

Advanced Reactor Safeguards: Nuclear Material Control and Accounting for Pebble Bed Reactors



Donald Kovacic
Philip Gibbs
Louise Worrall
Rachel Hunneke
Jason Harp
Jianwei Hu

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Nuclear Nonproliferation Division

**ADVANCED REACTOR SAFEGUARDS: NUCLEAR MATERIAL CONTROL AND
ACCOUNTING FOR PEBBLE BED REACTORS**

Don Kovacic, Philip Gibbs, Louise Worrall, Rachel Hunneke, Jason Harp

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ACRONYMS

ANL	Argonne National Laboratory
BUMS	burnup measurement system
BNL	Brookhaven National Laboratory
FHS	fuel handling system
FKMP	flow key measurement point
HALEU	high-assay low enriched uranium
HTGR	high-temperature gas-cooled nuclear reactor
IKMP	inventory key measurement point
INL	Idaho National Laboratory
LWR	light water reactor
MBA	material balance area
MC&A	material control and accounting
NDA	non-destructive analysis
NRC	U.S. Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PBMR	pebble bed modular reactor
PBR	pebble bed reactor
SNL	Sandia National Laboratories
SNM	special nuclear material
TRISO	tri-structural isotropic
TRL	technology readiness level

ABSTRACT

This report provides the preliminary work done under the DOE NE-5 Advanced Reactor Safeguards Program for Fiscal Year 2020. It focuses on material control and accounting (MC&A) for pebble bed reactors (PBR). It addresses some of the main challenges facing current PBR MC&A approaches that are still evolving, allowing for possible safeguards and security by design efforts. The goal is to identify areas most suitable for government/industry partnerships to support the emergence of this non-light water reactor design. The report focuses on the following main areas: packaging and handling for fresh and spent PBR fuel, the application of pebble counting systems, conducting physical inventories to establish nuclear material balances, and the evaluation of current approaches for burnup measurements of the spheres. These areas were previously identified as places where different or new MC&A approaches will likely be needed.

1. SCOPE OF WORK

1.1 Introduction

This report provides the preliminary work done under the DOE NE-5 Advanced Reactor Safeguards Program for Fiscal Year 2020 on the topic of material control and accounting (MC&A) for pebble bed reactors (PBRs).

As background, Title 10 of the Code of Federal Regulations (10 CFR) Part 74 defines MC&A requirements for special nuclear material (SNM). MC&A requirements are defined based on the strategic significance of the SNM. Light water reactor (LWR) fuel used in US commercial nuclear reactors is less than 10% enriched in the isotope ^{235}U ,* which is the lowest enrichment category.

Also, even though plutonium is present in LWR spent nuclear fuel,† LWR fuel assemblies are large, heavy, and highly radioactive, which significantly decreases the likelihood of theft. Because of this, the U.S. Nuclear Regulatory Commission (NRC) only requires LWRs to meet the sabotage design basis threat (DBT) and not the theft/diversion DBT. Therefore, the NRC's MC&A regulations for LWRs are less stringent and do not require the full implementation of Category I and Category II MC&A requirements when compared with other fuel cycle facilities.

This will not be the case with PBRs where the portability of spheres is a key difference, albeit the SNM content per sphere is small. Also, enrichment levels will exceed 10%, which moves into Category II MC&A requirements. Therefore, PBR designs will require different nuclear MC&A methods compared with the existing fleet of LWRs that are currently licensed in the United States.

The main differences stem from the movable nature of the fuel spheres (pebbles) during normal reactor operations. Spheres are continuously inserted and withdrawn from the reactor core and are moved throughout the reactor and associated systems via pneumatic (or hydraulic) pressure tubes, as well as other mechanical means. This is in notable contrast to LWRs, where the fuel bundles are fixed during the operations cycle and the reactor must be shut down and the reactor head removed to insert, remove, or shuffle the fuel.

Additionally, the several hundred fuel bundles at a LWR are uniquely identified, whereas fuel spheres, in most proposed designs, will not be. A PBR will likely have an inventory consisting of hundreds of thousands of fuel spheres and during the operational lifetime may encounter millions of spheres that arrive as fresh fuel and ultimately are dispositioned as spent fuel. The number of spheres and their portability constitute the key differences as they relate to MC&A and security. The concept of item control or monitoring as defined within 10 CFR Part 74 will apply as one of the key approaches to manage this large number of spheres.

* 10,000 grams or more of ^{235}U enriched to less than 10% is defined as Category III, SNM of low strategic significance (Nuclear Regulatory Commission 2017).

† The presence of plutonium would typically cause SNM to be categorized as Category I, strategic SNM (Nuclear Regulatory Commission 2017).

Even so, certain aspects of current LWR approaches were found to be applicable for fresh and spent fuel, as discussed in an Oak Ridge National Laboratory (ORNL) report to the NRC, *Model MC&A Program for a Pebble Bed Reactor* (ORNL/SPR-2019/1329) [1]. This is true for fresh and spent fuel. However, the report notes that MC&A approaches currently in use for fuel cycle facilities[†] are more closely aligned with anticipated PBR designs instead of LWR approaches—specifically, those MC&A approaches required for facilities handling SNM of moderate strategic significance (i.e., Category II) when it comes to the reactor vessel and recycle loops.

The low SNM content per sphere also needs to be balanced with the radiological aspects resulting from the theft of a single spent sphere. Considering only bulk amounts or groups does not address the potential consequence of the loss of an individual pebble if used in a radiological exposure device or a radiological dispersion device. A spent tri-structural isotropic (TRISO) pebble will have radiation levels equivalent to a Category 1 or 2 radiological source [2].

Current PBR MC&A approaches are still evolving and face several challenges. This allows for the possible consideration of safeguards and security in the designs of these facilities. The report focuses on the following main areas: (1) packaging and handling for fresh and spent PBR fuel, (2) the application of pebble counting systems, (3) conducting physical inventories to establish nuclear material balances, and (4) the evaluation of current approaches for burnup measurements of the spheres. This effort builds on the MC&A (domestic safeguards) challenges for PBRs as identified in the ORNL report *Model MC&A Plan for Pebble Bed Reactors* (ORNL/SPR-2019/1329) [1]. The referenced report was completed for the NRC in response to the emergence of this non-LWR design to analyze current policy and technical guidance.

1.2 Industry Partnerships and National Laboratories

The results of the work being done by this project are intended to be applicable to any PBR design. The industry partnerships described in this report provide important examples of leading PBR conceptual designs, and as such, it is worthwhile to use them in considering possible MC&A approaches because they give some detailed design information. Any results from this report should be applicable to any PBR design, within the given general reactor design characteristics, and can be used by any vendors/designers considering MC&A approaches for PBRs.

1.2.1 X-energy

One of the goals of this project is to identify areas most suitable for government/industry partnerships to support the emergence of this non-LWR design. In this regard, the project team has successfully completed nondisclosure and teaming agreements with X-energy. X-energy is a nuclear reactor and fuel design engineering company. They are developing Generation IV high-temperature gas-cooled nuclear reactors (HTGRs) and the TRISO-X fuel that will be used in the designs.* In January 2016 X-energy was awarded a 5-year \$53M United States Department of Energy (DOE) Advanced Reactor Concept Cooperative Agreement award to advance elements of their reactor development. In 2019, X-energy received funding from the United States

[†] The NRC distinguishes between nuclear reactors and fuel cycle facilities, such as enrichment facilities.

* <https://x-energy.com/>

Department of Defense to develop small military reactors for use at forward bases. In October 2020, the company was chosen by the DOE as a recipient of a matching grant for an initial \$80M this year as part of the Advanced Reactor Demonstration Program (ARDP) for the cost of building a Xe-100 demonstration reactor.

The project team is collaborating with engineers, scientists, and managers working on the Xe-100, an 80-MWe helium-cooled PBR that has a modular design that can be scaled to the needs of the site—up to 320 MWe or more. Each Xe-100 reactor contains approximately 220,000 TRISO fuel spheres* that are continuously inserted and removed so that no refueling outage is necessary. They are designed for a 60-year operating lifetime, have very high burnup rates (~160 GWd/tHM), use helium as coolant, can provide high-temperature process heat (750°C), and have a conventional steam balance of plant for power generation.

The project team has also leveraged ORNL’s partnership with the fabrication of the TRISO fuel. The fuel will use high-assay low enriched uranium (HALEU), which is currently not being produced in the United States. X-energy and ORNL are collaborating on developing the capability to manufacture TRISO-X fuel spheres that will be used to power the Xe-100 reactors. The fuel manufacturing process is crucial in considering the overall approach to MC&A for the life cycle of the reactors, from production (fuel fabrication), to utilization (reactors), and to disposition (used nuclear fuel and storage).

1.2.2 Kairos Power

ORNL signed a nondisclosure agreement with Kairos Power in October 2020. The Kairos Power fluoride salt-cooled high-temperature reactor (KP-FHR) is an advanced reactor technology that leverages TRISO fuel in pebble form combined with a low-pressure fluoride salt coolant.† The technology uses an efficient and flexible steam cycle to convert heat from fission into electricity and to complement renewable energy sources. The Kairos reactor produces 140 MWe and plans on using fuel enriched to 19.75% (HALEU).

1.2.3 National Laboratories

The project team had initial shared discussions with the following national laboratories: Sandia National Laboratories (SNL), Brookhaven National Laboratory (BNL), Argonne National Laboratory (ANL), and Idaho National Laboratory (INL). Each national laboratory brings unique skills and experiences. SNL is focusing on the security posture for the X-energy reactor licensing approach. The project team is working with SNL to determine characteristics of the fuel form as it relates to man-portability and the potential for sabotage and development of radiation exposure devices. In FY 2021 collaboration across the labs is an area that needs additional focus.

* Note the X-energy design documents refer to PBR fuel “spheres” as opposed to other industry nomenclature that uses the term “pebbles.” The two terms are interchangeable, and both are used in this report.

† <https://kairopower.com/technology/>

2. FISCAL YEAR 2020 FOCUS AREAS AND TASKS

2.1 Packaging and Handling for Fresh and Spent PBR Fuel

The purpose of this task is to investigate packaging and handling approaches for fresh and spent PBR fuel along with confirmation/measurement approaches. The implementation and effectiveness of the MC&A item control program will be affected by choices made regarding container size and design. The objective is to identify approaches that balance MC&A, operational, and safety goals plus possible packaging design options.

The team is beginning to engage with X-energy and reviewed design documents related to the packaging and handling of fuel spheres.

2.1.1 Fresh Fuel Containers

The designed being reviewed use fuel spheres of varying enrichments, as well as graphite-only spheres. Consequently, the MC&A system would need to identify an approach that clearly distinguishes different levels of enrichments and also precludes non-SNM items being mistaken for SNM items (Note: Section 7.4 of ANSI N15.8-2009 [3])

The main candidate for use as fresh fuel containers is the Versa-Pac (VP55).* The VP55 is a specially configured 55-gallon package for shipment of uranium oxides, uranium metal, uranyl nitrate crystals, and other uranium compounds (e.g., uranium carbides, uranyl fluorides and uranyl carbonates, uranium hexafluoride in the special cylinders, and TRISO fuel). In this configuration, the VP55 would contain approximately 350 pebbles with a total heavy metal (uranium) weight of 3 kg with a fissile content of less than 400 g uranium-235. Some key design characteristics are shown in Figure 1.

* <https://rampac.energy.gov/docs/default-source/certificates/1039342.pdf>

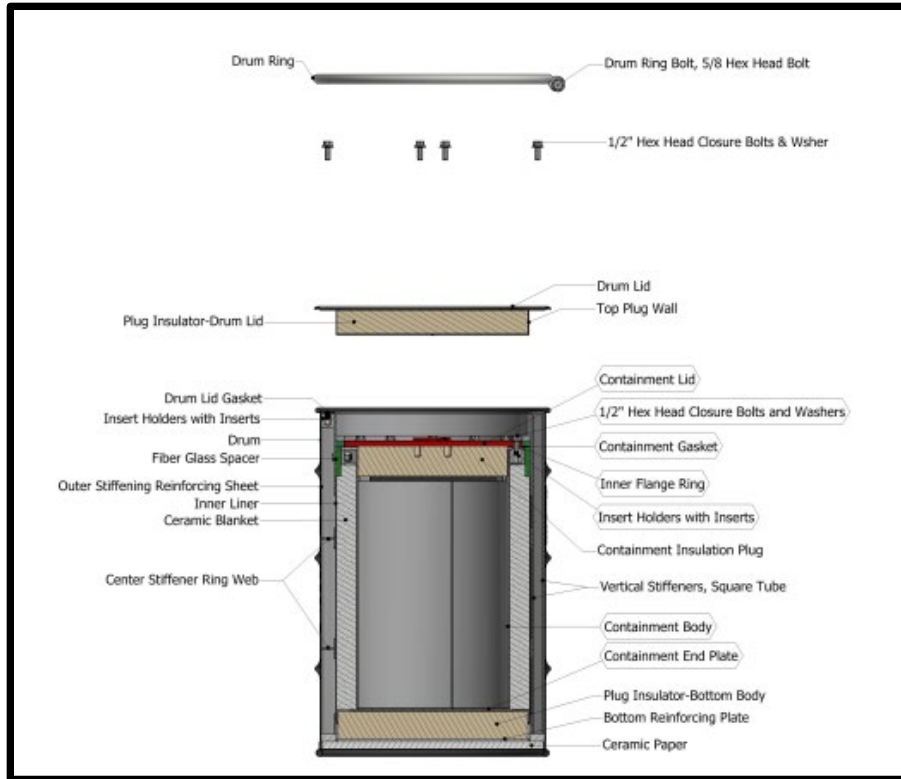


Figure 1. Versa-Pac (VP55) fresh fuel sphere storage container.

Each container is assumed to be sealed after it is filled with fuel spheres and prior to shipment from the fuel fabrication facility to the reactor. Once the containers are received at the reactor, they are placed into the fresh fuel storage area in an operating facility. The loaded and sealed VP55 containers are shown in Figure 2.



Figure 2. VP55 containers loaded and sealed.

Theft and diversion of fresh fuel containers also need to be considered. Any indication of tampering of the seals would require that the contents be remeasured and verified upon receipt. The containers are also vulnerable to abrupt theft, although with a total weight at approximately 750 kg each, they would not be considered man portable.

2.1.2 Spent Fuel Containers

The undamaged spent fuel spheres that exit the reactor will be placed in an area where they will cool for a period before they are loaded into spent fuel containers. These containers can be stored onsite until they are eventually shipped off-site and placed into concrete silos. This is based on the process description for HTGR pebbles that has been done in the past [4]. The silos are shown in Figure 3.



Figure 3. Example of a spent pebble container used for reprocessing HTGR fuel.

Prior to shipping the containers off-site, they will have to be characterized and accounted for. This could be done by weighing the containers once a uranium and plutonium content is established by either measurements or calculations (i.e., average burnup; see the discussion in Section 3 on burnup measurements). Due to the high radiation field, these would likely not be credible theft targets. Once they are loaded into the silos, this decreases the likelihood of theft as the concrete silo would have to be breached and then the containers accessed. Figure 4 shows the configuration of the containers in the silo. The threat of theft or sabotage would need to be determined by a vulnerability analysis.

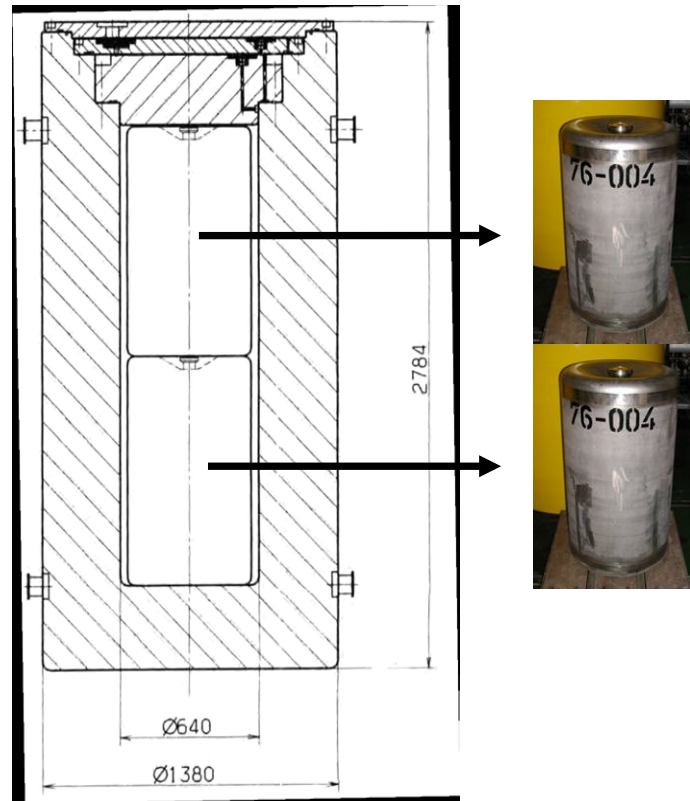


Figure 4. Example of spent pebble container used for reprocessing HTGR fuel.

In addition to these main containers, there may be other containers to convey fresh, spent, and damaged fuel spheres in the reactor system that have yet to be identified or designed. At any point in the reactor system where a fuel sphere exits the hydraulic tubing and is placed in a container, it should be considered as an accountancy or possible measurement point for the nuclear material accountancy system.

2.2 Pebble Counting Systems

The purpose of this task is to investigate current design approaches and efforts in the application of pebble counting systems which are used to add and remove pebbles from the reactor vessel. Historically, achieving an accurate pebble count has not been ensured. The objective would be to identify pebble counting system approaches and designs to address historical challenges and balance MC&A physical inventory and security containment surveillance goals with operational goals.

The project team has reviewed Xe-100 design information for the fuel handling system (FHS). The fuel and non-fuel graphite spheres are 6 cm in diameter and are continuously inserted and withdrawn from the reactor core and are moved throughout the reactor and associated systems via pneumatic (or hydraulic) pressure tubes, as well as other (mechanical) means. This includes the fresh fuel, irradiated fuel, spent fuel, and damaged fuel. This is in notable contrast to LWRs in which the fuel bundles are fixed during the operations cycle and the reactor must be shut down and the reactor head removed to insert, remove, or shuffle the fuel. Additionally, LWR fuel

bundles are uniquely identified, whereas fuel spheres are not. A PBR will likely have an active inventory consisting of hundreds of thousands of fuel spheres and during the operational lifetime may encounter millions of spheres that arrive as fresh fuel and ultimately are dispositioned as spent fuel. The number of spheres and their portability constitute the key differences as they relate to MC&A and security.

Once the containers arrive at the reactor, they will presumably be entered into the material accounting system. The containers are then opened and loaded en masse into a device (e.g., “hopper”) where the spheres are then loaded individually into the core via the FHS. The FHS and other reactor sub-systems handle the life cycle of each sphere, from insertion into the reactor core, exit from the reactor core, integrity verification (i.e., to detect damaged spheres), burnup measurement (to determine if the sphere is reinserted into the core), and exit from the active reactor inventory into the spent FHS. During this entire process, the spheres are counted and indexed. Every sphere that goes into the core is counted, and whatever comes out is counted as well. There will be a one-to-one correlation between the input and the output.

In previous work, there was some question as to the accuracy of this counting process, with one report quoting an error rate as high as 5%. However, discussions with one vendor indicated a more realistic number [5] is likely one failure per thousand measurements per instrument. They noted the FHS can be shut down if there is a discrepancy in the counting while the reactor is operating to resolve any discrepancy.

The counting and indexing are combined with the burnup measurement and sphere integrity verification systems to minimize the counting error rate. More detailed system and instrument design information is needed to determine a reportable uncertainty for the pebble counting systems and their impact on nuclear material accountancy and inventory uncertainty.

2.3 Physical Inventory of Reactor Vessel

The purpose of this task is to investigate approaches for physical inventory of the reactor vessel. The 2019 ORNL report [1] highlighted some of the challenges from both a technical and policy perspective for inventory of the reactor vessel.

In a PBR, the fuel would be received in the facility within a container that could be counted as an item with a defined nuclear material content and number of pebbles. This would be in the fresh fuel receipts and storage area and may be an item control area. Then, a set number of pebbles would be prepared for loading into the reactor through transfer into a feed hopper. Pebbles would be loaded as necessary into the reactor to replace pebbles removed from the reactor inventory.

When the reactor vessel of a traditional LWR is closed, safeguards practices in the United States consider the reactor vessel to be an item; however, the reactor vessel of a PBR will have a continual flow of nuclear material into and out from the reactor vessel and cannot be considered an item. At reactors under International Atomic Energy Agency (IAEA) safeguards, reactor vessels, even when sealed, are not considered to be an item, and the spent fuel content in the vessel is verified during every physical inventory performed while the core is open.

There is some discussion regarding the definition of the reactor material balance area (MBA) for a PBR and whether recycle loops, feed hoppers, and withdrawal containers would be included in the MBA. Each of these areas will have a continually changing quantity of nuclear material.

When pebbles exit the reactor vessel, they are sorted according to whether they are damaged or intact. Damaged pebbles are sent to a withdrawal station, where they are deposited into a container. After this container is filled and its nuclear material contents are determined, it would become an item that would be transferred to a storage area. The burnup of each intact pebble is measured individually, and the pebbles are either recycled back to the reactor core or sent to a withdrawal station for loading into spent fuel containers. After a container is filled with spent fuel pebbles and its nuclear material contents have been determined, it would become an item that would be transferred to a storage area. The spent fuel and damaged pebbles storage areas constitute item control areas (ICAs). It should be noted that cooling of the spent fuel spheres will likely be needed before transferring to containerized storage. As such, containerization may not occur for the first few years after removal from the core. In this case the contents of the cooling bins/hoppers/racks would need to be assessed/monitored.

Section 7.3 in NUREG-2159 [6] discusses processing and storage MBAs. A PBR will likely need to have at least one *processing MBA* because PBRs will perform routine transfers of nuclear material from one container to another, even though they will not perform processing activities that change the chemical assay or chemical and physical form.

There are five main expected inventory strata for proposed designs.

1. Fresh fuel or unirradiated pebbles—item
2. Spent fuel or irradiated pebbles—item
3. Reactor vessel and associated recycle loops—bulk/dynamic
4. Scrap (e.g., damaged, or broken pebbles or other residues)—bulk
5. Process holdup—bulk

Figure 5 shows a graphical representation of a potential organization of MBAs in a PBR. Please note that this is a theoretical application and represents potential MBAs and measurement points. The application of MC&A to specific designs may vary considerably.

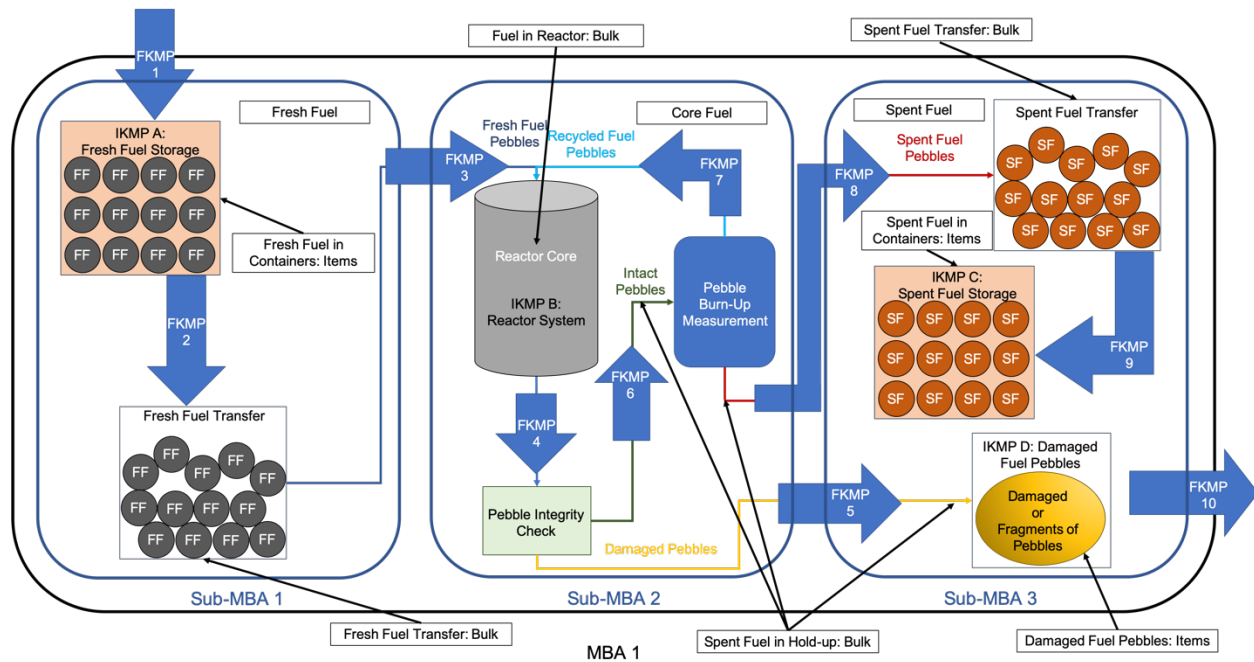


Figure 5. Example of MBAs.

The following is one potential arrangement of accounts (sub-MBAs), inventory key measurement points (IKMPs), and flow key measurement points (FKMPs) for a one MBA PBR.

- MBA-1: PBR facility
- Sub-MBA-1: Fresh fuel receipt and storage
- Sub-MBA-2: Reactor vessel system
- Sub-MBA-3: Spent fuel storage
- IKMP A: Fresh fuel storage area (items)
- IKMP-B: Reactor system
- IKMP C: Irradiated damaged fuel and waste storage area (items)
- IKMP D: Irradiated intact fuel storage area (items)
- FKMP 1: Fresh fuel receipt (items)
- FKMP 2: Recategorization of fresh fuel through transferred to reactor pebble feed system
- *FKMP 3: Fresh fuel insertion into reactor core
- *FKMP 4: Irradiated fuel removal from reactor core
- FKMP 5: Recategorization of irradiated damaged fuel and waste transferred to damaged pebble storage area
- *FKMP 6: Irradiated intact fuel transfer to burnup measurement system
- *FKMP 7: Irradiated intact fuel reinsertion to reactor core
- FKMP 8: Irradiated intact fuel removed from reactor system
- FKMP 9: Recategorization of irradiated intact fuel transferred to spent fuel storage area
- FKMP 10: Spent fuel, broken pebble, and waste shipment (items)

* These FKMPs are for recording internal flows and are not required for material accountability.

2.3.1 Item Areas

For fresh and irradiated fuel storage areas, the MC&A can be an item-based approach because the fuel spheres will be containerized. The approach must consider the appropriate measurement and measurement control systems and the application of statistical methods to reduce uncertainties. This is because the large volume of fuel pebbles will present challenges like those seen for pellets in a fuel fabrication process. There is likely to be some uncertainty in the ability to accurately count numbers of pebbles, even in these parts of the processes. For the MC&A approach, the options for applying containerization and tamper-safing to manage these challenges would be applicable. This would be analogous to the concept of fuel component container as discussed in ANSI N15.8-2009 [3].

Ideally there should not be any inventory differences in these two areas if high confidence in counting “whole” and broken pebbles can be achieved. However, if that is not the case, the MC&A plan and regulatory approach should discuss what level of accuracy is desired to meet domestic safeguards goals.

The approach for assigning SNM content to the fresh and spent fuel strata for inventory purposes is likely to be similar, if not identical, to that used for LWRs, which does not require changes to regulatory guidance. For fresh fuel, the assigned SNM content (and measurement uncertainty) in each pebble would or could be based on the value assigned by the fuel fabricator. The reactor facility may choose to perform independent confirmatory measurements, not with the goal of changing the assigned pebble value but rather to look for potential theft of pebbles, with and without substitution scenarios. These measurements might involve weighing containers and performing nondestructive analysis (NDA) measurements to verify the fissile content of the container or a sample from the container.

For spent fuel, the assigned SNM content is typically a calculated number based on weight, initial nuclear material content, and burnup calculations. However, because a design feature of a PBR is the measurement of individual pebbles to determine burnup to decide when to remove it from core circulation, this measurement could be used to replace, or augment, the calculated number, depending upon which is deemed the most accurate or appropriate for the application. See Section 2.4 for additional discussion on burnup measurements.

2.3.2 Reactor and Associated Recycle Loops

For the nuclear material quantities in the reactor vessel and potential scrap flows, a material balance based on measured inventories and flows would need to be established. Therefore, the procedure for performing a reactor physical inventory as described in current regulations would need to be changed because it assumes item accounting on spent fuel assemblies by serial number and location. The SNM in this part of the process would be considered *material in process* as defined in 10 CFR 74.4 and would be exempted from item control.

The initial reported quantity of pebbles within the vessel would be based on the quantity of pebbles used to fill the reactor vessel before the reactor went critical. After that, it would be based on additions and removals. The reported SNM content would be a sum of the nuclear material content of the pebbles. Entering the plutonium content and burnup into the accounting records upon removal of the spent fuel container from the withdrawal station is probably

preferred because declaring a running quantity of plutonium would likely not be practical or add value for MC&A purposes.

Using this approach, the SNM content reported for the reactor for MC&A purposes would be the quantity of unirradiated nuclear material representing the number of pebbles in the reactor. The quantity of nuclear material transferred into the spent fuel container for the physical inventory taking would be based on the fresh fuel values to enable a direct balancing with the input quantities. The plutonium and uranium depletion would be entered into accounting after this balancing. In summary, this approach determines and balances the inventory based on numbers of pebbles fed into, withdrawn from, and in the inventory of the reactor MBA.

Potential approaches for monitoring and providing some statement of confidence about the quantity of pebbles in the reactor MBA would be needed, which correlates directly to amount of nuclear material. The NRC would likely benefit from adapting its current approach to process monitoring to allow for data obtained from measurements within the process stream to be used more broadly (i.e., not just to meet the specific requirements for Category I SNM) to give confidence that nuclear material has not been diverted from any of the process streams. Designers and the NRC may choose to approach physical inventories in these facilities with a methodology like enrichment plants, where inventories are done in a facility under continuous operations with no cleanout or shutdown.

The physical inventory process for the reactor must also address the quantity of nuclear material in damaged or broken pebbles collected into a container at the withdrawal station and collected waste. The quantity of nuclear material in the damaged pebble strata would need to be determined during a physical inventory taking. The concept of damaged cladding as found in ANSI N15.8-2009 [3] and other guidance would apply to PBRs.

2.3.3 Documentation and SNM Element and Isotopic Calculations for Reporting

The regulations for reporting burnup (isotopic calculations) that support physical inventory declarations need to be updated or clarified to support anticipated PBR operations scenarios. The NRC regulations state that the net quantity of plutonium produced in the fuel of a reactor during the reporting period should be reported on the Material Status Report line 21, PRODUCTION [7].

Instructions for reporting the production of plutonium and depletion of uranium on the Material Status Report were written based on LWRs. If followed, these instructions would likely require that plutonium values for the PBR reactor vessel or in-process pebbles be declared at least every 9 months. While technically this could be done, the accuracy with which it could be done and the need to do this for MC&A purposes are questionable. It is recommended that recognition of isotopic changes be upon discharge of pebbles from the reactor based on the burnup measurement.

Another challenge is that while the amount of plutonium produced over a large group of pebbles is significant, an individual pebble is anticipated to be less than one-half of a reporting unit.* Further discussion about approaches for grouping and assigning plutonium values across a batch

* The reporting unit for plutonium is 1 g.

or group of pebbles is needed. This is not new for nuclear processes. The MC&A plan should discuss the approach used to manage the plutonium content reporting.

2.4 Burnup Measurements for PBRs, Domestic Safeguards Context, and Research Needs for Total Measurement Uncertainty

PBRs operate with a continuous refueling scheme. Such a refueling scheme means that within a PBR, these pebbles are fed into the core, exited from the core after being irradiated for a period of time, and recirculated into the core (recycled) until they achieve sufficient passes to meet their target burnup value (chosen to limit pebble burnup to the target maximum burnup value), at which point the pebbles are then discharged from the core. The target pebble burnup is typically achieved after several passes, depending on the specific reactor and fuel design parameters, including the neutron flux and pebble residence time in-core. Following their irradiation and exit from the core after each pass, pebbles may be measured by online gamma spectroscopy within a burnup measurement system (BUMS) to determine whether they have met their target burnup. Burnup measurement signatures include various fission-product gamma rays or ratios of these gamma rays.

From an operational standpoint, the purpose of the BUMS in a PBR is to measure and confirm the burnup of the pebble fuel. Therefore, the measured burnup value serves as the criterion for discharging the pebble from the reactor or passing it back through the reactor, i.e., recycling the pebble [8]. Additionally, by using the measured burnup value, the isotopic composition of the irradiated fuel can be calculated using a burnup analysis code. From a domestic safeguards or MC&A perspective, the purpose of the burnup measurement is to provide input to nuclear material inventory values, which are typically expressed as total plutonium content upon fuel discharge.

The BUMS typically detects and measures passive gamma-ray emissions from select fission products within the irradiated fuel pebbles. The burnup measurement itself does not provide a direct measurement of plutonium content. This is true for both gamma-ray and neutron measurements because in the case of gamma-ray measurements, plutonium gamma rays are masked by the much stronger gamma rays from fission products; and in the case of neutron measurements, the total neutron emission rate is dominated by transuranic isotopes such as ^{244}Cm [9]. Therefore, isotopic composition including plutonium content must be derived from coupling the burnup measurement to a burnup analysis code (e.g., ORIGEN in the SCALE code suite [10]).

A burnup analysis calculation can calculate the isotopic compositions (including total plutonium) in the irradiated fuel pebbles at any given time during irradiation or after discharge. The burnup value of the pebble is one of the input parameters required for such calculation. Having burnup value measured helps reduce uncertainties in the calculated isotopic compositions. On the other hand, the results from burnup calculations can be used to confirm the measured burnup values by comparing the calculated detector signals with the measured signals (e.g., gamma or gamma ratios). ORNL previously developed the ORIGEN Module software, which uses the ORIGEN burnup analysis code and Monte Carlo N-Particle code (MCNP) detector response functions, to predict the neutron and gamma detector signals based on declared burnup values and other

information regarding to the irradiated fuel being measured [11]. Such software can be adapted to confirm the measured burnup values of the pebbles.

Irradiated fuel pebbles emit thousands of gamma-ray lines, and the intensities of these lines vary dramatically with the pebbles' cooling time, burnup value, and irradiation power level. Without actually performing gamma spectroscopy measurements on the irradiated pebbles, it is challenging to determine which gamma lines can be detected above the strong gamma background often dominated by short-lived fission products and also be useful to determine burnup. However, such measurements can be simulated by coupling a burnup analysis code such as ORIGEN (calculates the gamma source term) and a gamma detector response simulator such as GADRAS [12]. Such simulations will offer great insights regarding what gamma lines from which nuclides can be detected and useful for determining the burnup value of the pebble on a given condition.

Improving the accuracy of the burnup measurement can lead to reduced uncertainty in the burnup code calculation of the total plutonium content per pebble. Furthermore, an accurate prediction of the total plutonium mass value (with reduced uncertainty) can lead to optimized waste container loading because the number of pebbles reloaded and/or discharged and dispositioned can be optimized. Several factors need to be investigated for their relative effects on the burnup measurement and associated uncertainty.

Research needs for deriving the total measurement uncertainty include evaluating the effect of the path of the pebbles in the reactor core and thus the neutron flux seen by those pebbles and effect on the resulting plutonium content. Burnup and plutonium content are not always directly correlated in a PBR. Pebbles can reach the same burnup by different paths that would lead to different plutonium contents. For example, a pebble that travels twice through the center of the core may have the same burnup as a pebble that travels through the periphery of the core three to four times. The pebble from the periphery would have more plutonium than the pebble from the center because the neutron spectrum is distinctly different. This will lead to greater uncertainties in plutonium content for any given burnup measured by a BUMS unless this research reveals secondary fission products that can be used to correct for this effect. Therefore, both the magnitude of this variation and correction factors should be investigated.

The time referred to as "cooling time," between the pebble exiting the core and performing the measurement, should also be investigated for its effect on the burnup measurement and associated uncertainty. PBRs operate with a continuous refueling scheme, and the burnup measurement will be performed online. Therefore, the effect of cooling time of the irradiated pebbles on the burnup measurement will also need to be investigated because there is the potential for high-intensity, short-lived fission product gamma rays to dominate the measured gamma-ray spectrum and thus mask the primary fission-product gamma rays of interest such as cesium.

2.4.1 Task Goal and Objectives

The goal of this task is to investigate proposed approaches for burnup measurements and calculations that can be applied to MC&A for PBR technologies. While the magnitude of the impact of the uncertainty in this measurement on the final disposition path for spent pebbles

(e.g., repository vs. reprocessing) remains to be determined, it will affect declared values for MC&A, safety, and waste disposition. The objective of this task is, therefore, to review proposed approaches and measurement methods for performing burnup measurements of irradiated pebble fuel and identify where further work may be needed to manage or improve this use in providing nuclear material values.

Other technical objectives of this task are to understand the current state of the art of the application of burnup measurements to PBRs Technology Readiness Level (TRL). Furthermore, to evaluate the needs for qualification of the pebble burnup measurement method for MC&A, part of this evaluation will include knowing the target measurement uncertainty of planned measurement systems and technologies. Also, part of this is knowing whether it is possible to distinguish burnup and/or plutonium mass between passes and account for pebble (plutonium mass) variability within the uncertainty bounds or whether a stream average needs to be adopted. An important part of this evaluation will be gathering industry input on their performance requirements, including partners X-Energy and Kairos. Experience with burnup measurements at INL will also be consulted. Finally, a proposed technology development plan to achieve TRL-9 will be documented.

The results of the work done under this project can be used to support designers in their effort to get BUMS qualified for both operations and MC&A, or to a TRL-9, which means commercial use. As part of work package development with X-Energy, ORNL is reviewing the X-Energy pebble burnup measurement system method as an example for how to identify what is needed to qualify it under a perspective as an MC&A system. This is relevant to the previously developed PBR MC&A Plan [1] section discussing this measurement, its performance, and how it is calibrated and maintained.

2.4.2 FY 2020 Progress/ Findings to Date

Literature Review and X-Energy Engagement and Teaming

During FY 2020, a literature review was begun to determine what BUMS technologies already exist for PBRs and which are qualified. BUMS technologies typically employ high-purity germanium detectors for gamma spectroscopy to measure fission-product gamma rays or ratios including from ^{137}Cs . The burnup can then be determined from the ^{137}Cs activity or the $^{134}\text{Cs}/^{137}\text{Cs}$ activity ratio. Research is being conducted to consider the use of other activity ratios, as well as to consider other types of detectors for gamma spectroscopy or even neutron counting [13,14,15].

Existing BUMS, according to the 2010 AREVA NA Inc. Pebble Bed Reactor Technology Readiness Study [16], include (1) Arbeitsgemeinschaft Versuchs-Reaktor (AVR) system (fully demonstrated during 21 years of reactor operation in Germany); (2) Pebble Bed Modular Reactor Demonstration Power Plant (PBMR DPP) 400 system (which was qualified for MC&A measurements by tests in the Institute of Nuclear Material, Zarechny, Russia, and reached the commercial stage of development); (3) German High-Temperature Modular Reactor, HTR-Module (tested in Jülich in the DIDO reactor; however, the manufacturer suggests more confirmatory tests are needed for final qualification); (4) Chinese HTR-PM (system

performances from numerical simulation); and (5) the Thermo Fisher Scientific Fuel Burnup Measurement System.

For a system to be qualified for use in measurements, the system must be demonstrated to produce acceptable data under realistic operating conditions, along with other requirements stated in the ASTM Guide [17]. Several of the systems mentioned above require more testing or analysis before they can be qualified. Qualification needs for pebble burnup measurement systems will be reviewed and captured as part of this task.

During FY 2020, ORNL also engaged with X-energy to begin to support the development of their BUMS. To date, X-Energy has identified the technologies that the company plans to move forward with for their BUMS [18] and Activity Measurement System [19]. The latter system is used as a first pass to identify whether a pebble is a graphite moderator pebble or a fuel pebble, prior to performing the burnup measurement on the fuel pebbles only. These systems appear to be the same technologies developed for the South African Pebble Bed Modular Reactor (PBMR). ORNL is working with X-Energy to understand calibration and testing plans for those systems and provide support on measurement qualification for MC&A as needed.

3. RESEARCH PLANS AND TECHNICAL APPROACHES FOR FY 2021

During FY 2020, significant progress was made in developing partnerships with industry, which is crucial for developing real-world solutions for applying robust MC&A approaches to PBRs. Specifically, the work with X-energy is proving very fruitful because they are aggressively pursuing the design and deployment of their Xe-100 reactor and the TRISO-X fuel. Additional partnerships are planned with Kairos Power as they pursue their unique molten salt coolant design. And finally, the project team will continue to work with the national laboratories to bring their unique resources and talent to bear to address these issues.

Emerging from the FY 2020 analysis was the overlap with physical protection based on the facility layout and implementation of remote handling, all of which would affect or complement the MC&A approaches for item control. In FY 2021 the project will further explore this interface with industry and a project being done at SNL for the security posture of a PBR, which will focus on the vulnerability for man-portable fuel and PBR vital areas regarding theft, sabotage, diversion, and misuse.

3.1 Packaging and Handling for Fresh and Spent Fuel

The containerization methods of the fresh and spent fuel will play a crucial part in the MC&A approaches developed at PBRs. FY 2021 work will focus on refining the types of containers that will be used in

- packaging and transporting fresh fuel from the fuel fabrication facility;
- receipt of fresh fuel containers in the reactor;
- disposition of spent fuel spheres, cooling time, and spent fuel containers; and

- in addition to these main containers, identification and analysis of other containers that may be used to convey fresh, spent, and damaged fuel spheres in the reactor system.

A main goal of FY 2021 will be to harmonize the MC&A approaches being used by the fuel fabrication facility to ensure that those values can be used during fuel receipt at the reactor with minimal reverification. This will include the seals and tamper indicators and measurement methods.

Additionally, measurement systems that can be used to verify the amount of fissile material that is placed in spent fuel containers will be reviewed with respect to use as accountancy measures. Once the spent fuel containers are sealed, these values can be used for movement of the spent fuel off-site to an external storage facility.

3.2 Pebble Counting Systems

In FY 2021, the project team will focus on determining what systems are being used to index and count fuel spheres in a PBR and to determine the potential accuracy and reliability of such systems to be used in an MC&A approach. Preliminary data have been received regarding failure rates for instruments used in spherical fuel counting. Additional design information is needed as well as further research to determine if an acceptable accuracy can be obtained to meet NRC measurement system requirements to be used in domestic MC&A applications.

3.3 Physical Inventory of Reactor Vessel

Taking physical inventories and establishing material balances are essential parts of material accountancy. However, due to the nature of the moving fuel, this will likely be significantly more challenging in a PBR. The traditional inventory approach developed for LWRs will not be sufficient. As discussed in this report, the MC&A approach will be a mix of item and bulk accountancy. After the spheres are placed in the reactor and its subsystems, an item approach cannot be used. Additionally, when the plutonium and residual uranium will be accounted for, and how, must be determined.

Security concerns regarding the potential for theft and sabotage of fresh and irradiated pebbles will drive the determination of what quantities must be accounted for as well as the times for detection. The focus of the project team in FY 2021 will be to work with industry partners to gain the following.

- Obtain detailed design information, including physical layouts and system descriptions
- Determine what the drivers will be for performing physical inventories in a PBR
- How the dynamic inventory in the reactor vessel, FHS, and other plant sub-systems will accommodate, or hinder, physical inventory taking
- How to account for damaged or broken fuel spheres
- How current NRC rules and regulations may need to be modified to take into consideration the efficacy of physical inventories in moving-fuel reactors that are not periodically shut down

- How to take into consideration off-normal events and plant upsets in which normal operations are disrupted and the status of systems that handle fuel spheres may be (temporarily) compromised

3.4 Burnup Measurements

During FY 2021, the project will continue FY 2020 research efforts on the measurement method itself and how to account for pebble-to-pebble variability, as well as incorporate an analysis of using a stream average and contrasting the two potential options and their impact on MC&A, safety, and disposition.

When developing a qualified measurement system for pebble burnup measurements, input from industry will be sought. This includes the design of the burnup measurement system, which is necessary to evaluate the sensitivity to specific fission products. It is also necessary to know the target maximum pebble burnup value as well as the burnup value for the discharge/recycle criterion necessary to meet this target maximum. According to the following NRC reference,

...determining a suitable value for the discharge/recycle burnup criterion will require consideration of in core pebble residence time spectra, together with supporting neutronics calculations, in order to statistically characterize the maximum burnup increment that might accrue during a pebble's final pass through the core. Burnup measurement uncertainties will also have to be considered. Furthermore, since pebble burnup measurements (unlike the pebble reactivity measurements used in THTR-300) cannot distinguish pebbles with different initial fuel enrichments, the same discharge burnup criterion must be applied to the initial charge of lower-enrichment fuel pebbles as to the higher enrichment pebbles that are added in transitioning to an equilibrium core. Neutronics calculations will be needed to bound the higher neutron fluence experienced by the lower-enrichment pebbles in reaching the maximum burnup levels allowed in the transitional cores [8].

However, note that neutron techniques are potentially useful to distinguish pebbles with different initial enrichments because higher enrichments offer higher multiplication of neutrons.

Neutronic modeling will include all possible paths through the reactor core, which can be used to make synthetic gamma-ray spectra and to begin to evaluate (and thus bound) pebble variability. Using modeling and simulation, generic facility-independent assessments will also be performed to assess the fission products or fission product ratios that are most sensitive to burnup, for example, ^{137}Cs , $^{134}\text{Cs}/^{137}\text{Cs}$, and $^{239}\text{Np}/^{132}\text{I}$. Varying the time to the measurement system may also be an option to access different fission products (short-lived vs. longer-lived). As part of these assessments, evaluating the fission products or fission-product ratios that are most sensitive to burnup content will be necessary, for example, relatively high-yield plutonium fission products, that is, Ru 106–112 mass number fission products. In addition, high-specific-activity actinides, for example, ^{239}Np will be investigated. Note that fission-product ratios tend to be better for decision making because they remove some of the detector biases from the evaluation.

A sample of pebbles may need to be measured for a longer term on an auxiliary burnup measurement system to capture MC&A accurately. This allows for decay and longer counting times, which is possibly logic driven in the main burnup measurement system.

Time and resource permitting, other possible techniques in addition to gamma-ray spectroscopy may be considered to verify the pebble burnup. These include destructive analysis or evaluation (as a gold standard but costly) and active interrogation of pebbles with a neutron source.

4. REFERENCES

- [1] Oak Ridge National Laboratory, *Model MC&A Plan for Pebble Bed Reactors*, ORNL/SPR-2019/1329.
- [2] D. Holcomb, internal communication with P. Gibbs, Oak Ridge National Laboratory, April 30, 2019.
- [3] American National Standard, “Special Nuclear Material Control and Accounting Systems for Nuclear Power Plants,” ANSI N15.8-2009.
- [4] *Process Description for Processing of HTGR Pebble Fuel at SRS*, SRNL-TR-2014-00209, October 2014.
- [5] Project communication between ORNL and X-energy 11/6/2020.
- [6] U.S. NRC, *Acceptable Standard Format and Content for the Material Control and Accounting Plan Required for Special Nuclear Material of Moderate Strategic Significance*, U.S. Nuclear Regulatory Commission, NUREG-2159, 2013.
- [7] U.S. NRC, *Instructions for the Preparation and Distribution of Material Status Reports (DOE/NRC Forms 742 and 742C)*, US Nuclear Regulatory Commission, NUREG/BR-0007, Revision 8, 2019.
- [8] Listing and Description of NRC Nuclear Analysis Issues for HTGRs, Accessed online 2020.
- [9] LANL, *Safeguards LWR Spent Fuel with the Fork Detector*, Los Alamos National Laboratory Report LA-11096-MS.
- [10] W. A. Wieselquist, R. A. Lefebvre, and M. A. Jessee, Eds., *SCALE Code System*, ORNL/TM-2005/39, Version 6.2.4, Oak Ridge National Laboratory, Oak Ridge, TN (2020).
- [11] S. Vaccaro, I. C. Gauld, J. Hu, P. D. Baere, J. Peterson, P. Schwalbach, A. Smejkal, A. Tomanin, A. Sjöland, S. Tobin, and D. Wiarda, “Advancing the Fork Detector for Quantitative Spent Nuclear Fuel Verification,” *Nuclear Inst. and Methods in Physics Research, A*, Vol. 888, pp. 202–217, 2018. <https://doi.org/10.1016/j.nima.2018.01.066>.
- [12] D. J. Mitchell, L. T. Harding, G. G. Thoreson, and S. M. Horne, *GADRAS Detector Response Function*, SAND2014-19465, Sandia National Laboratories, Albuquerque, NM, 2014.

- [13] Ayman I. Hawari and Jianwei Chen, “Computational Investigation of On-Line Interrogation of Pebble Bed Reactor Fuel,” *IEEE Transactions on Nuclear Science*, vol. 52(5), pp. 1659–1664, 2005.
- [14] Jason M. Harp, Paul A. Demkowicz, and John D. Stempien, “Fission product inventory and burnup evaluation of the AGR-2 irradiation by gamma spectrometry,” *Nuclear Engineering and Design* 329, 134–141 (2018).
- [15] Zhongxiang Zhao, *Investigation on using neutron counting techniques for online burnup monitoring of pebble bed reactor fuels*, dissertation, University of Cincinnati, 2004.
- [16] AREVA NP Inc., Pebble Bed Reactor Technology Readiness Study, Technical Data Record: 234 (2010).
- [17] ASTM International C1068-03, “Standard Guide Qualification of Measurement Methods by a Laboratory Within the Nuclear Industry” (Reapproved 2011).
- [18] *Thermo Gamma-Metrics, Operation & Instruction Manual, Burn-up Measurement System*, Rev. April 2002. Official Use Only (OUO), marked “Confidential and Proprietary Information.”
- [19] *Thermo Gamma-Metrics, Instruction Manual, Activity Measurement System*, Rev. December 2001. OUO, marked “Confidential and Proprietary Information.”