MUF Calculation of Indonesian 10-MWt RDE Experimental HTGR Using Combined Uncertainty Approach

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Abstract – A safeguards assessment for the 10-MWt RDE Experimental HTGR needs to be established in order to fulfill the requirements needed to construct it. Methods and instruments used for the RDE’s nuclear material accounting and safeguards system are reviewed in this paper. Material unaccounted for (MUF) is calculated using the uncertainty of each method and instrument. The effectiveness of the safeguards system is examined by comparing the resulting MUF with the number of SQ (= significant quantity, i.e. the approximate amount of nuclear material for which the possibility of manufacturing of a nuclear explosive device cannot be excluded). The total uncertainty from each KMP showed a number less than 10%. The number of MUF in each KMP according to total uncertainty showed a number below 1 kg of U-235 in one inventory period (~12 months). According to the number of MUF counted, it is impossible to reach 1 SQ if the diversion done is only by taking the advantage of MUF in the measurement. The result of total uncertainty and MUF calculation showed that the safeguards system and the material measurement designed for RDE is amendable. The sets of instruments and measurements designed will give a comprehensive data of each nuclear material in the RDE. The low number of MUF in comparison with the SQ showed that the RDE has a high proliferation resistance.

1. Introduction
BATAN has designed a 10-MWt high-temperature gas-cooled reactor (HTGR) named RDE. The reactor was planned to be built in its Serpong Nuclear Research Complex in Tangerang Selatan, Indonesia. A site permit has been issued by the national regulatory body, and to facilitate the issuance of a construction permit, a basic safeguards system for the reactor had been designed in 2016 and 2017 to complement the detailed engineering design. A detailed DIQ from the IAEA and a construction permit from Indonesian Nuclear Regulatory Agency (BAPETEN) are needed for RDE to begin its construction. RDE safeguards system amenability, including methods and instruments used, needs to be confirmed in order to complete the final design of RDE [1, 2].

The RDE will have 10-MWt of power with 27,000 TRISO-pebbles in the reactor. The reactor fuel is capable in both once-through-then-out (OTTO) cycle and multipass system [3]. A pebble-bed type HTGR uses pebbles with the diameter of 6 cm. The small size of the fuel and large number of pebbles in one reactor makes HTGR resembles a bulk handling facility rather than an item facility. The bulk characteristic of the nuclear material is present both in fuel storage and inside the reactor. The pebbles will have a bulk flow when each pebble is taken from the bottom of the reactor [4].
The pebble-bed type HTGR that uses fuel recycle system will utilize neutron economy and fuel burnup (reduced leakage) [5]. The recycle system will introduce partly burned fuel into the reactor that keeps the criticality in a steady level. The mixed state of pebble fuels makes a unique identification hard to be implemented on each pebble.

1.1. Key Measurement Points (KMPs) and RDE Safeguards System

![Figure 1. Key Measurement Points of RDE; KMP A: Fresh Fuel Storage; KMP B: Reactor; KMP C: Damaged Fuel Storage; KMP D: Spent Fuel Storage; 1: Receiver KMP; 2: Shipper KMP; 3 & 4: Flow Monitors [6]](image)

The bulk characteristic of RDE will make a diversion of nuclear material possible. The diversion of nuclear material can be done in the fresh fuel and spent or broken fuel storage. The pebble diversion problem addresses a safeguards-by-design to be implemented in the facility. A safeguards system for RDE is designed to control and supervise nuclear material in every sector of the RDE. There are four key measurement points (KMPs) located inside the RDE. Figure 1 shows each KMP in RDE along with the function and measurements that takes place inside the KMP.

KMP A will have fresh fuel stored. The storage of fresh fuel is filled with pebbles that each contains 5 g uranium with 17% enrichment [6]. The bulk characteristic of each pebble in the storage will limit unique identification of each pebble. All unidentified items (including fuel pebbles) can be an easy target for diversion [7]. HTGR reactor core uses semi-automatic recycling system that reduces human interaction with nuclear material. The flow of pebbles inside the recycling system is in linear state. The linear flow of pebbles makes it possible to use gamma multi-channel analyzer with a short measurement time. KMPs C and D have the same characteristic. Spent fuel pebbles will be stored in the storage cask. The cask is stored in a dry storage facility. Unique identification will be implanted on each cask.

1.2. Method and Instrument in RDE Safeguards System

The methods and instruments that will be in the safeguards system have the goal to give the same knowledge of nuclear material mass and other information. The knowledge is important for both operator and inspector related to safeguards activity. Each KMP in RDE have their own characteristic and unique method to measure nuclear material.

Fresh fuel storage in KMP A has uranium-235 which emits gamma radiation. The bulk characteristic of KMP A drives the measurement to use a sampling method. Some number of samples will be taken to do the measurement of uranium-235 concentration and material weight (i.e., pebble weight). The uranium-235 measurement will be done by using miniature multichannel
analyzer with NaI(Tl) detector. The measurement will take 300 seconds for each pebble. The activity of measuring uranium-235 concentration depends on the calculation of radiation counted in the specific gamma energy of uranium-235. Uranium-235 emits gamma radiation with energy ranged from 143.8 keV to 205.3 keV with total probability of 78.07% and highest probability 57.2% in the energy 185.7 keV. Measurement of uranium-235 concentration needs a high efficiency detector to capture uranium gamma radiation due to the gamma energy falls in the region of noise radiation that can also be captured by the detector. A scintillation NaI(Tl) detector has a high efficiency which enables isotope identification and attribute verification of uranium, plutonium, thorium, and americium isotopes [8].

Burn-up analysis in fuel handling system coupled with the reactor will be done using NaI(Tl) multichannel analyzer. The use of NaI(Tl) detector is chosen because of the high efficiency and simple detector construction. The simple construction of NaI(Tl) detector makes customization of detection system easier to do. The NaI(Tl) detector will be coupled with burn-up calculation program.

Damaged and spent fuels in KMPs C and D have the same characteristic. Both fuels will be stored in the storage cask. Measurement of material weight will be done using load-cell-based weighing system (LCBS), measurement of isotopes concentration will be done using NDA with neutron counting for plutonium and gamma spectrometry for uranium. LCBS will count the weight of a bulk material inside a medium by comparing the cord’s stress signal given by the load cell (reference weight) and signal given by the cask containing bulk material (measured weight). The uncertainty of LCBS comes from the environment and the weighing system. The sample cask will be hanged to measure the overall (bulk) weight of sample inside the container. Wind and atmosphere conditions are a natural cause that contributes to LCBS measurement due to the hanging position of sample [9]. The systemic parameter is hysteresis of the system and linearity of the cord that accommodates the sample cask.

Neutron multiplicity counter is also used in KMPs C and D. Neutron counter will measure total plutonium mass appeared within the sample. Total plutonium mass will be measured by measuring number of neutrons produced by plutonium in spontaneous fission. The spontaneous fission will produce high energy neutrons that will be measured using plutonium-scrap multiplication counter (PSMC). A neutron multiplication counter will count neutrons from single, double, and high order coincidence events simultaneously while coincidence counter only count single and double neutron events [10]. The PSMC has a better performance in measuring the total mass of plutonium in a dirty sample (high impurity) compared with coincidence neutron counter [10, 11].

Spent fuel in KMP D needs to be analyzed comprehensively. The plutonium in spent fuel can give so many information about the characteristic and material attractiveness of the spent fuel. The composition of plutonium-238 to total plutonium in weight percentage can give information about heat generated from each fuel. The isotopic composition of plutonium-239 to total plutonium weight percentage can determine the attractiveness of spent fuel that can determine proliferation resistance of the facility. The composition of plutonium-240 and plutonium-242 to total plutonium in weight percentage can determine number of spontaneous neutrons expected to be measured per period of time. A detailed isotopic composition of plutonium is also needed to count total plutonium weight in bulk sample before the measurement with PSMC takes place [12]. The isotopic composition of plutonium can be measured with gamma spectrometry multi-channel analyzer. The detector used in measurement of isotopic composition must have high resolution in order to produce better spectrum that can distinguish each isotope correctly [13]. High-purity germanium (HPGe) detector is used for its performance in producing high resolution spectra. The measurement will be done to the storage cask filled with spent fuel pebble. Each isotopic composition will be used to count total mass of plutonium-239 that will be reported for safeguards purpose.
1.3. Measurement Uncertainty and Safeguards System Amenability

Safeguards are a set of technical measures that are established in a nuclear facility to verify a state’s legal obligation that nuclear facilities will only be used for peaceful purposes and will not be diverted. One of the important parameters to verify the amenability of safeguards system is the ability to derive material that cannot be accounted in a facility. The derivation of “material unaccounted for” (MUF) can be done by determining a statistical limit error for each measurement and combined uncertainty in the facility [14,15].

An item facility such as an LWR reactor is normally expected to have almost zero MUF due to the characteristic of the nuclear material that can be exactly known for each item. A high-temperature gas-cooled reactor is a type of reactor that resembles a bulk-handling facility rather than an item facility. The lowest expected MUF in an HTGR is equal to total uncertainty in the facility [16]. The calculated MUF can give a number of nuclear materials that have the possibilities to be diverted.

2. Description of the Actual Work

2.1. Parameters in Uncertainty Calculation

The uncertainty of each instrument can be counted using two indicators random error (U_r) and systemic error (U_s). Random error (U_r) is a divergence of measurement value that is obtained with the same method and instrument used to measure identical item. Random error characteristic is when value of measurement varies in an unexpected manner in repeatable conditions. Systemic error (U_s) is a variance in measurement resulted due to the inability of a system or instrument to measure the actual value, for example the difference of efficiency of HPGe detector and NaI(Tl) detector. Random error and systemic error are both present in each measurement done and must be calculated in the determination of combined uncertainties [17, 18]. The combined uncertainty of a key measurement point using number of instruments can be counted using equations (1) to (3) below.

\[
U_c(r) = \sqrt{\frac{\sum_{i} U_i^2(r)}{n_i}} 
\]

\[
U_c(s) = \sqrt{\sum_{i} U_i^2(s)} 
\]

\[
U_c = \sqrt{U_c^2(r) + U_c^2(s)} 
\]

The combined uncertainty calculated from random error is shown by equation (3) symbolized as U_c(r). The combined random error uncertainty is counted by dividing random error known for each measurement (U_i(r)) with the number of sample or repetition done in the measurement (n_i). The division must be done because random error is affected by the number of repetitions taken to determine the true value of measurement. On the other hand, combined uncertainty from systematic error is counted by adding each value of error and does not have to be divided by the number of sample nor the repetition of measurement. The total combined uncertainty (U_c) is the number that shows how big the divergence of value can be produced by series of measurement in one system, for this case in one KMP.

The value of U_r and U_s of each instrument used for combined uncertainty calculation is taken from International Target Values (ITV) 2010 for measurement uncertainties in safeguarding nuclear material [17]. The value of each error shown in ITV document can be used to calculate and estimate the value of combined uncertainty of a safeguard design when no other reliable performance values available. Every error value will then be calculated using equations (1) to (3) above.
2.2. MUF Calculation Using Total Uncertainty

The value of “material unaccounted for” (MUF) can be determined using the value of combined uncertainty (\(U_c\)) [19]. Value of MUF can be counted by multiplying the combined uncertainty (\(U_c\)) with number of pebbles in a period of time. The period of time used in calculation can be one inventory period ranged about 12 months. The value of MUF can also be determined in unit of uranium mass or uranium-235 mass by further multiplying the MUF in number of pebbles with the data of uranium mass in a pebble and isotopic composition of uranium-235 in each pebble. The calculation of each MUF is shown in equation (4) for MUF in number of pebbles, equation (5) for MUF in uranium weight, and equation (6) for MUF in uranium-235 weight. The information of MUF shown in uranium-235 mass can be used to determine the number percentage of MUF to uranium significant quantity (SQ) and to calculate the time needed to reach 1 SQ by diverting nuclear material as much as the MUF in each period. The SQ for uranium used is SQ for low-enriched uranium, the value is 75 kg of uranium-235.

\[
MUF_{\text{pebble}} = U_c \times \text{number of pebbles in KMP}
\]

\[
MUF_{\text{total}} = MUF_{\text{pebble}} \times \text{mass of uranium in pebble}
\]

\[
MUF_{\text{fissile}} = MUF_{\text{total}} \times \%\text{fissile material}
\]

\[
\%\text{SQ} = \frac{MUF_{\text{fissile}}}{SQ_{\text{fissile}}}
\]

3. Results

3.1. Combined Uncertainty of Each KMP

The calculation of combined uncertainty was done using the data of each step, method, and instrument taken from IAEA ITV 2010. The data is distinguished by steps or parameters measured. \(n_i\) is the number of samples taken or measurement repeated, \(U^2(r)\) and \(U^2(s)\) are parameter used to count combined uncertainty. The complete data are shown in Table 1.

**Uncertainty in KMP A:** KMP A has two parameters measured, the weight of nuclear material and the concentration of uranium-235. Every measurement in KMP A was done by sampling pebbles in KMP A. The samples taken are 10 pebbles for both weight measurement and uranium-235 concentration. The sampling must be done because pebbles in KMP A have the characteristic of bulk material due to unavailability of unique identity for each pebble. The sample needs to be taken for the measurement to represent the population of pebbles. The sampling step (activity of choosing sample for measurement) also contribute to combined uncertainty and have both random error and systemic error. The random error of sampling can appear due to the different properties such as weight or number of uranium contained in each pebble. Each pebble in KMP A has 5 grams uranium in the form of TRISO particle spread inside every space inside the pebble. A difference of uranium mass can always present but not in significant values, therefore contributing to both random and systemic error.

The weighing in KMP A will be done using electronic balance with random error and systemic error have been calculated for combined uncertainties. The uranium-235 concentration measurement will be done using miniature multi-channel analyzer with NaI(Tl) detector (MMCN). NaI(Tl) detector is chosen because the energy that needs to be measured is exactly known (185.4 keV). The fresh nuclear fuel in KMP A only has uranium as its dominant radiation emitter, so the energy spectrum will not have much noise except from the background and backscatter. The fresh pebble is classified as LEU pure material or the same as pellet as a pure and stable nuclear fuel. This classification of measured material gives the value of measurement random error value of 3 and measurement systemic error value of 2. The final result of combined uncertainty from KMP A is 2.215%, making it the lowest value of combined uncertainty compared to other KMPs.
Uncertainty in KMP B: KMP B is a reactor where the only measurement done is burn-up measurement. The pebble bed reactor has high temperature.

Table 1. Calculation of Combined Uncertainty

| KMP   | Measurement (Step) | Method/Instrument | ni | U_r  | U_s  | U_i²(r)/n_i | U_i²(s) |
|-------|-------------------|--------------------|----|------|------|-------------|---------|
| A     | Pebble Sampling   | EBAL               | 10 | 0.05 | 0.05 | 0.00025     | 0.0025  |
|       | Weight U-235     | MMCN (NaI(Tl))    | 10 | 0.05 | 0.05 | 0.00025     | 0.0025  |
|       | Concentration     |                    | 10 | 3    | 2    | 0.9         | 4       |
|       | Sum of Variance  |                    |    | 0.901| 4.01 |
|       | Combined Standard Uncertainties (U_(c)(r) and U_(c)(s)) | |    | 0.949| 2.001|
|       | Combined Uncertainties (%) | |    | 2.215|      |
| B     | MCA (burnup)      | MMCN (NaI(Tl))    | 1  | 15   | 5    | 225         | 25      |
|       | Sum of Variance  |                    |    | 225.000| 25.00 |
|       | Combined Standard Uncertainties (U_(c)(r) and U_(c)(s)) | |    | 15.000| 5.000 |
|       | Combined Uncertainties (%) | |    | 15.811|      |
| C     | Bulk Weight       | LCBS               | 1  | 0.05 | 0.05 | 0.00025     | 0.0025  |
|       | Total Pu Mass     | PSMC               | 1  | 5    | 1    | 25          | 1       |
|       | U-235 Conc        | IMCG               | 1  | 10   | 2    | 100         | 4       |
|       | Sum of Variance  |                    |    | 125.003| 5.003 |
|       | Combined Standard Uncertainties (U_(c)(r) and U_(c)(s)) | |    | 11.180| 2.237 |
|       | Combined Uncertainties (%) | |    | 11.402|      |
| D     | Bulk Weight       | LCBS               | 1  | 0.05 | 0.05 | 0.00025     | 0.0025  |
|       | Pu-238            | IMCG               | 1  | 1    | 2    | 1           | 4       |
|       | Pu-240            | IMCG               | 1  | 1    | 1    | 1           | 1       |
|       | Pu-241            | IMCG               | 1  | 1    | 1    | 1           | 1       |
|       | Total Pu Mass     | PSMC               | 1  | 5    | 1    | 25          | 1       |
|       | U-235 Conc        | IMCG               | 1  | 10   | 2    | 100         | 4       |
|       | Sum of Variance  |                    |    | 128.003| 11.003|
|       | Combined Standard Uncertainties (U_(c)(r) and U_(c)(s)) | |    | 11.314| 3.317 |
|       | Combined Uncertainties (%) | |    | 11.790|      |

According to design it can reach above 700°C in steady state operation condition. The high temperature and random distribution of pebbles inside the reactor make measurement hard to do. The burn-up measurement will be done in the fuel handling system of the pebbles. Each pebble will be measured one by one when they go through the fuel handling system. The burn-up measurement will measure isotopic composition of uranium-235 and other radionuclides such as cesium as the fission product. The isotopic composition will be used to calculate burn-up of each pebble by using...
burn-up calculation code. High resolution detector may be needed to distinguish each energy thoroughly, but to achieve the desired construction of detector coupled with burn-up calculation system.

Nuclear material in KMP B is classified as high impurity material because of other radionuclides produced in the fission process. The fission product will also emit gamma radiation that will interfere with each other increasing both random and systemic error. The value of random error is 15 and systemic error is 5, the combined uncertainty value in KMP B is 15.811%.

Uncertainty in KMP C: KMP C is a storage for damaged fuel from the reactor. The damaged fuel in KMP C have similar radioactivity as spent fuel. The damaged fuel pebble can range from low burn-up high burn-up because of the multipass system. The damaged fuel will send directly from fuel handling system to fuel storage cask without human interference. Every measurement will be done with damaged fuel located inside the cask.

The bulk weight measurement will be done using LCBS with random error and systemic error of 0.05. The systemic error from LCBS can come from the respond of load cell and the effect of hysteresis in the system [21]. Uranium concentration measurement along with determination of plutonium will be done using Inspector 2000 multichannel analyzer with HPGe detector (IMCG). High-purity germanium (HPGe) detector is selected because of its high resolution. Uranium-235 concentration measurement with IMCG have the random value of 10 and systemic error value of 2. High value of random error is present due to the characteristic of damaged fuel which also have a lot of radioactive impurities that will interfere with the measurement process. The determination of plutonium will then lead to plutonium total mass measurement using plutonium scrap multiplication counter (PSMC). The PSMC will determine total mass of plutonium in each case that can be divided by number of fuels inside each cask and give mass of plutonium in each pebble. The measurement of plutonium total mass has random error value of 5 and systemic error value of 1. The combined uncertainty in KMP C is 11.402%

Uncertainty in KMP D: KMP D is a storage for spent fuel that have reached maximum burn-up allowed in the reactor. The irradiation inside RDE reactor will reduce the uranium-235 enrichment from 17% to 3% or will reduce uranium-235 in each pebble as much as 0.7 g uranium-235 per pebble [5]. Uranium-235 concentration, bulk weight, and total plutonium mass will be measured once again in KMP D. Plutonium isotopic composition will be determined in this KMP. Isotopic composition of plutonium will be used to determine heat generation, material attractiveness, and neutron coincidence produced to support the calculation and determination of actual plutonium-239 mass in each spent fuel cask. The plutonium-239 mass is needed for detailed burn-up calculation and safeguards report.

KMP D have similar value of combined uncertainty but slightly higher. The measurement of isotopic composition not only help in calculating detailed mass of each plutonium isotopes but also increase combined uncertainty. The increased number of instruments used in KMP D affect the value of combined uncertainty in KMP D that give the result of 11.790%.

3.2. MUF to SQ Ratio of Indonesian 10-MWt RDE
Material unaccounted for (MUF) in RDE have been calculated according to the design of RDE pebble fuel, expected burn-up, and combined uncertainty of each KMP. Calculating MUF using the expected combined uncertainty need to be done using several assumptions due to unavailability of actual fuel and burn-up properties. The assumption and data in calculating MUF in RDE facility are as follows:

a. Every pebble in fresh fuel has the same amount of uranium and exact same enrichment;
b. The burn-up in KMP C is the same as burn-up in KMP D decreasing U-235 enrichment from 17% to 3%;
c. KMP C and KMP D have 0.15 gram of uranium-235 in spent fuel;
d. 20% of uranium in pebble turned into plutonium-239;
The SQ of low-enriched uranium (LEU) is 75 kg of uranium-235 and SQ of plutonium is 8 kg [20].

The complete data of MUF and MUF to SQ ratio calculation from each KMP are shown in Table 2.

KMP A has a possible MUF of 515.775g of uranium-235 in one inventory period. The small number of MUF expected makes the MUF to SQ ratio below 1%. The data shows that it is impossible to reach 1 SQ if the diversion done only by taking the advantage of MUF uncertainty. This calculation shows that the measurement instruments and methods are amendable.

KMP B has a possible MUF of 3682.013g of uranium-235 that accounts to 4.9% of LEU SQ. The number is far higher than MUF in KMP A. The different characteristic of each KMP contributes to the value of combined uncertainty making each KMP has different possible number of MUF. KMP A has the lowest number due to assumption that sample will represent all pebbles population while KMP B has larger uncertainty and larger MUF due to the assumption that irradiated fuel will increase radiation impurity that will interfere burn-up measurement. KMP B shows the highest number of MUF in fissile material because KMP B has the highest pebble inventory with a high combined uncertainty.

Table 2. MUF and MUF to SQ Ratio of Every KMP in RDE

| KMP | Total Uncertainty | Inventory (Pebble) | MUF (Pebble) | \(\text{MUF}_{\text{U, total}}\) (gram) | \(\text{MUF}_{\text{Pu, 235}}\) (gram) | \%SQ\textsubscript{U} | \%SQ\textsubscript{Pu} |
|-----|-------------------|--------------------|--------------|---------------------------------|---------------------------------|----------------|----------------|
| A   | 2.215%            | 27000              | 598          | 2990.000                        | 515.775                        | 0.000         | 0.688%         | 0.000%         |
| B   | 15.811%           | 27000              | 4269         | 21345.000                       | 3682.013                       | 0.000         | 4.909%         | 0.000%         |
| C   | 11.402%           | 2250               | 257          | 1285.000                        | 38.550                         | 0.051%        | 3.213%         |
| D   | 11.790%           | 9000               | 1061         | 5305.000                        | 159.150                        | 0.212%        | 13.263%        |

The overall results of MUF calculation show that the RDE has a total MUF possibility of uranium-235 as much as 4395.488 g and plutonium-239 as much as MUF 1318 g. Ratio of MUF to SQ for uranium-235 is 5.861% and for plutonium-239 is 16.475%. IAEA Innovative Nuclear Energy System Assessment in Proliferation Resistance [22] states that the ratio of a total MUF to SQ below 10% score very high in proliferation resistance and a total MUF to SQ ratio above 10% but below 50% score high in proliferation resistance. Table 2 shows that both uranium-235 and plutonium-239 have MUF to SQ ratio lower than 50% that confirms that the measurement used in RDE safeguards system is amendable and accountable.

4. Conclusions

“Material unaccounted for” (MUF) of Indonesian 10-MWt RDE has been calculated using combined uncertainty from IAEA International Target Value. KMP A show the lowest value of uncertainty because of the pebble characteristic in KMP A that contains LEU with low impurities making the measurement easier and has less interference. The reactor in KMP B has the highest uncertainty among all KMPs because the pebbles have more radioactive impurity that interfere with the measurement in KMP B. The biggest MUF to SQ ratio (%SQ) is in KMP D where spent fuels are stored. The total MUF to SQ ratio in RDE both for uranium and plutonium are below 50% which indicates strong proliferation resistance and amendable measurement system. The
improvement of RDE safeguards system might be needed in the spent fuel storage. The spent fuel storage needs strong containment and surveillance in order to prevent the possible diversion in KMP C and D that will add up to 16% MUF to SQ ratio.

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