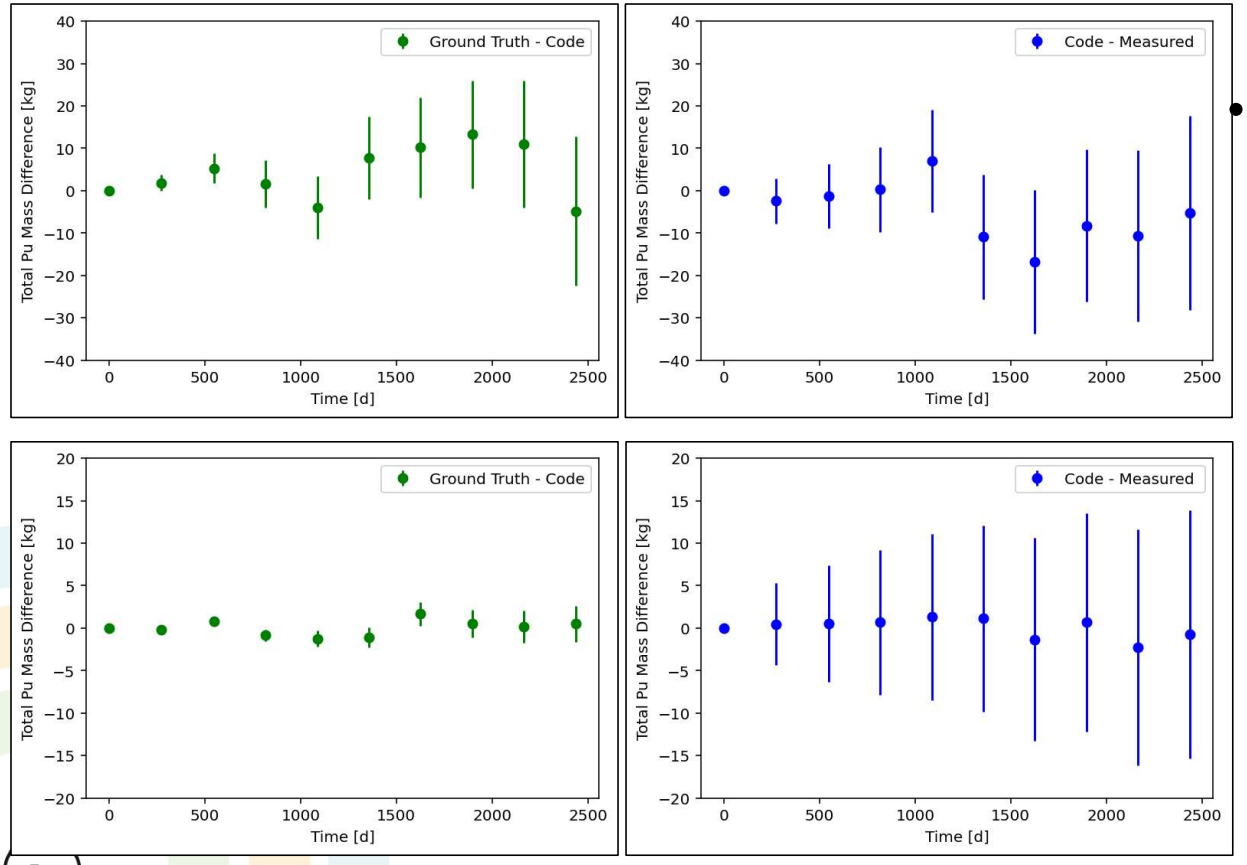
- Domestic safeguards: any reactor license applicant will need to include a description of the MC&A program.
- MSRs are unique in that the fuel is in a liquid form, so item accounting while in the reactor is not an option.
- MSR design vary widely:
  - The most common design assumes limited processing of the salt for gaseous fission product and noble metal removal and 4 to 8 years fuel replacement.
  - Some proposed designs include additional separations of fission products
- The NRC regulations were not written for this type of system, but NRC has been getting up to speed on the technology and MC&A options.
- The MC&A approach may pull from both existing reactors and regulations for bulk processing facilities.

Impact of uncertainties in code predictions and measurements on physical inventory

- **The four MSR designs studied**

Parameter	MSBR variant	MSDR variant	180 MW_{th} NMCFSR	1,200 MW_{th} NMCFSR
Power (MW_{th})	2,250	750	180	1200
Initial fuel salt (mole %)	$LiF–BeF_2–UF_4$ (60–30–10)	$LiF–BeF_2–UF_4$ (67–28–5)	$NaCl–UCl_3$ (66.7–33.3)	$NaCl–UCl_3$ (66.7–33.3)
Initial salt ^{235}U enrichment (wt.%)	2.29	2	13.3	11.7
Makeup salt ^{235}U enrichment (wt.%)	5	5	19.75	No makeup salt used
Length of reactor operations simulated (years)	4	7	7	7

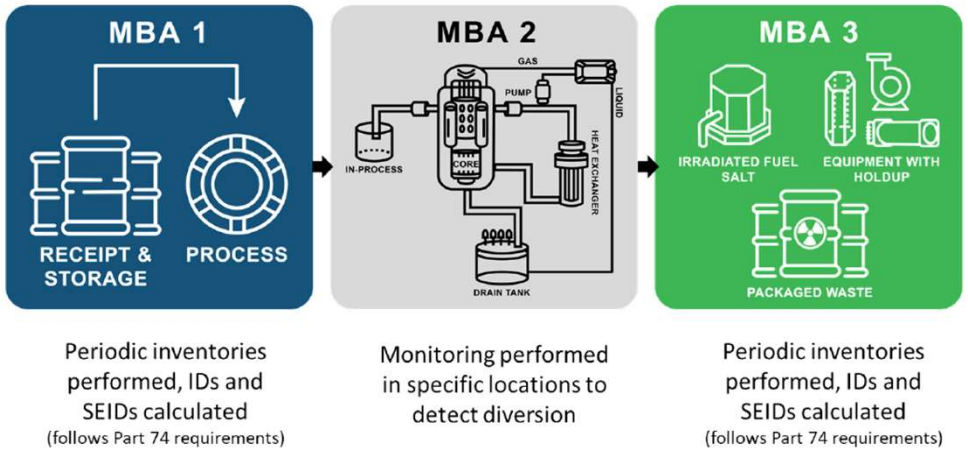
Impact of uncertainties in code predictions and measurements on physical inventory (continued)



- Pu inventory difference for NMCFSR (180 MWth) with a baseload power history
  - 8% relative uncertainty for code predictions (top)
  - 5% relative uncertainty for measurements (top)
  - 1% relative uncertainty for both (bottom).

High-level MC&A Concept: Control measures–based MC&A approach for the MBA containing reactor primary system

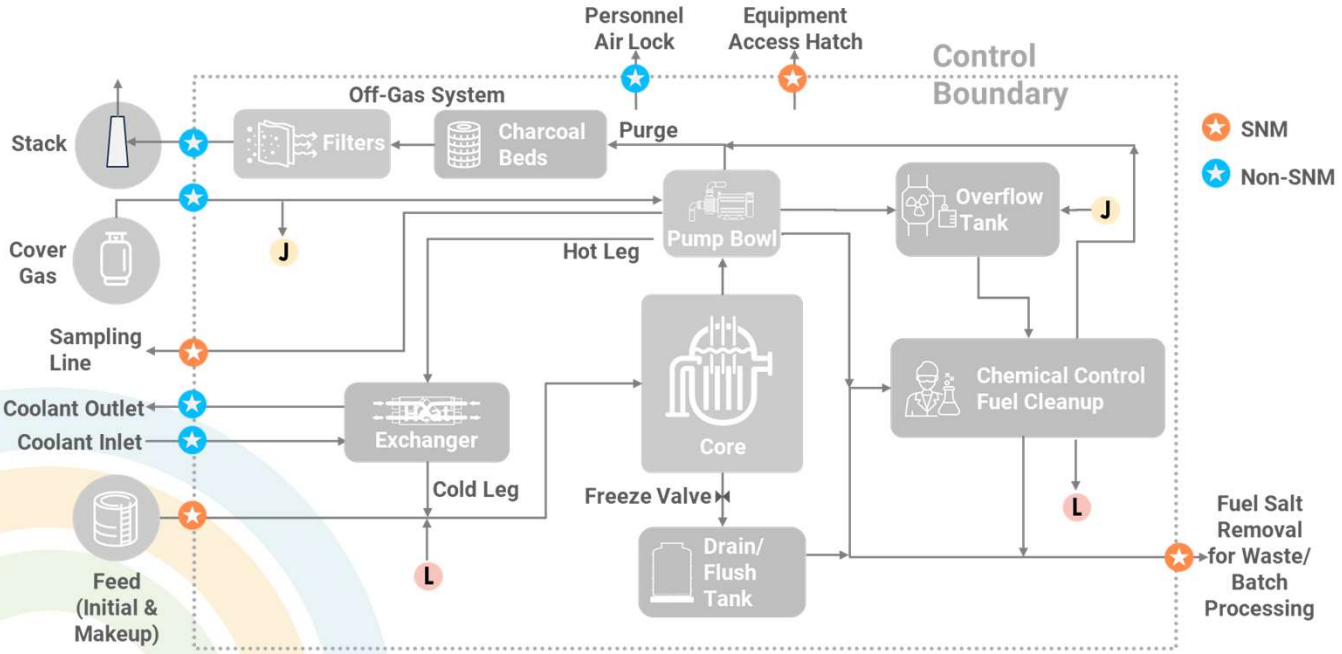
- The MC&A approach will likely break up the reactor into 3 MBAs or 3 sub-MBAs to be consistent with other reactor designs.
- Front end and back end utilize item accounting for fresh and spent fuel salts and can also perform inventory differences while loading or unloading.
- For MBA 2 (reactor loop), control measures are used along with in-situ or process monitoring to gain knowledge on benchmarking codes.



Hogue et al., ORNL Report No. ORNL/SPR-2023/3181, Jan 2024: Image reproduced with permission from ORNL.

High-level MC&A Concept: Control measures–based MC&A approach for the MBA containing reactor primary system (continued)

- Identified potential penetrations to the control boundary to monitor material transfer using control elements



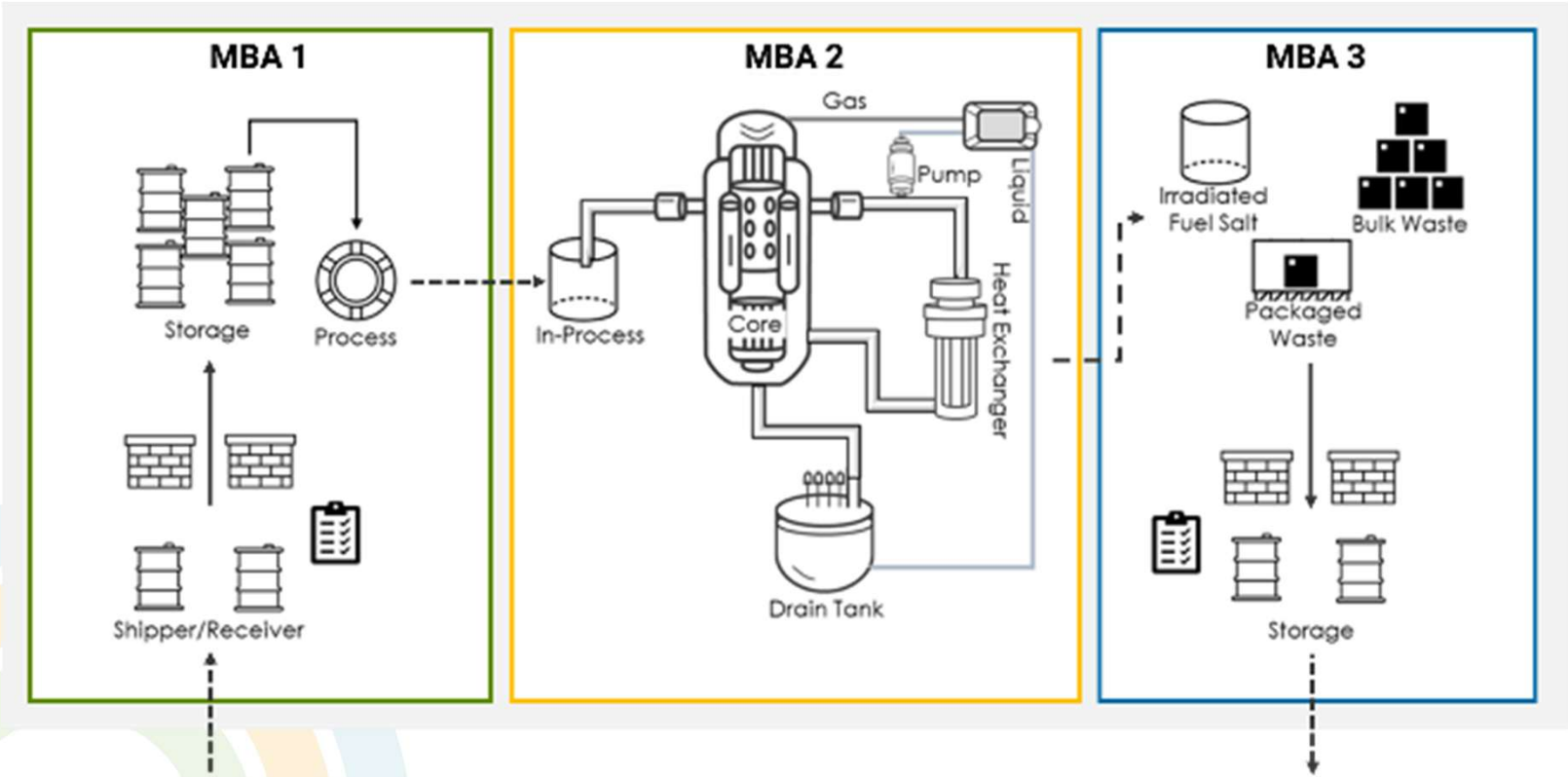
Shah et al., ORNL Report No. ORNL/SPR-2024/3555, Sept 2024. Image reproduced with permission from ORNL.

- Control elements identified for detecting SNM theft via the nine penetrations
- Considered both traditional and nontraditional techniques and measures
- For non-SNM penetrations, we leveraged safety-related or operational measures

High-level MC&A Concept: Control measures–based MC&A approach for the MBA containing reactor primary system (continued)

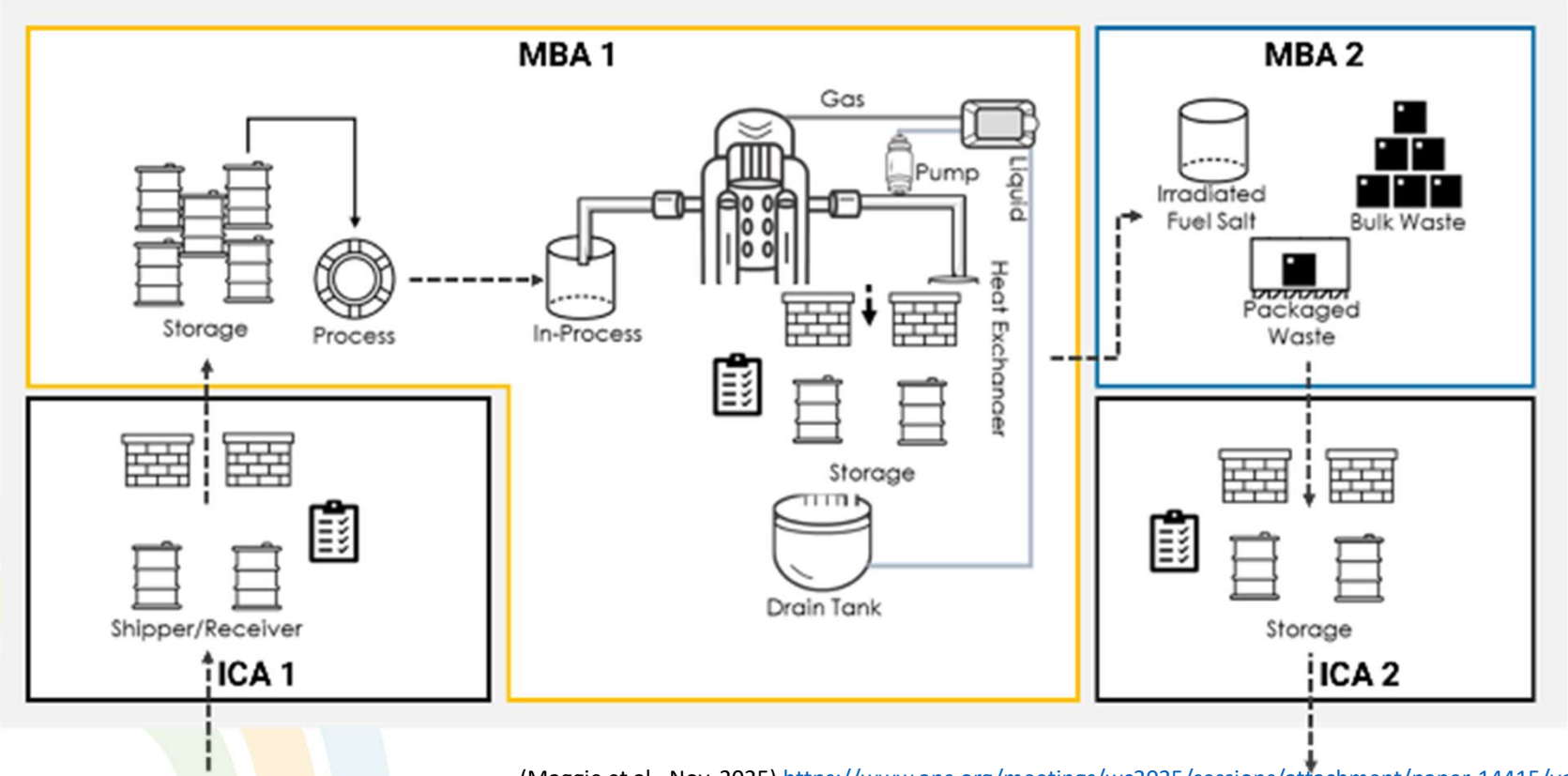
- A set of hypothetical SNM theft scenarios were identified to determine the efficacy of the selected control elements at certain penetrations of the MSR control boundary.
- The hypothetical theft scenarios considered were for fresh fuel feed, sampling line, and irradiated fuel removal line penetrations.
- These penetrations were selected because SNM is expected to move through all these penetrations during reactor operations.
- In all these theft scenarios, each selected control element was considered to discuss the role it would have in detecting the theft of SNM via the selected control boundary penetration.

Material Balance Area (MBA) Structure Options



(Maggie et al., Nov. 2025) https://www.ans.org/meetings/wc2025/sessions/attachment/paper-14415/version-2/

Material Balance Area (MBA) Structure Options



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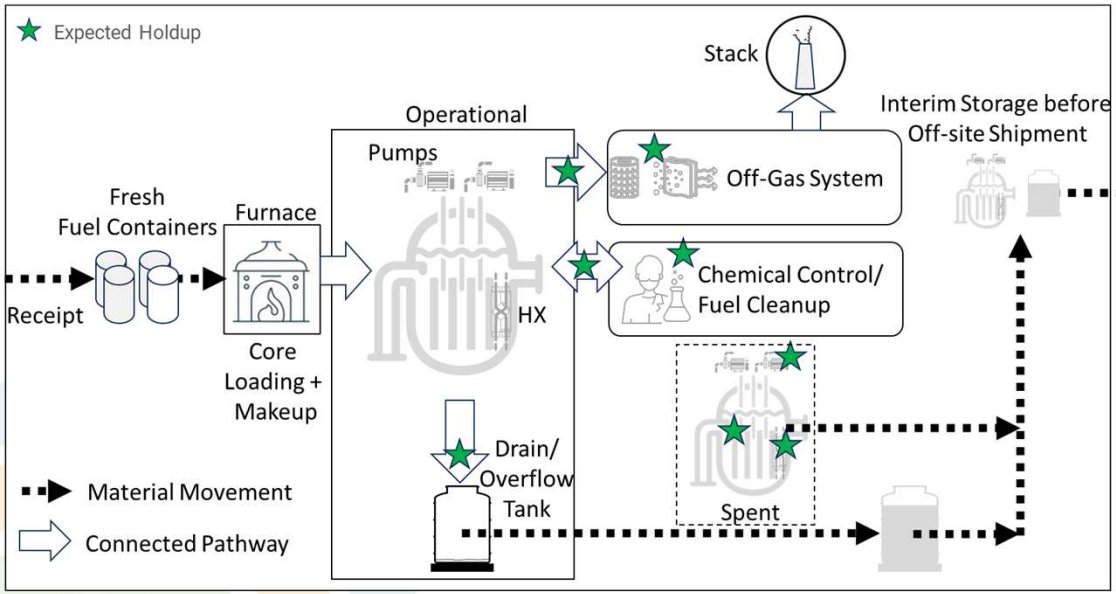
SNM Holdup Monitoring and Measurement Strategies

- Holdup has led to issues in bulk handling facilities in the past



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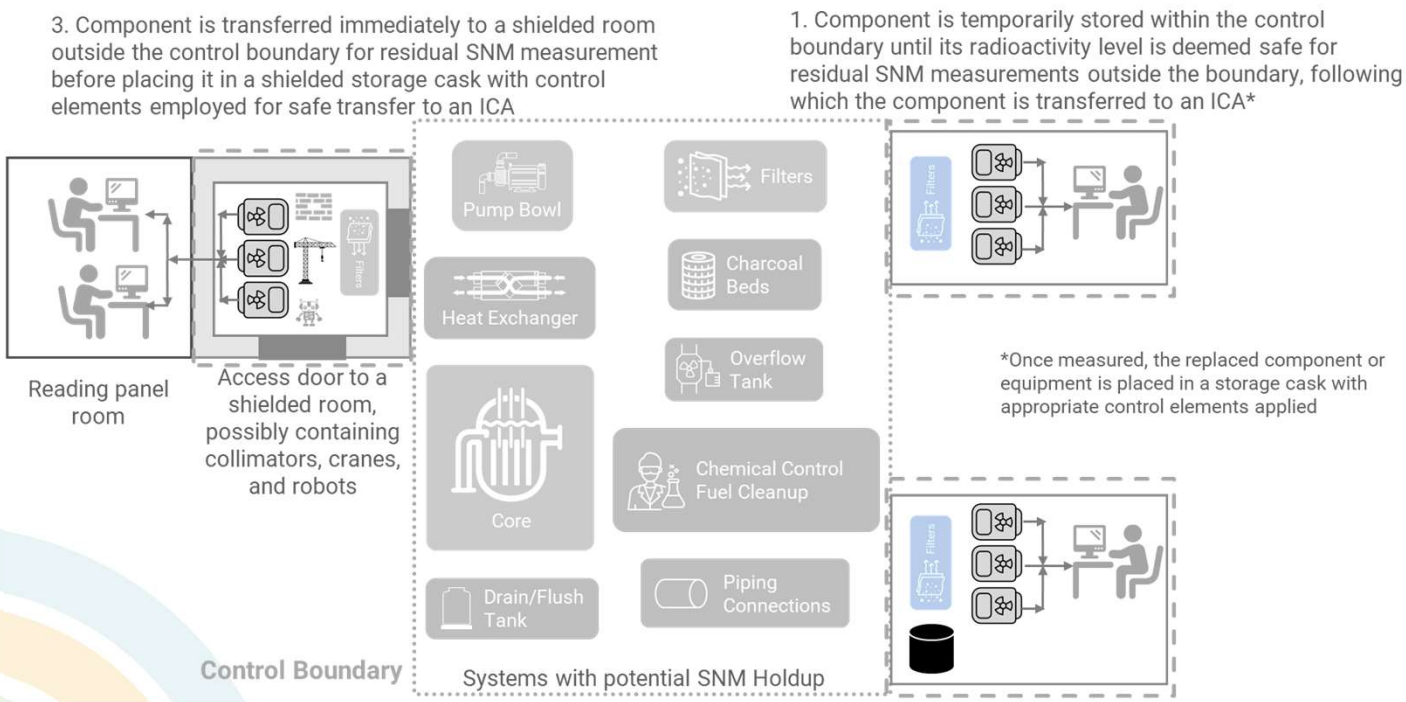
- Could be measured periodically during reactor shutdown
- Monitoring SNM holdup evolution in real time by deploying radiation detectors at strategic locations, such as filters, pump bowl, inlet and outlet of each HX, shell side of HXs that contain fuel salt, and inlet and outlet of the fuel cleanup and chemical control system.
- These fixed detectors fitted with collimators placed within the control boundary can be based on gross count instruments (such as plastic scintillator detector).

Measurement Strategies for Estimating Residual SNM in Components



Reporting to NMMSS

- NMMSS reporting options for special nuclear material (SNM) quantities in the reactor system for “MBA 2”
  1. Measure SNM quantities in the reactor system during operation and report those values.
  2. Use computational codes with operating parameters as inputs to predict SNM quantities expected during operation. Report these into NMMSS.
  3. Report the SNM as the types and quantities that entered the reactor system (e.g., unirradiated U in feed salt) until it is removed and measured (e.g., Pu in irradiated salt).

Summary

- MSRs will utilize item accounting of fresh and spent fuel salt and burnup code predictions for the reactor and salt loop, but these codes will be informed by salt measurements for improvement over time.
- Additional material control measures using control elements for the boundary penetrations around MBA 2 should be considered.
- Identified control elements for detecting the unauthorized removal of SNM via the nine penetrations of a conceptual control boundary
- A detailed analysis of various options for MBA structures conducted to determine the benefits and challenges associated with these options.
- Strategies for monitoring the evolution of SNM holdup and subsequent ground truth measurements within the control boundary were identified and further estimating the residual SNM in components when they leave the control boundary were investigated.

Acknowledgements

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- The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof