Safeguards Technology Considerations and Research Needs for Thorium Fuel Cycles and Molten Salt Reactors

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

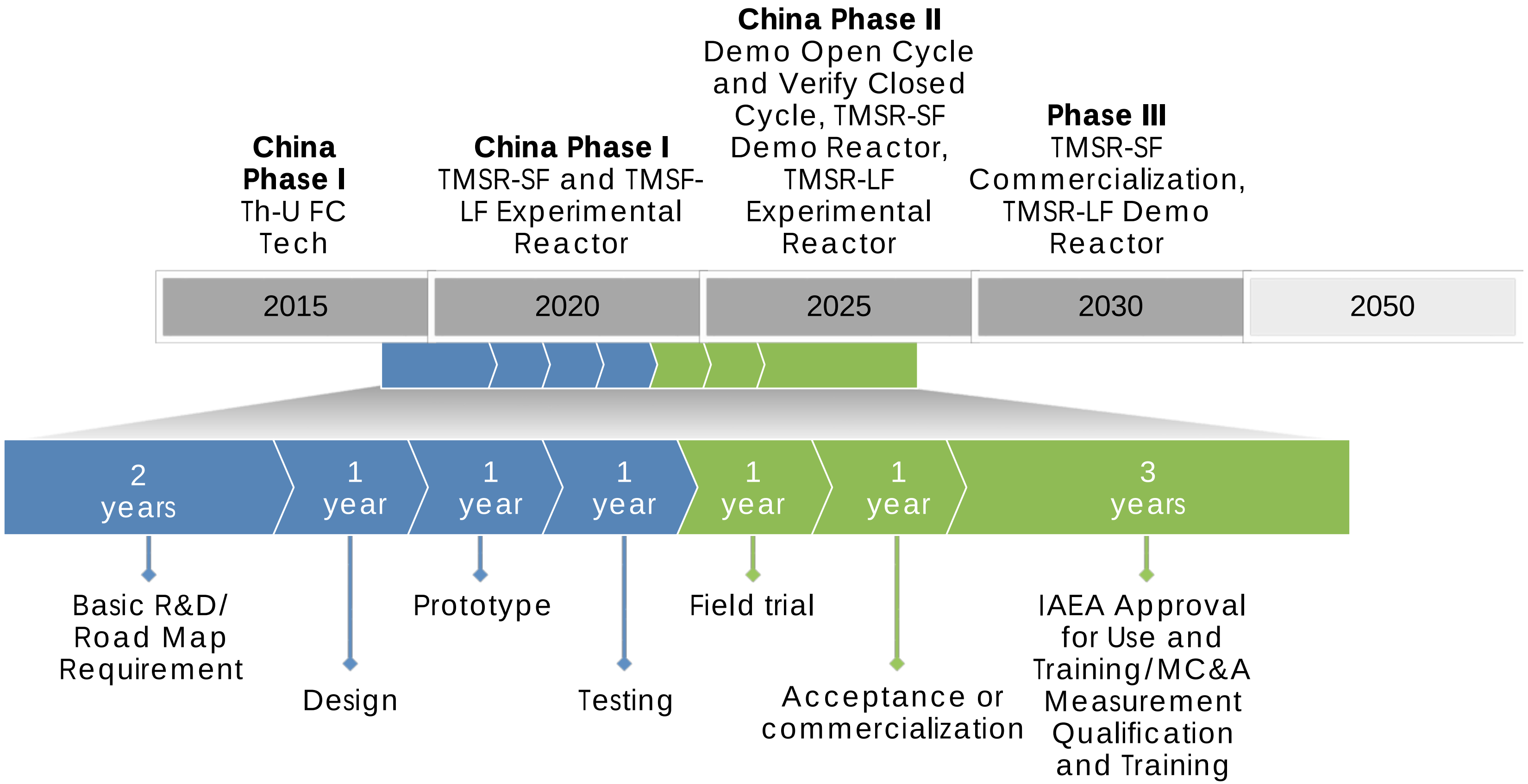
Louise Evans-Worrall
Senior R&D Scientist, Oak Ridge National Laboratory

October 15, 2021

Research focus

Advancing nondestructive measurement technologies and methods to meet future safeguards and nonproliferation challenges

- **What are the next big challenges?**
  - Advanced reactors
  - Emerging fuel cycles including Th/^{233}U
  - Fuels e.g., new forms and compositions
- **Assess gaps in current detection technologies**
  - Drive innovation
  - Overcome inertia to implement safeguards technology solutions by getting out ahead of the technology lifecycle



OAK RIDGE National Laboratory

Safeguards technology is central to nuclear material accounting, monitoring, and timeliness of detection

Nuclear material measurements

MC&A Measurement Systems for safeguarding and securing nuclear facility operations

- Physical inventory and tracking nuclear material
- **Nuclear Material Accounting System:** Provide assurance that all material quantities are present in the correct amount; provide timely detection of material loss or theft; estimate quantity of material loss and location

Safeguards verification technologies for IAEA in-field activities in support of the global non-proliferation regime

- Nuclear material accountancy is the main activity in the technical measures that comprise IAEA safeguards
- **IAEA Safeguards:** Provide timely detection of nuclear material diversion

Key research questions to consider…

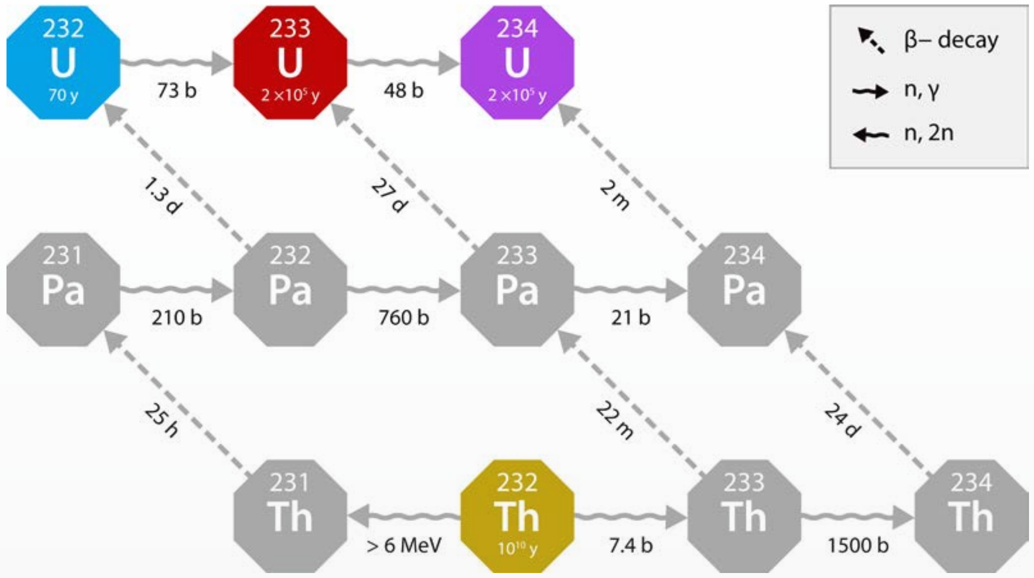
- Why does safeguards technology need to be explored for Th/^{233}U fuel cycles?
- Why are Th/^{233}U fuel cycles more complex than U and U/Pu fuel cycles from a nuclear material measurement perspective?
- How do thorium fuel cycles lead to the need to modify current safeguards technologies and develop new analysis methods?
- Why can't safeguards technologies for ^{235}U assay be adopted "out of the box" for the assay of ^{233}U, and how does this lead to research needs?
- Why are Molten Salt Reactors (MSRs) considered to add another level of complexity?
- What safeguards technology R&D is needed to drive progress?

Key research questions to consider...

- Why does safeguards technology need to be explored for Th/^{233}U fuel cycles?
- Why are Th/^{233}U fuel cycles more complex than U and U/Pu fuel cycles from a nuclear material measurement perspective?
- How do thorium fuel cycles lead to the need to modify current safeguards technologies and develop new analysis methods?
- Why can't safeguards technologies for ^{235}U assay be adopted "out of the box" for the assay of ^{233}U, and how does this lead to research needs?
- Why are Molten Salt Reactors (MSRs) considered to add another level of complexity?
- What safeguards technology R&D is needed to drive progress?

Why does safeguards technology need to be explored for thorium fuel cycles?

- **Challenge:** Commercial thorium fuel cycles (Th/^{233}U) are evolving worldwide
  - Unirradiated, separated pure **^{233}U** is a direct-use fissile material
- **Gap:** Current detection technologies and methods in the safeguards and nonproliferation mission space are tailored for ^{235}U and plutonium isotopes
- **^{233}U** detection is complex
  - **^{232}U** presence and isotopic mixtures
  - Unique identifiers and signatures
  - Direct vs. indirect verification/ quantification



Oak Ridge National Laboratory

Key research questions to consider…

Why does safeguards technology need to be explored for Th/^{233}U fuel cycles?

Why are Th/^{233}U fuel cycles more complex than U and U/Pu fuel cycles from a nuclear material measurement perspective?

How do thorium fuel cycles lead to the need to modify current safeguards technologies and develop new analysis methods?

Why can't safeguards technologies for ^{235}U assay be adopted "out of the box" for the assay of ^{233}U, and how does this lead to research needs?

Why are Molten Salt Reactors (MSRs) considered to add another level of complexity?

What safeguards technology R&D is needed to drive progress?

Differences in characteristics between Th/^{233}U fuel cycles and U/Pu fuel cycles that impact safeguards technology

Significantly more diverse in fuel types and forms because of the diversity of reactor options

Different nuclear materials and isotopic mixtures e.g., Th, ^{233}U

Reprocessing is not a consideration for many countries, but is a main consideration for resource utilization in thorium fuel cycles

Possible to produce pure ^{233}U from short-lived ^{233}Pa precursor depending on reactor design and fuel cycle processing

Need ^{235}U and ^{239}Pu production to support ^{233}U production (fissile driver for fertile fuel) because first generation not mature enough to startup on ^{233}U

Signatures and indicators are different for thorium fuel cycles

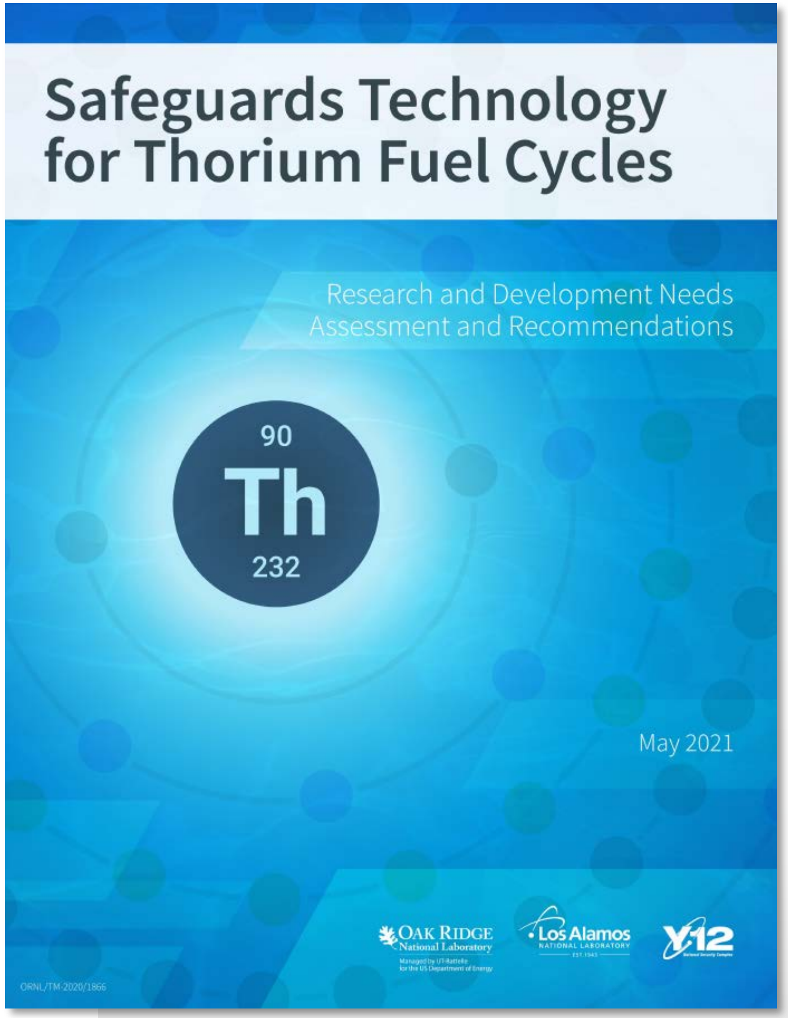
“Difficult to safeguard” does not mean “more proliferation vulnerable” e.g., ^{232}U

Key research questions to consider…

- Why does safeguards technology need to be explored for Th/^{233}U fuel cycles?
- Why are Th/^{233}U fuel cycles more complex than U and U/Pu fuel cycles from a nuclear material measurement perspective?
- How do thorium fuel cycles lead to the need to modify current safeguards technologies and develop new analysis methods?
- Why can't safeguards technologies for ^{235}U assay be adopted "out of the box" for the assay of ^{233}U, and how does this lead to research needs?
- Why are Molten Salt Reactors (MSRs) considered to add another level of complexity?
- What safeguards technology R&D is needed to drive progress?

Thorium R&D Plan

- **Lead Authors:** Louise Worrall, Nick Luciano, Richard Reed, Vlad Henzl, Alicia Swift, Karen Hogue
- **Acknowledgement:** DOE NNSA Office of Defense Nuclear Nonproliferation R&D Safeguards Program, Program Manager: Christopher Ramos
- **Understand the R&D that is necessary to transition the current safeguards technology toolkit to meet the verification needs of thorium fuel cycles**
  - Identify leading candidate thorium fuel cycles and their characteristics that impact safeguards technology
  - Provides the scientific basis for strengthening existing instrumentation capabilities or developing new instrumentation that may be needed to fill any potential capability gaps within the international nuclear safeguards community to properly verify declarations of any ^{232}Th and ^{233}U bearing materials



Recognized by the IAEA as a future consideration

- **IAEA report on the 2018 Symposium on International Safeguards** cites the challenge of developing verification techniques for the thorium fuel cycle

Safeguarding selected new reactor designs

New and advanced reactors—including those for small modular and transportable reactors—are transforming the market for nuclear energy. Participants provided overviews of changes in nuclear fuel cycles, designs of new facilities, safeguards implementation for existing facilities, or descriptions of technologies being developed for safeguards at such new facilities. Their discussions identified safeguards challenges that need to be addressed, and how to more effectively incorporate safeguards into these new designs.

Challenges

- Developing verification techniques—especially nuclear materials accountancy, containment, and surveillance—in facilities using closed-core Small Modular Reactors (SMRs).
- Developing verification techniques for the thorium fuel cycle.
- Introducing novel ways of thinking to develop innovative and improved safeguards approaches for new facilities.

Three leading candidate thorium fuel cycles

The Three Leading Candidate Thorium Fuel Cycles

Multi-stage fuel cycle with continuous recycle of ^{233}U

HWR
Generates Pu for Stage 2

SFR
Breeds ^{233}U and Pu

AHWR
^{233}U continuous recylcle

e.g., India

Once-through or continuous recycle in a pressurized water reactor

PWR
Th-bearing fuel

e.g., Norway (fuel R&D), USA (historic)

Continuous recycle of ^{233}U in a molten salt reactor

MSR
Fissile fuel salt with fertile ^{232}Th blanket salt

e.g., China (T-MSR), Indonesia (ThorCon), USA (Flibe Energy)

Several fuel forms and isotopic mixtures were identified

Key research questions to consider...

Why does safeguards technology need to be explored for Th/^{233}U fuel cycles?

Why are Th/^{233}U fuel cycles more complex than U and U/Pu fuel cycles from a nuclear material measurement perspective?

How do thorium fuel cycles lead to the need to modify current safeguards technologies and develop new analysis methods?

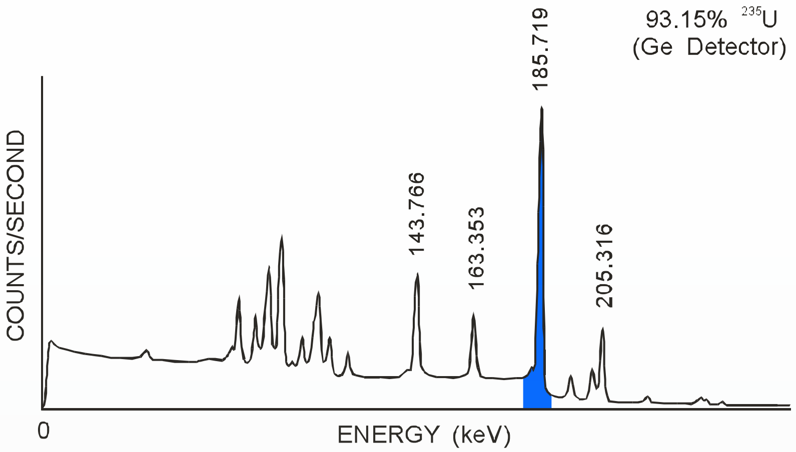
Why can't safeguards technologies for ^{235}U assay be adopted "out of the box" for the assay of ^{233}U, and how does this lead to research needs?

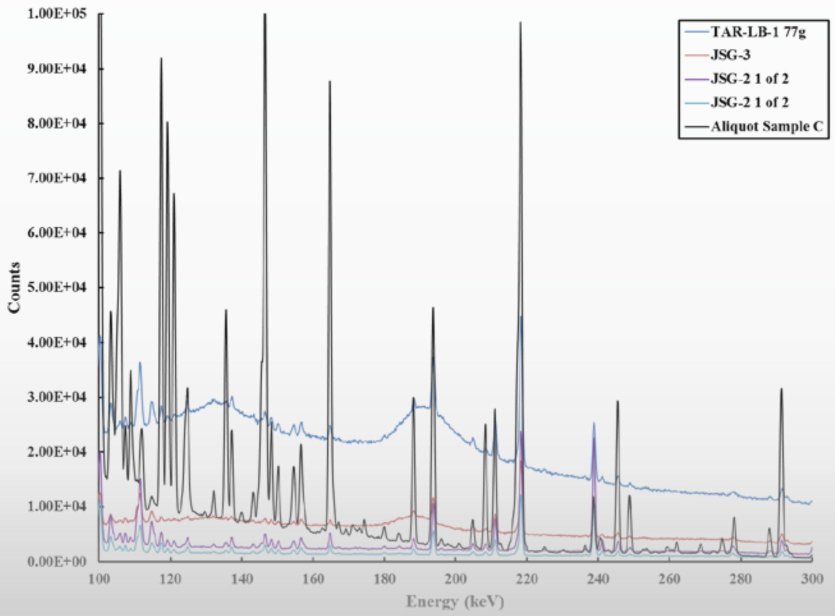
Why are Molten Salt Reactors (MSRs) considered to add another level of complexity?

What safeguards technology R&D is needed to drive progress?

Prompt identification of ^{233}U is challenging using gamma measurements, especially if shielded

- **Challenge:** ^{233}U emits relatively low-energy, low-intensity gamma-rays. Due to its short half life, the progeny of ^{232}U grow in quickly and dominate the gamma-ray signature of thorium fuel cycle materials
  - Items are likely to require shielding
- **Recommendations**
  - Evaluate effect of increasing inspection assay times to increase sensitivity and optimize use of inspection resources
  - Safeguards technology may require modifications to equipment or conduct of operations e.g., identiFINDER HM-5 detector not tailored to identify shielded ^{233}U using current analysis





OAK RIDGE National Laboratory

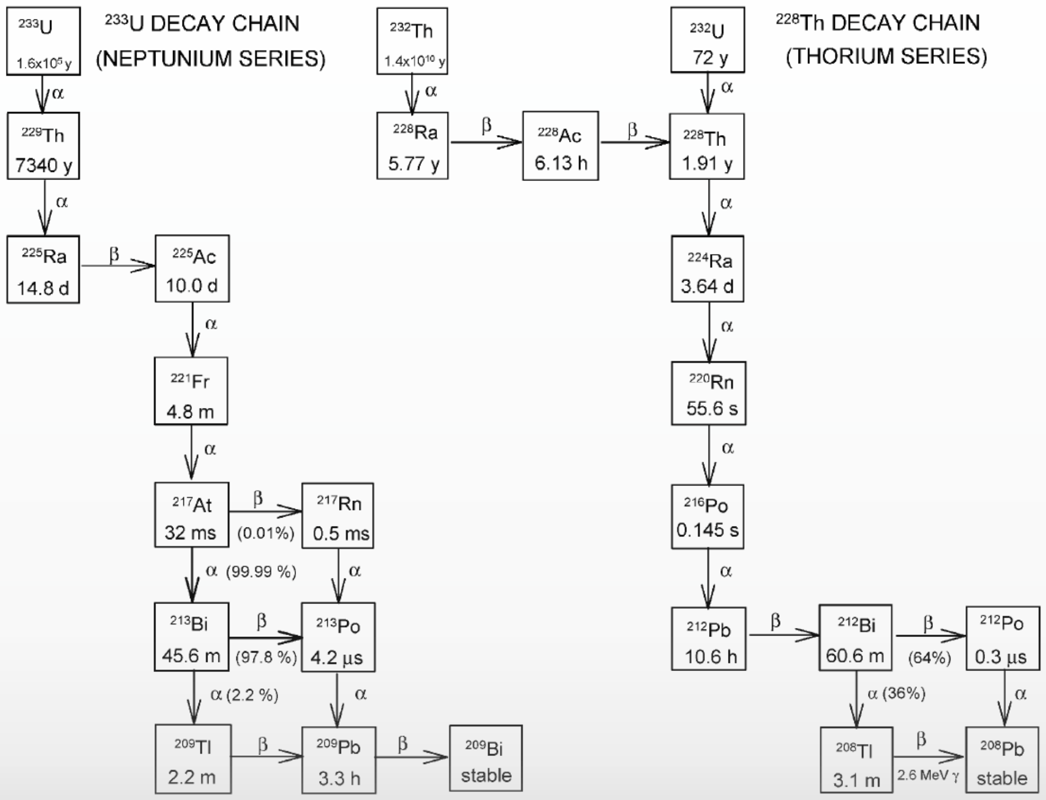
Quantitative assay of ^{233}U total mass using neutron signatures requires research, especially in mixtures

- **Challenge:** No "out of the box" nondestructive analysis method exists for the quantification of ^{233}U mass
  - Passive neutron assay is not possible
  - Development of active neutron interrogation techniques is possible – however, method needs to be distinct from ^{235}U induced fission as similar properties
    - Potentially achieved by algorithms including timing windows or exploration of a range of interrogating neutron spectrum energies

- **Recommendations:**
  - Draw analogies between current and anticipated safeguards technologies and methods for method development
  - Explore a range of neutron interrogation sources for a range of neutron interrogation energies for the assay of ^{233}U in the presence of other fissile nuclides
  - Idea: Develop a self-interrogation neutron NDA method for ^{233}U
    - Where ^{233}U is in the presence of other fissile isotopes: explore self-interrogation approaches if oxide or fluoride compound (not metal)
    - Driver: (α, n) reactions on surrounding light elements

Distinguishing between ^{232}Th- and ^{232}U-bearing items is challenging, especially for freshly separated thorium

- **Challenge:** Once the ^{232}U progeny grow in, the ^{232}U and ^{232}Th gamma-ray signatures are similar
- **Recommendations:**
  - Idea: ^{232}U decay chain does not include ^{228}Ac, which contributes several significant gamma-rays: 338 keV, 911 keV, 969 keV
  - Evaluate performance of automated radio-isotope identifiers, such as the identiFINDER, for isotopic identification using the 911/969 keV complex to improve current analysis
  - Evaluate the use of high-resolution gamma detectors for freshly separated Th because of the need to distinguish weak contributions from ^{232}U direct gamma-rays

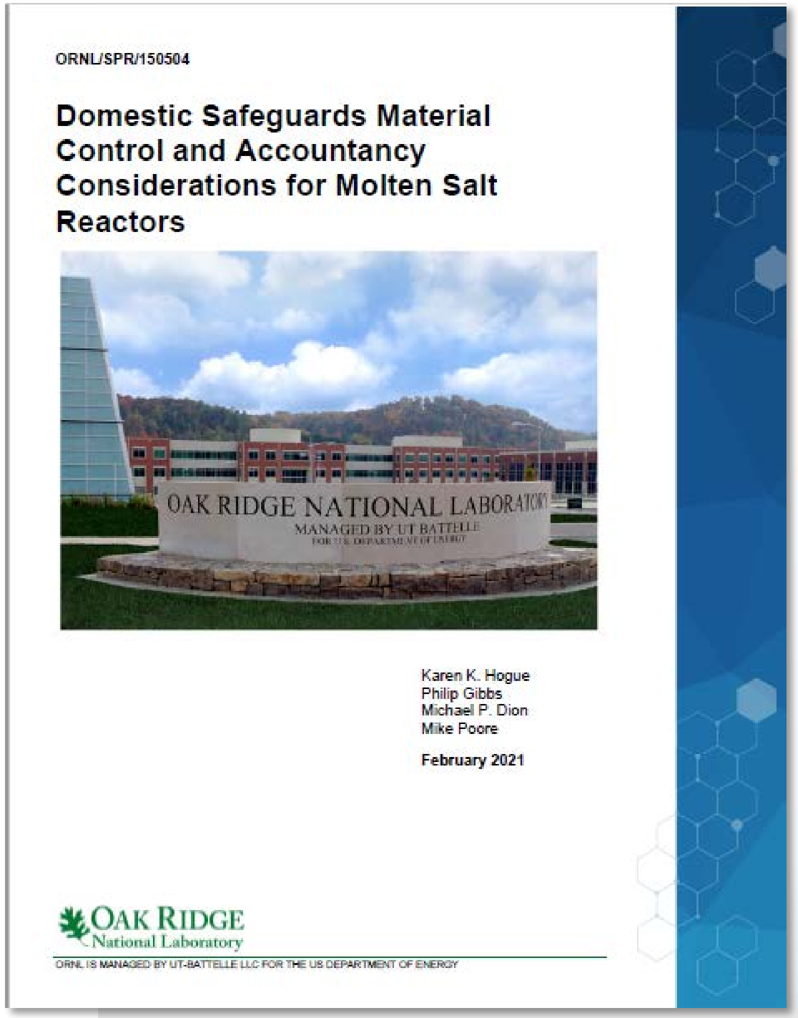


Key research questions to consider…

- Why does safeguards technology need to be explored for Th/^{233}U fuel cycles?
- Why are Th/^{233}U fuel cycles more complex than U and U/Pu fuel cycles from a nuclear material measurement perspective?
- How do thorium fuel cycles lead to the need to modify current safeguards technologies and develop new analysis methods?
- Why can't safeguards technologies for ^{235}U assay be adopted "out of the box" for the assay of ^{233}U, and how does this lead to research needs?
- **Why are Molten Salt Reactors (MSRs) considered to add another level of complexity?**
- What safeguards technology R&D is needed to drive progress?

MSR MC&A Considerations

- **Lead Author:** Karen Hogue **Program Lead:** Michael Dion
- A new mode of operation combining the safeguards needs of fuel fabrication, reactor, separations, and waste in one facility
  - **No design basis scenarios**
  - **Access to SNM** while operational
    - High radiation and temperature, considered online inventory
  - Inventory and confirmation of **online (re)fueling**
    - SNM during refueling will require methods for quantification
  - **Chemical processing** and/or online separations
    - Timely detection **cannot** only rely on material balance and surveillance - NDA or direct measurements (volumes, tank levels, etc.) are needed
    - Protactinium removal from the reactor, which would potentially need to be monitored in the chemical processing system as part of ^{233}U accountancy (INMM Paper, Eva Uribe, Sandia National Laboratories)


ORNL/SPR/150504

Domestic Safeguards Material Control and Accountancy Considerations for Molten Salt Reactors

Karen K. Hogue
Philip Gibbs
Michael P. Dion
Mike Poore

February 2021

Oak Ridge National Laboratory

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

Key research questions to consider…

- Why does safeguards technology need to be explored for $Th/^{233}U$ fuel cycles?
- Why are $Th/^{233}U$ fuel cycles more complex than U and U/Pu fuel cycles from a nuclear material measurement perspective?
- How do thorium fuel cycles lead to the need to modify current safeguards technologies and develop new analysis methods?
- Why can't safeguards technologies for ^{235}U assay be adopted "out of the box" for the assay of ^{233}U, and how does this lead to research needs?
- Why are Molten Salt Reactors (MSRs) considered to add another level of complexity?
- What safeguards technology R&D is needed to drive progress?

Key Recommendations

Safeguards technology development is needed for emerging nuclear technology

- Safeguards technology is currently tailored for conventional U/Pu fuel cycles
- MSRs and thorium utilization in advanced reactors have a low technology readiness level (TRL), but the safeguards technology has an even lower TRL than the reactor and fuel cycle technology

Safeguards technology requirements need to be defined

- Technology development will be dependent on the fuel cycle stage, as well as the composition of the nuclear material

Safeguards technology development timelines may potentially be shortened by aligning the development lifecycle to the licensing and deployment lifecycle of advanced reactors

- Assigning “safeguards level” categories analogous to TRL categories to the advanced reactor development and licensing stage may better align the safeguards technology development lifecycle to advanced reactor technologies; thus, could help better map technology requirements to these stages

Safeguards technology research needs for thorium fuel cycles

- Existing safeguards technologies are tailored towards ^{235}U and Pu detection, identification, and quantification, and thus R&D is needed for their application to thorium fuel cycles

- Research is needed to address significant technical challenges including:
  - Prompt, shielded detection of ^{233}U
  - Co-assay of ^{233}U in isotopic mixtures containing ^{235}U and Pu
  - Basic nuclear data

- For neutron signatures, it is possible to draw analogies between isotopes based on their fundamental nuclear properties and use this for method development
  - ^{232}Th vs. ^{238}U
  - ^{233}U vs. ^{235}U

Key recommendations from Thorium R&D Plan report

Materials and infrastructure needs for experimental validation

Concept development and laboratory demonstration for neutron nondestructive NDA of ^{233}U and ^{232}Th → technology development

Concept development for gamma NDA of ^{233}U and ^{232}Th → technology development

Perform nuclear data scoping on nuclear data needs for thorium fuel cycle safeguards

Compile "virtual International Target Value (ITV) definitions" for thorium fuel cycles to support long-term R&D efforts

Safeguards technology research needs for MSRs

- Functional requirements of instruments need to be defined based on nuclear material accounting requirements
- Too early to target specific instrumentation development prior to a fundamental evaluation of the potential signatures (e.g., radiation, chemical, heat) and their correlations to fissile content
- Experimental test beds are needed to test instrumentation performance and reliability
- System-level dynamic modeling is needed to understand the MSR fuel cycle and related signatures
- Multi-modal approaches could be considered since it is unlikely that there will be a single monitoring scheme for all areas of an MSR facility that is applicable to all MSR variants
- Understand how to leverage operator's measurements and their development including remote operations and maintenance

U-233 Detection Science informs ORNL program of work on Thorium Fuel Cycle Safeguards

Basic science under ORNL Uranium Science area	**Uranium-233 Detection Science** Sponsor: NSSD LDRD Team: ORNL
Technology planning & development	**Thorium Safeguards Technology R&D Plan** Sponsor: NA-22 Team: ORNL, LANL, Y-12 **Uranium-233 Advanced Neutron NDA** Sponsor: NA-22 (FY22) Team: LANL, ORNL, Y-12, SNL
International Safeguards Technology, Concepts & Approaches	**Protactinium-233 Monitoring** Sponsor: NA-24 ARISE Team: SNL, ORNL **Uranium-232 Reduction** Sponsor: NA-24 ARISE Team: SNL, ORNL **Uranium-233 Counting Standards Production** Sponsors: NA-24 SGTech, NBL PO Team: ORNL
Industry Engagements/ Nonproliferation Applications	**Preliminary Safeguards Assessment for Flibe Energy Liquid Fluoride Thorium Reactor (LFTR)** Sponsor: DOE-NE GAIN Team: ORNL, Flibe Energy **Signatures of Uranium-233 Production in a Weapons Context** Sponsor: NA-22 Team: ORNL

Backup Slides

- Thorium R&D Plan report recommendations
- NDA science
- NDA systems requirements
- Proposed MC&A approaches for MSRs
- Ongoing research MSR MC&A

Recommendations from Thorium R&D Plan report

Materials and Infrastructure Needs for Experimental Validation

- Assemble a representative set of sample materials for experimental evaluation. Materials relevant to the three leading thorium fuel cycles are identified in Sections 1.2.6 and 1.3.1. These supplies should be maintained across the DOE complex to support R&D and technology development to strengthen verification capabilities.
- Leverage nuclear materials from other scientific communities within the DOE complex, including the nuclear forensics community and the DOE Isotope Program.

Concept Development and Laboratory Demonstration for Neutron NDA of ^{232}Th and ^{233}U

- Draw analogies between current and anticipated safeguards technologies and methods for concept development based on similarities among ^{233}U vs. ^{239}Pu, ^{233}U vs. ^{235}U, and ^{232}Th vs. ^{238}U.
- Verify that current neutron detectors can work with shielded and bare ^{233}U in different chemical forms (e.g., oxide, fluoride salt).
- Address the safeguards measurement challenge of the quantitative assay of ^{233}U total mass by modifying or developing active neutron NDA techniques because the passive neutron NDA of ^{233}U is not possible. This is not possible because ^{233}U does not have a high enough SF neutron yield and, therefore, does not have a practically usable passive neutron signature.
- Evaluate neutron NDA techniques used for ^{235}U for their applicability to ^{233}U.
- Develop active neutron interrogation methods and corresponding analysis algorithms for the quantitative mass assay of ^{233}U. Adapting the standard active interrogation technique using ^{241}AmLi (α,n) neutron interrogation sources, currently used for the mass assay of LEU and HEU, provides a starting point.
- Develop and demonstrate a self-interrogation neutron NDA method for pure ^{233}U based on its high (α,n) neutron yield.

Concept Development and Laboratory Demonstration for Neutron NDA of ^{232}Th and ^{233}U

- Develop self-interrogation neutron NDA techniques for which ^{233}U is in the presence of other fissile isotopes and present in an oxide or fluoride compound (not metal). The driver will be (α,n) reactions on surrounding light elements.
  - Demonstrate that ^{233}U can be discriminated from ^{235}U by neutron methods based on self-interrogation.
- Evaluate active neutron NDA methods for the quantitative assay of ^{232}Th total mass, as passive neutron NDA is not possible. The SF rate of ^{232}Th is low (i.e., 1.02×10^{-7} neutrons/g/s). Self-interrogation is also unlikely because ^{232}Th is a weak α-particle emitter.
- Demonstrate the active neutron assay of ^{232}Th with a neutron generator or high-energy isotopic source toward the goal of quantitative assay of ^{232}Th total mass.
- Evaluate the most appropriate fast neutron energy interrogation sources for the mass assay of ^{232}Th. ^{232}Th is fissionable; therefore, thermal neutrons are not suitable for the assay of ^{232}Th. ^{232}Th has a low IF cross-section at low energies. Only fast neutrons with energies above ~1.5 MeV can yield a practically significant amount of IF on ^{232}Th, although suppressed by a factor of three to four compared to ^{238}U. Consider neutron sources >1.5 MeV for ^{232}Th active assay. However, ^{238}U has a similar fission threshold; therefore, methods to distinguish between these two isotopes must be developed.
- Evaluate neutron NDA techniques used for ^{238}U for their applicability to the assay of ^{232}Th.
- Develop a concept for active neutron interrogation and perform mass assay of ^{233}U in the presence of other isotopes of uranium including fissile ^{235}U and fertile ^{238}U, or fissile ^{239}Pu, or all these isotopes.
  - Evaluate the signature contributions from (α,n) neutrons vs. correlated neutrons from fission.
  - Evaluate the use of multiple interrogation sources (with different neutron energies) or the dual-energy interrogation method for applicability to the assay of ^{232}Th in the presence of ^{238}U, as well as the assay of ^{233}U in the presence of ^{235}U.
  - Use at least two or three different neutron interrogation spectrum energies for composite materials. Possible neutron source options to be evaluated include AmLi, ^{252}Cf, and neutron generators.
- Develop active neutron interrogation techniques for ^{233}U that are distinct from ^{235}U-induced fission. This could potentially be achieved by algorithms including timing windows or exploration of a range of interrogating neutron spectrum energies.
- Explore a range of neutron interrogation sources for a range of neutron interrogation energies for the assay of ^{233}U in the presence of other fissile nuclides.
- Investigate the effect within the thorium MSR fuel cycle of performing neutron measurements of isotopes of safeguards interest in the presence of protactinium and its fissile and fertile isotopes (e.g., ^{231,232}Pa). For example, when circulating in the salt or when it is present in the decay tank,

Recommendations from Thorium R&D Plan report

Concept Development for Gamma NDA of ^{232}Th and ^{233}U
• Address the significant safeguards measurement challenge of promptly identifying ^{233}U, especially if shielded.
• Address the safeguards measurement challenge of verifying ^{232}U concentrations in ^{233}U. Develop methods to assay ^{233}U in the presence of ^{232}U. The authors are not aware of any COTS analysis software for this application. We recommend that the FRAM code (or other gamma ray isotopic analysis codes) be modified for use with high-resolution gamma detectors to incorporate this analysis.
• Assay the isotopic composition of bulk ^{233}U-bearing material in the presence of ^{232}U and in shielded configurations. Identify the dynamic range of feasibility of different gamma-based NDA methods considering different $^{232}U/^{233}U$ ratios and in the presence of shielding with different shielding configurations.
• Distinguish between ^{232}Th material and other materials bearing ^{232}U. Due to the short half-life of ^{232}U, its progeny grow in quickly and dominate the gamma ray signature of thorium fuel cycle materials. Once the ^{232}U progeny grows in, the ^{232}U gamma ray signature is similar to the ^{232}Th signature. Furthermore, the intense high-energy gamma rays of the ^{232}U daughters lead to a significant Compton continuum, especially in shielded configurations.
• Explore methods to distinguish between ^{232}Th and ^{232}U in freshly separated thorium, which is a significant challenge.
• Evaluate the use of high-resolution gamma detectors, including the DNN R&D Safeguards Program–developed high-resolution microcalorimeter, for freshly separated thorium, considering the need to distinguish weak contributions from ^{232}U direct gamma rays.
• Utilize the ^{228}Ac gamma ray signatures in analysis method development. The ^{232}U decay chain does not include ^{228}Ac, which contributes several significant gamma rays: 338 keV, 911 keV, and 969 keV. Using the 911/969 keV complex to distinguish between ^{232}U-containing items and ^{232}Th shows potential.
• Develop concepts for inverse analysis to determine the amount of shielding present. Unlike other uranium-bearing materials, ^{233}U-bearing items can have a large gamma ray dose, which is mostly due to the ingrowth of ^{208}Tl (2614 keV gamma ray) in the ^{232}U decay chain. The high radiation drives shielded requirements, and the impact of shielding on the assay of ^{233}U needs to be quantified.

Technology Development for Neutron NDA
• Develop detectors and electronics components for use in high-radiation environments.

Technology Development for Gamma NDA
• Develop detectors and electronics components for use in high-radiation environments.

Develop Safeguards Concepts and Approaches, and Policy Specific to $^{232}Th/^{233}U$
• Distinguish an analogy of LEU and HEU for ^{233}U-bearing items.
• Develop protactinium safeguards concepts and approaches, including monitoring, as a precursor to pure ^{233}U.
• Evaluate the potential benefits of monitoring thorium source material earlier in the fuel cycle for continuity of knowledge throughout other fuel cycle stages.
• Understand dose rates and shielding considerations as they relate to inspector access and measurement access (i.e., remote and unattended monitoring) for the development of safeguards concepts and approaches for monitoring thorium fuel cycle items.

Recommendations from Thorium R&D Plan report

Materials and Infrastructure for Experimental Validation
• Design and build a mock-up fuel assembly with thorium and uranium pins for experimental measurement campaigns and laboratory testing of developed NDA systems. This is important to testing and verification of fresh fuel attributes. o A mock-up fuel assembly represents the highest fidelity for testing and verification of fresh fuel attributes while also representing some of the most important spent fuel characteristics (e.g., multiplication, source distribution, self-shielding).

Materials and Infrastructure for Experimental Validation
• Stage composite items or materials (e.g., ^{233}U + Pu, Th + Pu, Th + U) for experimental measurement campaigns and laboratory testing of stand-alone detectors and developed NDA systems. o First steps could be to measure groupings of individual sealed sources of these isotopes. o Bulk materials are required for neutron NDA measurements.
• Use high-fidelity simulations to prescreen the significance of certain source arrangements and properties prior to procurement, and for experimental campaign design, in case of resource-intensive scenarios.
• Use high-fidelity simulations to benchmark any measurements, and for extrapolation into realistic or probable scenarios that are not achievable under laboratory conditions.

Recommendations from Thorium R&D Plan report

Technology Development for Neutron NDA
• Adapt INCC analysis software for the automatic evaluation of neutron-counting rates from thorium fuel cycle isotopes.
• Understand and overcome the practical constraints of applying existing neutron-counting systems to the mass assay of ^{233}U in the presence of ^{232}U gamma background (i.e., ^{208}Tl). Understand the impact of neutron NDA system settings (i.e., high-voltage reduction needed to compensate for any background gamma dose), which, for example, might lead to longer counting times.

Technology Development for Gamma NDA
• Evaluate the concept of operations to move from high-resolution to low-resolution detectors in some cases. High-resolution detectors do not necessarily have the same automated analysis as FLIR's identiFINDER. Because the identiFINDER is currently the only gamma spectrometer in the IAEA's CA Toolkit, the concept of operations needs to be identified and the software adapted accordingly.
• Evaluate the performance of automated RIIDs, such as FLIR's identiFINDER HM-5, for isotopic identification using the 911/969 keV complex to improve current analysis.
• Adapt isotopic composition analysis software and supporting nuclear data/analysis libraries for automatic evaluation of gamma ray spectra from thorium fuel cycle isotopes.
• Consider modifications to equipment and conduct of operations needed for CA Toolkits and MCIKs. For example, FLIR's identiFINDER is not capable of identifying shielded ^{233}U using current identiFINDER HM-5 analysis.

Recommendations from Thorium R&D Plan report

• Evaluate effects of increasing inspection assay times (for the assay of low-intensity gamma rays associated with ^{233}U) to improve sensitivity and optimize use of inspection resources. Evaluate concept of operations to move from low- and medium-resolution detectors to high-resolution detectors for thorium fuel cycle applications.

Feasibility Study for DA
• Perform a feasibility study to ascertain whether the current distribution system of cotton swipes by the IAEA to NWAL is fast enough to allow accurate ^{233}Pa measurements before significant radioactive decay has occurred. This feasibility study could be performed using a cotton swipe doped with ^{233}Pa.

Perform Nuclear Data Scoping and International Target Value (ITV) Definitions (Nuclear Data for Thorium Fuel Cycle Safeguards)
• Undertake scoping effort on uncertainty implications of nuclear data for safeguards measurements.
• Begin compiling "virtual ITVs for thorium fuel cycles," which in turn could help us prioritize mid- to long-term R&D efforts.
• Explore signatures feasibility and the significance of the nuclear data input.
• Perform sensitivity analysis and evaluate whether the uncertainty in the nuclear data is sufficient once methods are demonstrated or assumed feasible.
• Revisit prior studies citing the need to improve the relative uncertainties in the gamma ray absolute emission probabilities for ^{233}U [90].

NDA Science

^{233,235}U or ^{239}Pu

	Mass	Isotopic Composition	Location
	Neutrons	Gamma-Rays	
	Temporal Correlations	Energy, Intensity	Imaging

Safeguards Measurement

Information required – attribute of interest

Radiation signatures

Analysis

NDA System

Verifying ^{232}U concentrations in ^{233}U-bearing items using gamma signatures requires more research

- **Challenge:** Not aware of any commercial off-the-shelf analysis software for this application

- **Recommendations:**
  - Modify the main safeguards isotopic codes for use with high-resolution gamma detectors to incorporate this analysis
  - Evaluate concept of operations to move from low-medium resolution detectors to high-resolution detectors for thorium fuel cycle applications

Several MSR characteristics are not addressed by current nuclear material accounting approaches

A new mode of operation combining the safeguards needs of fuel fabrication, reactor, separations, and waste in one facility

Diverse reactor and fuel cycle variants with unique feed and removal schemes

Fissile material is present outside the reactor vessel in pipes, storage tanks, heat exchangers, and salt processing system

Challenges include continuous processing, material feed and removal, reactor and fuel cycle feedback (timeliness), and evolving fuel salt composition

Online fissile material separations are possible

Accountability is based on physical units for existing reactor fleet, so liquid-fueled MSRs will require new MC&A approaches

Unique refueling schemes e.g., accumulating additional fissile material outside of vessel (breeder)

Several MSR characteristics lead to safeguards technology implementation challenges

- **No design basis scenarios**
  - MC&A and safeguards measurement requirements need to be defined
- **Environmental conditions present a challenging measurement environment**
  - High operating temperature >450°C up to 800°C; corrosive environment; high in-containment radiation levels
  - Reliability issues
  - Access for maintenance, periodic upgrades of instruments and supporting software
- **Radiation signature of molten salts varies depending on the out of core cycle time and location**
  - Liquid fuel salt exiting the core is essentially freshly irradiated
  - Unique signatures not important for cooled solid fueled assemblies (e.g., LWR)
- **Accessibility issues while operational**
  - Use of operator measurements or online process monitoring may be required
  - Remote and unattended monitoring
- **Continuously flowing material and potential online separations**

Different safeguards implications of MSR designs that use thorium fuel cycles compared to other fuel cycles

There is limited experience in detecting and measuring ^{233}U

The ^{232}U co-produced with ^{233}U has ^{208}Tl daughter products that emit highly energetic (2.6 MeV) gamma rays with high absolute emission probability

Protactinium removal from the reactor can lead to the production of pure ^{233}U, which would need to be monitored in the chemical processing system as part of ^{233}U accountancy (e.g., INMM Paper by Eva Uribe, Sandia National Laboratories)

Some designs require onsite storage for thorium fuel

Contrast against Safeguards Technology Requirements

NDA SYSTEMS REQUIREMENTS

In-Plant Use

Does not interfere with plant operations
Joint-use

Field Operations (Inspections)

Remote (data storage)
Unattended or attended

Reliable

Calibration

Physical
Computational

Safeguards Inspector Use

Independent
Portable or installed

Maintenance

Diagnosis
Simple

Safeguards technology areas are being developed and questions remain

Fundamentally, need to understand the specific licensing requirements before designing safeguards technology against pre-requisites

Karen Hogue & Mike Dion, ORNL have worked on the MC&A elements that would be needed to start to define the measurement objectives, which represents the first step in a technology development plan

Another major consideration is the state-of-health of safeguards technology that is subject to the MSR environmental conditions, such as the corrosive nature of salt, which could lead to support instruments

Consider areas of the plant that are more challenging to implement technology than others e.g., salt and actinide salt components in a storage location and knowing when it's in the reactor containment might be straightforward, but more difficult for transient conditions/ transition areas

Not a constant volume system and necessary to know bulk fuel salt inventory

Proposed MC&A Recommendations - Mike Dion

- **Fresh and end-of-life material/structure/component**
  - Quantify SNM in fresh fuel upon arrival
    - Verify S/N, container (tare) weights, intact TID (leverage item counting methods)
  - Incorporate monitoring (e.g., camera surveillance, in situ NDA) to account for all fuel added to the system
    - Direct sampling for DA analysis (in coordination w/ primary loop sampling)
- **Online Physical Inventories→Potential Measurement Locations:**
  - Drain tank – confirm quantities and material inventory
  - Off-gas system – determine removal efficiency, identify potential SNM or progeny accumulation (e.g., I, Cs, Sr)
    - *Progeny isotopes* should be considered in maintenance plan
- **Accumulation Points:**
  - Off-gas system, salt & air filtration, heat exchanger, pipe baffles, etc.

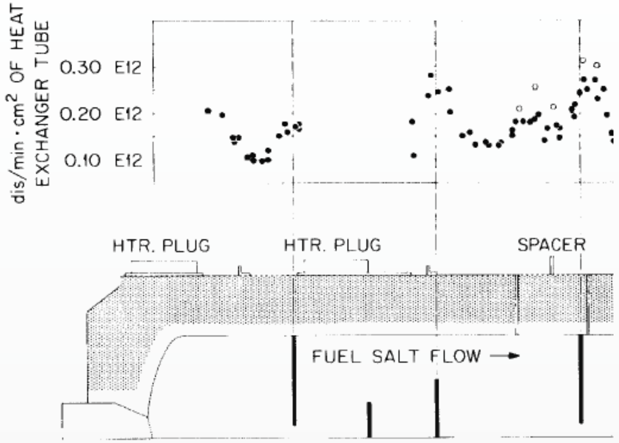


Image of isotope activity variation influenced by MSRE pipe geometry. Image reproduced from ORNL-TM-3151.

Several safeguards technology areas are being developed for MSRs (ORNL lead - Mike Dion)

- ORNL and PSU are developing gamma spectrometry measurements during operations.
  - Potential indicators of reactivity changes
  - Online monitoring to detect re-fueling

Potential Technologies for MSR MC&A – Mike Dion

Existing Technology for MSR MC&A:

- HPGe/Gamma Sensors – heavily collimated for online in-operation measurements OR traditional lab grade setup
- HKED (Hybrid K-Edge Densitometry) – Applied to molten salt samples or 'bypass' loop for actinide concentration measurements
- NPP instrumentation – in-core, out-of-core neutron detectors, contamination monitors, etc.
- Methods and techniques from the Uranium Cylinder Verification System (UCVS), CANDU online fuel bundle verification systems, and reprocessing/pyroprocessing facility designs.

Technology Under Development (*ARS*):

- *Ultra high resolution (low energy) (TES) - SOFIA @ LANL (M. Croce)*
- *Neutron methods – LANL High Dose Neutron Detector (HDND – D. Henzlova)*
- *UV/Vis/Raman – PNNL (A. Lines)*
- Flow measurements
- *Electroanalytical sensors & modular test bed (ANL – N. Hoyt)*
- (Radiometric? – coolant loop activation or elsewhere)
- New materials for high-rate n/g discrimination @ temp – SBIR Radiation Monitoring Devices

Conclusions and Takeaways for MSRs - Mike Dion

No design basis scenarios exist

MC&A Key Points

- Quantification of fresh fuel additions will likely be needed.
- “Dual use” physical inventories during operation. e.g., determine off-gas removal eff + confirm or deny presence of SNM.
- Minimizing accumulation points (in design) could reduce potential salt/SNM holdup.

Infrastructure

- Needed to validate modeling efforts AND provide critical testing structures.
- Provides a test platform for MC&A technology (what works/what doesn’t).

Dynamic Modeling

- System-level dynamic modeling is needed to understand the MSR fuel cycle and related signatures.
- Inform and support MC&A measurement plan including frequency (direct and sampling), dose, technology evaluation, process monitoring, …

Oak Ridge National Laboratory