**A Safeguards Perspective on Pebble Bed Modular Reactors (PBMR) – Considerations, Approaches and Challenges**

Authors: Adrián Méndez Torres (A.Mendez@IAEA.org), Kihyun Kim (SGOA), Traci Newton (SGCP), Jae-Sung Lee (SGCP), Christophe Portaix (SGIM), Marie Cronholm (SGOA), Irene Antonelli (SGOA)

# ABSTRACT

Many States are expressing interest in commercialization of small modular reactor (SMR) technology. One of the SMR designs under consideration is the Pebble Bed Modular Reactor (PBMR). The distinctive fuel of the PBMR consists of small-diameter spheres, or "pebbles," that are roughly the size of billiard balls. Fresh pebbles containing uranium fuel are fed into the reactor from a fresh fuel storage bin, creating a sea of unidentifiable pebbles in the core. Each pebble is recirculated through the reactor several times to achieve optimal burn-up, at which point the irradiated pebbles, now also containing plutonium, flow out of the reactor and are kept in spent fuel (SF) storage bins. Traditional safeguards consider currently operating power reactors as "item facilities" because the fuel is in the form of discrete and integral items that can be individually identified and verified. The PBMR design, and its variants, are more akin to "bulk handling facilities" in which the fuel is transferred in bulk form from the fresh fuel drums to the core, and then to the SF storage containers and silos in a large number of small units (i.e. pebbles) that are not each individually identified for nuclear material accountancy purposes. Maintaining continuity of knowledge (CoK) and safeguarding thousands of continuously moving pebbles is a daunting task. This paper identifies some of the challenges associated with safeguarding PBMRs and discusses the safeguards considerations and approaches needed to preserve CoK. Dialogue among stakeholders during the early design and construction process, in accordance with the principles of safeguards-by-design, is discussed as a strategy to facilitate the efficient and effective implementation of appropriate safeguards measures and minimize the impact on the operator.

# INTRODUCTION

Small Modular Reactor (SMR) concepts and designs, such as Pebble Bed Modular Reactors (PBMRs), can be dated back to the 1940s; however, their deployment to date has been limited. Recently, in 2021, China reported[1] the construction and operation of a high temperature pebble bed modular reactor (HTR-PM) which has two 250 MWt units. The HTR-PM design, if successful, has the aim to be commercialized and exported to other countries.

PBMRs consist of a bed of uranium and graphite pebbles that is refueled continuously by the flow of pebbles through the reactor core. Uranium-containing pebbles are the nuclear fuel and graphite pebbles serve as moderator. As the pebbles exit the bottom of the core, they are examined by radiation monitors to infer burn-up. Pebbles with low burn-up are recirculated back to the top of the reactor and continue to cycle through until reaching an optimal fuel burn-up. When a pebble reaches the optimal burn-up, it is removed and stored as spent nuclear fuel. Fresh pebbles replace the removed pebbles to maintain the reactivity and equilibrium needed for the operation of the reactor. In the case that a defective pebble is detected it is removed to a secondary storage for damaged pebbles. The total number of pebbles in a single core depends on specific core designs; typically, a core will contain approximately 300–500 thousand pebbles. The on-line fueling of the fresh pebbles occurs at the rate of approximately 300–500 pebbles per day, with similar numbers of discharged spent fuel pebbles.

*Fresh fuel (FF)* - The fuel consists of coated-particle microspheres or "kernels" containing uranium incorporated in a graphite-coated sphere, a proprietary technology that uses high temperature carbide and pyrolytic carbon coat (TRISO). The typical diameter of each pebble is 5–7 cm, similar to a billiard ball with a uranium content of each pebble around 7–9 grams and a $^{235}$U enrichment of 5–10%, although new development of TRISO fuel reported by the USA has involved $^{235}$U up to 19.9% enrichment. The fissile material used as

[1] https://en.cnnc.com.cn/2021-12/20/c_692103.htm

fuel in the pebble is not limited to uranium, as other fertile material, such as thorium, has been successfully used to sustain a chain reaction in a PBMR.[2]

From a safeguards perspective, the approximate amount of nuclear material (NM) for which the possibility of manufacturing a nuclear explosive device cannot be excluded is referred to as the significant quantity (SQ). SQs are used in establishing the quantity component of the International Atomic Energy Agency (IAEA) inspection goal. Table 1 shows the SQ per pebble assuming 8g U and three enrichment levels. Notice that even for enrichment up to 19.9%, also referred to as high-assay low-enriched uranium (HALEU), more than 47000 pebbles are required to reach one SQ of low-enriched uranium (LEU).

Table 1. Total number of fresh pebbles with initial U mass per pebble and different $^{235}$U enrichment to reach 1 SQ of LEU (75kg $^{235}$U)

| Utot (g) | $^{235}$U% | $^{235}$U (g) | SQ per Pebble | # of pebbles for 1 SQ |
|---|---|---|---|---|
| 8 | 6.5 | 0.52 | 6.9E-06 | 144231 |
| 8 | 9.6 | 0.768 | 1.0E-05 | 97656 |
| 8 | 19.9 | 1.592 | 2.1E-05 | 47111 |

Table 2. Fresh fuel drums (batches) assuming each drum contains ~1000 pebbles

| Utot and $^{235}$U% per pebble | $^{235}$U (g) per drum | # of drums/SQ |
|---|---|---|
| 8g 6.5% | 520 | 144 |
| 8g 9.6% | 768 | 98 |
| 8g 19.9% | 1592 | 47 |

For safeguards, an "item" consists of an accounting unit, where the form and integrity remain unaltered during the residence at the facility and each item can be uniquely identified and verified (e.g., by item counting, verification of the continued integrity of the item, non-destructive assay (NDA) measurement). In the case of a PBMR, it would require the unique identification of hundreds of thousands of pebbles. An alternate concept can be to define the accountancy units in "batches;" for example, the same type, physical and chemical form and enrichment grouped as a single unit (e.g., uniquely identified storage drum). Assuming that each batch consist of storage drums each containing 1000 pebbles, Table 2 shows the amount of $^{235}$U per drum and the number of drums required to reach 1 SQ of LEU. Notice that in the case of HALEU it will require at least 47 drums to obtain 1 SQ, or 98 drums for the case of 9.6% $^{235}$U.

*Core fuel (CF)* - In a typical light water reactor (LWR), the amount of fuel in the core is constrained to a relatively small number of fuel elements that can be uniquely identified (and verified if needed) and that operate in a quasi-static condition (no fuel element is removed or added during an operation cycle, typically around 14 months). In contrast, the core of a PBMR contains hundreds of thousands of indistinguishable U pebbles (in addition to graphite pebbles) and operates in a dynamic condition. The fuel pebbles are continuously recirculated in the core until they have reached an optimal burn-up (typically around 6 cycles) when they are eventually discharged to a spent fuel storage and substituted in the core by fresh pebbles.

Table 3. Hypothetical core size and corresponding amount and SQs of Pu and $^{235}$U total in the core

| Pebbles in core | g Pu | Pu SQs | g $^{235}$U | $^{235}$U SQs |
|---|---|---|---|---|
| 350 000 | 28000 | 3.5 | 175000 | 2.3 |
| 450 000 | 36000 | 4.5 | 225000 | 3.0 |
| 550 000 | 44000 | 5.5 | 275000 | 3.7 |

Due to the dynamic nature of the core, consisting of hundreds of thousands of moving elements and online refueling and defueling, a possible approach is to treat a PBMR more like a bulk handling facility. The PBMR may be organized into multiple material balance areas (MBAs) for safeguards purposes, for example, by separating activities relating only to the storage of fresh and spent pebbles from those involving the processing of bulk material (e.g., core). For comparison purposes, Table 3 shows the average

[2] IAEA TECDOC 1450, Thorium fuel cycle – Potential benefits and challenges, May 2005, https://www.iaea.org/publications/7192/thorium-fuel-cycle-potential-benefits-and-challenges

amount of NM and SQs (8kg Pu) for three core sizes, assuming that on average there is ~0.08g Pu and ~0.5g of $^{235}$U per pebble during steady-state operation.

A single core will exceed the amount of NM equivalent to one SQ of Pu or $^{235}$U. In the scenario of a diversion of one SQ of NM, at least 100000 pebbles will need to be diverted without compromising the reactor operation (assuming average 0.08g Pu per pebble; during operation, 300–500 pebbles will be discharged and fresh pebbles (0g Pu) will be loaded every day).

*Spent fuel (SF)* - The total amount of plutonium in each SF pebble depends on the burn-up, number of cycles in the reactor, initial mass of U, and $^{235}$U enrichment. On average, approximately 0.08–0.15 grams of plutonium is contained in each pebble at optimal burn-up. After achieving the optimal burn-up, the pebble is discharged from the core and stored in SF silos or bins. Depending on the SF storage design, each silo can contain from thousands to hundreds of thousands of SF pebbles. The silos/bins will be a high-radiation area and human access would be restricted, which precludes direct (individual pebble) verification of the SF in storage. If an average of 0.12g of Pu per pebble is assumed, diversion of more than 66700 pebbles would be required to reach 1 SQ of Pu. Silo/bin design and capacity are an important aspect to establish the safeguards measures. For example, a silo of ~3300 pebbles will contain ~0.05 SQ Pu, while a silo of ~33000 pebbles will contain 0.5 SQ Pu.

## SAFEGUARDS CONSIDERATIONS for PBMR

The IAEA implements safeguards measures to detect potential diversion of declared NM and/or misuse of declared facilities for undeclared purposes (e.g., undeclared receipt, transfer, irradiation, or removal of nuclear fuel).

In a PBMR, in order to assure that no diversion of NM has occurred, the IAEA will likely need to maintain CoK on previously verified NM and to verify the declared amount of NM at specified locations within the facility, called key measurement points (KMPs). The verification of NM may include i) the verification of the receipt of FF pebbles at the facility/MBA prior to introduction into the reactor, ii) the verification of transfers of SF from the reactor core to SF storage, and iii) the verification of FF, CF, and SF inventories in comparison with operating records and State reports. In comparison to LWRs, there are several safeguards-relevant features of PBMRs that make them unique and require additional safeguards considerations in order to maintain CoK, to facilitate the verification of NM and to provide assurance that the facility has not been misused. Some of the key differences between the PBMR and an LWR are:

- The PBMR is an on-load refueled reactor with hundreds of thousands of fuel elements circulating in the core and hundreds of FF pebbles loaded and SF pebbles discharged every day.
- The number of items in a facility/MBA and at different locations (KMPs) are in the hundreds of thousands, are more challenging to count, and cannot be individually identified.
- Start-up of the PBMR core requires a mixture of graphite moderator pebbles and fuel pebbles; the IAEA will need to distinguish between fuel pebbles and non-fuel moderator pebbles.
- The flow of fuel to and from the PBMR core follows an elaborate flow scheme and requires greater attention to monitor all fuel transfer and diversion pathways.
- If CoK is lost, the reverification of all NM, even just item counting of all pebbles, would be extremely challenging if not impossible.

LWRs are safeguarded under the concept of an item facility, however due to the large number of pebbles in the inventory, each with small NM content, the safeguards for a PBMR would be more akin to bulk handling facilities. Such is the case with fuel fabrication plants where hundreds of thousands of pellets can be produced and processed, but the safeguards measures are not based on “pellet counting.”

*Accountancy and Material Balance Evaluation (MBE) considerations for PBMR*

From an accountancy point of view, the two main differences between a PBMR and an LWR are both related to the fuel: i) in a PBMR, fuel pebbles have an increased mobility as they are in constant movement in the reactor during normal operations, ii) in a PBMR, the number of fuel pebbles in the inventory is very large (on the order of several hundred thousands), and there may be several million fuel pebbles flowing through the facility over its lifetime.

These differences may have a major impact on the safeguards approach, and must be taken into account when designing the safeguards measures deployed to cover the credible diversion and misuse scenarios. In particular, confirming the consistency of the balance in the number of fuel pebbles may be an effective measure to address these scenarios. This may however mean that PBMRs would be considered in some ways more as bulk handling facilities rather than as item facilities, as is the case for LWRs.

In a bulk MBA, flow and inventory values declared by the facility operator are typically verified by the IAEA through independent measurements and observation. For bulk MBAs, a non-zero material unaccounted for (MUF) is expected due to measurement uncertainties on NM inventories and due to the nature of processing of NM in bulk form, for example the presence of broken pebbles, hold-up, or waste materials. Hence, for all the materials in the reactor vessel and lines, scrap, hold-up, waste and in-process material, a material balance based on the measured and declared inventories and flows would need to be established. MBE by the statistical evaluation of MUF and operator-inspector differences would be an appropriate measure to support a conclusion on the absence of diversion.

*Item, bulk or a hybrid safeguards approach*
The result of combining safeguards measures for item facilities (e.g., FF storage drums, SF storage silos) and safeguards measures for bulk handling facilities (e.g., MBE) in a hybrid approach may allow the IAEA to optimize the safeguards measures for each KMP. A possible hybrid approach could consist of the following elements. The FF and SF KMPs may conceivably be verified by item (batch) counting and attribute verification in combination with operator records and reports (e.g., new FF receipt, transfer to core, and SF discharge). Containment and surveillance (C/S) measures could potentially provide assurance that diversion of NM has not taken place. The reactor core could potentially be treated as a separate bulk MBA, allowing for the accountancy of NM flow and Pu production in a straightforward manner. Further, the circulation of pebbles in the reactor may conceptually be more easily approached from a material process flow perspective, where the transactions (inventory changes) between FF and SF are reported as flows entering and leaving the bulk MBA.

## SAFEGUARDS APPROACHES for PBMRs

*Possible Safeguards Measures and Activities* - In developing a safeguards approach, possible safeguards measures and activities are identified to address each technical objective to cover the relevant proliferation scenarios. Applicable safeguards measures and activities are selected considering State and facility specific factors. Table 4 shows proliferation scenarios, concealment methods, and indications which may be considered to identify safeguards measures and activities for a PBMR.

*Verification activities* - The following verification requirements and activities were being considered during the development of a safeguards approach for the PBMR that had been planned by South Africa. Although the safeguards measures and equipment were specific to the South African PBMR project, they are a good reference from which to develop a safeguards approach for similar PBMR designs.

For FF verification, drums or barrels containing fresh LEU fuel pebbles are counted, identified by serial number, and verified for gross defect (attribute test and/or enrichment level measurement) with NDA at the annual physical inventory verification (PIV). FF transfer is verified during any inspection or at the PIV. FF inventory of the same type at other facilities in the State (e.g., similar type of reactors or fuel fabrication plants) is subject to verification to provide assurance that NM presented for the PIV has not been borrowed.

For the verification of CF, likely not accessible for direct verification, the flow of the fuel through the core is expected to be verified rather than the inventory at the time of the PIV by ensuring that no unrecorded removals of SF from the core have taken place since the previous PIV. Fuel discharges are counted and the fuel flow is evaluated by balancing the insertion and removal of fuel pebbles. Detailed analysis of the measurement data and operational parameters would be performed and compared with the operator’s NM declaration. The confirmation of the absence of unrecorded production of direct-use NM is achieved through the measures to verify fuel discharges and through the application of C/S measures covering potential ex-core irradiation locations.

Table 4. Possible scenarios, concealment methods, and indications for PBMRs

<table>
<tr><td>Scenario</td><td>Concealment methods</td><td>Indications</td></tr>
<tr><td>Diversion of irradiated pebble<br>- from fuel transfer system (core, tanks, pipe, PIE port)<br>- from SF cask in collection<br>- from SF cask in silo<br>- from SF cask transfer out</td><td>Substitution with dummy/graphite pebble<br><br>Falsification of accountancy/operating records<br><br>Unreported (or understated) transfer of irradiated pebble</td><td>Inconsistencies in the operator’s records and/or State’s reports,<br>Inconsistencies in the IAEA’s inspection results,<br>Change in the facility design,<br>Change in the SF storage capacity,<br>Missing SF casks,<br>Presence of dummy pebbles,<br>Presence of undeclared cask/shielded containers,<br>Unreported movement of the SF casks/shielded container out of the facility,<br>Undeclared change in the reactor power level,<br>Extension of reactor maintenance periods.</td></tr>
<tr><td>Diversion of fresh pebble<br>- from FF drum<br>- from fuel transfer system (loading box, intermediate tanks)<br>- from transfer</td><td>Substitution with dummy/graphite pebble<br><br>Borrowing FF from other reactor or fabrication plant for substitution<br><br>Falsification of accountancy/operating records<br><br>Unreported transfer of FF</td><td>Inconsistencies in the operator’s records and/or State’s reports,<br>Inconsistencies in the IAEA’s inspection results<br>Change in the facility design,<br>Change of the FF storage capacity,<br>Missing fresh fuel container,<br>Presence of dummy pebbles,<br>Presence of unreported FF container.</td></tr>
<tr><td>Undeclared production of Pu through irradiation of targets in PBMR</td><td>Undeclared design changes allowing targets to be introduced into the core<br><br>Falsification of accountancy/operating records<br><br>Change in the reactor operation</td><td>Presence of undeclared targets,<br>Presence of undeclared cask/shielded container,<br>Undeclared movement of cask out of the facility,<br>Missing NM from the inventory,<br>Unusual fuel loading and discharging pattern,<br>Undeclared opening/closure of the reactor,<br>Change in the reactor power,<br>Presence of SF with lower burnup,<br>Change in the SF storage capacity,<br>Design change in the reactivity control system,<br>Core or fuel design change.</td></tr>
<tr><td colspan="3">Possible safeguards measures and activities</td></tr>
<tr><td colspan="3">Applicable safeguards measures may include:<br>- Nuclear Material Accountancy;<br>- Physical Inventory Verification, Random/Unannounced Inspection;<br>- Design Information Examination/Verification;<br>- C/S (with or without remote monitoring);<br>- Radiation monitoring (attended/unattended);<br>- AP declaration review, Complementary Access, Environmental Sampling (ES, if necessary);<br>Safeguards activities may include:<br>- Examination of accounting and operating records;<br>- Nuclear material verification (item counting, ID/tag check, NDA);<br>- Install and service of C/S and monitoring equipment (e.g., seals, cameras, fuel flow monitors);<br>- Review of C/S data</td></tr>
</table>

- Comparison of information provided by the State with declaration or verification results;
- Visual observation, ES taking (if necessary);
- MBE, transit matching, open source analysis (at IAEA HQ)

SF inventory is verified by a combination of SF flow monitoring, fuel counting at the inlet of the SF tanks, and NDA methods. SF in tanks is verified for gross defect using external NDA methods at the annual PIV and interim inspections. Other containers and points where the discharged fuel can be removed (e.g., damaged fuel tanks, PIE sampling port) should be under C/S. For the storage silos, as the final destination of all discharged fuel in the facility, silo fill status is verified with NDA. The empty status of unfilled silos and full status of fully loaded silos will need to be controlled with C/S or regularly reverified. SF burn-up and quantities should correlate with reactor operation and power production. Establishment of the correlation of safeguards data would be required to detect undeclared SF removal as well as unreported Pu production either by computer modeling or by detailed analysis of facility data. Although no SF shipments are anticipated for the life cycle of the reactor, for the shipment of SF, either CoK is maintained until the shipping container is placed under IAEA seal at the receiving facility; or the shipping container is under IAEA seal after the completion of loading and the seal verified at the receiving facility.

*Design Information* - Design information refers to the information concerning NM subject to IAEA safeguards under the relevant agreement and the features of facilities relevant to safeguarding such material (see para. 8 of INFCIRC/153; see also para. 32 of INFCIRC/66). Design information includes: the facility description; the form, quantity, location and flow of NM to be or being used; layout and containment features; and procedures for NM accountancy and control. Important design information relevant to a PBMR will include the following:

- Description of how and how frequently fuel would be received and shipped
- Design of all storage vessels and areas including vessels for storing fresh, damaged and spent pebbles, and graphite moderator
- Design of the pebble fuel reactor vessel(s) and *all* pebbles (fuel and graphite)
- Design of pneumatic transfer routes for all pebbles
- Detailed procedures for NM accountancy including the code used to determine burn-up
- Other drawings and information deemed necessary by the IAEA for safeguarding the facility

Such information is used by the IAEA, inter alia, to design the facility safeguards approach, to determine MBAs and select KMPs and other strategic points, to develop the design information verification (DIV) plan and to establish the essential equipment list. The IAEA has the right to perform DIVs throughout all phases of a facility's lifetime for the purpose of verifying the correctness and completeness of the design information provided by the State and to confirm the safeguards measures applied to the facility are still valid. States concluding a comprehensive safeguards agreement (CSA) are committed to providing preliminary design information for new facilities to the IAEA as soon as the decision to construct or to authorize construction has been taken, whichever is earlier.

## SAFEGUARDS BY DESIGN

Safeguards by Design (SBD) is the integration of safeguards considerations early in the design process of a nuclear facility or component, from initial planning through design, construction, operation, modification, waste management, and decommissioning. SBD is a voluntary process which does not replace a State's existing obligations for provision of information to the IAEA under its safeguards agreement, but which can lead to additional benefits for all stakeholders in terms of effectiveness and efficiency of international safeguards implementation as well as the reduction of operator burden. SBD provides guidance to State authorities, designers, equipment providers and prospective purchasers on the importance of taking international safeguards into account when designing a nuclear facility or process. A voluntary best practice, SBD allows for informed design choices that optimize economic, operational, safety and security factors, in addition to international safeguards. For new nuclear facilities, especially in the case of innovative designs such as PBMRs, the earlier the discussion of safeguards the better. SBD allows for safeguards to be built 'into' the system, rather than around it afterwards. Adopting SBD in the early stages allows for a better understanding of safeguards obligations by all stakeholders. It can also provide possible marketing advantages for vendors.

SBD benefits not just the IAEA but all parties involved including State, regulatory agencies, vendors, developers, operators, etc.

## SAFEGUARDS CHALLENGES

The development of novel technology and progress in the peaceful use of nuclear energy around the world is not new for the IAEA. However, the potential rapid licensing and deployment of SMRs, such as PBMRs, will result in new challenges to the IAEA. For example, the IAEA may need to develop, test, and implement new safeguards tools and methodologies to safeguard such facilities. PBMRs are one example of a type of reactor that poses unique challenges as they have characteristics not fitting the category of "item" facility and operating in practice more like a "bulk" facility. From a safeguards perspective, the following challenges need to be addressed;

1. Identifying methods for verification of the fresh and irradiated fuel pebbles and the fuel flows.
2. Identifying methods for maintain CoK over previously verified inventories.
3. Identifying NDA methods to distinguish graphite pebbles from fuel pebbles.
4. Determining which operational data will be required to confirm the absence of misuse.

Other challenges arise from the implementation of sensors and monitoring systems to confirm reactor operation and flow rate of pebbles. A sensible approach may include sharing operator instrumentation and raw data to potentially alleviate the need for the IAEA to develop and install their own sensors and reduce the burden on the operator to facilitate access points for the installation and service of IAEA equipment. However, shared data would need to be validated as authentic. Accurate simulation and modelling need to be developed and validated. During a reactor lifetime the number of pebbles will be several SQs of NM and can surpass a million pebbles in some cases. The question of how to effectively and efficiently apply C/S and other safeguards measures arises. The challenges are aggravated by the continuous on-line refueling and defueling capability of this reactor type.

For States intending to acquire SMRs, the legislative and regulatory framework must be in place to effectively implement safeguards. SQP States may require assistance in establishing and/or strengthening a State or regional authority responsible for safeguards implementation (SRA) to ensure they are able to fulfill their legal commitments under the CSA. The IAEA is prepared and ready to support and work in close cooperation with the States in the early stages to ensure the State and the SRA are prepared to fulfill their safeguards duties.

## INNOVATIVE APPROACHES

*Digital twin* - A digital twin is a virtual model designed to accurately reflect a physical object. The object being studied—for example, a PBMR—is outfitted with various sensors related to vital areas of functionality. These sensors produce data about different aspects of the reactor performance, such as energy output, temperature, reactivity, etc. This data is then relayed to a processing system and applied to the digital copy. "Once supplied with such data, the virtual model can be used to run simulations, study performance issues and generate different scenarios, all with the goal of generating valuable insights and gain confidence that no diversion or misuse has occurred".[3] A digital twin can potentially enable inspectors and analysts to make informed inferences of the potential to detect a deliberate misuse of the facility or diversion of NM from the core through analysis of available signals coupled with independent models of reactor operating conditions.

*Statistical modelling, machine learning* - The inability to uniquely identify fuel pebbles presents a challenge for international safeguards verification that NM is not being diverted. Statistical methods have been proposed and studied with applications on the safeguards field, for example determining if a reactor is within a declared range of operation by examining the statistical distribution of fuel burnup as pebbles are discharged from the core. Preliminary results provide a basis and framework for exploring the further use of statistical methods, and possibly machine learning, to capture if diversion of pebbles in a PBMR is occurring. For example, "utilizing statistical models provides a framework for differentiating declared operations from diversion

[3] Digital Twin to Detect Nuclear Proliferation: A Case Study, ASME annual meeting, C.Ritter, R.Hays, J.Browning, R.Stewart, S. Bays, G. Reyes, M.Schanfein, P.Sabharwall

scenarios. When a realistic scenario was devised with a constant power density and constant power, the statistical model provided an accurate representation of the core and whether diversion was occurring."[4]

*Sensor technology (SHM and Piezo resistors sensors)*[5] **-** The IAEA relies heavily on the use of radiation-based detection and monitoring system. However, there is a possibility to implement new sensor technology that measures key parameters of the reactor's operation such as coolant inlet and outlet temperature, flow of pebbles and thermal power generation. For example, structural health monitoring (SHM) sensors, or piezo electric sensors have been studied in the past and proposed in the nuclear industry due to robustness and resilience to irradiation damage. They have been successfully used in various applications, such as in medical, aerospace, and nuclear instrumentation. An array of different sensors can make up a 'fingerprint' of the reactor operation by using advanced sensing techniques and further data processing. SHM has experienced advancements during recent years due to the developments in sensing techniques. SHM has been extensively applied in several fields, such as aerospace, automotive, and mechanical engineering.

*Advances in C/S techniques, 2D laser curtain and 3D scanning* **-** The IAEA is developing new C/S techniques based on 2D laser curtains and 3D scanning. The system is a fixed installation based on multiple real-time laser scanners that continuously acquire depth information to monitor an area of interest. The sensors use the time-of-flight principle to measure the distance to objects in their field-of-view. Each sensor is composed of multiple laser-detector pairs arranged along the vertical axis that are continuously rotating to generate several scans per second. On a server, all data is fused into a single 3D data set and analyzed in real-time to monitor and track safeguards-relevant activities. Since the analysis works on geometric measurements in 3D space, event detection can be restricted to pre-defined areas of interest.

## CONCLUSION

PBMRs, with their hybrid nature combining aspects of item and bulk facilities, present a unique challenge for IAEA safeguards. Safeguards approaches are being considered throughout the development of these new reactors, thereby avoiding the need to make incremental changes once construction has already been completed. The IAEA is currently interacting with several IAEA Member States on SBD for SMRs, including PBMRs, through MSSPs.[6] MSSPs and their support and development of safeguards approaches for PBMRs is of paramount importance. Expertise in Member States can help to develop and refine possible safeguards approaches. Furthermore, MSSPs can provide access to facilities under construction or operation with the aim to gain experience, knowledge, and to serve as test beds for new instruments or concepts. The IAEA will continue to work with States, developers, and stakeholders to assure safeguards measures are applied in an effective and efficient manner.

[4] Utilizing Advanced Statistics to Determine Anomalistic Conditions in Pebble-Bed Reactors, S. X. Wen, R. H. Stewart, F. N. Gleicher, S. E. Bays, G.A. Reyes, M.J. Schanfein, C.S. Ritter

[5] Lin, B, Gresil, M, Mendez-Torres, AE & Giurgiutiu, V 2012, Structural health monitoring with piezoelectric wafer active sensors exposed to irradiation effects. in ASME 2012 Pressure Vessels & Piping Conference. Toronto, Canada, ASME 2012 Pressure Vessels & Piping Conference, Toronto, Canada, 1/01/24.

[6] https://www.iaea.org/topics/assistance-for-states/safeguards-by-design