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Advanced Reactor Safeguards and Security

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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

Advanced Reactor Safeguards (ARS) Program Overview

- The Advanced Reactor Safeguards (ARS) program was established in 2020 as part of appropriations for the Advanced Reactor Demonstration Program (ARDP) within the Office of Nuclear Energy in DOE.
- The ARS program applies laboratory R&D to address near term challenges that advanced reactor vendors face in meeting domestic materials accountancy and physical protection requirements for U.S. builds.
- Our vision is to help reduce roadblocks in the deployment of new and advanced reactors by solving regulatory challenges, reducing safeguards and security costs, and utilizing the latest technologies and approaches for plant monitoring and protection.

ARS Program Objectives

- New projects started in June, 2020, and most were written as 2-year proposals. We are emphasizing near-term results in order to provide useful R&D to vendors in time to influence their designs.
- Several of the projects have completed interim reports and are on schedule to complete final reports at the end of FY21.
- ARS is funded at $5 million per year to support R&D at the national laboratories and hopefully 2-4 university and small business awards through the NEUP and SBIR programs.
- ARS focuses on the reactor site itself. Safeguards and security requirements for the rest of the fuel cycle (enrichment, fuel fab, transportation, reprocessing) would be covered by the MPACT program.
- ARS recently held a stakeholder workshop to present the work and solicit feedback from U.S. reactor vendors.

Design Variation

- The ARS work is meant to be applicable across different reactor classes as opposed to focusing on specific designs.
- Prioritization may occur depending on which designs are more likely to be deployed in the near term.
- ARDP Award Winners:
  - Demonstration Projects: Terrapower and Ge Hitachi Natrium Reactor; X-Energy Xe-100 Reactor
  - Risk Reduction: Kairos Hermes Reduced Scale Test Reactor; Westinghouse eVinci Microreactor; BWXT Microreactor; Holtec SMR-160; Southern Company and Terrapower Molten Chloride Reactor Experiment.
  - ARC-20: Advanced Reactor Concepts SMR; GA Fast Modular Reactor; MIT HTGR.
- Vendors in Licensing or Pre-licensing with NRC: Nuscale, Oklo, GA, X-Energy, Kairos, Terrestial, Terrapower MCFR, Westinghouse eVinci, GE-Hitachi BWXR-300, Ultrasafe.

ARS Program Goals

Physical Protection Systems
- **Reduce number of on-site responders**
- **Reduce upfront costs**
- **Evaluate enhanced safety systems**
- **Evaluate unique sabotage targets**

HALEU Regulatory Gaps
- **Implications to MC&A and the PPS**
- **Evaluate cross-over into the fuel cycle**

Pebble Bed Reactor MC&A
- **Evaluate regulatory gaps and issues**
- **Determine driving requirements**
- **Evaluate new monitoring technologies**

Microreactor PPS and MC&A
- **Develop a licensing framework based on gaps and issues**
- **Develop approaches appropriate to the very small scale**
- **Evaluate new monitoring technologies**

Liquid Fueled MC&A
- **Evaluate regulatory gaps and issues**
- **Develop baseline accountancy approaches**
- **Evaluate new measurement and monitoring technologies**

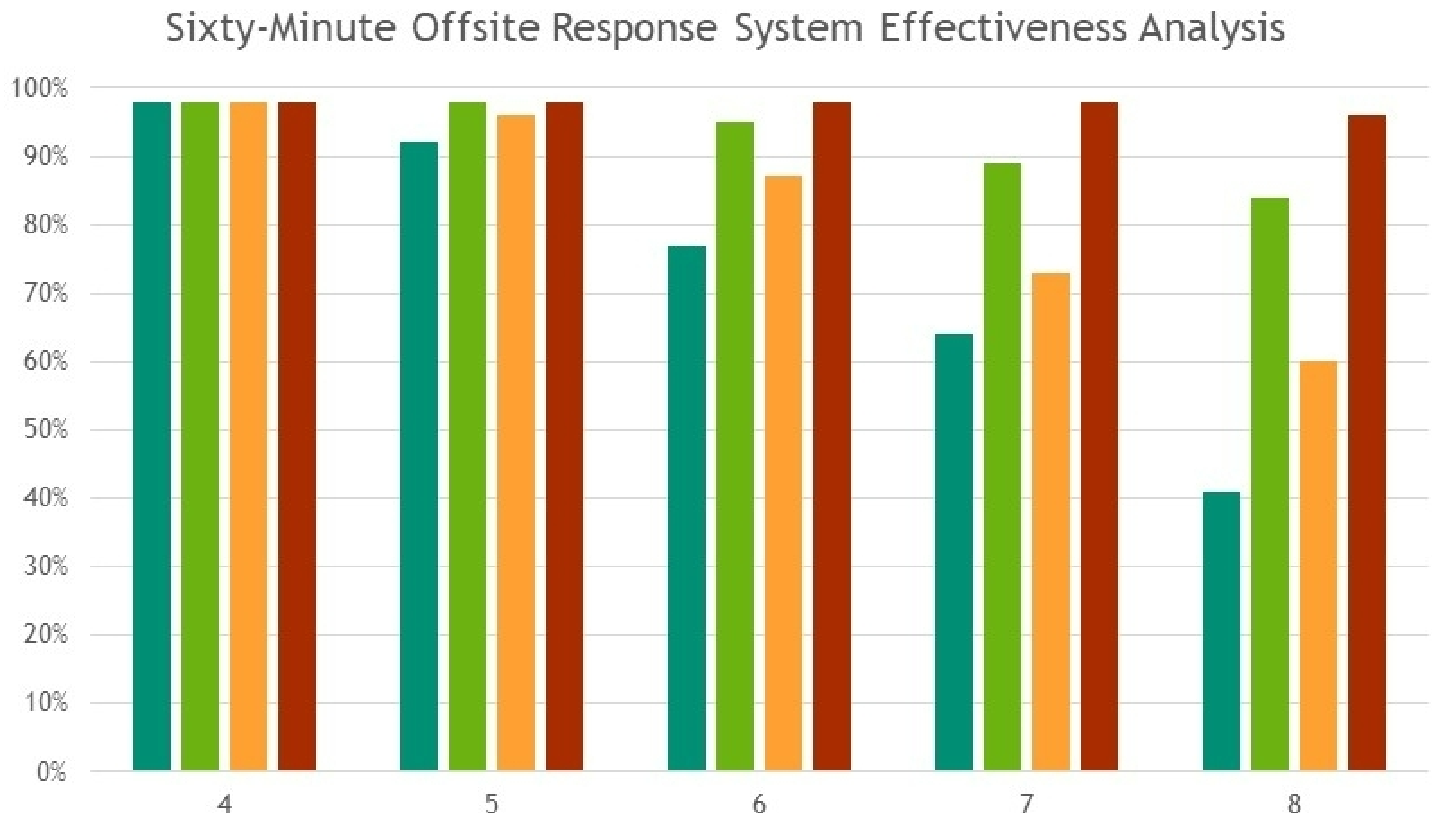
International Considerations
- **Consider international safeguards requirements**
- **Interface with international safeguards and security programs**
- **Support the Gen-IV PR&PP working group**

Goal: Develop Robust and Cost Appropriate Physical Protection Systems

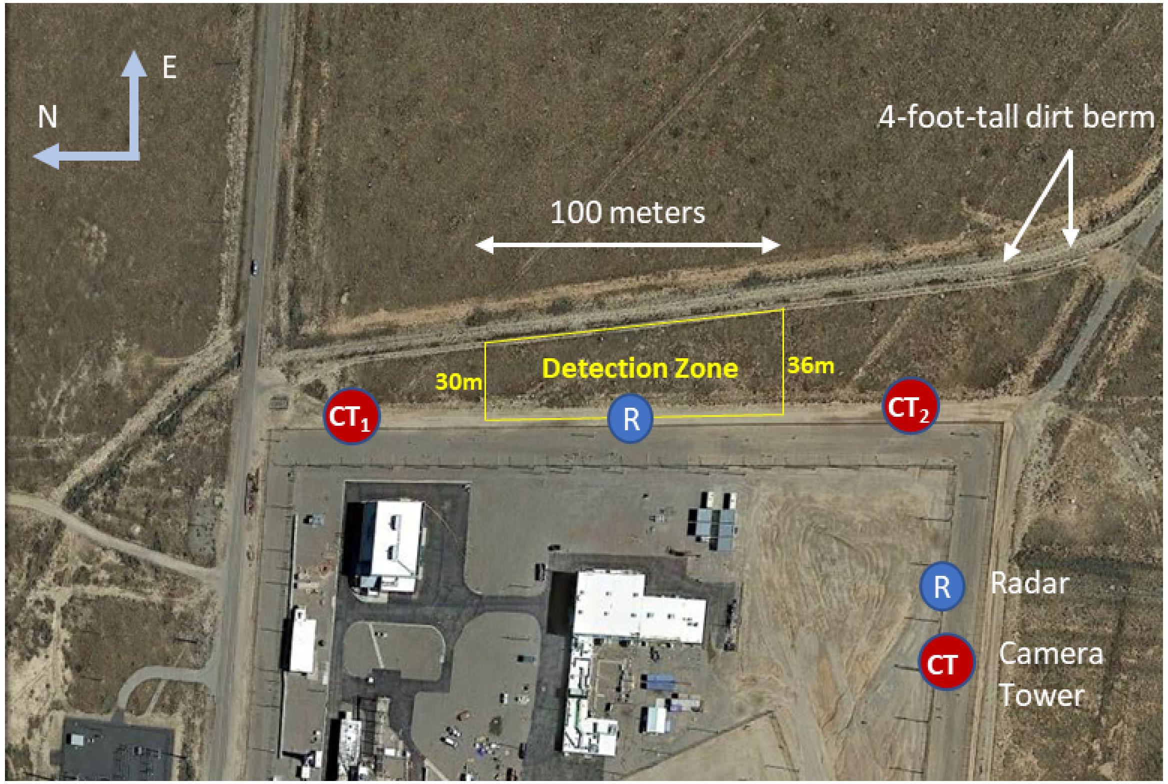
- Large numbers of on-site responders would be a significant economical roadblock—Evaluate PPS approaches that increase delay and rely on local law enforcement.
- Reduce upfront costs through new technology and Security by Design—Develop PPS designs and provide performance results.
- Evaluate how enhanced safety systems may be utilized—Links to new NRC rulemaking.
- Evaluate unique sabotage targets and stay ahead of emerging threats--Ensure robustness for new coolants and fuels.

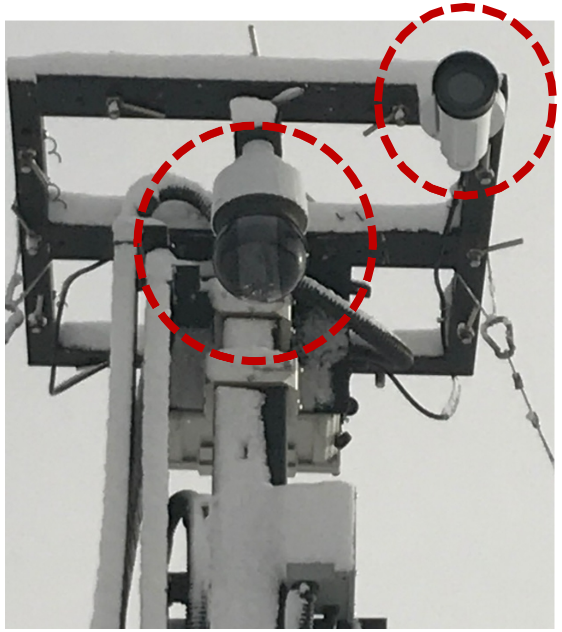
PPS Modeling

- Using generic advanced reactor plant models, both path analysis and force-on-force tools are being used to examine alternative PPS designs
- Goals include reducing reliance on on-site staffing and evaluating new PPS technologies
- Strong emphasis on performance testing results to prove (or disprove) the concepts.



Deliberate Motion Algorithm for Enhanced Detection

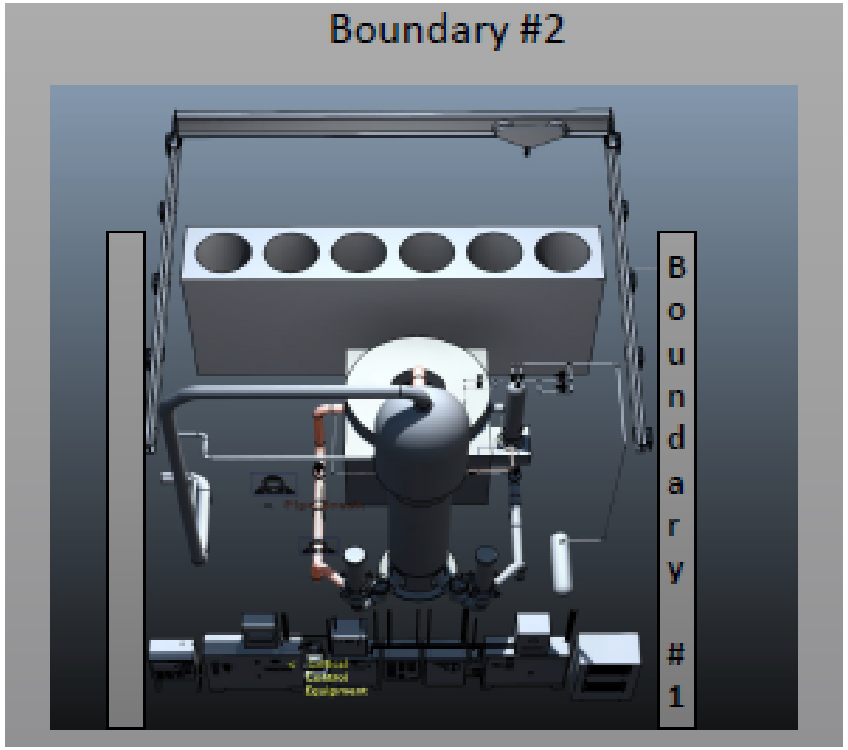


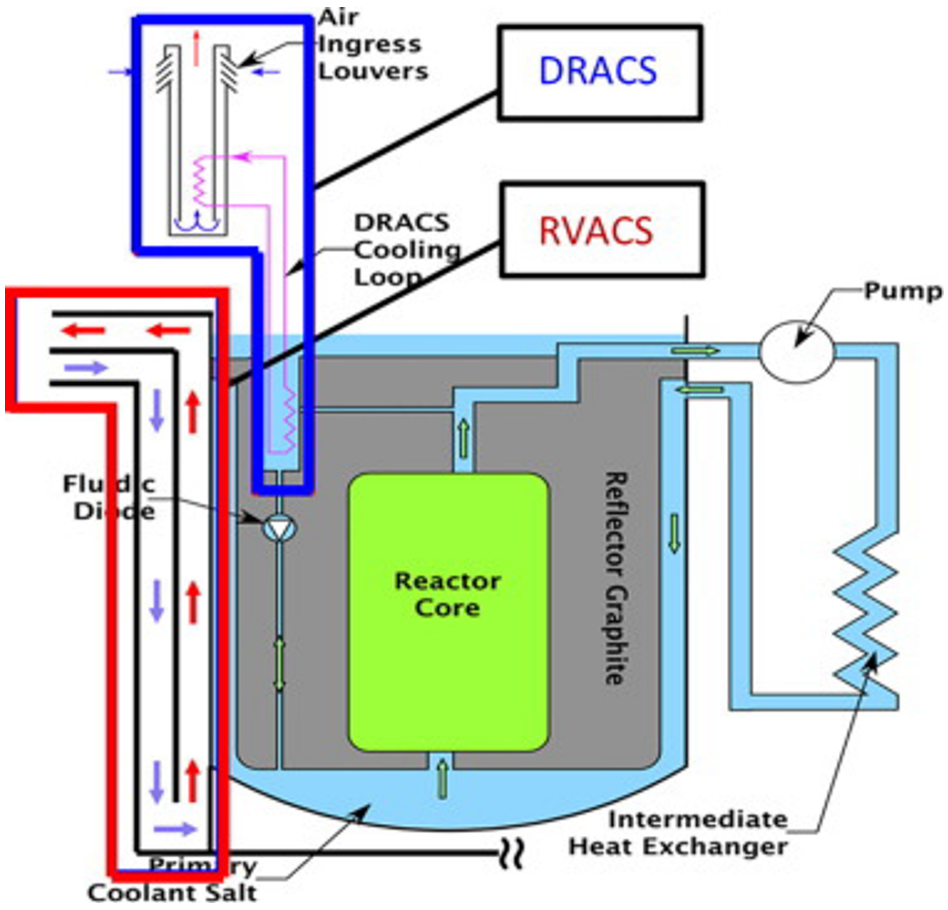


Risk-Informed Security

Zohuri, Bahman. (2019). Dire ct Re a ctor Auxilia ry Cooling System. DOI 10.1007/978-3-030-05882-1_7.

- NRC's new rulemaking allows advanced reactor vendors to take credit for enhanced safety systems, but how to prove that? We want to provide tools to prove these concepts





- Advanced reactors also need to consider unique sabotage targets early in the design process to avoid potential future issues.

Goal: Examine HALEU Regulatory Gaps

- Most advanced reactor vendors plan to use HALEU, but the use of HALEU places reactors in a different Category.
- The implications to MC&A and the PPS are being examined—Implications may vary depending on reactor class.

Category I - Strategic SNM (SSNM)

5 kgs or more of U-235 (contained in uranium enriched to 20 percent or more in the U-235 isotope)

Category II - SNM of moderate strategic significance

Less than 5kgs but greater than or equal to 1kg of uranium-235 (contained in uranium enriched to 20 percent or more in the U-235 isotope); or

10kg or more of uranium-235 (contained in uranium enriched to 10 percent or more but less than 20 percent in the U-235 isotope)

Category III - SNM of low strategic significance

Less than 1kg but more than 15 grams of uranium-235 (contained in uranium enriched to 20 percent or more in the U-235 isotope)

Less than 10kgs but more than 1kg of uranium-235 (contained in uranium enriched to 10 percent or more but less than 20 percent in the U-235 isotope); or

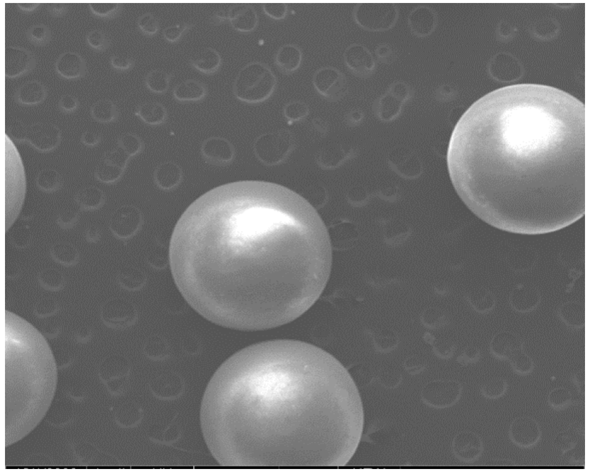
10 kgs or more of uranium-235 (contained in uranium enriched above natural but less than 10 percent in the U-235 isotope)

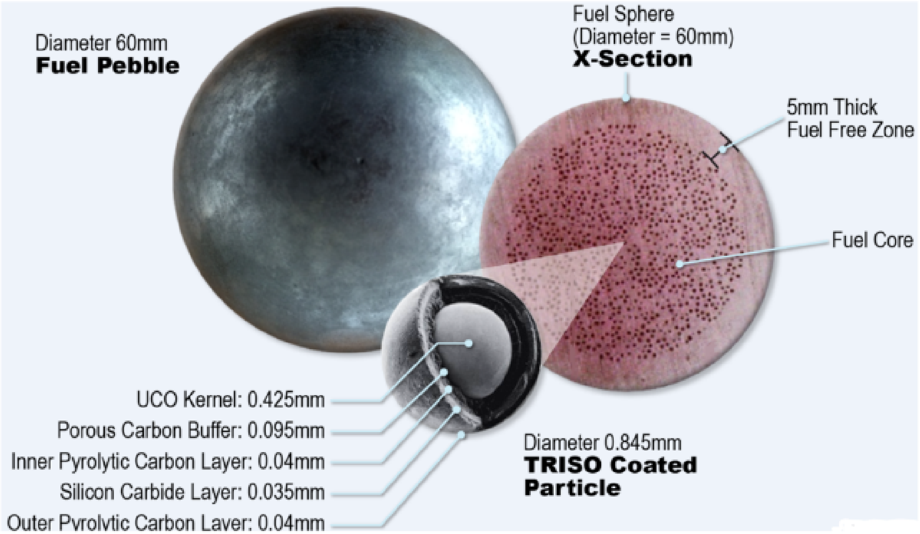
Preliminary Conclusions for HALEU Work

- Existing NRC regulations for physical protection that would apply to HALEU fuel are likely outdated and inappropriate for the needs of regulating ARs.
- NRC intended to update regulations for Cat II as part of rulemaking on Enhanced Security for SNM, but rulemaking was cancelled in 2018. Licensing decisions will be conducted on a case-by-case basis. But NRC staff have indicated that they will use the technical basis from the cancelled rulemaking to inform the process.
- Reactor designers will need to consider Cat II protection requirements for fresh fuel.
- MC&A requirements going from Cat III to Cat II are less impactful, but still need to be evaluated.

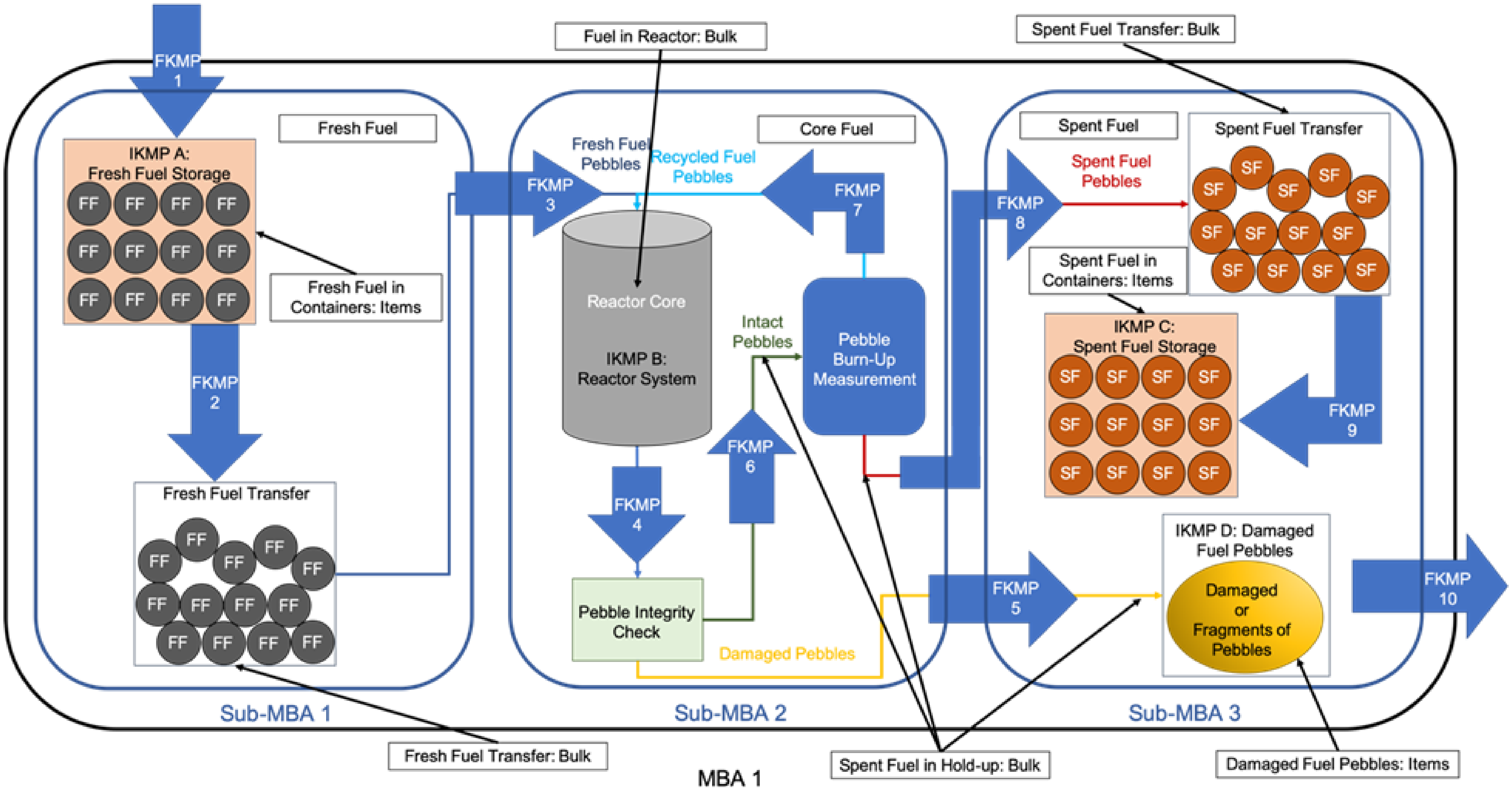
Goal: Develop MC&A Approaches for Pebble Bed Reactors

- Evaluate regulatory gaps/issues for pebble bed reactors with a focus on pebble handling systems and storage.
- Determine driving MC&A requirements—there are different drivers including accountability vs. rad. sabotage vs. process control needs.
- Evaluate new monitoring technologies (Pebble identification, burnup measurements, C/S approaches).

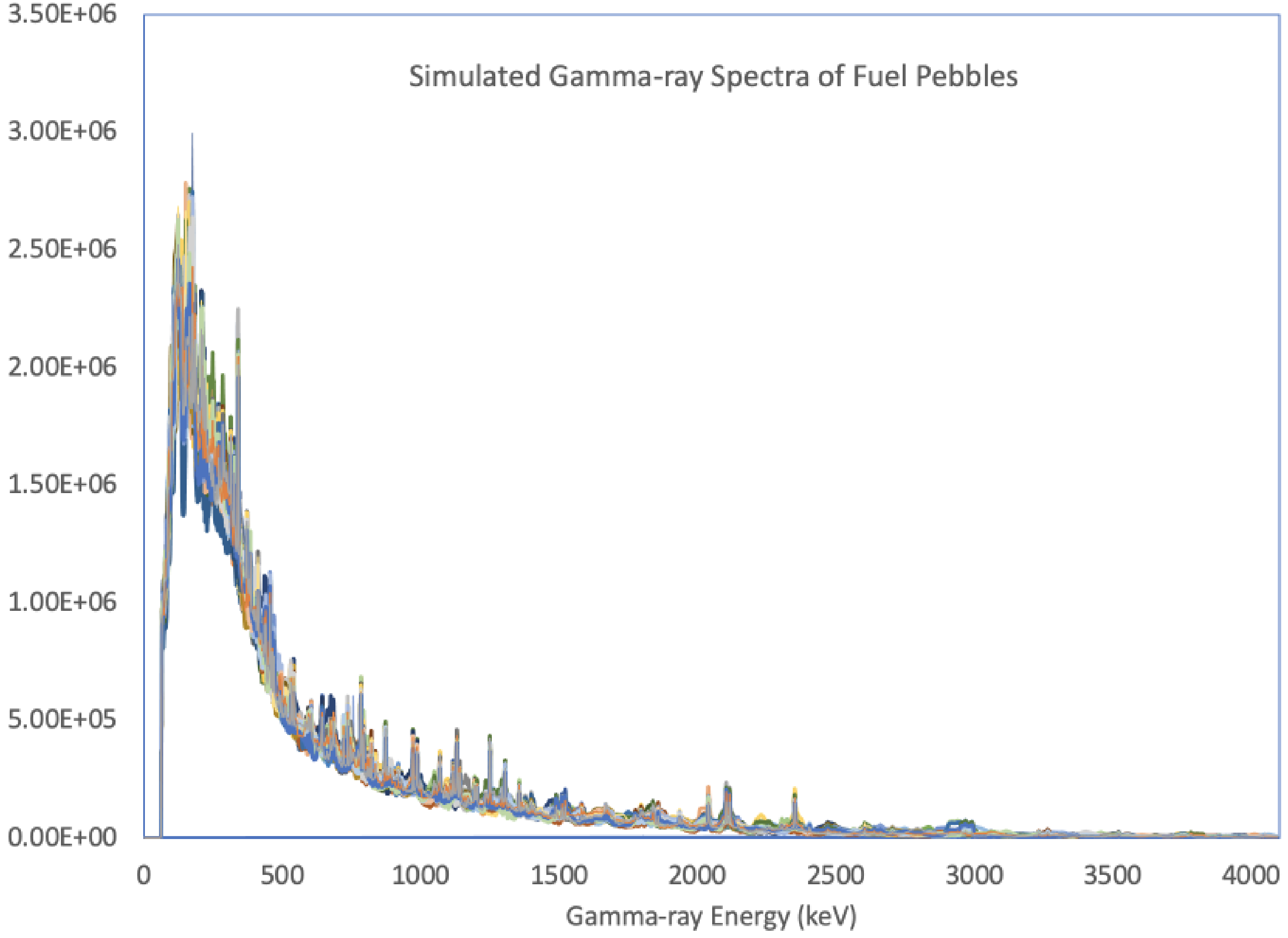


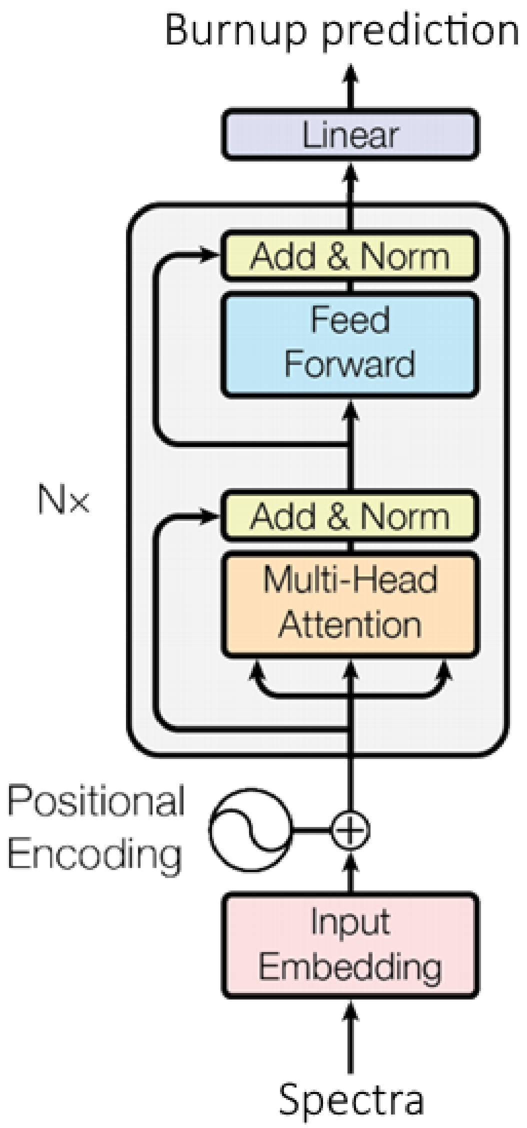


PBR Accountancy Approach



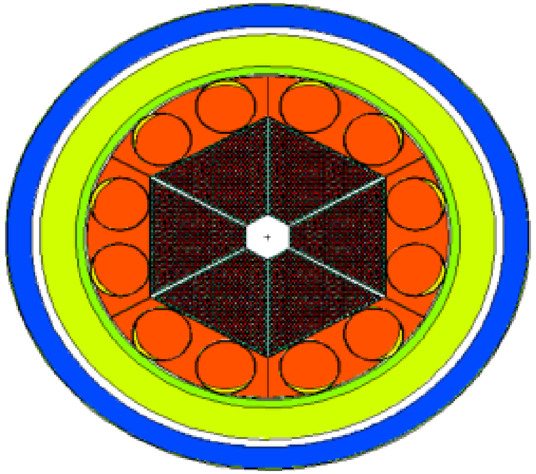
The Burnup Measurement is Critical for the Vendors



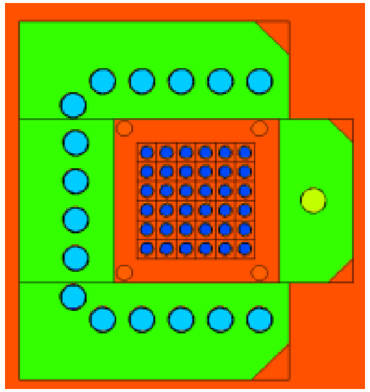


Goal: Develop MC&A and PPS Requirements for Microreactors

- Evaluate regulatory gaps/issues for microreactors with attention to approaches which will be appropriate to the very small scale.
- Develop a licensing framework based on reactor design choices.
- Consider new theft/sabotage pathways.
- Evaluate new monitoring technologies (Process monitoring, sealed core measurements).


LANL Megapower model

Linatron 15 MeV x-ray generator

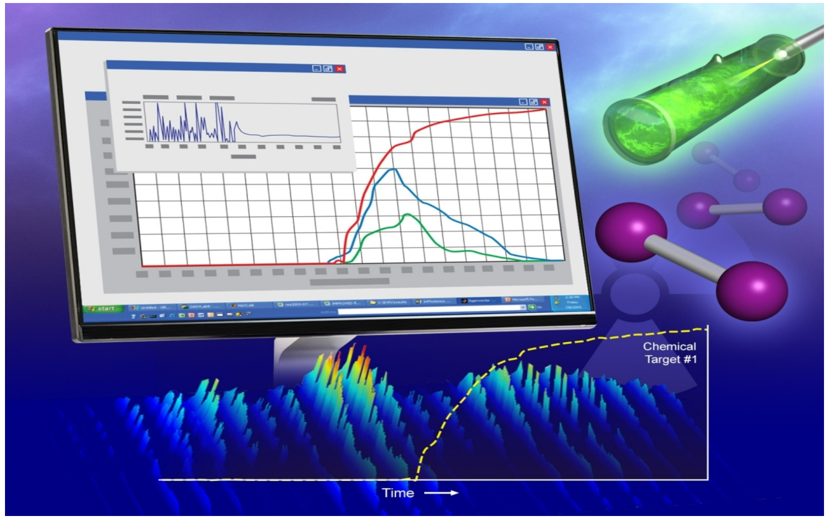

LANL 6x6 BWR fuel assembly measurement and simulation

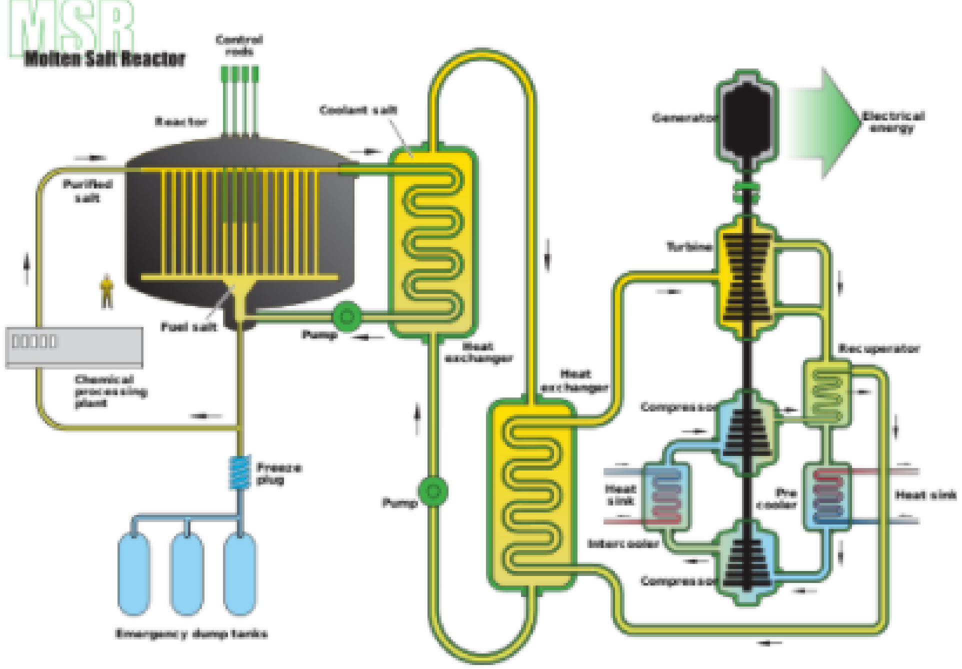
Licensing Framework for Microreactors

Reactor concept	Residence	Core Features	Safety Features
Metallic-fueled, heat-pipe cooled, stationary reactor	• One location for its entire life cycle	• May or may not be sealed core • Possible need to rearrange fuel	• Secondary structures expected • Below-grade siting
TRISO-fueled, heat-pipe cooled, mobile reactor	• Multiple locations for an unspecified amount of time at each location	• May be sealed core • Onsite refueling will not be pursued	• Reactor in a mobile-at-will or mobile-at-ready operational mode. • No additional, onsite infrastructure
TRISO-fueled, gas-cooled, mobile reactor	• Multiple locations for an unspecified amount of time at each location	• May be sealed core • Onsite refueling will not be pursued	• Reactor in a mobile-at-will or mobile-at-ready operational mode. • No additional, onsite infrastructure
TRISO-fueled, gas-cooled, stationary reactor	• One location for its entire life cycle	• Most likely a sealed core • Cartridge refueling swap	• Secondary structures expected • Below-grade siting

Goal: Develop MC&A Approaches for Liquid-Fueled Reactors

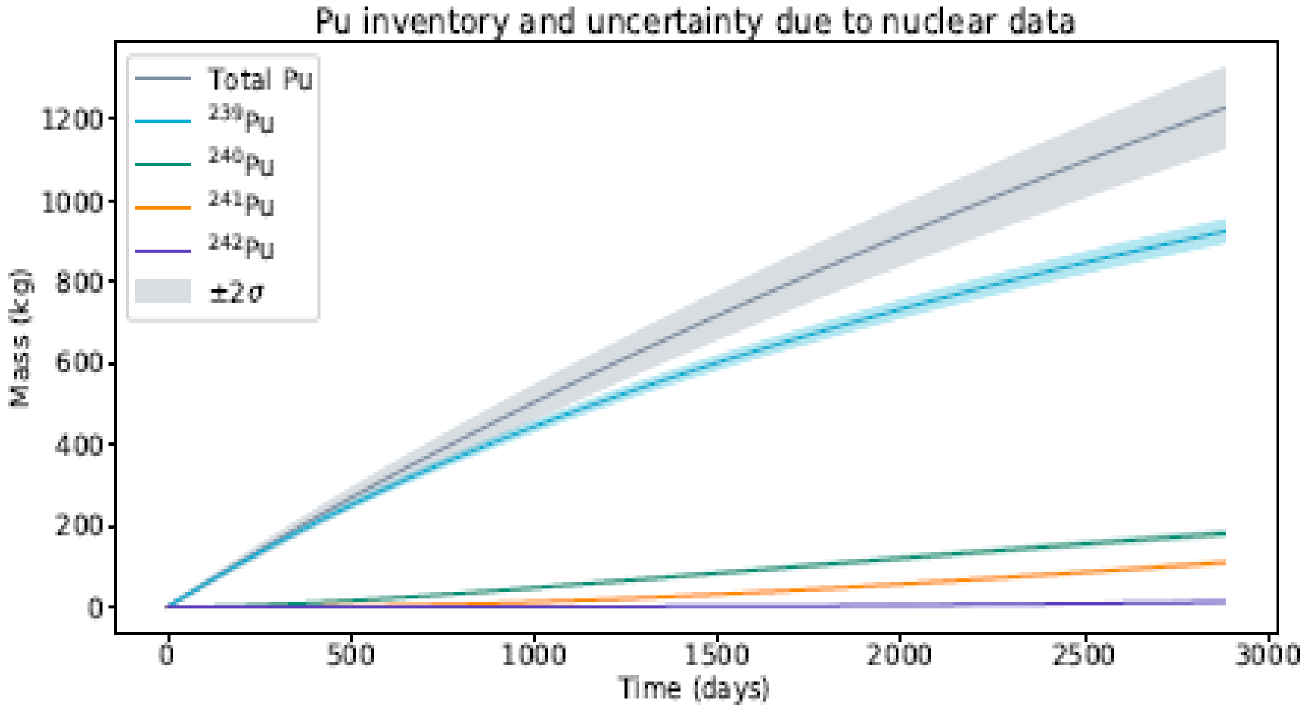
- Evaluate regulatory gaps/issues for molten salt reactors—how much of 10 CFR 74 applies here?
- Develop baseline accountancy approaches and determine performance (Tie in measurement technology work)
- Evaluate new measurement/monitoring technologies including on-line and NDA measurements.





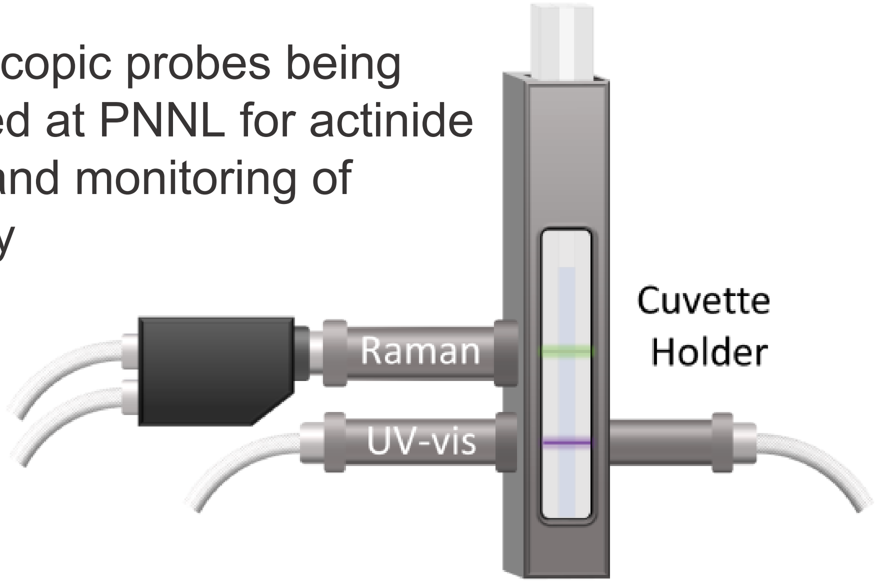
MC&A Approach Preliminary Conclusions

- NRC favors a *modified* MC&A approach utilizing process monitoring techniques for salt-fueled MSRs.
- Quantification of fresh fuel additions will likely be needed.
- Minimizing accumulation points (in design) could reduce potential salt/SNM holdup.
- In some designs, the buildup of Pu in the reactor results in high overall error on the Pu measurement.
- Need to consider the high rad environment as part of the overall approach.

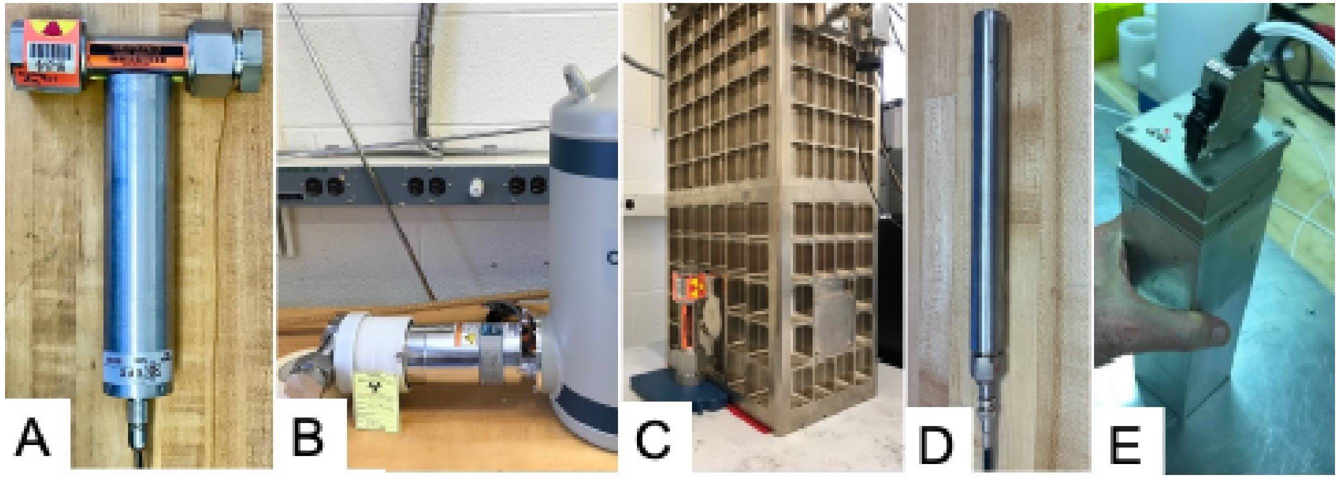


Measurement Technology to Support MSRs

Spectroscopic probes being developed at PNNL for actinide content and monitoring of chemistry



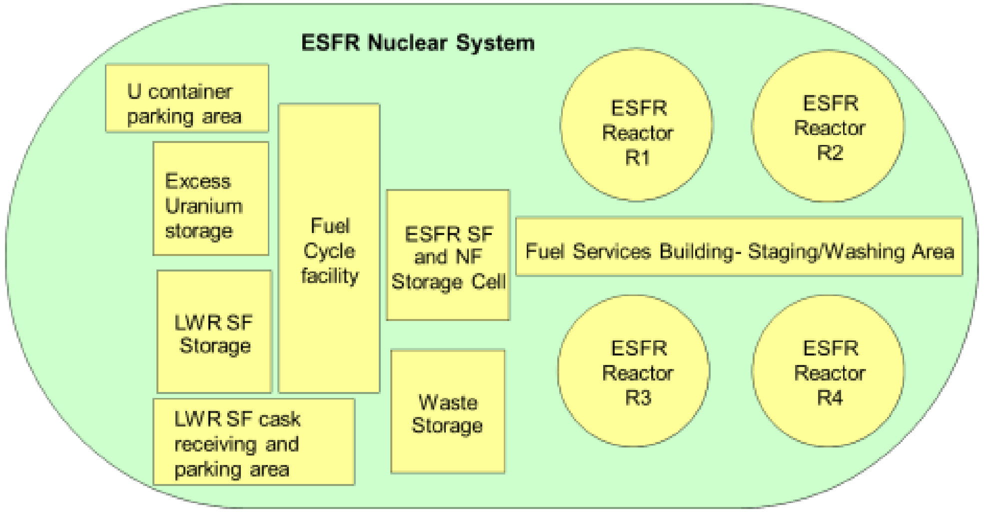
Molten Salt test loop at ANL for testing flowing voltametric probes



MSR NDA measurement campaign being led by LANL (partnership with ORNL, INL, and UC)

Goal: Consider International Requirements

- Take into account international safeguards requirements as part of a Safeguards by Design approach.
- Interface with other programs supporting international safeguards and security, and determine where there may be synergy between domestic and international needs.
- Support the Gen-IV PR&PP working group (many lessons learned can be applied).



Key Questions

1. Where are the intersections and distinctions between U.S. domestic and IAEA safeguards?

   There are many technologies that have application both for meeting domestic MC&A requirements and international verification.

2. What advanced reactors have been under IAEA safeguards and what can we learn from the IAEA safeguards approaches? What R&D from the IAEA safeguards domain might be relevant?

   Case studies on Monju (SFR), Pebble Bed Reactors (THTR-300 in Germany), and reprocessing experience are being examined to explore application to advanced reactors.

3. How can U.S. reactor developers prepare for potential IAEA safeguard requirements?

   We want vendors to be aware of IAEA requirements for international deployment and work with our NNSA colleagues.

Gen-IV PR&PP Efforts Supported

GIF System	System Options considered in update	Design Tracks considered in update	Comment
GFR	Reference Concept	2400MWt GFR ALLEGRO as a GFR demonstrator (EU)	Other GEN IV designs include: EM2 (GA) ALLEGRO (V4G4) HEN MHR (High Energy Neutron Modular Helium Reactor) (CEA-ANL and GA-AREVA)
LFR	Large System	ELFR, (EU))	These are the three reference design configurations discussed in the GIF LFR System Research Plan
	Intermediate System	BREST-OD-300, (RF)	
	Small Transportable	SSTAR, (US)	
MSR	Liquid-fueled with Integrated Salt Processing	MSFR (EU), MOSART (RF)	There is a wide variety of MSR technologies, encompassing thermal/fast spectrum reactors, solid/fluid fuel, burner/breeder modes, Th/Pu fuel cycles, and onsite/offsite fissile separation.
	Solid-fueled with Salt Coolant	Mk1 PB-FHR (US)	
	Liquid-fueled without Integrated Salt Processing	IMSR (Canada)	
SCWR	Pressure Vessel	HPLWR (EU) (Thermal)	Most concepts are based on "familiar' technology, such as light-water coolant, solid fuel assemblies, and batch refuelling. Implementation of Th and Pu fuel cycles creates additional special nuclear materials of concern.
		Super FR (Japan)	
		Super LWR (Japan) (Thermal)	
		CSR 1000 (China) (Thermal)	
		Mixed spectrum (China)	
		Fast core (RF)	
	Pressure Tube	Canadian SCWR (Canada) (Thermal)	
SFR	Loop Configuration	JSFR (Japan)	Expect key PR&PP issues to be tied to fuel handling, TRU inventory and fuel cycle options.
	Pool Configuration	ESFR (EU), BN-1200 (RF), KALIMER-600 (RoK)	
	Small Modular	AFR-100 (US)	
VHTR	Prismatic Fuel Block	Modular HTR, Framatome (ANTARES)	SC-HTGR is a follow on of the ANTARES and the GA GT-MHR development. Expect some PR&PP differences between the prismatic block and pebble bed design.
		SC-HTGR, Framatome (US)	
		GT-MHR General Atomics (US)	
		GT-MHR OKBM (RF)	
		GTHTR300C, JAEA (Japan)	
		NHDD,KAERI (RoK)	
	Pebble Bed	Xe-100, X-Energy (US)	
		HTR-PM (China)	

Key Takeaways

- The regulatory structure for reactors was built up around large LWRs which is not always suitable to advanced small and microreactor designs.
- As reactor designs get smaller, the burden of safeguards and security could get disproportionally larger.
- Our goals in the ARS program are to provide recommendations and guidance to advanced reactor vendors as well as inform NRC to help fill gaps and find a cost-effect path forward.
- A large focus with security is to examine design alternatives that may reduce on-site staffing or develop recommendations as to how the vendors can take credit for their enhanced safety systems and smaller source terms.
- The focus of MC&A related work is to develop approaches that are appropriate to the use of different types of fuel.