Advanced Reactor Safeguards and Material Accountancy Challenges

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Sandia National Laboratories, USA

30 March 2023

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Meet the Presenter

Dr. Ben Cipiti is a Distinguished Member of the Technical Staff in the Nuclear Energy Fuel Cycle program area at Sandia National Laboratories with over 18 years of experience in safeguards and security analysis for advanced nuclear reactors and fuel cycle facilities.

He is a co-chair of the Generation IV Proliferation Resistance and Physical Protection Working Group and the National Technical Director for the Advanced Reactor Safeguards Program in the Office of Nuclear Energy within the Department of Energy.

Dr. Cipiti has a deep technical background in safeguards and developed the Separation and Safeguards Performance Model (SSPM) for analysis and design of materials accountancy systems for nuclear facilities. Safeguards, Security (including Cyber), and Safety by Design is a core principle in Dr. Cipiti 's work. He works to promote the need for consideration of the 3S's early in the design process to help the nuclear industry develop robust yet cost effective system designs.

Dr. Cipiti earned a Ph.D. in Nuclear Engineering from the University of Wisconsin-Madison and a B.S. in Mechanical Engineering from Ohio University-Athens

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Proliferation Resistance and Physical Protection (PR&PP) Working Group Objectives

- Facilitate introduction of PR&PP features into the design process at the earliest possible stage of concept development

→ **PR&PP by design**

- Assure that PR&PP results are an aid to informing decisions by policy makers in areas involving safety, economics, sustainability, and related institutional and legal issues
- The PR&PP Working Group includes members from Canada, China, Euratom, France, IAEA, Japan, NEA, Republic of Korea, Russia, South Africa, UK, USA.

"Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism."

https://www.gen-4.org/gif/jcms/c_9502/generation-iv-goals

PRPPWG Key Points

- PR&PP considers both intrinsic features and extrinsic measures.
- Intrinsic features are typically more associated with the fuel design and unique performance of the reactor system.
- Extrinsic measures include technologies for materials accountancy and international safeguards and may include monitoring, surveillance, or measurements.
- So when we talk about materials accountancy or international safeguards, those aspects are part of extrinsic measures so only one part of Proliferation Resistance, but these measures are driven by the intrinsic features.

Domestic vs. International Safeguards & Security

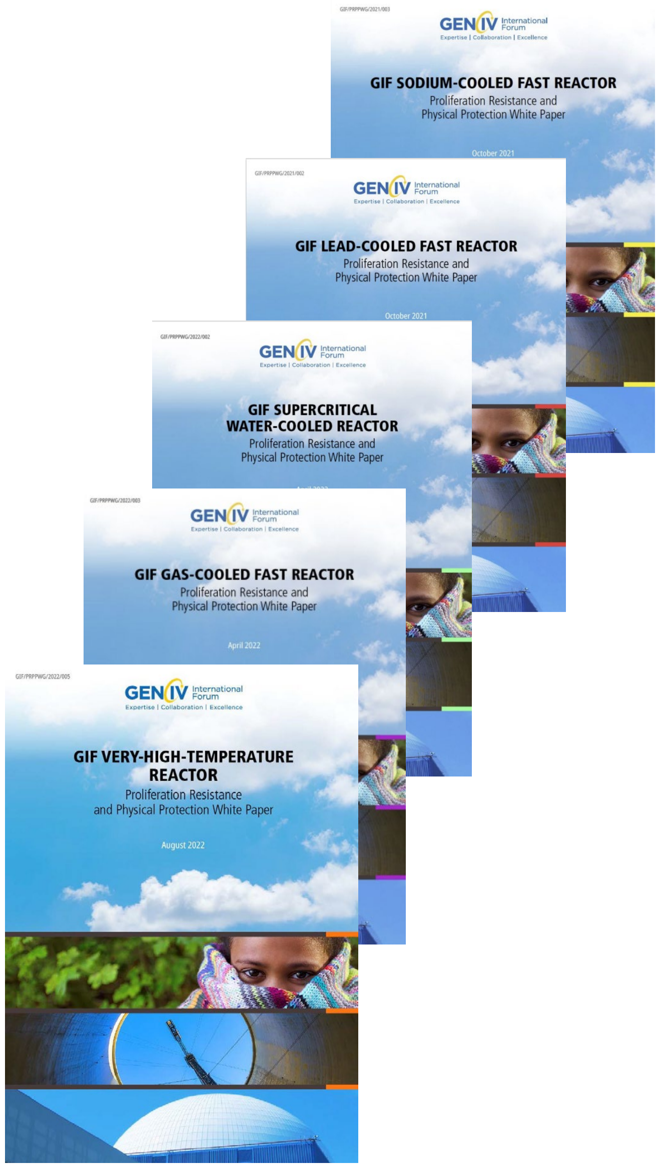
- **Domestic Material Control & Accounting and Physical Protection Systems** address the risk that non-state actors could perpetrate malicious acts involving nuclear material. This includes unauthorized removal of nuclear material or the sabotage of nuclear facilities. The state authority prescribes standards for protection, control, and accounting of nuclear materials, including cybersecurity.
- In contrast, **International Safeguards** are designed to confirm that countries do not use nuclear activities under their jurisdiction to illicitly divert or produce nuclear materials for nuclear weapons in violation of international commitments. Because the country is the potential adversary, verification is performed by the IAEA or other international regulatory body. Nuclear material accounting data declared by the state generally originates from the domestic MC&A system, comprising a basic linkage between state and international safeguards.
- **International Security**, like domestic MC&A and physical protection, focuses on preventing theft of material and mitigating sabotage risks at nuclear sites, with each country responsible for establishing their own regulatory body and requirements. These standards may vary globally particularly related to design basis threat and response strategies.

PR&PP by Design versus Safeguards and Security by Design

- The PR&PP Methodology considers intrinsic features of the designs as opposed to only the extrinsic measures.
- These intrinsic features can apply to both PR and PP.
- PR&PP by Design is mainly about understanding where advanced nuclear energy systems have advantages or challenges that will affect how extrinsic measures need to be used.
- The PR&PP working group does not perform evaluations to pick winners, but rather to better inform designers and regulators on threats and ways to mitigate those threats.

PR&PP WG Resources for Industry

- PR&PP white papers on the six Gen-IV reactor systems have been updated with five currently available publicly:
- A companion crosscut document is being finalized that discusses PR&PP considerations that crosscut all reactor designs.
- The technology-neutral methodology, developed through a succession of revisions, is currently in Revision 6 (Japanese and Korean translations)
- A “Case Study” approach (example sodium-cooled modular fast reactor system used to develop and demonstrate the methodology) resulted in a major report
- GIF Updated PR&PP Bibliography



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All current reports can be obtained at:
https://www.gen-4.org/gif/jcms/c_9365/prpp

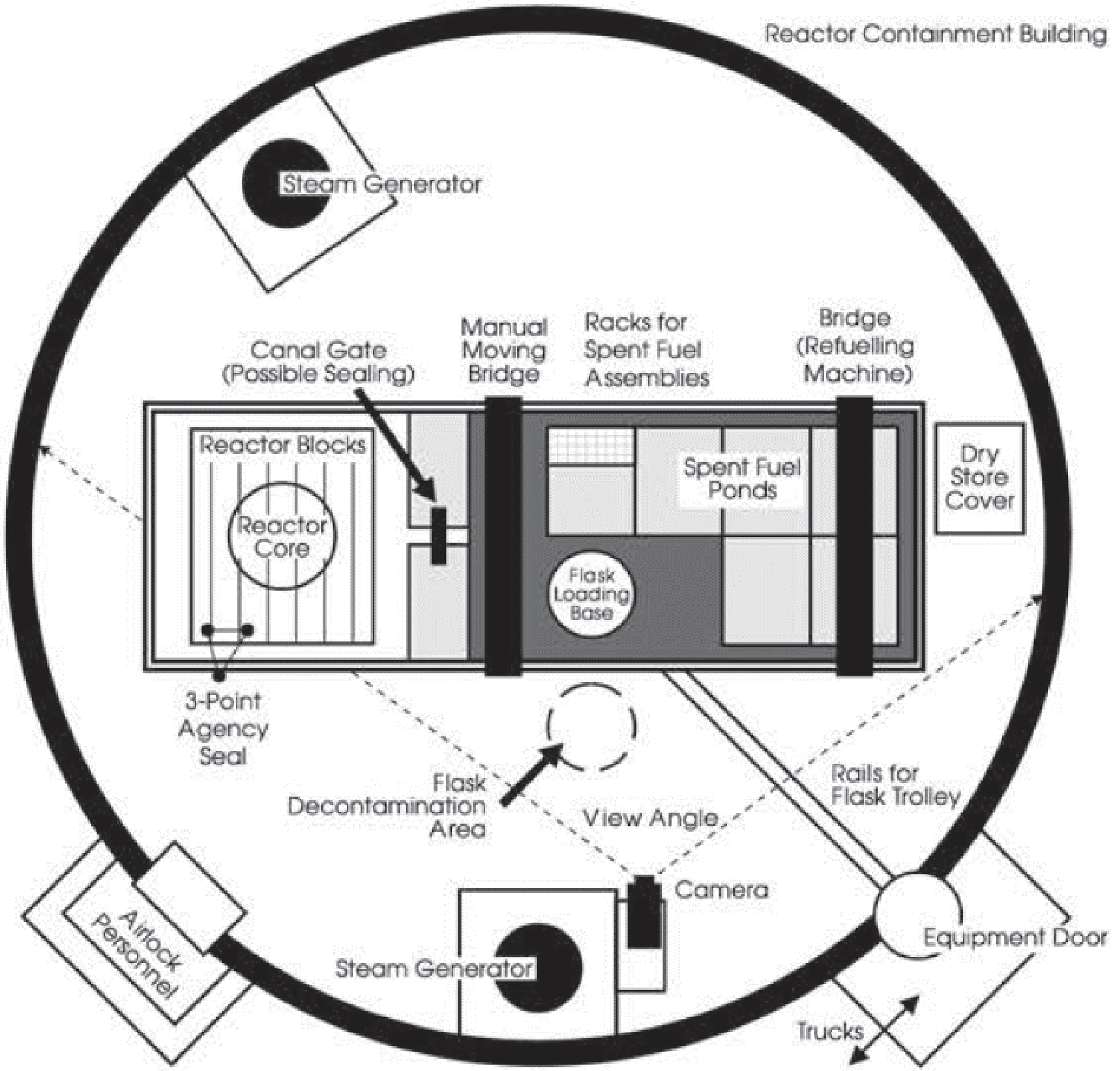
Safeguards and MC&A Challenges for Advanced Reactors

Domestic MC&A Challenges

- From a domestic MC&A perspective, advanced reactors that utilize traditional fuel assemblies (light water reactor designs, sodium fast reactors, microreactors with solid/fixed fuel, or prismatic cores) will follow MC&A approaches that are well-defined:
  - Item accounting for all fuel elements
  - Burnup codes used to estimate fissile content
- Pebble Bed Reactors (PBRs) that utilize solid TRISO fuel pebbles flowing through the core and liquid-fueled Molten Salt Reactors (MSRs) require different MC&A approaches.
  - The MC&A regulatory approach for both will pull from requirements that were built up around large LWRs and bulk handling facilities.

International Safeguards at Existing Reactors

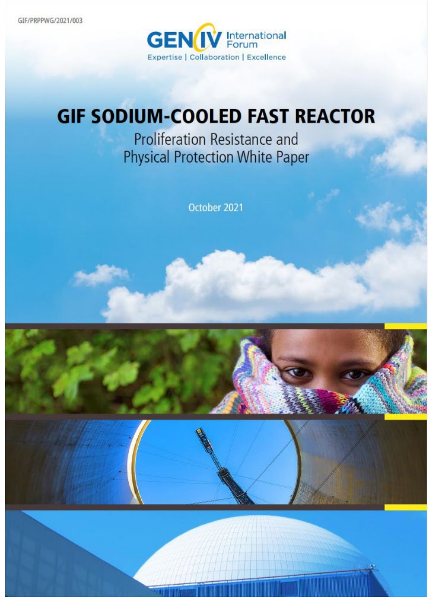
- Surveillance cameras on reactor, spent fuel pools, and fuel transfer areas.
- Seals on containment penetrations and fuel transfer channels.
- NDA measurements on fresh and irradiated fuel.
- Item accounting and verification of assemblies in storage areas.
- Power monitoring, spent fuel discharge monitors, and fuel bundle counters protect against misuse scenarios.

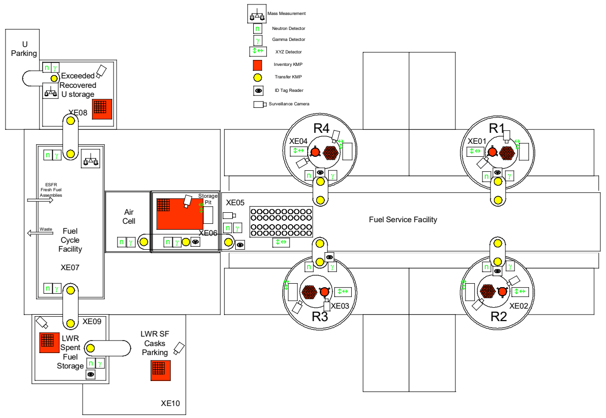


“International Safeguards in the Design of Nuclear Reactors,” IAEA Nuclear Energy Series, No. NP-T-2.9 (2014).

Sodium Fast Reactor PR&PP White Paper

- Five reference designs: JSFR (compact loop), KALIMER-600 (pool configuration), ESFR (pool configuration), BN-1200 (pool configuration), AFR-100 (small modular).
- Little PR&PP variation was found between the different systems, and many PR&PP considerations were similar to any fast system.
- Fast systems generally have higher actinide content than large LWRs and smaller assemblies, but item accounting of assemblies can be applied easily.
- High radiation doses and operations under sodium (requiring specialized equipment) provide PR&PP advantages.
- The use of blankets could present a PR challenge, but extrinsic measures to detect blanket misuse/diversion scenarios are fairly mature.





Example Sodium Fast Reactor (ESFR) PR&PP Case Study:

GIF PRPP Working Group, "PR&PP Evaluation: ESFR Full System Case Study," Final Report, GIF/PRPPWG/2009/002, Gen-IV International Forum, (October 2009).

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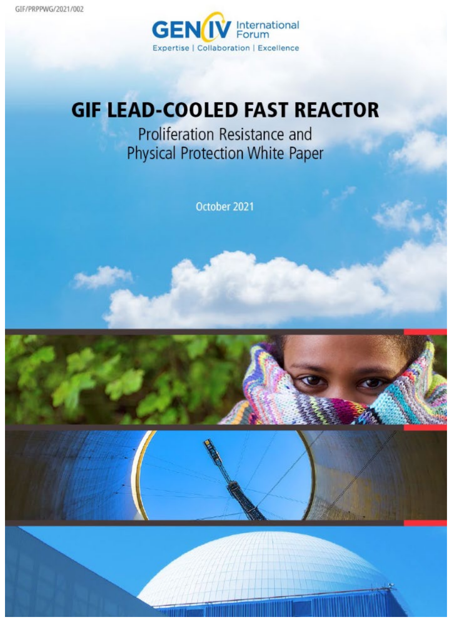
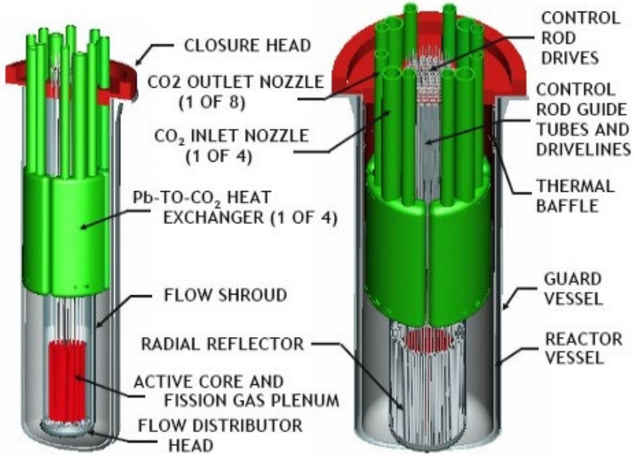
Lead Fast Reactor PR&PP White Paper

- Three reference designs: ELFR, BREST-OD-300, SSTAR
- Closed fuel cycle assumed; Pu fuel containing minor actinides helps avoid the presence of pure Pu streams versus no enrichment required.
- Pin removal on-site is not part of the ELFR design, and SSTAR uses a lifetime sealed core. Difficult to access cores and high automation provide PR&PP advantages.



SSTAR (one of three reference systems):

J. J. Sienicki, A. Moisseytsev, D. C. Wade and A. Nikiforova, "Status of development of the Small Secure Transportable Autonomous reactor (SSTAR) for Worldwide Sustainable Nuclear Energy Supply," in *Proceedings of the International Congress on Advances in Nuclear Power Plants (ICAPP)*, Nice (F), 2007.



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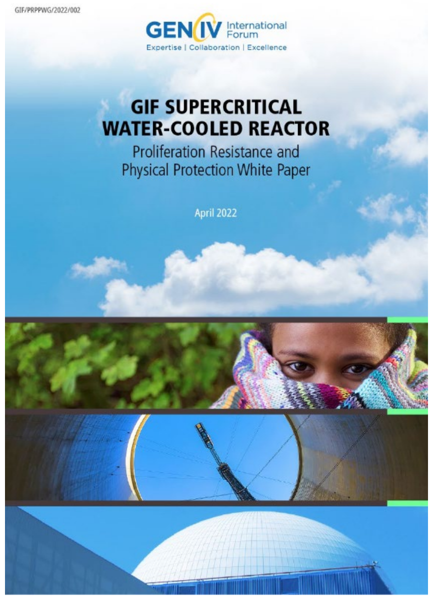
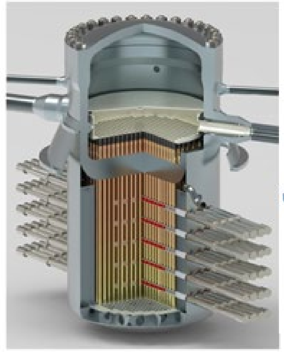
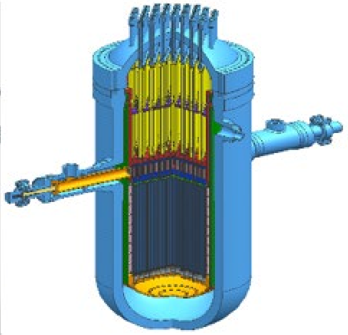
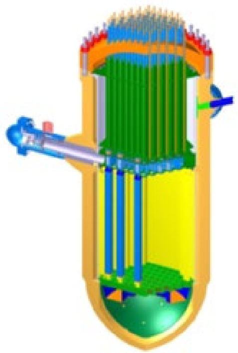
Supercritical Water Reactor PR&PP White Paper

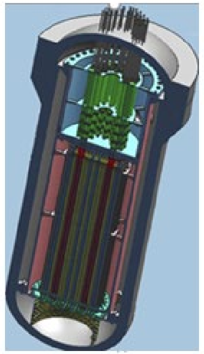
- Eight design tracks considered: HPLWR (Euratom), Super FR & Super LWR (Japan), CSR1000 (thermal and mixed spectra; China), SCWR (Canada), VVER-SCP-600 & VVER-SKD (Russia)
- SCWR designs can utilize well-established safeguards and security approaches due to similarities to LWRs.
- All reference systems (both pressure vessel and pressure tube designs) utilize batch refueling (not continuous).
- Newer fuels utilize HALEU, so have slightly higher material attractiveness.




Canada's Pressure-Tube Type SCWR Core Concept


China's Pressure-Vessel Type SCWR Core Concept


EU's Pressure-Vessel Type SCWR Core Concept


Japan's Pressure-Vessel Type SCWR Core Concept

Gas Fast Reactor White Paper

- One design track considered: 2400MWt GFR reference design, but other designs like ALLEGRO and EM2 are discussed.
- System assumes a closed fuel cycle, fuel contains Pu with minor actinides.
- Fuel pins are not separated from fuel assemblies on site.
- High radiation levels for both fresh and spent fuel hinder theft.


GIF/PRPPWG/2022/002

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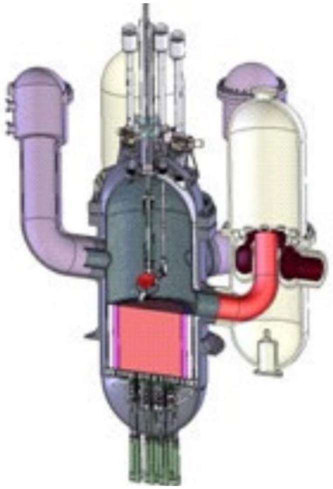
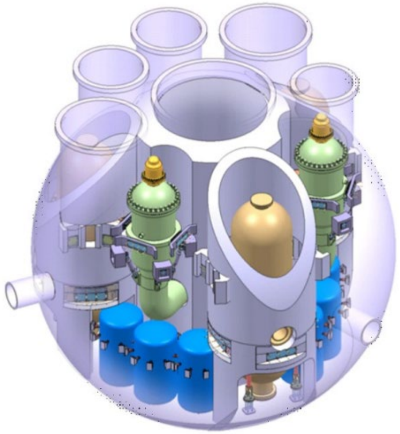
GIF GAS-COOLED FAST REACTOR
Proliferation Resistance and
Physical Protection White Paper

April 2022





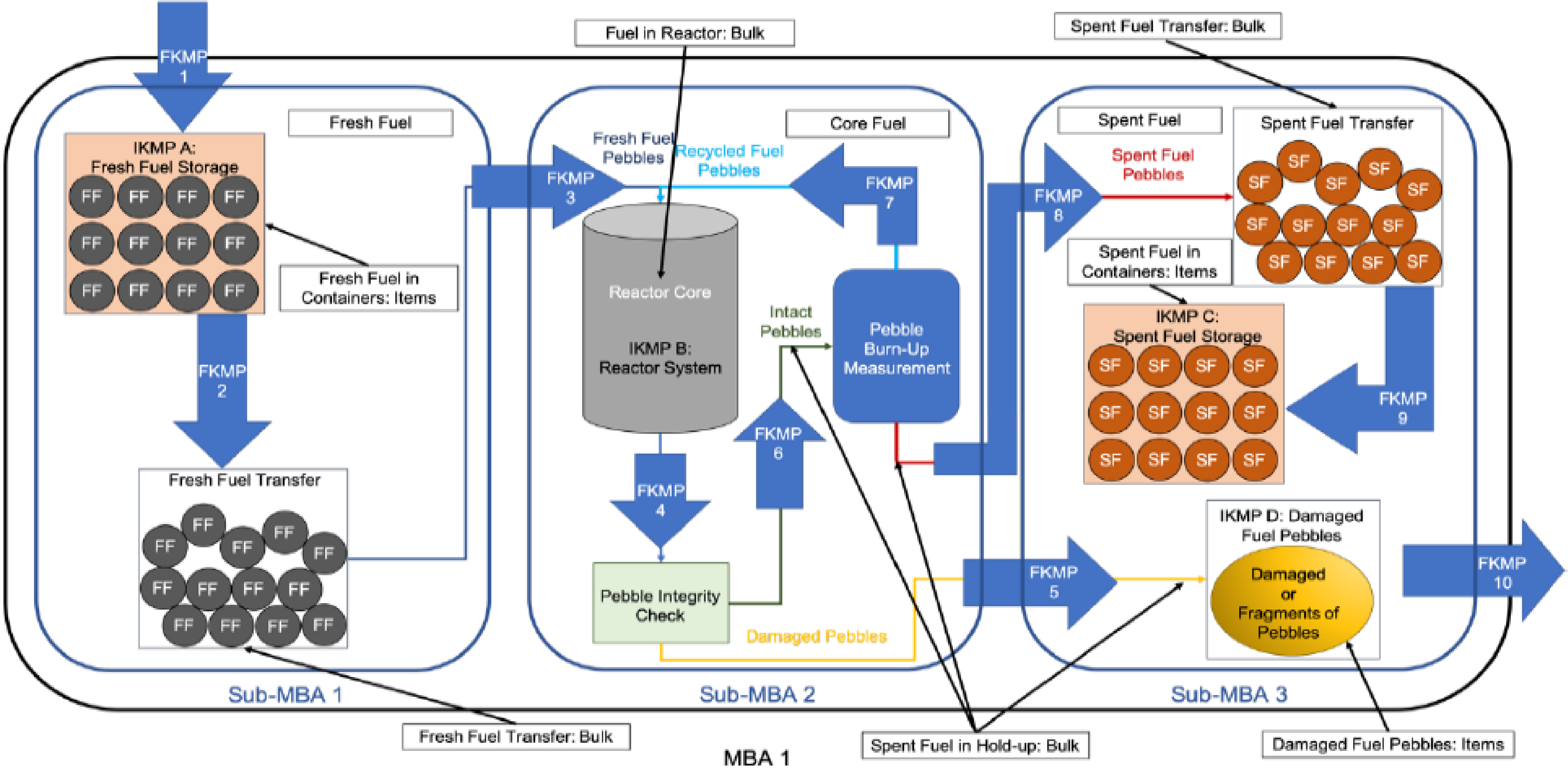
2400 MWt GFR
Reference System

Pebble Bed Reactors: MC&A Challenges

- Pebble Bed Reactors utilize hundreds of thousands of pebbles containing nuclear fuel which circulate through a fluidized bed. Some key considerations:
  - One pebble contains very small amount of nuclear material, so it takes thousands of pebbles to acquire a significant quantity
  - The pebbles leave the core at a rate of one every 30-60 seconds and must be checked for integrity and burnup—those that haven't reached the burnup limit will be circulated back into the core.
  - One spent pebble may represent a significant source of radioactive material.
  - Input fresh fuel and spent fuel will be stored in canisters.

Material Balance Area Structure

P. Gibbs et al, "Pebble Bed Reactor Domestic Safeguards: FY21 Summary Report," ORNL/SPR-2021/169124, Oak Ridge National Laboratory (September 2021).



Sub-MBA 1: Fresh Fuel Receipt and Storage

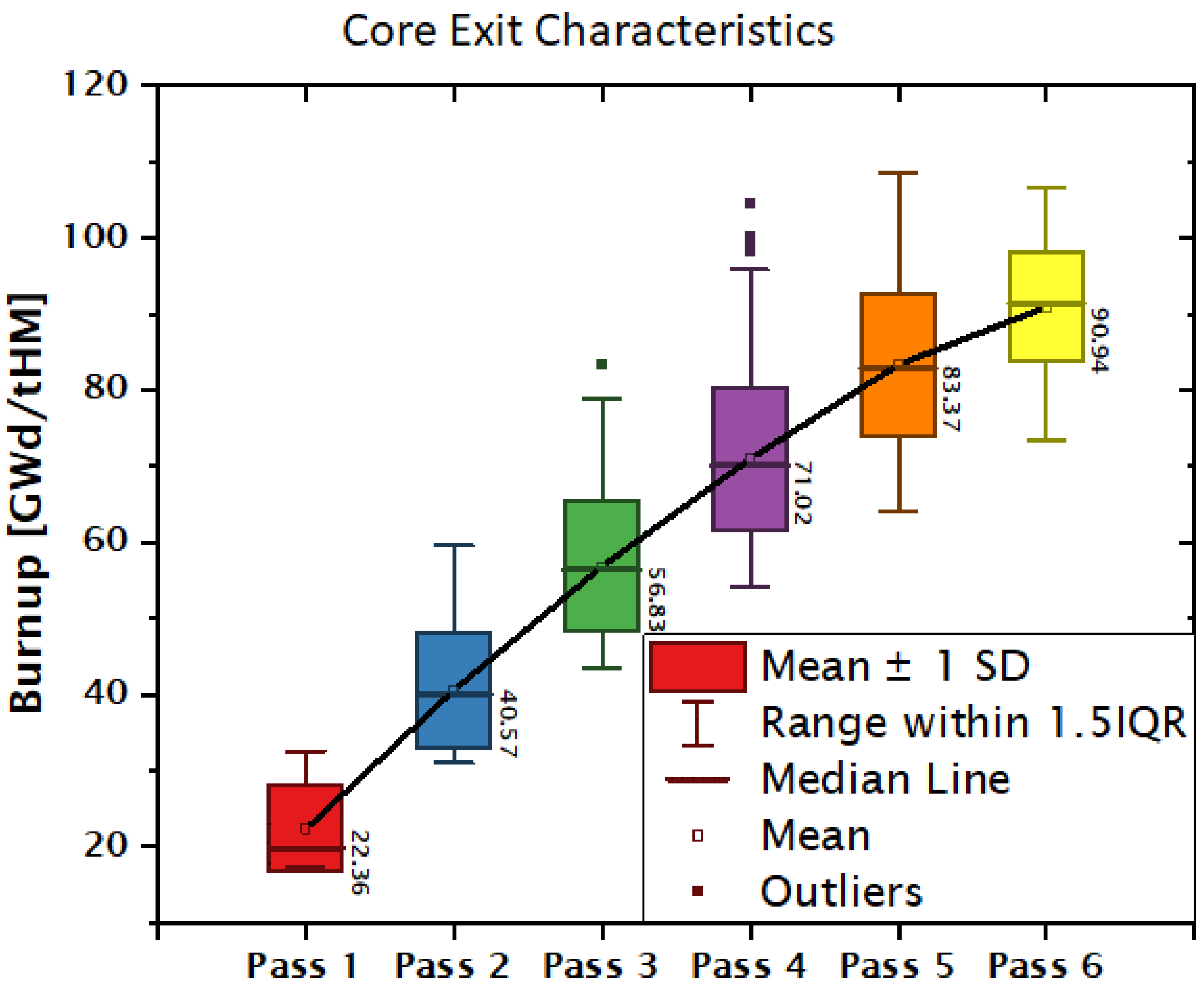
- Sub-MBA 1 is an item control area since the fresh pebbles will be shipped and stored in canisters.
- The Versa-Pac VP55 is a candidate for transportation and storage of fresh fuel pebbles—this container can hold about 350 pebbles.
  - Note that from a U.S. perspective, NRC Cat II MC&A detection thresholds are set at U-235 (300 g) which would be about 300-350 pebbles or essentially an entire container. (An IAEA significant quantity is much larger.)
- If there is high confidence in the fuel fabrication and fuel transfer process, an acceptable approach will be to confirm the canister ID and inspect the seal for tampering. Pebble counting and sampling is unlikely to be needed from a domestic MC&A perspective. Also pebble counting can occur when transferring pebbles to the reactor.

Sub-MBA 2: Reactor and Pebble Handling System

- The pebble handling system is likely the most complex area with pebble cooling, pebble counting in multiple locations, imaging for pebble integrity, potential batch identification, burnup measurement, and rejection for damaged pebbles and pebbles at the burnup limit. Pebble accounting drivers:
  - MC&A-for domestic or international safeguards purposes, pebbles need only be accounted for on the canister level.
  - Process Control-the operator needs a burnup measurement on every pebble exiting the reactor to determine which pebbles can be recirculated versus which have reached the burnup limit.
  - Protection of rad materials-from a physical protection standpoint, an operator would not want to lose even one spent pebble.
- A pebble integrity measurement is required to check for damaged pebbles. While lessons learned from the past help reduce the number of damaged pebbles, operational experience is needed to determine damaged fuel rates.
- Operators may consider additional measurements to track fuel batches.

Sub-MBA 2: Reactor Inventory

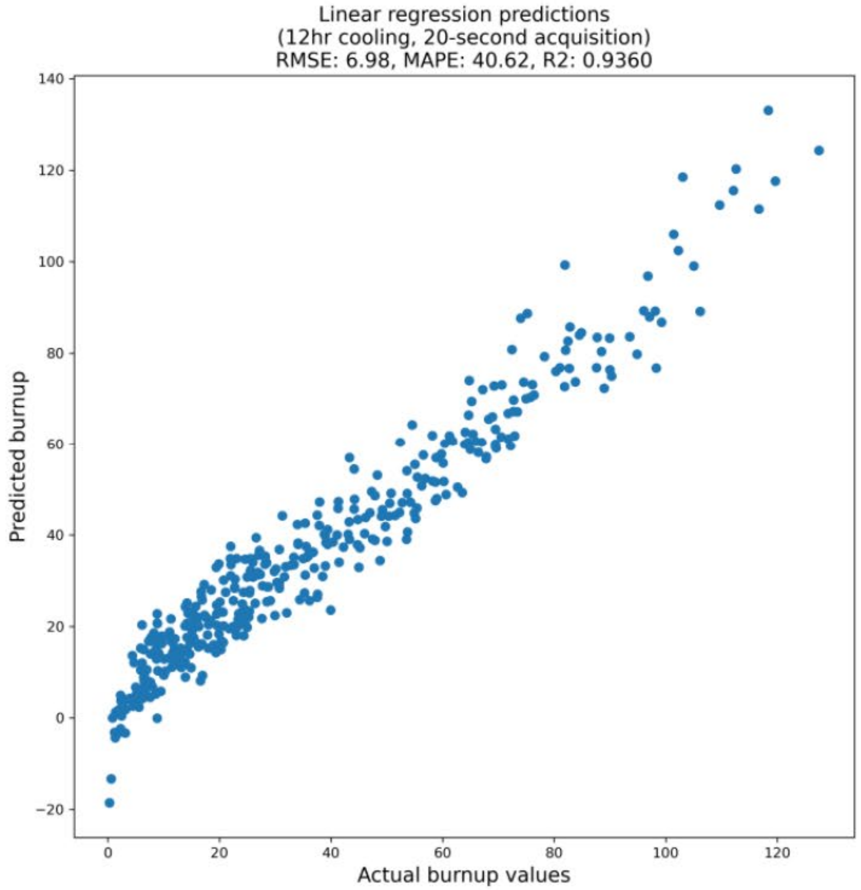
- Reactor inventory will likely utilize number of pebbles and depletion calculations (similar to what LWRs do), supplemented with burnup measurements on pebbles.
- Operators will likely utilize sampling and DA (especially at startup) to verify burnup measurements and help validate depletion calculations.
- The range of number of pebble passes can vary considerably depending on the path through the reactor (see figure).

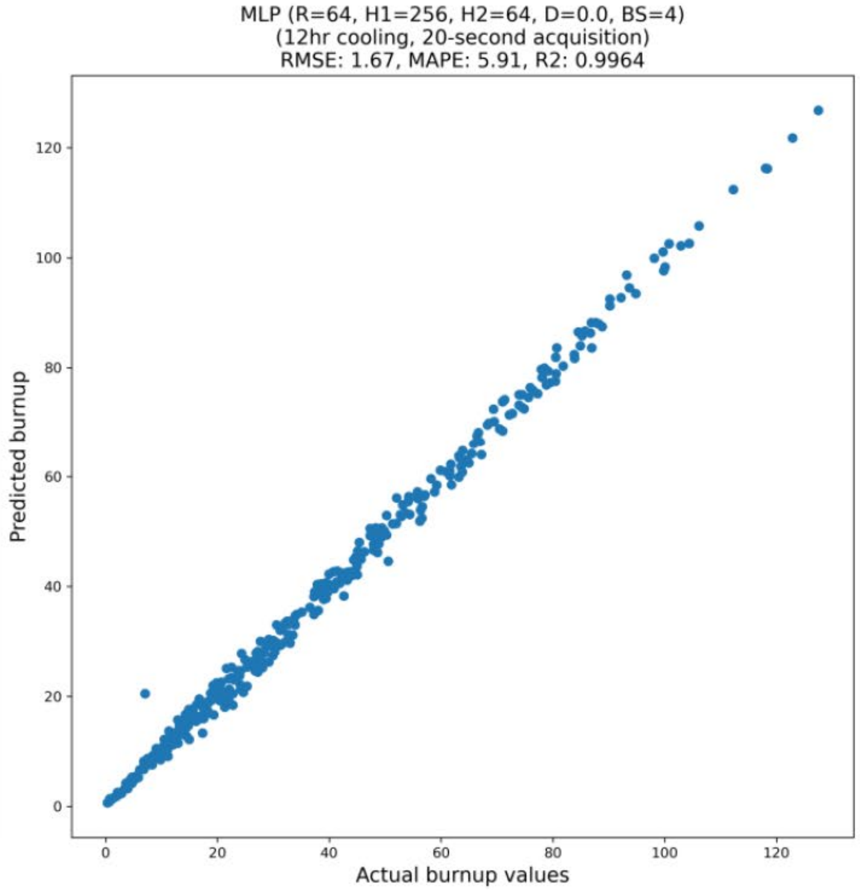


D. Kovacic et al, "FY2022 Summary Report – Pebble Bed Reactor Domestic Safeguards: Fuel Burnup and Fissile Material Loss and Production for Pebble Bed Reactor Nuclear Material Accounting," ORNL/SPR-2022/2635, Oak Ridge National Laboratory (November 2022).

Sub-MBA 2: Burnup Measurements

- Gamma spectroscopy will likely be used for the burnup measurement system, but faces a number of challenges:
  - 30-60 second measurement time
  - Short-cooled (only hours of cooling)
  - 24/7 measurement system
- Machine learning approaches have been found to lower the uncertainty of the burnup estimate for short-cooled pebbles.





Y. Cui et al, "Use Machine Learning to Improve Burnup Measurement in Pebble Bed Reactors," BNL-222200-2021-FORE, Brookhaven National Laboratory (September 2021).

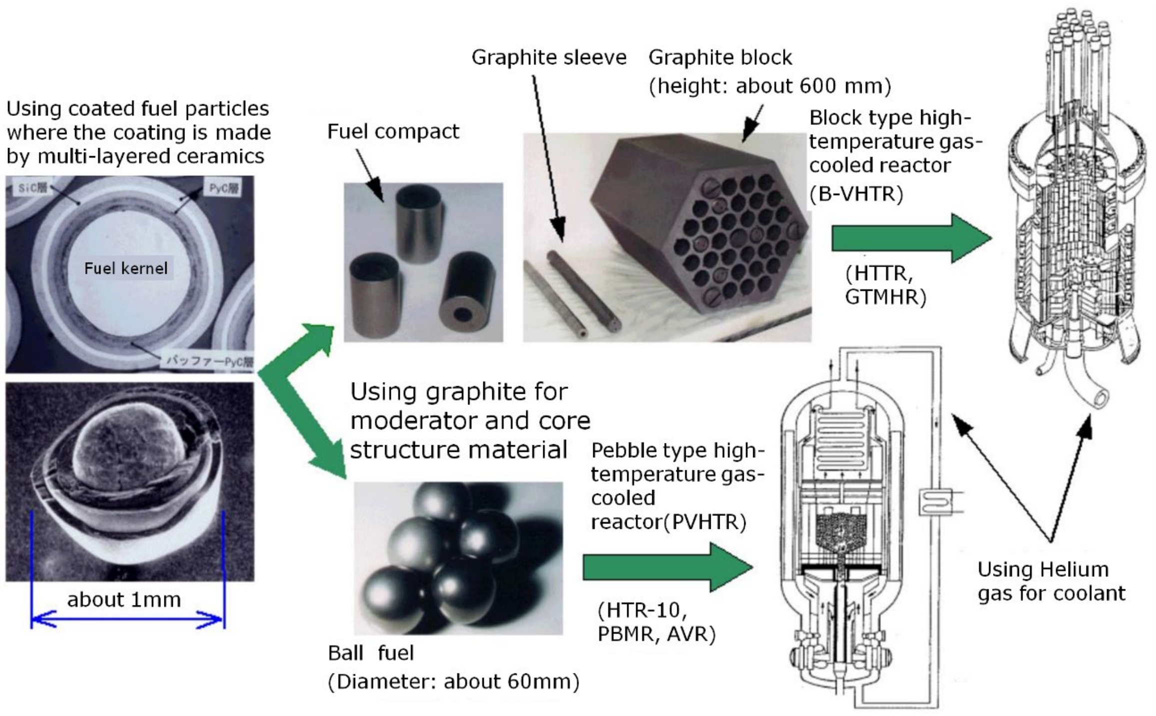
Sub-MBA 3: Spent and Damaged Fuel Storage

- Sub-MBA 3 is an item control area since the spent or damaged pebbles will be stored in canisters.
- Each canister will be characterized through summing of burnup measurement estimates and likely weighing of canisters.
  - One particular challenge may be burnup measurements on damaged fuel.
- Canisters will be sealed and accounted for in storage.

Very High Temperature Reactor PR&PP White Paper

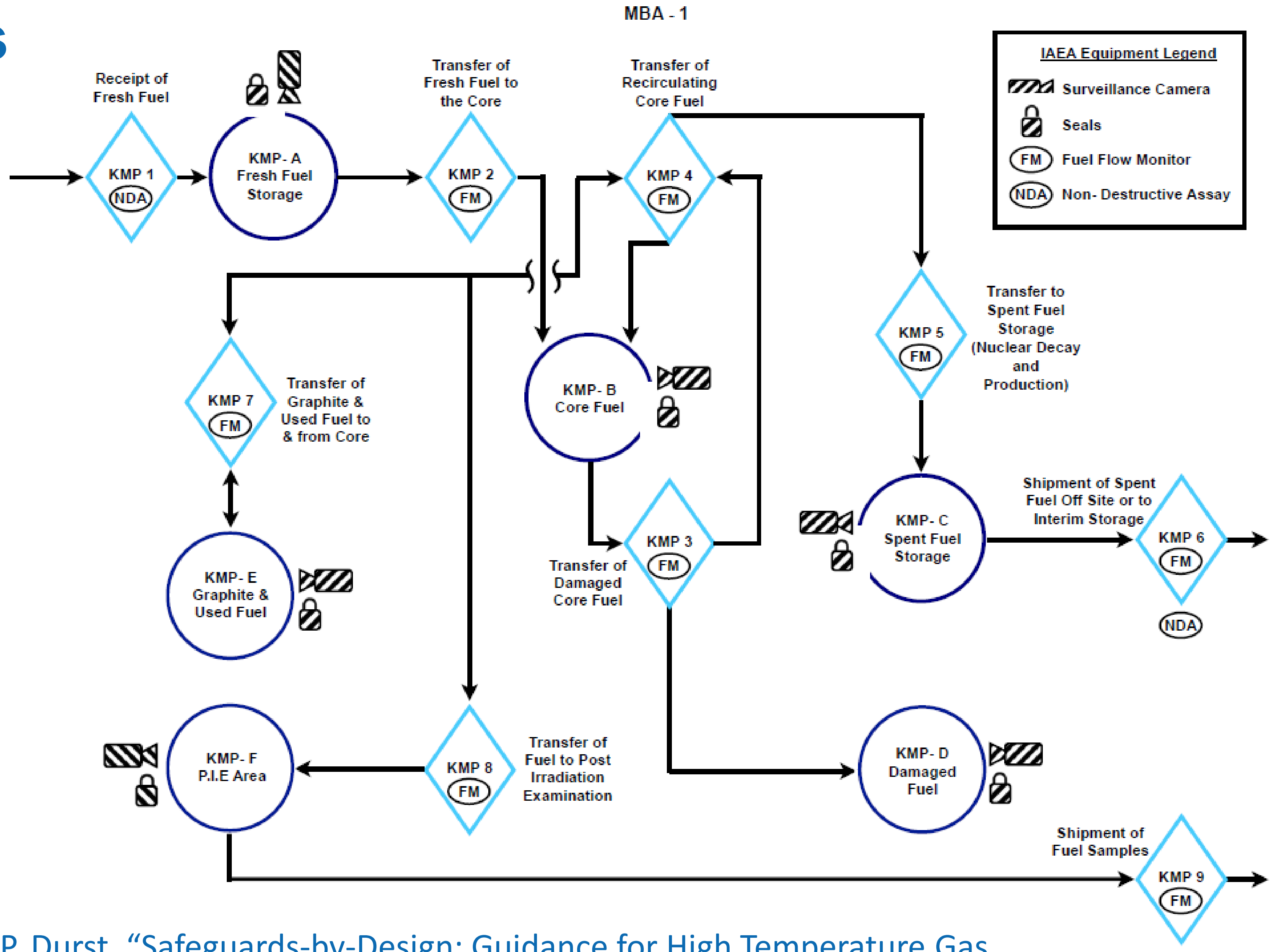
- Both pebble and prismatic concepts are considered that use TRISO fuel, which is robust to high temperatures (relative to existing LWR fuel).
- The high dilution factor of the fuel along with the lack of maturity for industrial reprocessing provides a PR advantage.
- Prismatic designs can benefit from item accounting of fuel assemblies, while pebble designs have additional safeguards considerations requiring more monitoring/measurements. A PR advantage is that it takes 50,000-100,000 pebbles to acquire an IAEA significant quantity.

Prismatic vs. Pebble Fuel Designs:



International Safeguards Approach

- Key equipment may include surveillance cameras, seals, pebble counters, and non-destructive assay.
- As we learn more about how vendors plan to meet domestic MC&A requirements, burnup measurements could be considered for Joint Use Equipment.



P. Durst, "Safeguards-by-Design: Guidance for High Temperature Gas Reactors (HTGRs) With Pebble Fuel," INL/EXT-12-26561, Idaho National Laboratory (August 2012).

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IAEA Safeguards Experience with the HTR-PM Reactor in China

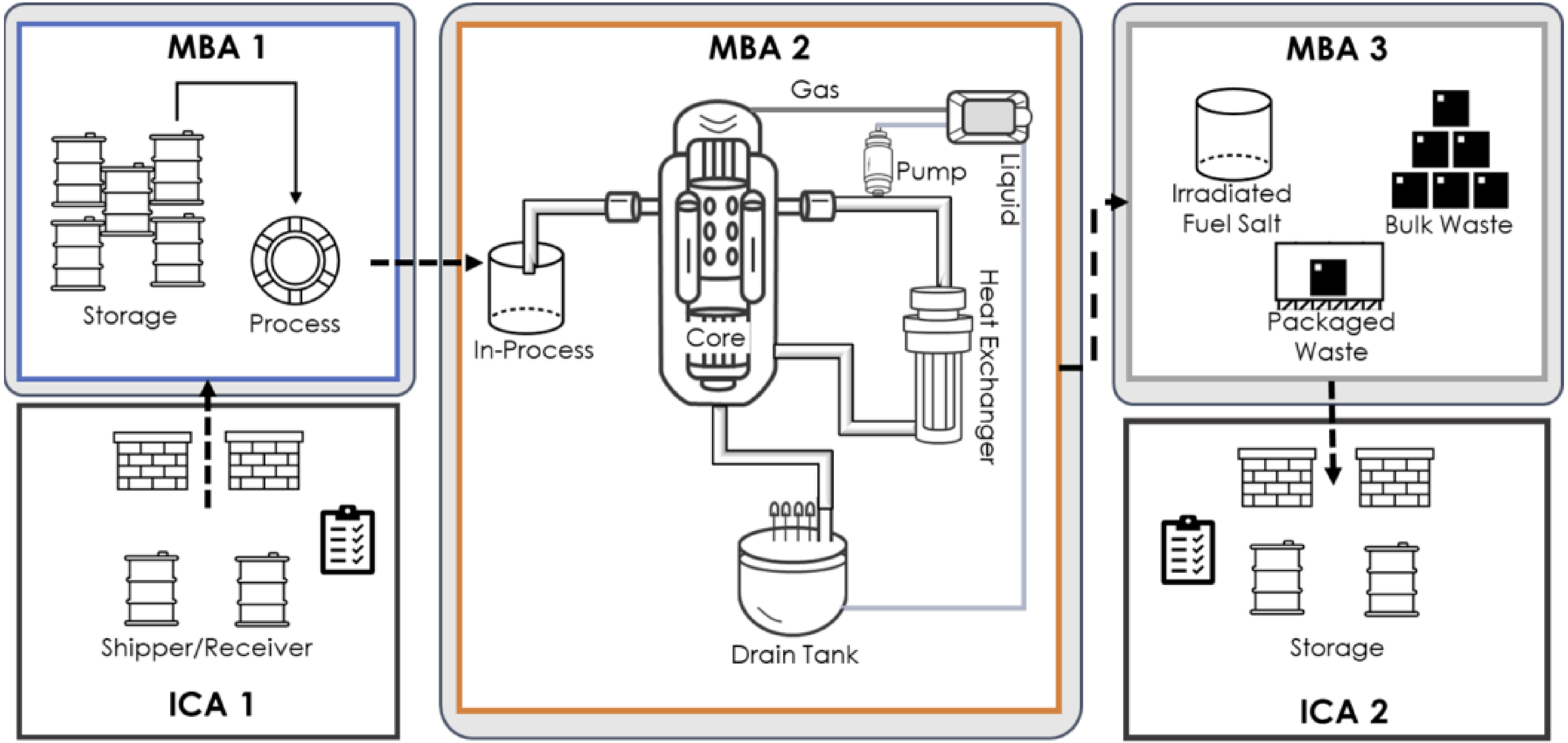
- The main technical objectives of IAEA safeguards are to:
  - Detect diversion of fresh fuel containers with or without substitution by dummy fuels prior to reactor loading
  - Detect diversion of core fuels or irradiated target materials with or without substitution by dummy fuels and falsification of operating records,
  - Detect diversion of spent fuel pebbles with or without substitution by dummy fuels
- Sub-MBA 1: Accountability of all canisters, and some will be randomly selected for pebble counting, and one pebble taken for NDA measurement. Surveillance on the loading area.
- Sub-MBA 2: Surveillance and radiation detectors applied to key penetrations
- Sub-MBA 3: Re-measurement is not possible, so dual containment/surveillance strategy. NDA measurements of pebbles during packaging, and surveillance and NDA to track material movements. Stacked storage silos may require a vertical pipe next to each silo for a gamma detector. Seals on the silo plug.

P. Becker et al., "Implementation of Safeguards Measures at the High Temperature Gas-Cooled Reactor Pebble Bed Module (HTR-PM) in China and Proposed Safeguards by Design for Units to be Exported to Other States," IAEA-CN-267, IAEA Symposium on International Safeguards (November 2018).

Liquid Fueled Molten Salt Reactors: MC&A Challenges

- MSRs see considerable design variations, but we'll break up the liquid-fueled reactors into two general categories.
- MSRs with limited on-site salt processing:
  - MSRs will need noble metal recovery and off gas processing at a minimum, but some designs do not remove fission products and instead replace the salt or entire reactor vessel every 7-8 years.
  - These reactors will have periodic, large inventories of fresh salt and spent salt that will need to be handled.
- MSRs with fission product processing on-site:
  - MSRs can be designed to continuously process the salt for a 60 year+ design life.
  - Less makeup salt and recovered wastes will be needed/produced at any one time, but will occur continuously over the life of the reactor.

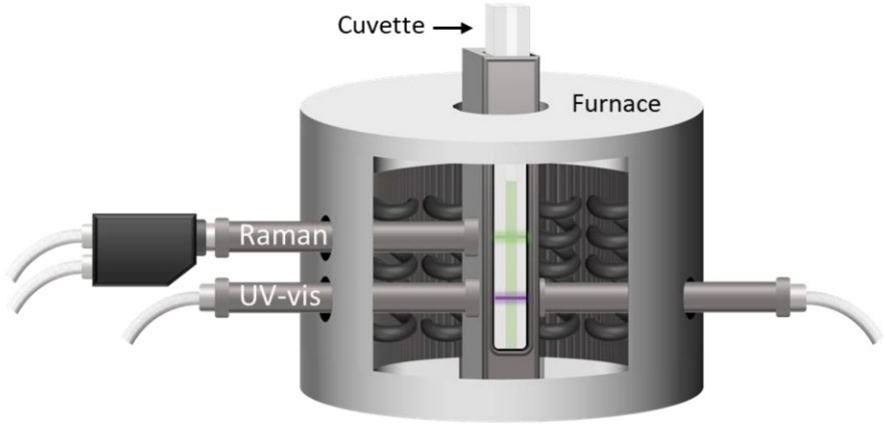
MC&A Approach for Liquid-Fueled MSRs



M. Dion & K. Hogue, "Domestic MC&A Recommendations for Liquid-Fueled MSRs," ORNL/SPR-2022/2673, Oak Ridge National Laboratory (September 2022).

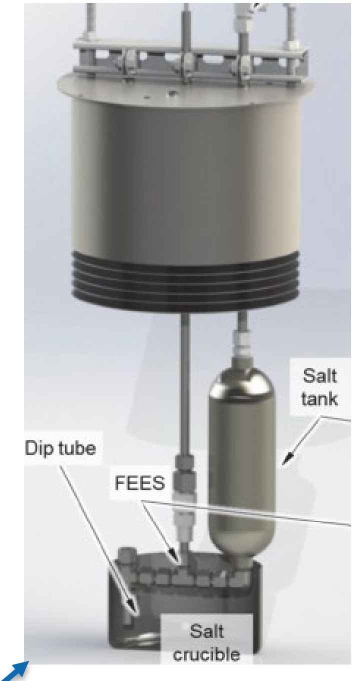
Reactor Inventory Challenges

- Domestic MC&A will likely require a process monitoring approach for MSRs which means the periodic salt measurements will be required.
- Both an actinide concentration and total salt volume measurement are needed to determine total fissile inventory.
  - Sampling and DA is possible for the concentration measurement, but the operator would prefer an on-line measurement. Both on-line spectroscopy and voltammetry measurements are being examined.
  - Salt volume is challenging due to the complex geometry of the reactor and salt processing loops. An isotope dilution technique is being examined.



On-Line Spectroscopy Measurement

A. Lines et al., "On-line Monitoring for Molten Salt Reactor MC&A: Optical Spectroscopy-Based Approaches," PNNL-33367, Pacific Northwest National Laboratory (September 2022).

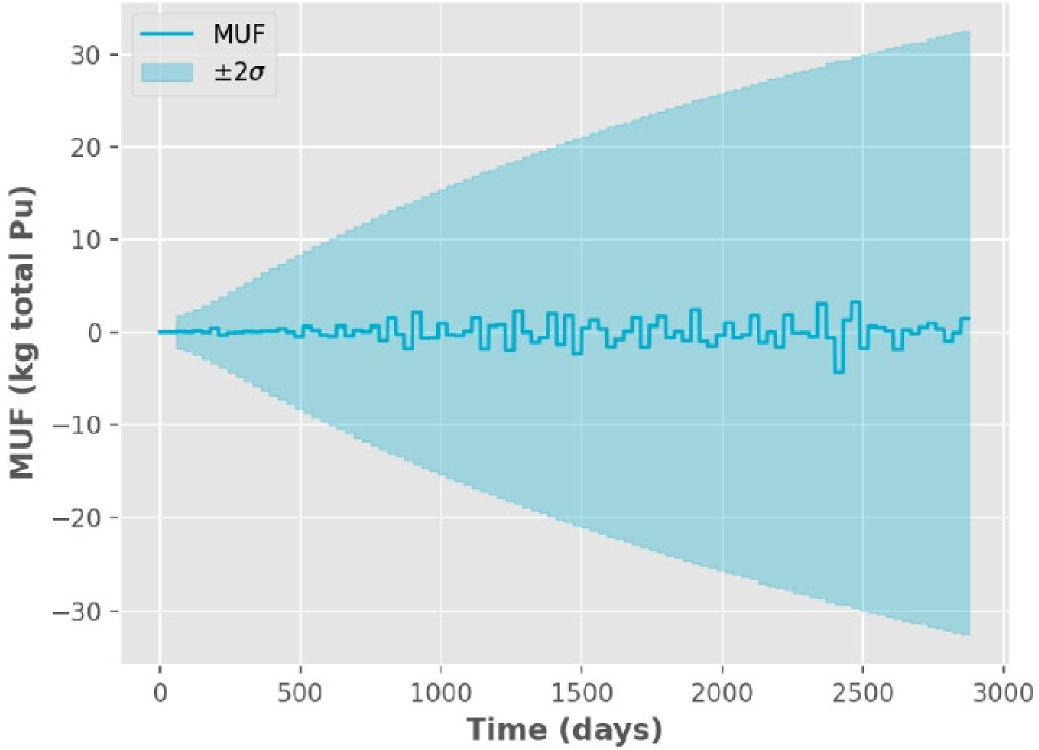


On-Line Voltammetry Measurement

C. Moore et al., "Assessment of Flow-Enhanced Sensors for Actinide Quantification in MSRs," ANL/CFCT-22/34, Argonne National Laboratory (September 2022).

Measurement Uncertainty Challenges

- Recent work has shown high error for actinide measurements due to buildup of actinides in the salt over time.
- The actinide content in an MSR is no larger than an equivalent-sized LWR, but what's unique is trying to measure that entire content.
- These limitations in measurement uncertainty will likely push for more reliance on containment and surveillance (and physical protection) from a domestic standpoint.
- International safeguards may require more use of monitoring of reactor conditions.

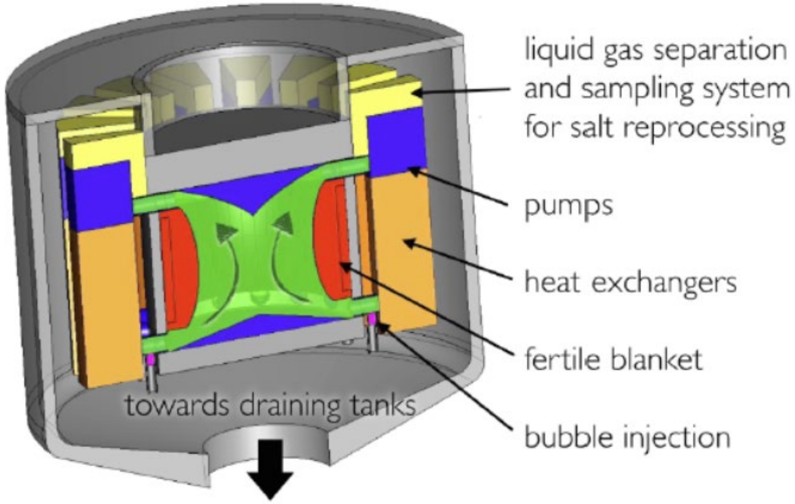


M. Higgins et al., "Limitations of Overall Measurement Error or Molten Salt Reactors," Proceedings of the INMM & ESARDA Joint Virtual Annual Meeting, August 23-26 & August 30-September 1, 2021.

Molten Salt Reactor PR&PP White Paper

- Three design classes considered: Liquid-fueled with integrated salt processing (MSFR), solid-fueled with salt coolant (Mk1 PB-FHR), liquid-fueled without integrated salt processing (IMSR).
- Liquid-fueled designs with on-site fission product removal will have more PR challenges in that they resemble bulk handling facilities—more extrinsic measures needed.
- Liquid-fueled reactors without fission product removal are designed to replace the salt or core every 7-8 years, which adds complexity to the fuel cycle.
- Solid fueled designs that use molten salt as the coolant will have PR&PP features similar to the VHTR.
- The high radiation field, rather dilute actinide content, and remote handling are a barrier to theft.

Schematic view of the MSFR fuel circuit:



Summary

- It's an exciting time to be in the nuclear industry as we see the advanced reactor designs move from paper studies to deployment.
- The Generation-IV International Forum is also transitioning to help the nuclear industry as vendors move from R&D to deployment.
- While there are domestic MC&A and International Safeguards challenges with advanced reactors, we do have a lot of experience with designs that utilize solid, fixed fuel assemblies.
- Pebble Bed Reactors and Liquid Fueled Molten Salt Reactors do have more R&D needs, but there has already been a great deal of progress in recent years to establish the technologies and approaches that may be used to safeguard these systems.

Upcoming Webinars

Date	Title	Presenter
05 April 2023	Overview of Nuclear Graphite R&D in support of Advanced Reactors	Dr. Will Windes, Idaho National Laboratory, USA
24 May 2023	Graphite-Molten Salt Interactions	Dr. Nidia Gallego, Oak Ridge National Laboratory, USA
21 June 2023	Panel Session: International Knowledge Management and Preservation of SFR	Joel Guidez, Hiroki Hayafune, Ron Omberg, Cal Doucette, and Patrick Alexander