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# SAFEGUARDS AND SECURITY BY DESIGN FOR A/SMRS AT ARGONNE



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U.S. DEPARTMENT  
of **ENERGY**

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# OUTLINE

- Domestic Safeguards and International Safeguards
  - *Compare and contrast*
- Nuclear Material Control and Accounting
- Safeguards
  - “... *by design*”
- Security
  - “... *by design*”
- USG-funded safeguards and security research aimed to help advance domestic and international deployment
  - “*Who is helping reactor designers with safeguards and security?*”
- Argonne’s contribution

## Domestic Safeguards

- Special nuclear material
- Physical **security**
- Access control
- Facility licenses
- Nuclear material control
- Information security
- Cyber security
- Threat: non-state adversary
- Oversight: NRC
- Responsibility: Licensee



## International Safeguards

• Nuclear material accounting

- Special fissionable material
- Process monitoring
- Facility attachments
- Containment & Surveillance
- Reporting: quantities and activities
- Export controls
- Threat: state adversary
- Inspectorate: IAEA
- Responsibility: IAEA

# NUCLEAR MATERIAL ACCOUNTING

## ▪ Nuclear Material Control and Accounting (MC&A)

- Per 10 CFR 74, licensee tracks and verifies SNM that is on site
- Licensee must maintain knowledge of its SNM and manage the program for securing and protecting the SNM ensuring **material is not stolen or otherwise diverted** from the facility
- MC&A, together with physical protection of facilities and information security requirements, make up the primary elements of the NRC's SNM safeguards program

## ▪ Nuclear Material Accounting and Control (NMAC)

- As part of the **State's system of accounting and control** (SSAC), the State accounts and reports material quantities and locations to the IAEA through the State's responsible authority
- Additional to State inspectorate, **independent verification** of declared locations, quantities, and characteristics of materials and activities must be made by IAEA
- NMAC must maintain and report accurate, timely, complete, and reliable information on the locations, quantities, and characteristics of nuclear material in a facility

# WHAT DO IAEA SAFEGUARDS ACCOMPLISH?

- International safeguards are a set of legal instruments, technical measures, and administrative procedures that allow the IAEA to **independently verify** that nuclear materials and technologies are used only for peaceful purposes.
- These support the **international safeguards system** which is comprised of NMAC, reporting, inspections, and design information verification efforts
- All work in concert to help the IAEA achieve its three main objectives:

*Detect diversion of declared nuclear material*

*Detect misuse of declared facilities*

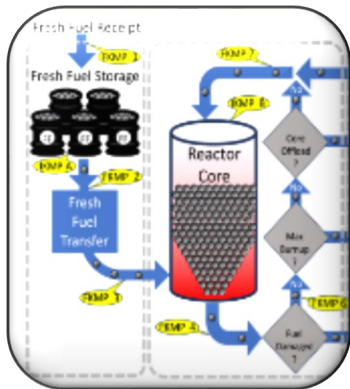
*Detect undeclared nuclear material or activities*



# TECHNICAL MEASURES FOR SAFEGUARDS

The IAEA uses an array of tools to verify that States are not diverting nuclear material, misusing their declared facilities, or building/operating undeclared facilities.

Nuclear Material  
Accountancy



NDA and DA  
Measurements



Containment  
& Surveillance



Environmental  
Sampling



Material Balance  
Evaluation

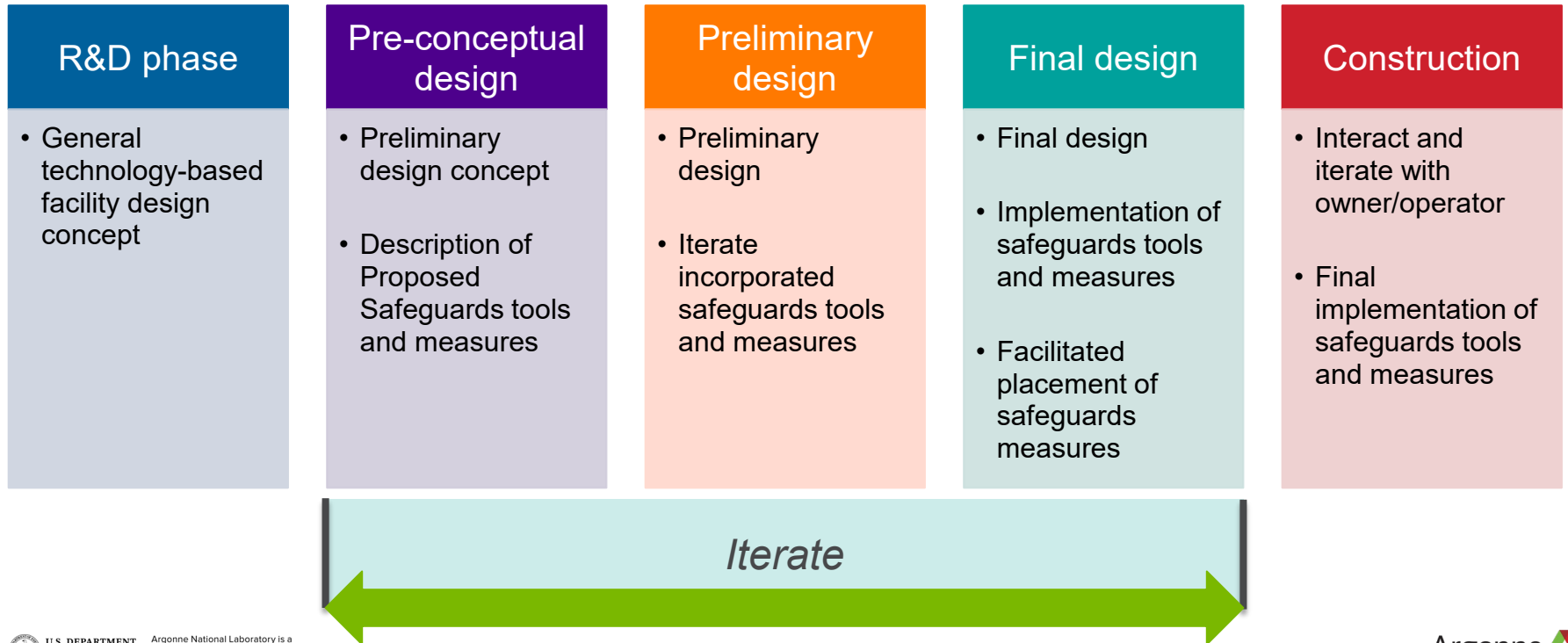


# SAFEGUARDS BY DESIGN

- SBD is the early consideration of safeguards technical measures in the design process of nuclear facilities
  - Brings down barriers to future technology deployment
  - Completely voluntary, driven by the designer
- Certain design features may improve safeguards
  - Sealed cores
  - Long refueling cycles
  - Fuels with low concentrations of special nuclear material
  - Fuels that are difficult or time-consuming to reprocess
- Per the IAEA, *safeguards* are considered part of extrinsic **proliferation resistance**

# SAFEGUARDS BY DESIGN

## Responsibilities of the designer:



# NUCLEAR SECURITY:

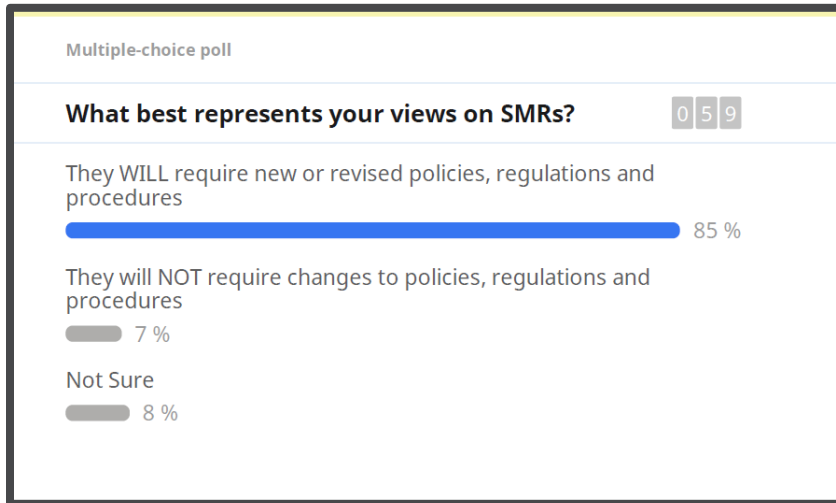
## A National Responsibility

- Nuclear security focuses on the prevention and detection of, and response to, criminal or intentional unauthorized acts involving or directed at nuclear material, other radioactive material, associated facilities or associated activities.
- Examples of Nuclear Security events:
  - **Theft** or unauthorized removal of nuclear and other radioactive material
  - **Sabotage** of facilities or transports of nuclear and other radioactive material
  - Other malicious or unlawful acts involving nuclear or other radioactive material

*From IAEA SMR School 2025 (Bangkok, Thailand)*

# NUCLEAR SECURITY FOR SMRS

- 2023 IAEA Technical Meeting on Nuclear Security survey results for SMRs
  - Identified security considerations:

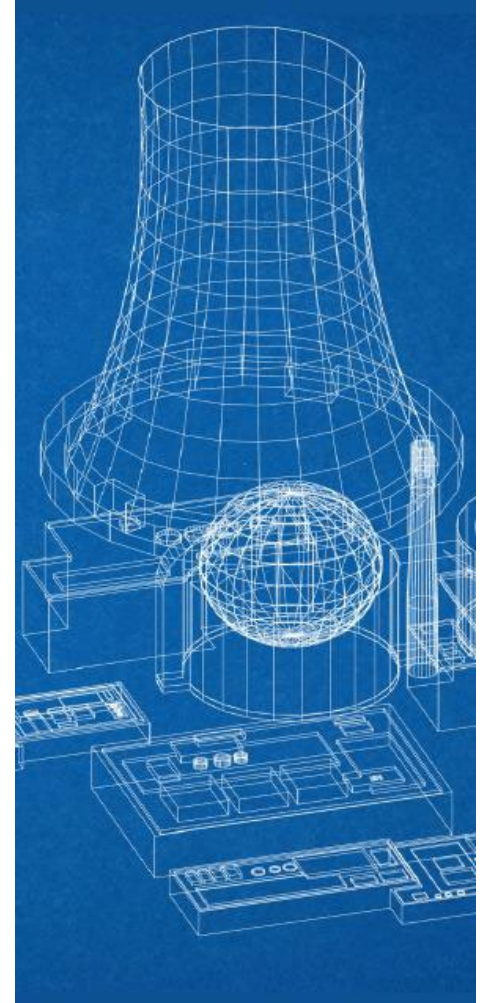


From IAEA SMR School 2025 (Bangkok, Thailand)

# SECURITY BY DESIGN (PER IAEA)

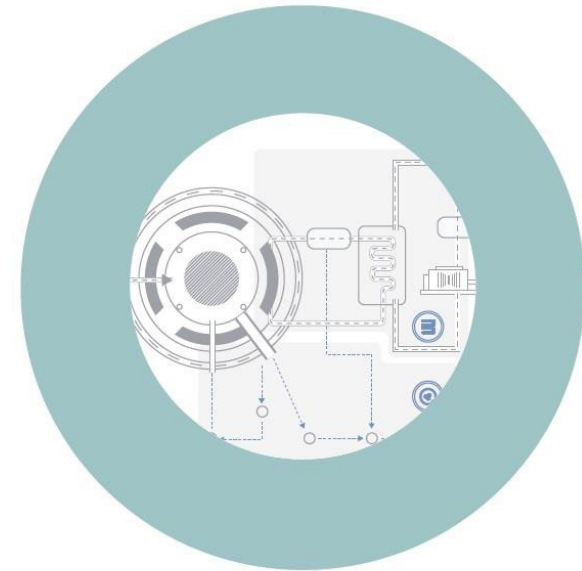
- Considering security during early design phases
- Provides cost-effective security over the entire lifetime
- Potential SMR designs should incorporate SeBD principles, considering
  - Operational logistics;
  - Control of access to sensitive areas;
  - Maintenance periods;
  - Availability of redundant power sources

*From IAEA SMR School 2025 (Bangkok, Thailand)*



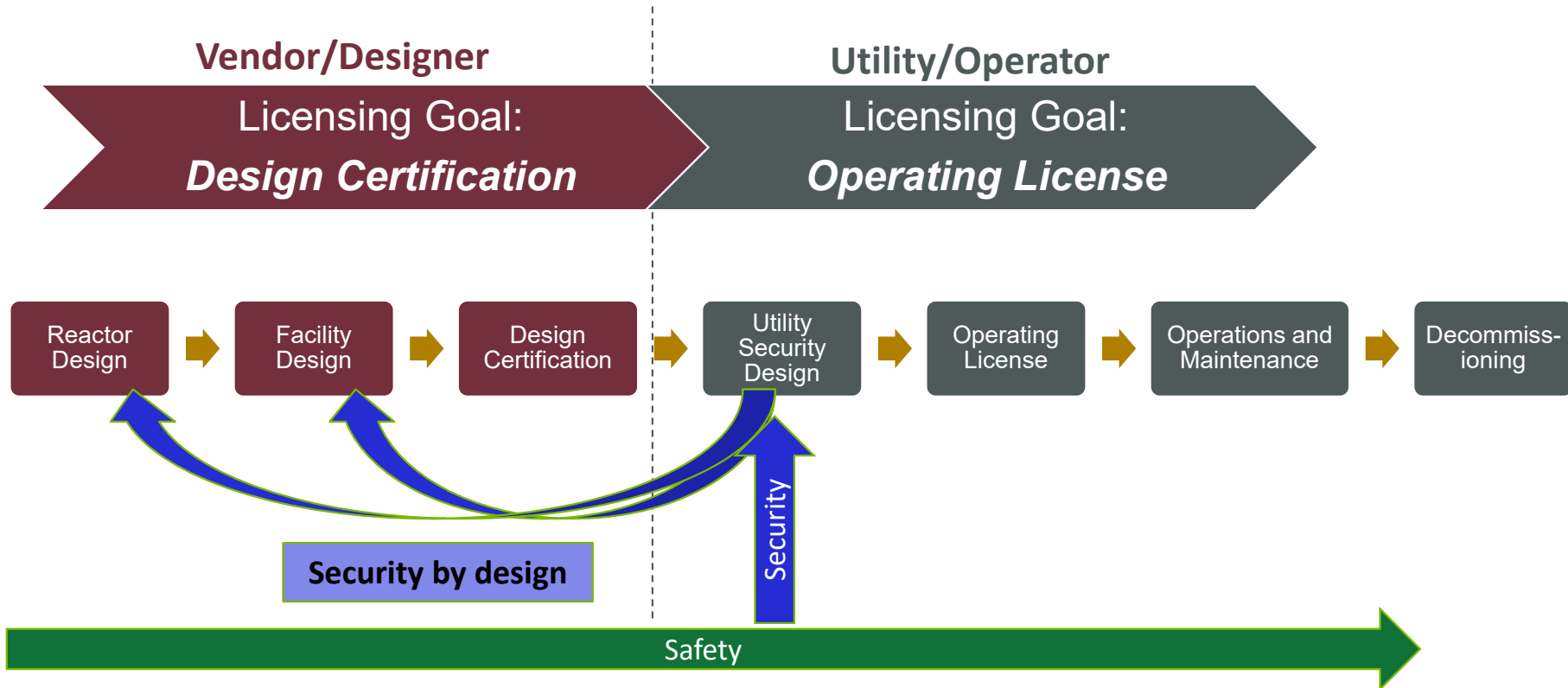
# SECURITY BY DESIGN: PASSIVE SAFETY

- Passive Safety features can help the consequence mitigation element of a security event (i.e., sabotage)
- Inherent passive features that reduce the risk of sabotage may include:
  - Passive heat removal/containment cooling
  - Lower core power designs
  - Low pressure designs
  - Use of accident tolerant fuel
- SMR passive security features **do not** address threats from theft of material.



*From IAEA SMR School 2025 (Bangkok, Thailand)*

# WHEN IS SECURITY CONSIDERED “BY DESIGN”?



# OPPORTUNITIES TO LEARN SAFEGUARDS AND SECURITY

- DOE/NNSA have programs especially focused on facilitating engagements between national laboratory subject matter experts and reactor designers:

Office of International Nuclear Security (NA-211):  
International Nuclear Security of Advanced Reactors (INSTAR)

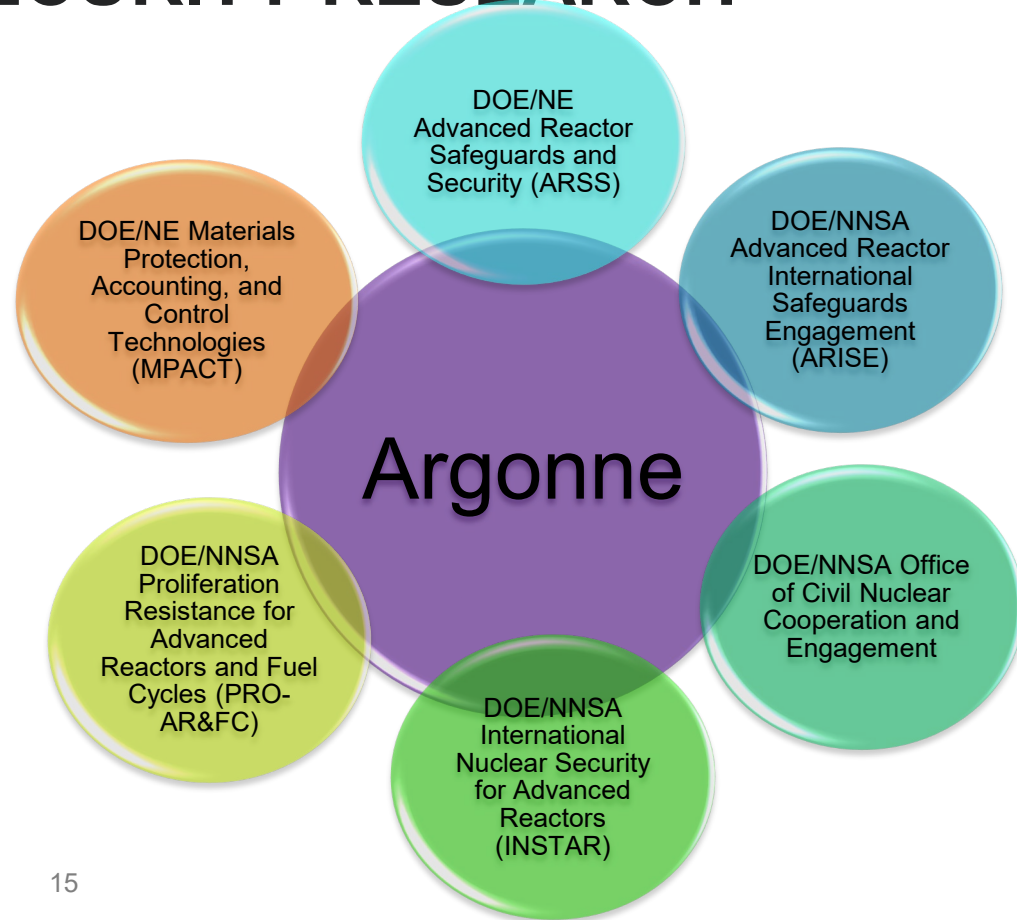
Office of International Nuclear Safeguards (NA-241):  
Advanced Reactor International Safeguards Engagement (ARISE)

- Opportunities for learning sponsored by these offices include
  - SSeBD Workshop: 2026 @ INL (September 21-25)
  - Experiential learning endeavors like NFASE and DFENS (both executed by Argonne)
    - Next [Nuclear Facilities and Safeguards Experience \(NFASE\)](#) in October 2026
    - Next [Domestic Facilities Experience for Nuclear Security \(DFENS\)](#) in March 2027
  - Deep dives on special topics (lab wide)
  - Other training courses unique to specific national labs (POCs available upon request)

# SAFEGUARDS AND SECURITY RESEARCH

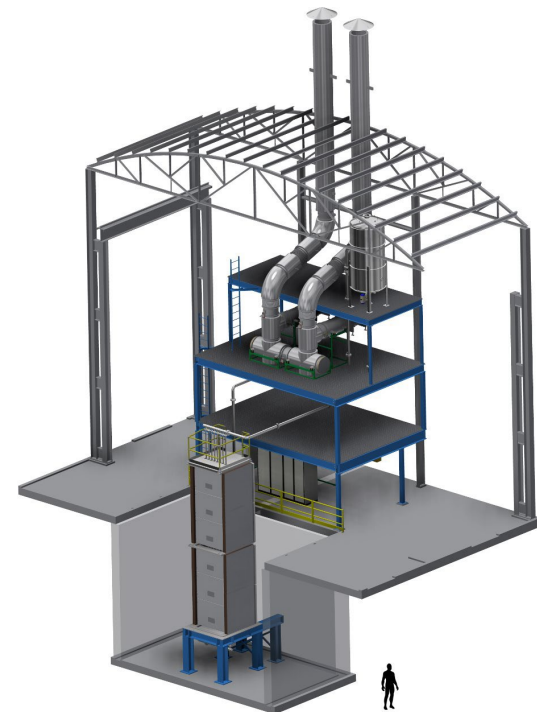
- Leveraging multi-disciplinary expertise in A/SMR development and practical experience, Argonne is **engaging with industry partners** on incorporating nuclear security and safeguards measures and principles
- Nonproliferation contributions range from **technological assessments** to direct vendor engagements

Specific engagements with individual and multiple vendors funded by DOE/ARSS, DOE/NNSA ARISE, and DOE/NNSA INSTAR



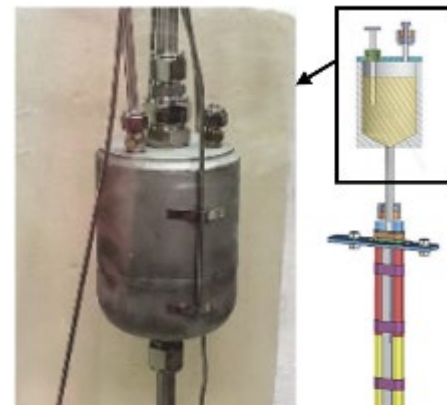
# DOE/NNSA INSTAR PROJECTS

- Identifying and Testing Realistic and Credible Security Threats to Passive Decay Heat Removal Systems for Advanced Nuclear Reactors (D. Lisowski, NSE)
  - Testing **vulnerabilities of passive decay heat removal systems** are being conducted at the Natural Convection Shutdown Heat Removal Test Facility (NSTF) to address possible novel security threats to A/SMRs
- Study on Intersection of Insider Threat and Enhanced Due Diligence Training for A/SMR Designers and Operators (T. Du, SSS)
  - Leveraging expertise on **know-your-hire and enhanced due diligence** practices to mitigate insider threat scenarios
  - Analysis enhancing **nuclear security culture**

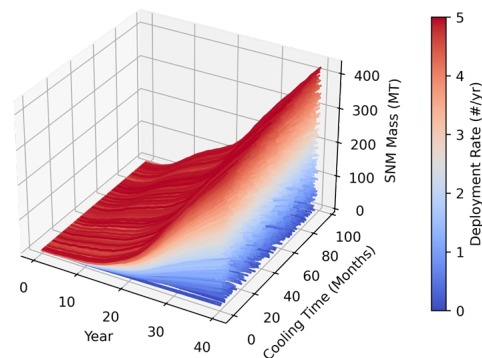


# DOE/NNSA ARISE PROJECTS

- Salt Sampling Techniques for Molten Salt Reactors (A. Polke, CFCT)
  - For effective NMAC, MSR require the ability to **extract salt samples** which will lead to definitive analysis of concentrations of fissile content and other radioisotopes
- Safeguarding Commercial Breed and Burn Sodium-Cooled Fast Reactors (E. Hoffman, NSE)
  - **Fleet-level** safeguards analysis of large scale, HALEU-fueled SFR technology
  - Long term growth reliant on irradiated fuel transfers which may prove challenging for international safeguards regime



Molten salt sampling system for electrochemical reprocessing



# DOE/NNSA ARISE PROJECTS

## ■ Safeguards Considerations for Particle Fuel Fabrication Facilities (R. Suh, SSS)

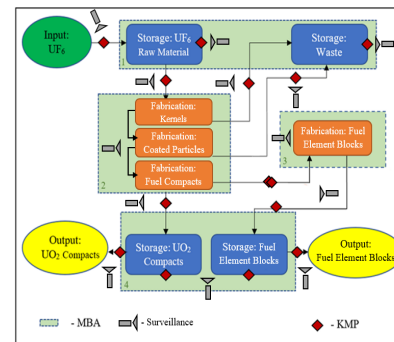
- **Safeguards approaches** for bulk to item accounting measures in a TRISO fuel fabrication facility
- Concerns include protracted theft and bulk accounting uncertainties for effective MC&A

## ■ Developing Safeguards-relevant Remote Monitoring Techniques for MSR (S. Shahbazi, NSE)

- Simulating detectable **characteristic NMAC signatures** through radiochemical transport analysis for MSR
- Predictive modeling on gamma/neutron spectroscopy and leveraging machine learning of simulated detector responses

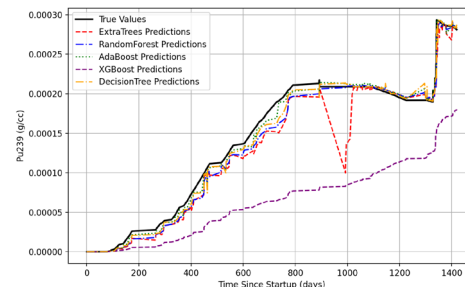
## ■ Decommissioning and Termination of Safeguards for A/SMR Gap Analysis (S. Martinson, SSS)

- Implementation and **termination of international safeguards** measures when decommissioning novel A/SMR designs
- Joint scoping study with LANL SMEs



Comprehensive NMAC approach for pebble fuel fabrication facility

Sequential predictions of  $^{239}\text{Pu}$  by various regressor models based on iterative training and testing on chronological data



# DOE/NE MPACT PROJECTS

- Automated Molten Salt Sampler for Reprocessing Material Control and Accounting (A. Polke, CFCT)

- Using novel sample tube mechanisms to support rapid sample delivery to lower temperature/lower radiation areas for high-precision non-destructive analysis



Samples obtained in extraction tubes

- Molten Salt Electroanalytical Sensors for Process Monitoring & Material Control and Accounting (N. Hoyt, CFCT)

- Deploying safeguards-enabling multielectrode array electrochemical sensors to provide salt composition, salt level, and salt redox potential measurements during a variety of electrorefining operations for spent nuclear fuel

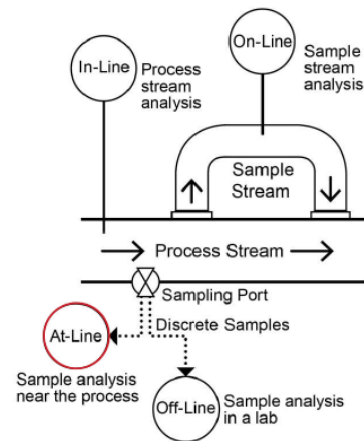
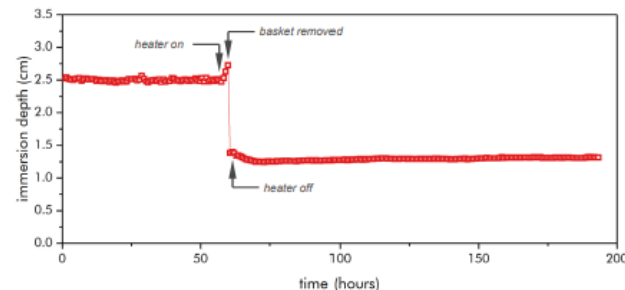


Diagram of sampling approaches.

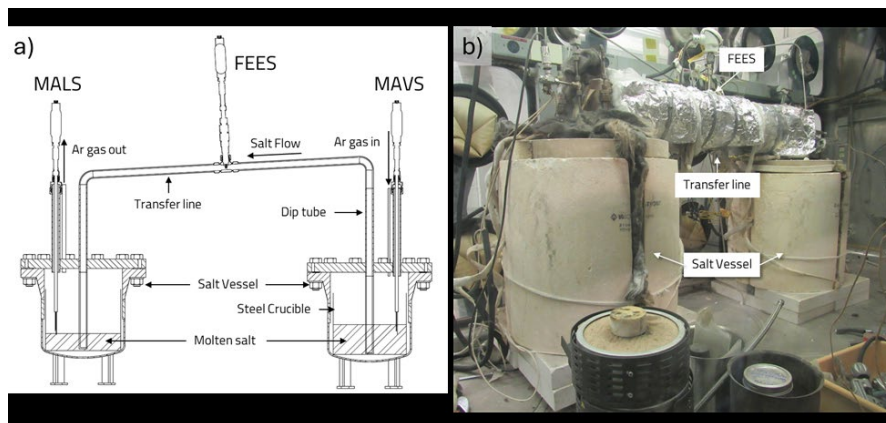
Automated molten salt sampler for at-line analysis of electrorefiner samples.



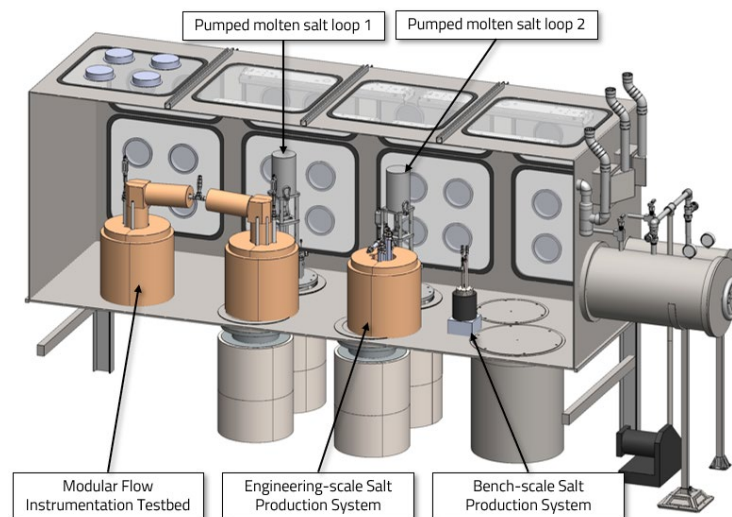
Immersion depth of sensor in salt versus time during basket removal

# DOE/NE ARSS PROJECTS

- Modular Flow Instrumentation Testbed (MFIT) for MSR Material Control and Accounting (W. Doniger, CFCT)
  - Experimentally evaluating the efficacy of electroanalytical tools for **domestic safeguards**
  - Safeguards-relevant scenarios include synthesis of highly-loaded uranium-bearing chloride salts and flowing salt systems



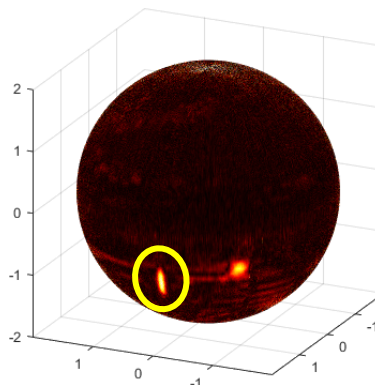
Dual tank modular flow instrumentation testbed (a) schematic and (b) system assembled in inert atmosphere radiological glovebox



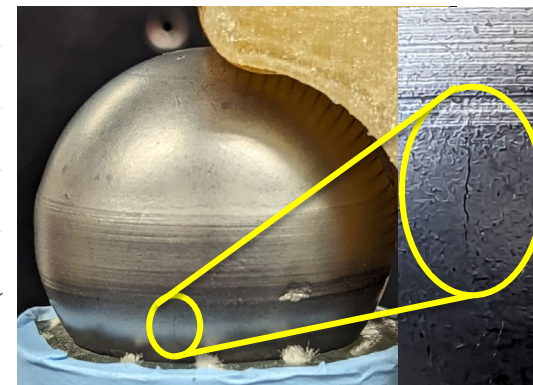
Rendering of Argonne's Molten Salt Flow Systems Glovebox along with installation location for various experimental systems

# DOE/NE ARSS PROJECT: PEBBLE MONITORING

- Dual-purpose Pebble Monitoring System (T. Elmer, NSE)
  - Sensor, Instrumentation, and NDE laboratory capabilities for imaging novel fuel forms in adverse conditions
  - Analyzing eddy current (EC) imaging for monitoring pebble type for domestic safeguards and structural integrity
  - Project began as detecting definable characteristics to categorize types of pebbles for MC&A
  - Evolved into pebble monitoring for structural integrity



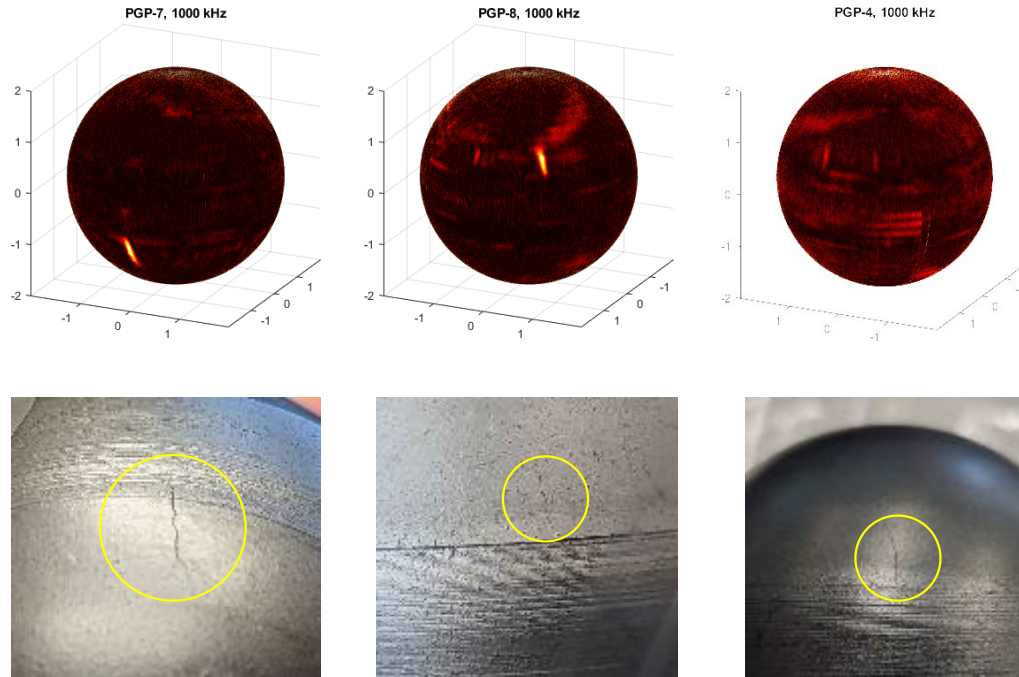
Spherical projection of 2 scans from an array probe



Photographic confirmation of surface-breaking flaws

# DOE/NE ARSS PROJECT: PEBBLE MONITORING

## Visual confirmation of surface-breaking cracks

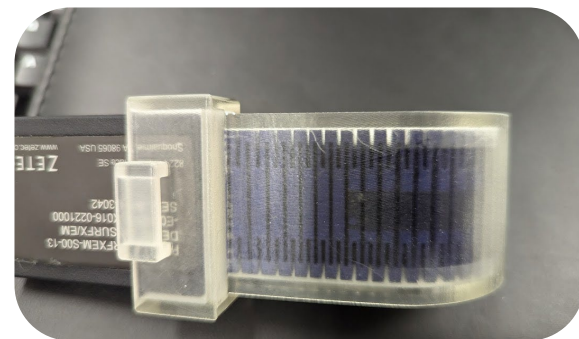
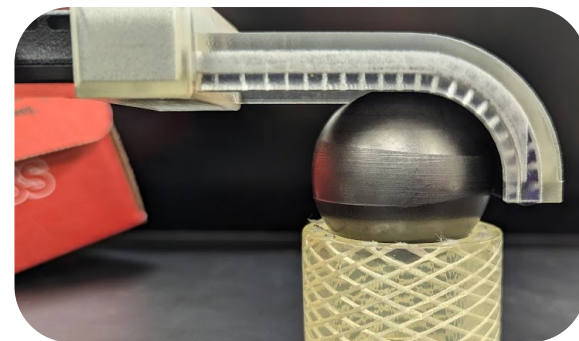


- All but two pebbles showed evidence of cracking, many with multiple cracks
  - Almost all were extending from the equatorial band, implying a manufacturing process defect
- Macro photography confirmed surface-breaking cracks in most instances
- A few flaws with detectable EC signals were not visible on the surface, implying sub-surface defects
- Horizontal cracks were observed by visual inspection

# DOE/NE ARSS PROJECT: PEBBLE MONITORING

## Development of flexible EC array probe

- A new array probe was developed with larger coil diameter and wider frequency range
  - Greater sensitivity at the 5mm depth of the outer shell
- Two pressed graphite pebble samples were modified to create voids at specific depths for quantifying depth measurements
- High temperature probe received and tested December 2025



# DOE/NE ARSS PROJECT: PEBBLE MONITORING

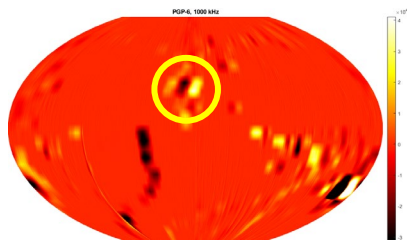
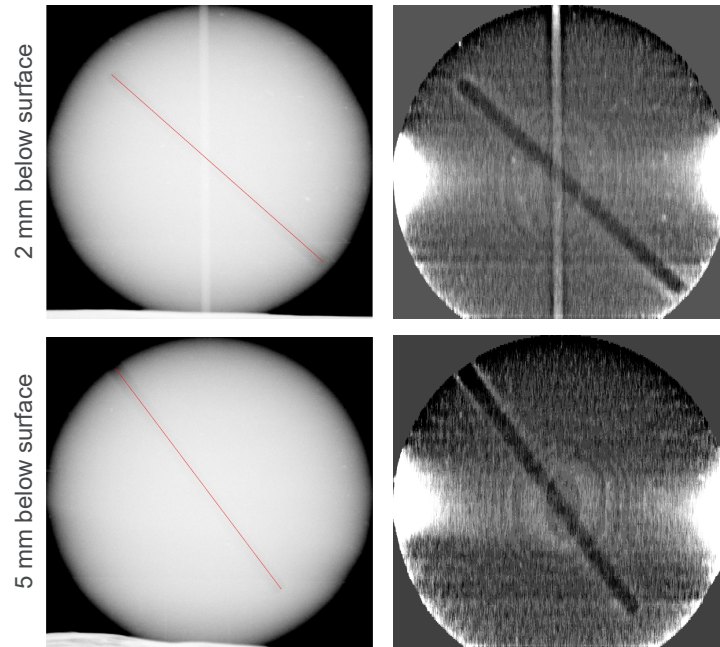
## Void depth standards

- To validate depth simulations, two pebbles were selected to create depth standards, with voids at 2mm and 5mm below the surface
- Measurements from X-ray radiographs confirm that depths are within  $\pm 0.1$ mm of target

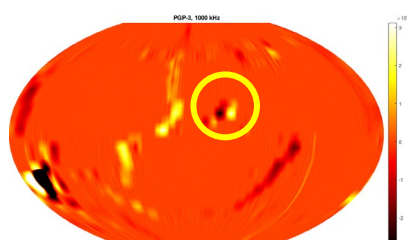


X-Ray Radiographs

Filtered images



Depth standard with void 2mm below the surface



Depth standard with void 5mm below the surface

*Validate NDE technologies in ambient conditions and report on the limits of both superficial and subsurface artefacts of pebbles (in preparation for elevated temperature validation experiments).*

# DOE/NE ARSS PROJECT: PEBBLE MONITORING

## Conclusions

- EC imaging able to differentiate between surface denting and cracking
- More than 80% of pebbles in our set exhibited vertical cracks, primarily at the edge of the equatorial band
  - Consistency of locations of the cracks seems to indicate possible manufacturing issues
  - Ease of detecting small defects lends credence to the possibility of detecting manufacturing batch identifiers embedded in the outer shell
- Demonstrated ability to detect voids at 2mm and 5mm below the surface
- Material property differences were sufficient to distinguish between annular/fuel pebbles and surrogate, pressed graphite pebbles
  - Likely due to manufacturing differences

# SUMMARY

- Argonne is contributing safeguards and security expertise to help advance international and domestic deployment of U.S. nuclear technology through numerous technical research projects and direct engagements with industry
- Leveraging experience in applied international safeguards, nuclear security, safety analysis, consequence management, export controls, and applied policy benefit U.S. mission and interests
- For further information on presented work in safeguards and security, please reach out
- For training on safeguards by design or security by design, we can help connect you with appropriate NNSA and DOE/NE programs and subject matter experts

# THANK YOU

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