Capability of Indonesian Hot cell Towards Pebble Bed Post Irradiation Examination

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Abstract. Post irradiation examination is one of the requirements to obtain licensing of nuclear fuel, and the purpose of this activity is to represent the performance of nuclear fuel itself. Currently, Indonesia is developing the 10 MWth high-temperature reactor type with its fuel in the form of pebble bed. Indonesia has a hot cell installation that has a function to do post-irradiated examinations. This hot cell mainly used for plate and rod type fuel. This paper wants to show this installation capability to perform the post-irradiation examinations based on its documents and current status. We also show the future possibility of performing pebble bed post-irradiation examinations. The hot cell installation in Indonesia, mainly divided into two areas. First areas are to perform the examinations in the intact form of fuel and second areas are to perform in the small specimen of fuel. For the future pebble bed examinations, Indonesian hot cell structure is possible to perform these examinations. These examinations are possible with limiting amount and stay time of fuel inside the hot cell. The current status gap with requirements for pebble bed tests such as handling tool, deconsolidation apparatus, simulation accident test apparatus also is described.

1. Introduction
Indonesia is developing an Experimental Power Reactor (RDE) 10 MWth, which is a type of high-temperature reactor (HTR) [1]. This reactor should generate equal to 3 MWe [2]. Design of this reactor will be operated at 700 ºC [3], higher than commercial reactor that operated at 320 ºC. Research on coated particle already starts since the 1950s in the United States and Europe for High-Temperature Gas-cooled Reactor (HTGR) program [4]. The reactor designs for HTR based on their fuel are the pebble bed reactor and prismatic-block gas-cooled reactor. Indonesian RDE's design will use pebble bed fuel. The pebble bed fuel consists of the coated particles that disperse in the graphite pebble. For future self-sustainability of RDE's fuel, a research program in Indonesia, in this case, is BATAN massively started since 2014. This research program, necessary to irradiation program and post-irradiation examination (PIE), also arises. Indonesia has a facility to do PIE, that takes place on Radio-metallurgy Installation (RMI). The RMI facility contains hot cell to perform the PIE on nuclear fuel and its structural components. In this paper, the RMI hot cell's readiness and the gap will describe.

2. RMI hot cell facility overview
RMI is one facility under the Center for Nuclear Fuel Technology (CNFT/PTBBN) management in BATAN. This facility was built in 1991 and commissioning in 1992 from German Consortium Nuclear Facility (GCNF). The layout of the RMI laboratory showed in Figure 1.
Figure 1 showed the layout of the laboratory and the hot cell in RMI. The hot cell itself denoted by number 101, 102, 103 through 112. Each cell consists of two manipulators and Pb glass window/s. Equipment’s and task to be done in a cell is very specific. Mainly, the hot cell structure type distinguishes into two sections. The first section is the structure of the cells made by high-density concrete. These cells denote by 101, 102 and 103. The concrete density is 3.6 g/cm³, with a thickness of 110 cm. The second section is the structure of the cells made by steel, and these cells denote by 104 through 112. The steel cells density is 7.8 g/cm³ with thickness 70 cm. Each cell capability describes as follows:

2.1. Hot cell 101
Design of the cell 101 structure is high-density concrete that purposes for radiation shielding. This cell meant to be receiving cell for irradiated fuel, in the cell equipped by fuel element rack for plate type and welding machine. Inside of this hot cell showed in Figure 2.

![Figure 2](image)

(a) Receiving cell 101 and (b) It is the supporting system.

2.2. Hot cell 102
Cell 102 as showed in Figure 3, designed for dismantling and a visual inspection of the fuel element. Beside two manipulators, also equipped by power manipulator in order to handling material with high load. This power manipulator can move to cell 103 vice versa. Equipment in this cell is dismantling machine fuel element for plate type and cutting machine for fuel rod. Outside the hot cell, there is a periscope to enlarge the view inside the cell. At present, equipment for dismantling machine is changed into cutting machine for single fuel plate. Another task in this cell is waste extracting to the outside of the hot cell through Drum Lifting Device (DLD) to ZG 001 at -5.50 m. This DLD system recently repaired.
Figure 3. (a) Cell 102 and (b) ZG 001 Drum Lifting Device system.

2.3. Hot cell 103
Cell 103 designed for physical test for fuel plate or fuel rod. This cell showed in Figure 4. In this cell, physical tests are Gamma spectrometer, X-ray radiography, leak test device, laser puncturing for gas sampling, fuel rod welding, and measurement bench. Inside the cell 103 as shown in Figure 4, the ultrasonic test (UT), and X-Ray radiography are available.

Figure 4. Equipment’s in cell 103 (a) Gamma spectrometer; (b) Ultrasonic test; and (c) X-ray radiography.

2.4. Hot cell 104 through 107
Cell 104 through Cell 107 designed to conduct the metallography process until observation in the optical microscope. The cell 104 equipped with a small cutting machine, grinder, ultrasonic cleaner and vacuum impregnation. Inside the cell 105 equipped with grinder and polisher. For, the cell 106 equipped with by the polisher, ultrasonic cleaner, electrolytic etching and desiccator. Each of these cells also is equipped by storage rack for the specimen. At present, these cells are well operated. Cell 107 equipped with by optical microscope and also designed for microhardness. At present this microhardness still in the under repair.

2.5. Hot cell 108 and 109
Cell 108 and cell 109 are showed in Figure 6. These cells are designed for chemistry analysis. Cell 108 designed for physical chemistry equipped with analytical balance, desiccator, thermography metric furnace, and deposition plate. For cell 109 designed for wet chemistry analysis, it equipped with support plate thermostat, rabbit station, and laboratory balance. The rabbit station is designed for transfers sample into a glove box in the laboratory area R.135.
2.6. Hot cell 110 and 111
The mechanical test carried out inside the cell 110 and cell 110 as showed in Figure 7. Cell 110 equipped with Low Cycle Fatigue (LCF) machine, tensile creep machine, burst test machine and annealing furnace. At present, cell 110 not fully used. The cell 111 are equipped with the tensile machine, impact test machine, macrohardness tester and blister test equipment. At present, the macrohardness and tensile test are actively for aluminum cladding testing irradiated in G.A Siwabessy Reactor.

2.7. Hot cell 112
Cell 112 designed for SEM/TEM Specimen preparation showed in Figure 8. This cell equipped with microhardness Vickers test machine, sputtering device, ultrasonic cleaner and storage rack.

Fuel element inside the hot cell is transferred from cell 101 to 102 using transport carriage (rolled conveyor) and from 102 to 103 using transport trolley vice versa. For specimen transfer to the steel-cell is using conveyor line. Conveyor line II (two) serve the specimen transfer from cell 103 through cell 107. For specimen transfer from cell 107 through cell 112 is using conveyor line I (one).
3. RMI post irradiation examination program

During all this time, IRM hot cells’ activities were conduct PIE of U3O8-Al, U3Si2-Al fuel plate type and pin dummy of PWR fuel. Another activity was the development of LEU foil target for Molybdenum-99 production during the period 1995 until 2009. Activity for PIE fuel plate in RMI showed as follows in Figure 9.

Figure 7. (a) One of the test equipment in cell 110, creep test apparatus, and (b) macrohardness, tensile test and blister test apparatus in cell 111.

Figure 8. (a) Sputtering device, and (b) microhardness test machine, inside cell 112.

Figure 9. Flows of PIE activity for fuel plate in RMI.
The irradiated fuel plate received at cell 101. The irradiated fuel plate could be transferred from the reactor using transfer cask/container or through transfer channel connected to the G.A Siwabessy reactor. The first step of the examination is the non-destructive test. This test is about visual inspection, dimension measurement and the gamma scanning. A sampling of specimens was chosen based on the standard position of sampling at the top, middle and bottom positions. It is also chosen at the place where the anomalies occurred. The specimen's destructive test then continued to start from metallography and ceramography, O/U ratio, fissile product analysis, burn-up analysis, and fissile product into cladding analysis. All of this data, collected as PIE data of nuclear fuel plate, was analyzed as feedback for quality improvement in the production process and used for feasibility analysis of nuclear fuel for use in the reactor. All of the radioactive waste produced in RMI was not stored permanently in RMI. These radioactive wastes sent to the Center for Radioactive Waste Technology (CRWT/PTLR).

4. Pebble bed post irradiation examination in RMI

The pebble bed fuel to do the examination shows several differences in examination process due to different dimension and material characteristic of fuel. Learn from the US, Europe (especially Germany), Japan and China. There are several examinations which should be done as follows [5,6].

Dimension measurement is needed to examine the dimensional comparison changes before and after irradiation such as measurement for diameter fuel sphere and measurement sphericity of pebble bed. From these two measurements can get supporting data about quality control for the fabrication process [7]. This measurement was chosen based on the structure of the hot cell own by RMI. The dimension measurement tools will be placed in hot cell 102, as hot cell after the reception so only large-scale measurement can be performed.

The visual inspection is the standard of inspection with the non-destructive testing method. It is the process of looking over a piece of equipment using the naked eye or with help from an optical tool to look for flaws. Visual inspection for pebble bed will be conducted in hot cell 102, and the operator takes a look from the operating area through glass lead hot cell.

Weighting measurement used to weight the sample in this case pebble bed. The results of this weighing will be useful for calculating burn-up from fuel. It can be done both at hot cell 102 after dismantling the fuel for a destructive test or being done at metallographic and physicochemical.

X-ray radiography test is useful for examining the material’s structure and quality with a non-destructive test using x-rays radiographic sources. Examination on structure and quality material of pebble bed is to determine whether there is an effect of radiation in the reactor for determining the reliability of pebble bed. The most important observation on pebble beds using x-ray radiography is to determine the thickness consistency of each layer of pebble bed and irradiation behavior the pebble bed, and it is Tristructural Isotropic (TRISO) particle [8-10].

Gamma analyzer used to analyze radioactive substances that emit gamma radiation. One of the tools that can be used is gamma spectroscopy to analyze it. Reactor fuel, in this case, is the pebble bed that has been irradiated in the reactor will experience a chain fission reaction, after being irradiated there is a split product from fission reaction which is then analyzed by gamma analyzer for being scanning to an obtained indicator of burn-up distribution.

Deconsolidation is the process of separating loose particle from pebble bed, in other words, to separate the kernel from the graphite matrix. This process is needed in post-irradiation testing. Graphite particles separated from the kernel can be tested for analysis of burn-up factors and kernel can be moved for further testing after non-destructive testing.

Ceramography is the science of ceramics microstructure preparation, examination and evaluation. This technique is one of the methods used in destructive testing after going through non-destructive testing in the previous tests, where when the non-destructive test is carried out to determine the location of the sample points indicates as defect then it will be further proven by ceramography testing. Ceramography testing is an observation of microstructures such as grain size, secondary phase, grain boundaries, pores, micro-cracks, and microhardness. Ceramography is usually reserved for high-performance ceramic materials, so selecting ceramography techniques for testing damaging pebble beds can be used more optimally.
Microstructure analysis is carried out to compare the pebble bed’s microstructure from the irradiation with the pre-irradiation. Using a microstructure lens with bigger magnification to analyze it by comparing the microstructure results from pre-irradiation to post-irradiation material [11]. From this microstructure, analysis treatment can later be known if defects occur due to the irradiation process and can be known phases formed from the irradiation process.

The accident simulation test is a series of simulation tests to determine the condition of pebble bed when it is on abnormal condition. An abnormal condition referred to here is by conducting high temperature to pebble bed. After pebble bed is irradiated up to 7th phase, then an accident test will be conducted to determine the effect on the pebble bed when given a high temperature.

These nine examinations are seeming mandatory to obtain minimum PIE data. Not limited to these examinations, many tests should be done in order to obtain comprehensive PIE data. For the future PIE program in RMI based on the existing facility, we do the conceptual design for its needed. The examinations for pebble bed fuel based on existing facility described in Figure 10.

The gap on equipment that should be conducted for PIE on pebble bed with currently existing equipment’s described as follows.

Capsule for irradiating the pebble bed in the reactor serves as a fuel test container to be irradiated in the reactor. Making a new capsule as a container for pebble bed samples must be done to be irradiated in the reactor. The capsule itself is designed according to the character and dimensions of the sample pebble bed. The new design may be required to make changes to the existing capsule, which is the pin's fuel test capsule. It can use the same material that ever existed because it was proven to accommodate the fuel test type pin when irradiation takes place. The new design has to be done because the reactor itself has provided a Power Ramp Test Facility (PRFT). PRTF is an experimental facility outside the reactor core used for testing fuel power reactor.

The transfer cask for pebble bed and waste container are different from current existing. The existing transfer cask and waste container are used for fuel power reactor and MTR type. Transfer cask serves to move pebble bed that has been irradiated at the reactor to the RMI for post-irradiation testing. Removal of pebble bed from the reactor through transfer channel underground connected to hot cell 101 from RSG-GAS. New transfer cask needs to be made according to the pebble bed capsule and easy to handle using manipulators and handling during transfer through transfer channel.

The waste container is used for storage of spent fuel pebble bed or after sampling. The waste container must be made comfortable in handling by manipulator from the operating area. It can be made according to the dimension of the pebble bed. The waste container must be made so that it can reduce radiation exposure so that the remaining sample pebble bed from the test can be stored in temporary waste storage.

Manipulator clamp should be modified to suitable with pebble bed fuel, where the physical shape of pebble bed resembles a ball with diameter 6 cm, so suitable handling tools are needed. The existing manipulator clamps not suitable for it, because the clamp is flat. Therefore, it should be modified into a suitable clamp for handling the pebble bed. The clamp itself must be modified into concave shape so it can grip pebble bed tightly.

The handling tool for pebble bed fuel and coated particle should be specially designed. To handle pebble bed, especially for a coated particle, the dimension much smaller than the pebble bed and it is really hard to handle with manipulator clamp. Modification is done by adding a new tool that looks like a needle and its function to gather the coated particle using a pneumatic system. Tools that look like a needle used because it has a tiny hole in the edge. Furthermore, when the pneumatic system is on, it can suck the coated particle to stick in the edge of the needle to move easily.

Transfer container for pebble bed and coated particle should be specially designed. Transfer container for pebble bed and coated particle is needed to accommodate transfer between hot cells. The design should be unique, which means it must efficiently operate using a manipulator from the operating area. Including the cover can easily be opened-closed and there is a handgrip so a manipulator can easily move it.

Design of an apparatus for deconsolidation pebble bed is to obtain loose particle from pebble bed for further analysis and determine the distribution of solid fission and activation products in the matrix graphite. In other words, it can separate the kernel from the matrix graphite, and then the kernel can be
moved to another test while the matrix graphite can be used to analyze fission and activation product from irradiation process. An apparatus for deconsolidation will be placed in the hot cell 102, dismantling the fuel cells. Therefore, it must be designed according to the dimension of space in hot cell 102.

Design an apparatus for accident simulation test used to analyze when pebble bed simulated under abnormal conditions. This tool will be placed in hot cell 103, which is used for non-destructive testing. The accident simulation test is non-destructive because pebble bed, which has been irradiated until the seventh order, will be taken and transferred to RMI and put in this device. Accident simulation test that will be to conduct, such as high-temperature effect, aims to get data about the effect of a pebble bed under operated in the abnormal situation. Nevertheless, because it will place inside the hot cell 103, it needs to be designed to fit the space.

![Figure 10. PIE route for pebble bed fuel PIE in RMI.](image)

5. Final remarks
PIE for pebble bed is a big challenge for RMI. Preliminary information for the hot cell structure as primary radioactive shielding has met the criterion to confine and containment the pebble bed fuel. There is so much equipment to fulfill minimum PIE data used as feedback to nuclear fuel fabricator. In 2018 and 2019, RMI has been designing an additional apparatus for gripping TRISO and pebble bed, the container for transfer and used the existing X-ray radiograph to simulate non-destructive test for pebble bed fuel.

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References
[1] Taswanda T Ridwan Geni R S Meniek R 2018 The Strategy to Support HTGR fuels for the 10 MW Indonesia’s Experimental Power Reactor (RDE). Urania Jurnal Ilmiah Daur bahan bakar Nuklir 24(1) pp 1-16.
[2] Helmi F R et al 2018 Analysis of Irradiated Pebble Bed Fuel Transfer System in Hot Cell 101 Radiometallurgy Installation. SENTEN 2018 Palembang
[3] Maman K A et al 2018 Analisis Kesiapan Sistem Handling Fasilitas Hotcell 104 – 107 Instalasi Radiometalurgi Untuk Uji Pasca Irradiasi Bahan Bakar Reaktor Daya Eksperimental. SENTEN 2018 Palembang
[4] Konings R 2011 Comprehensive nuclear materials. Elsevier
[5] Sawa K et al 2001 Integrity confirmation tests and post-irradiation test plan of the HTTR first-loading fuel. Journal of nuclear science and technology 38(6) pp 403-410
[6] Taowei Wang, H.Z., Gang Xu, Xiaotong Chen, Bing Liu, Chunhe Tang. New Hot Cell Laboratory and Post Irradiation Examination Research Project on HTR Spherical Fuel Element in INET. in Hot Lab Conference. 2016. Karlsruhe, Germany.

[7] Maurits C R H Sander G Jan A V 2017 Comparison of Irradiation Behaviour of HTR Graphite Grades. Journal of Nuclear Materials. 492: p. 148-156. 2017.

[8] Sri Ismarwanti et al 2020 Performance Analysis of Digital X-Ray Radiography System in Radiometallurgy Installations for Pebble Bed Fuel Imaging IOP Conf. Series: Journal of Physics 1436 012131

[9] Dong L Steven K Jon E Harold B Mark D Jan A V Robert O 2020 R, X-ray Tomography Study on The Crushing Strength and Irradiation Behavior of Dedicated Tristructural Isotropic Nuclear Fuel Particles At 1000 °C Material and Design 87 108382

[10] Lowe T et al 2015 Microstructural analysis of TRISO particles using multi-scale X-ray computed tomography Journal of Nuclear Materials 461 pp 29-36

[11] Ploger S A et al 2004 Microscopic analysis of irradiated AGR-1 coated particle fuel compacts Nuclear Engineering and Design, 271 pp 221-230