

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

P. BECKER, A. RIALHE, J. WHITLOCK, J. DOO

International Atomic Energy Agency (IAEA)

Vienna, Austria

Emails: P.Becker@iaea.org, A.Rialhe@iaea.org, J.Whitlock@iaea.org, J.Doo@iaea.org

B. XIA, J. GUO, H. WANG

Institute of Nuclear and New Energy Technology (INET), Tsinghua University

Beijing, China

Emails: xiabing@tsinghua.edu.cn, guojiong12@tsinghua.edu.cn, wanght@tsinghua.edu.cn

Abstract

The International Atomic Energy Agency (IAEA) is developing safeguards measures for the High Temperature gas-cooled Reactor Pebble-bed Module (HTR-PM) under construction in the People's Republic of China (China), which is under a voluntary safeguards agreement (VOA) with the IAEA. China has successfully operated an experimental prototype 10 MWth high temperature pebble-bed reactor (HTR-10) since 2000. Based on the experience gained with HTR-10, China has designed and is constructing a Demonstration HTR-PM at Shidao Bay in China's Shandong province, which comprises twin HTR-PM reactor modules driving a single 211 MWe steam turbine. The Chinese HTR-PM was added to the list of eligible facilities for IAEA safeguards and the IAEA selected the facility for the application of safeguards in September 2017. Since the design of HTR-PM was complete and the field construction work is almost completed, the development and application of international safeguards measures to the facility have presented challenges to both operators and the IAEA. As there has been no IAEA safeguards experience at the HTR-PM, China expressed interest to work closely with the IAEA to develop safeguards measures for the HTR-PM. Currently, safeguards measures are under discussion for the HTR-PM with the China Atomic Energy Authority (CAEA) and the IAEA. To date, a number of aspects that are important for an optimized safeguards implementation for this type of reactor have been identified, and might be considered for potential modification of the design for the future export market. This paper describes the HTR-PM fuel handling characteristics, provides a summary of the current status of the application of safeguards measures under development by the IAEA, and discusses safeguards-related research topics for potential modification of the design for the future HTR-PM export.

1. INTRODUCTION

Generation IV nuclear power systems includes high temperature gas-cooled reactors [1] based on the tri-structural-isotropic (TRISO) [2] fuel. TRISO fuel is based on small uranium oxide spheres coated with four layers (ceramic based) that assure containment of all fission products while supporting operation at high temperatures. There are basically two types of reactors depending on the configuration of the fuel: "prismatic" and "pebble bed (PB)". Germany constructed a 300 MWe PB reactor unit that was in operation for about 3 years until 1986 [3]. Later South Africa started to develop PB reactors, and a generic safeguards approach was proposed by the IAEA for that design.

China has been developing High Temperature Gas-cooled Reactors based on the pebble bed technology for almost 30 years. It started with HTR-10, a small research pebble-bed reactor constructed for gaining experience and data for the development of power reactors based on the same technology. The HTR-10 has been successfully operated up to now and has been subject to IAEA safeguards since 2001.

Since 2012, China has been constructing a 211 MWe nuclear power plant which includes two 250 MWth pebble-bed reactors for driving a common turbine. This plant is expected to be connected to the grid by end of 2019.

As will be described later, the PB reactor operation is unique and cannot be directly compared to any other technology used currently for nuclear power reactors. This poses some challenges for designing a safeguards approach.

In 2017, the HTR-PM was added to the list of eligible facilities in China for IAEA safeguards, and the IAEA selected the facility for the application of safeguards. The main objectives of IAEA's HTR-PM designation are for "learning and gaining experiences at the HTR-PM" and to use this experience in the design of the pebble-bed HTGR that may be exported to Non-Nuclear Weapon States (NNWS) in the future.

The working level discussions for the application of safeguard measures started in May 2017 when the IAEA carried out the first technical visit to the HTR-PM. During IAEA's technical visits, designers from the Institute of Nuclear and New Energy Technology (INET) at Tsinghua University in China and the HTR-PM operators provided the IAEA with detailed information on the HTR-PM design and fuel handling operation, while the IAEA explained procedures for the implementation of international safeguards. Through the field technical visits and meetings with INET designers, the HTR-PM operators and China Atomic Energy Authority (CAEA) officers, the IAEA was able to identify safeguards challenges and possible safeguards measures including the installation of IAEA safeguards monitoring equipment (e.g., Non-destructive assay (NDA) and surveillance, etc.) at the facility under construction. Since HTR-PM construction was already well advanced, the application of safeguards by design concepts was not possible. The safeguards measures for the current HTR-PM cannot be the same as those considered for the units to be exported in the future which possibly takes into account "safeguards by design concepts".

2. PEBBLE BED REACTOR TECHNOLOGY AND HTR-PM SHORT DESCRIPTION

Pebble bed high temperature gas-cooled reactors feature high levels of safety and efficiency. Inherent safety is an essential feature of PB reactors, which are based on the fuel technology of TRISO coated particles, a large negative temperature coefficient, large heat inertia and the rational core design. The inherent safety of PB reactors reduces the risk of core melt due to decay heat, as well as the risk of mass release of radioactive materials due to core melt, and the risk of an off-site radiological emergency. The reactor outlet temperature of more than 750 °C enables high efficiency power generation, as well as opportunities for multiple applications such as hydrogen production and sea water desalination.

The technical scheme of the HTR-PM includes the modular pebble bed high temperature reactor design, the single-zone pebble bed reactor core and two reactors with two steam generators driving a common turbine. The thermal power of each reactor is 250 MW_{th} and the total power output of the plant is about 211 MWe. From the initial core filled with a mixture of lower enriched (4.2%) uranium fuel pebbles and graphite moderator pebbles, the reactor transits to the equilibrium core gradually, in which the major core parameters remain time-independent. For the equilibrium core, fresh fuel pebbles with 8.5% enrichment are loaded into the core top and recycled through the reactor core for an average of 15 times in order to reach an average discharge burnup value about 90,000 MWd/tU. The outlet temperature of the primary coolant loop is 750 °C. The decay heat after shutdown can completely be removed by the heat conduction and heat radiation within the pebble bed and in the side reflector. That means the maximum fuel temperature after even the most severe accidents, such as the depressurized loss of forced circulation accident, remains below the safety threshold, i.e. 1620 °C, indicating that there is no realistic possibility of mass release of radioactive materials. This is the basic technical feature of the inherent safety of the HTR-PM.

The on-line continuous refuelling of the HTR-PM provides flexible possibilities for complicated refuelling strategies, during which the fuel pebbles are continuously unloaded from the core bottom and the pebble bed core remains flowing. Afterwards, the gamma spectrum of an unloaded pebble is measured by an HPGe spectrometer to determine the burnup value of each pebble. If each pebble's burnup exceeds the predefined threshold, the pebble is regarded as spent fuel to be discharged and a corresponding fresh fuel pebble is added to the core top; otherwise, the pebble is recycled to the core top. Two reactor modules employ one fresh fuel storage room and one spent fuel storage building. All the spent fuel pebbles will be stored in the spent fuel building during the plant lifetime. For the equilibrium core of the HTR-PM, the refuelling process and the depletion of fissile materials keep dynamic balance. Hence, the average discharge burnup of a batch of spent fuels can be directly determined by the integral of power history and the refuelling speed. Consequently, the operational parameters including integral power

history and the refuelling data are the important safeguards parameters for the nuclear material accounting of the HTR-PM.

3. 3. CONSTRAINTS ON SG BY DESIGN AT A FUTURE HTR-PM TYPE FACILITY AND A PROPOSAL FOR FEASIBLE SG MEASURES AT THIS HTR-PM RESULTING FROM THE CURRENT STAGE OF CONSTRUCTION.

Generic safeguards approaches and guidance for pebble bed reactors were reviewed during the preparation of safeguards measures to be applied to the HTR-PM. [4] [5] [6]

HTR-PM poses several specific nuclear safeguards challenges. The reactor operates with hundreds of thousands of small fuel spheres (420,000 spheres per reactor) containing small amount of low enriched uranium nuclear material that do not have unique identification numbers. Until the reactor reaches the equilibrium phase, graphite moderator spheres are used to control reactivity, which are loaded along with lower enriched uranium (4.2%) fresh fuel spheres during the initial core loading [7] [8]. The fuel spheres will be circulated on average 15 times until they reach their discharge burn-up and will then be discharged to spent fuel containers. Each spent fuel container hold approximately 40,000 spent fuel pebbles. Each spent fuel pebble would contain approximately 0.1 gram plutonium at discharge burn-up. Approximately 80,000 spent fuel pebbles would be needed to reach one significant quantity (SQ) of plutonium, while approximately 126,000 fresh fuel pebbles are required to reach one SQ of U-235. The diversion of one SQ would require a huge number of spent or fresh fuel pebbles and should be easily detected by the IAEA’s effective containment and surveillance measures. The spent fuel pebble storage silos were designed to hold all spent fuel pebbles discharged from the reactors during the facility lifetime (40 years).

The credible diversion pathways associated with the HTR-PM are “diversion of fresh fuel pebble containers or pebbles from fresh fuel storage building, ways to loading or loading areas”, “diversion of core fuel pebbles from the reactor containment building or prior to being discharged to spent fuel containers”, and “diversion of spent fuel pebbles from the spent fuel storage building, which were discharged from the reactor containment building”. For the scenario of misuse to produce undeclared Pu or U-233 at the HTR-PM, target materials may also be loaded and irradiated in the core or reflector areas. In order to detect the credible diversion pathways, the main technical objectives of safeguards at the HTR-PM are the followings:

- Detect diversion of fresh fuel pebble containers or pebbles, with or without substitution by dummy fuels prior to loading to the reactor;
- Detect diversion of core fuels or irradiated target materials, with or without substitution by dummy fuels and falsification of operating records; and
- Detect diversion of spent fuel pebbles with or without substitution by dummy fuels

The HTR-PM operates with two reactors located in one reactor containment building but the reactors commonly share the fresh fuel storage and loading areas as well as the spent fuel storage area. Once the reactor core is installed in the reactor containment building and starts its operation, it is not expected to be accessible for the whole operational life time. After loading, the fuel pebbles will only be verified when they are discharged as spent fuel pebbles. The following three main blocks have been considered as storage key measurement points (KMP) for the application of safeguards measures:

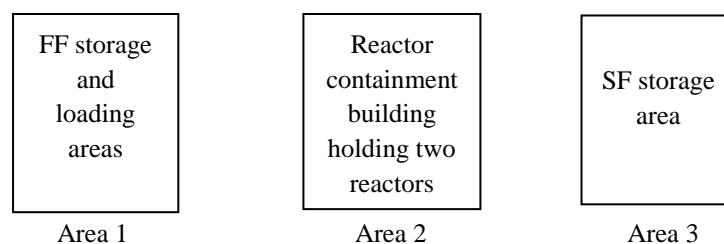


Figure 1: Blocks considered for the application of safeguards measures

Fresh fuel pebbles containing low enrichment uranium are verified and accounted prior to being stored in area 1. There will be two levels of verification. The drums will be accounted, their tags checked and some drums

andomly selected for non-destructive analysis (NDA) to verify the existence of ^{235}U . For the verification of pebbles, drums will be randomly selected, pebbles accounted and at least one pebble per selected drum will be taken for NDA. Spectrometry will be applied to verify the enrichment of ^{235}U . A methodology, based on a fixed geometry, has been developed and it is expected that the measurement can be calibrated with ^{235}U mass. Surveillance measures will be applied to the loading area, mainly to understand and learn the fresh fuel pebble loading process.

Area 2 is the reactor containment building holding two reactors that is inaccessible during the reactor operation and shut-down periods. In order to maintain a continuity of knowledge of fuel pebbles loaded to the reactor, NDA (radiation detectors) and surveillance system will be applied to key penetrations areas where irradiated fuel pebbles could be removed.

Area 3 is the spent fuel storage area that is proposed to be maintained under the dual containment and surveillance system (dual C/S) because it will be difficult to re-measure spent fuel pebbles stored in casks and silos. Due to the restrictions posed by the advanced state of the facility construction, there will be no facility modification to accommodate the re-measurement of spent fuel pebbles stored in casks and silos. Therefore the re-measurement of spent fuel pebbles stored in casks and silos is not feasible. Prior to spent fuel pebbles loading into the cask, it has been proposed to install an NDA system that will be able to account and verify that the pebbles loaded into the SF cask are irradiated nuclear material. In addition, an NDA system to confirm the level of filling of spent fuel pebbles into the cask has been proposed. For complementing the dual C/S system, both surveillance and NDA equipment for registering the movement of any material emitting gamma radiation and/or neutrons has been proposed to be installed in the hatches of the SF storage area and at the gate of the truck bay to verify the absence of undeclared nuclear material transfers.

However, the above safeguards measures are not ideal as there are no technical means of recovering the continuity of knowledge if the applied containment and surveillance system fail. Since the reactivity is sensible to the number of pebbles in the core, mathematical models based on Monte Carlo calculations are being developed in the IAEA. The reactor physics characteristics may potentially support the IAEA to compare power production records with fuel usage to determine potential discrepancies. The following figure 2 shows proposed nuclear material balance area and key measurements points for the HTR-PM.

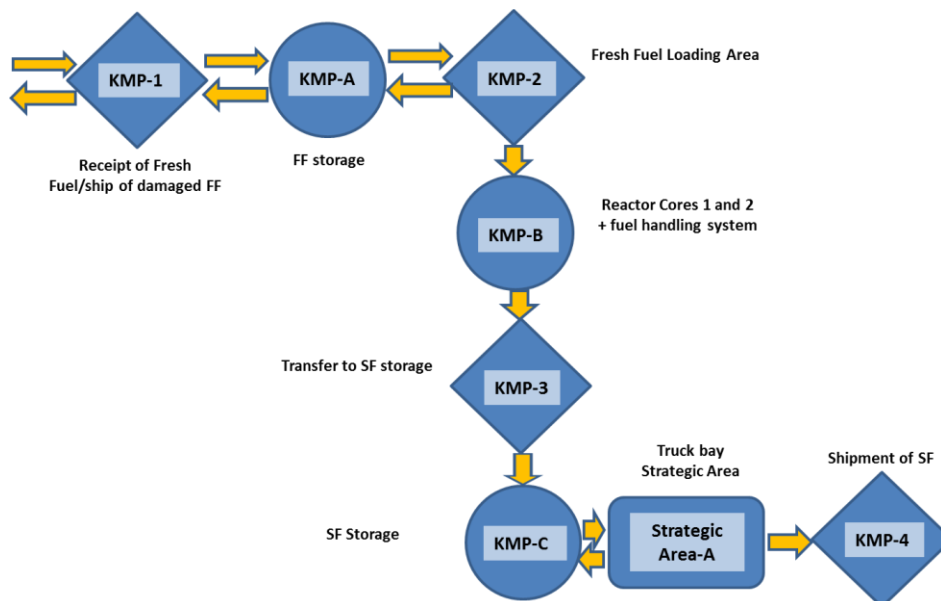


Figure 2: Proposed nuclear material balance area and key measurements points for the HTR-PM.

4. RESEARCH TOPICS ON IAEA SAFEGUARDS BY DESIGN FOR UNITS TO BE EXPORTED TO OTHER STATES

For the FF storage and loading areas, a specific “FF loading monitoring system” is being considered to determine the material and account every pebble going to the reactor containment building. The measuring principle would be gamma spectrometry using a fixed geometry. This equipment will allow the IAEA to have its independent verification and account nuclear material being loaded into the cores. In addition, operational information on the material going to the core is proposed to be available “on line” to the IAEA data acquisition system. The FF loading monitoring system must be reliable and have a minimum interference with the normal operation of the reactor. The following Figure 3 shows a diagram of how the system would be installed.

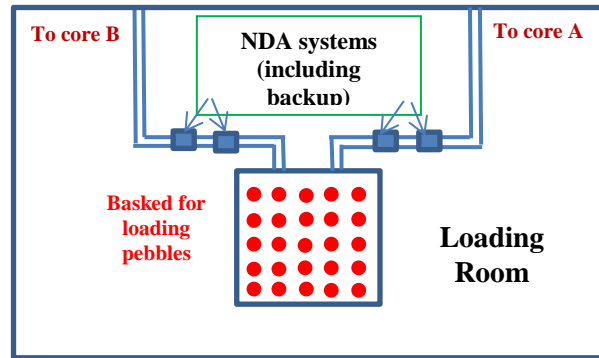


Figure 3: Proposed FF loading monitoring system for the future pebble-bed HTGR

The reactor containment area, holding the two reactors, will still be considered “difficult to access” and all penetrations will be maintained under the IAEA containment and surveillance system. In addition, operational information on the material circulating in the reactor containment building is proposed to be available “on line” to the IAEA data acquisition system server. If the containment and surveillance system fails, the information will be used as technical means of recovering the continuity of knowledge.

For the SF storage area, the installation of an “SF unloading monitoring system” capable of identifying irradiated pebbles and possibly the discharge burnup of each pebble is considered (Figure 4). This monitoring system will use gamma spectrometry for measuring the ^{137}Cs peak for estimating the burnup. This instrument will allow accounting the SF pebbles and also estimating the content of Pu. A NDA instrument for monitoring the cask filling level is also been considered. In addition, operational information on the material discharging to the cask in the SF storage area is proposed to be available “on line” to the IAEA data acquisition system so that IAEA can independently confirm the FF loading and SF discharging balance. The installation of a neutron detector on the cask transportation machine for monitoring the silo loading and unloading activities is also been considered (Figure 5).

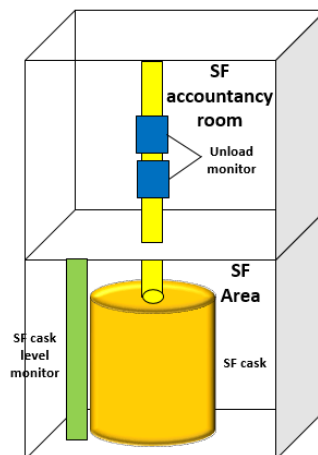


Figure 4: SF unloading and cask filling monitoring systems

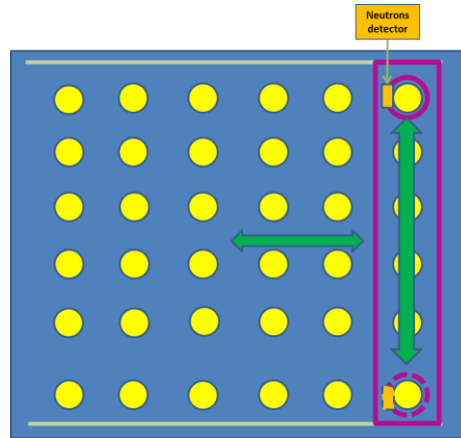


Figure 5: Neutron detector in the cask transport machine

For verification of SF casks, each silo is proposed to have a “verification pipe” located next to it (Figure 6). This pipe would allow the IAEA to use a collimated detector (gamma detector) to determine the radiation profile of the NM inside each silo and therefore the number of SF casks. Even the decay of the NM could be followed and reconciled with the data of the original filling of the SF casks. Sealing of the silo plugs is safeguards measure being considered to avoid frequent re-measurements of SF casks loaded into silos (Figure 7).

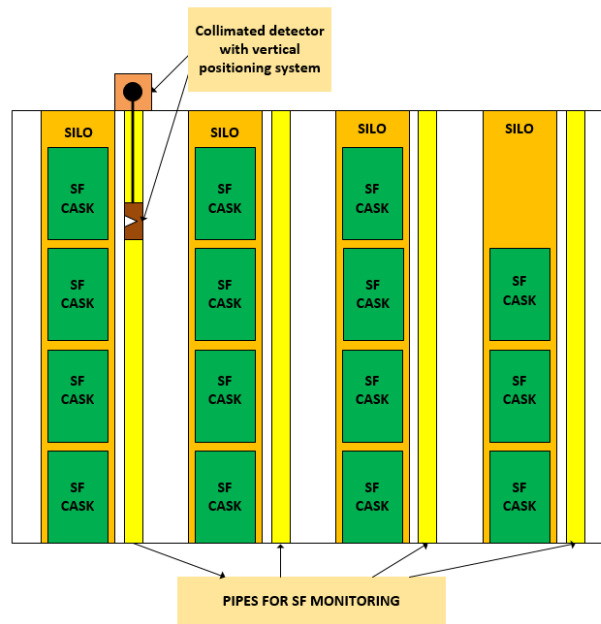


Figure 6: Silo verification pipe for monitoring SF casks

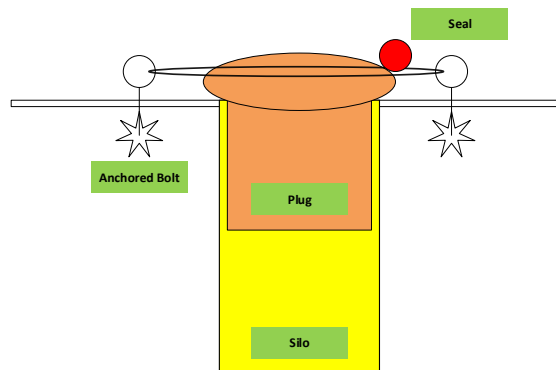


Figure 7: Sealing the silo plug

5. CONCLUSIONS AND FUTURE ACTIVITIES

Safeguarding pebble bed reactors is a challenge to the IAEA due to the use of hundreds of thousands of small fuel spheres containing small amounts of nuclear material, which do not have unique identification numbers. Due to the advanced stage of the HTR-PM construction, the application of “safeguards by design” concepts to these units is no longer possible.

The safeguards measures to be applied to the HTR-PM under construction in China are primarily for the IAEA to learn and gain experience. Specifically, the HTR-PM has provided a unique opportunity for the IAEA to test safeguards concepts and measures including IAEA verification and monitoring equipment. In parallel, “safeguards by design” concepts have been discussed with CAEA officers and INET designers for future pebble-bed HTGRs that possibly may be exported to other States.

The IAEA plans to apply safeguards to HTR-PM within a limited time period only for learning and gaining experience, which is required for the development IAEA safeguards measures including verification and monitoring equipment. With the lessons learned and strong cooperation with China, it is expected that optimized safeguards measures incorporating “safeguards by design” will be applied to future pebble-bed HTGR designs.

Acknowledgement

The work from INET side has been supported by the National S&T Major Project (Grant No. ZX069).

REFERENCES

- [1] Andrew C. Kadak, “A future for nuclear energy: pebble bed reactors”, *Int. J. Critical Infrastructures*, Vol. 1, No. 4, 2005.
- [2] J.J. Powers and B.D. Wirth, “A Review of TRISO Fuel Performance Models,” *Journal of Nuclear Materials*, 405 (2010): 74-82.
- [3] Urban Cleve, “Die Technik der Hochtemperaturreaktoren - Konstruktion - Bau - Inbetriebnahme – Betrieb des AVR Jülich und des THTR-300”, *International Journal for Nuclear Power – Vol. 54,-2009 - Heft 12*.
- [4] P. C. Durst, D. Beddingfield et al, “Nuclear Safeguards Considerations for the Pebble Bed Modular Reactor - Idaho National Laboratory”, INL/EXT-09-16782. (2009)
- [5] C. W. Forsberg and D. L. Moses, “Safeguards Challenges for Pebble-Bed Reactors Designed by People’s Republic of China”, Oak Ridge National Laboratory, ORNL/TM-2008/229, (2008)
- [6] P. C. Durst, “Safeguards-by-Design Guidance for High Temperature Gas Reactors (HTGRs) With Pebble Fuel” – NIS Office of Nuclear Sefeguards and Security (NGSI-SBD-004). (2012)
- [7] Zuoyi Zhang, Zongxin Wu, Yuliang Sun, Fu Li, “Design aspects of the Chinese modular high-temperature gas-cooled reactor HTR-PM”, *Nuclear Engineering and Design* 236 (2006) 485-490.
- [8] Jingyu Zhng, Fu LI and Yuliang Sun, “Physical analysis of the Initial Core and Running-In Phase for pebble-Bed Reactor HTR-PM”, *Hindawi, Science and Technology of Nuclear Installations Volume 2017*, Article ID 8918424. <https://doi.org/10.1155/2017/8918424>