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Investigation of the air to water conversion factor dependency to the spent fuel cooling time, irradiation history and burnup for gamma dose rate determination of TRR spent fuels

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HIGHLIGHTS

- Determination of gamma dose rate ratio in air to water helps the air gamma dose rate be estimated.
- The ratio has not any dependency to cooling time at special detector positions in air and water.
- The ratio has not any dependency to irradiation history at special detector positions.

ABSTRACT

Routine gamma dosimetry of spent fuels in nuclear power stations is mandatory to manage their storage in dry or wet spent fuel storages. Mostly the spent fuel gamma dose rate measurements out of the spent fuel pool is impossible because of the high exposures of the operators. Therefore, determination of a conversion factor as precise as possible is important that could be applied to convert the measured gamma dose rate inside the water shield to the air values. Simulation methods are powerfully applied to investigate the conversion factor variation trends due to different burnup, cooling time and irradiation history of the spent fuels. The present work uses MCNPX Monte Carlo-based code to determine the trend. The obtained results of this computational study showed that the conversion factor would not have any dependency to the cooling times, burnup values and irradiation history if the detector is placed at special positions in air or water environments. Comparison of the simulation and experimental data showed an acceptable conformity, so that the experimental verified the simulation data trend.

KEYWORDS

Gamma dose rate
Conversion factor of air to water
Computational calculations
ORIGEN code
MCNPX code

HISTORY

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1 Introduction

Nuclear technology as one of the powerful energy resources is being developed while it is an environmental-friendly energy because of its carbon free characteristic. At present era, nuclear installations are more customary than ever before. Therefore, with the rapid development and wide applications of nuclear technology, many new technologies have been emerging to guarantee its reliability and safety, where measuring devices and techniques that can exactly measure and monitor the nuclear installations show particular importance (Qiu-kuan et al., 2012).

A key component of safeguard protocols at storage area facilities of nuclear fuel is the verification of the gamma dose rates in intact spent fuel assemblies or storage casks. In cargo screening, for example, the primary goal is one of detection so that the collection of any induced-fission signature (delayed or prompt neutrons, delayed or prompt gamma rays, or some combination thereof) achieves the goal of alarming on anomalous vehicles or packages (Campbell et al., 2011).

Different gamma and neutron detectors are used to monitor a spent fuel assembly during transportation or storage in the spent fuel pools or storage casks.

Tightness and temperature of loaded casks placed in the storage are permanently controlled. Neutron survey meters and ionization chambers firmly installed on the walls of the storage building enable to determine trends of dosimetry quantities in dependence on number of loaded casks (Kralik et al., 2000).

Whereas the spent fuel gamma and neutron dosimetry is the most important section of the storage sites, many activities are done for precise data acquisition and documentation of the dose rates. For instance, in Swe-

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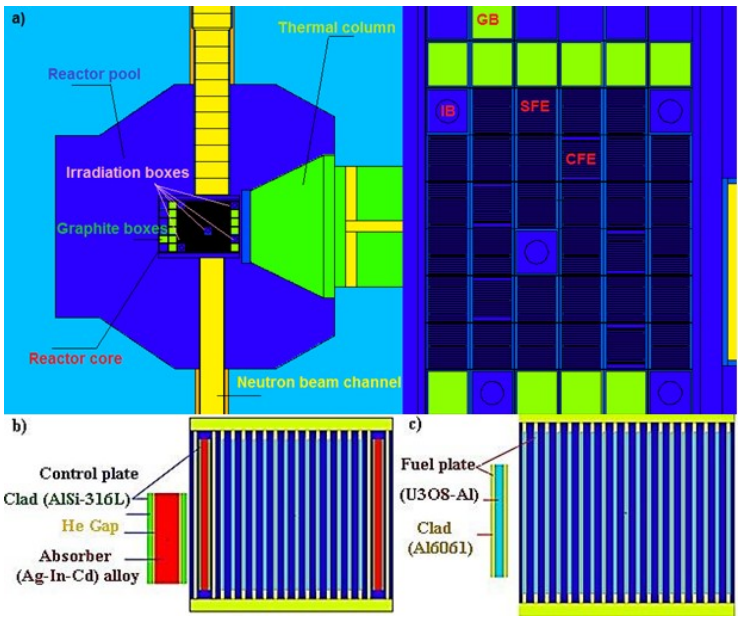

Figure 1: Cross sectional view of a) the modeled TRR core b) (SFE) c) (CFE).

den, a pilot gamma scanning system is being developed as part of the research and development program for the planned spent nuclear fuel encapsulation plant. For this system, a software package has been developed with modules for fast automatic repetition of spectrum acquisition and consecutive spectrum analysis. The software is also able to interact with a database of fuel information, including operator-declared data and measured data (Osifo, 2007).

Different nuclear detectors are used to measure gamma dose rates, which the most common detectors are ionization chambers. Application of different computational codes to model the spent fuel assemblies is useful to estimate the spent fuel gamma dose rates, avoiding the operator gamma ray exposures. Kryuchkov et al. (Kryuchkov et al., 2005) used the computer code packages of SCALE-4.3 and MCNP-4C to model a transport spent fuel container. They indicated that the comparison of the dose parameters obtained from different models of the transport container with experimental data allow to be made certain conclusions about the errors of numerical results caused by the approximate geometrical description of the transport container. Also Ko et al. (Ko et al., 2014) modeled the spent fuels during ten years of cooling using the SAS2H/OGIGEN-S module of the SCALE5 to calculate gamma dose rates of the spent fuels loaded inside a dry cask.

It is mandatory to benchmark the conformity of the computational codes with experimental data. Hence, some measurements of the spent fuels at different cooling times are carried out in nuclear sites. Measurement of gamma dose rate of a spent fuel assembly in the air is usually impossible because of the operator exposure or even the limited measurement range of a detector. Therefore, the measurements are carried out in the water and then are converted to the air values. The present work investigates the dependency of air to water gamma dose rate ratios (are called as conversion factor in this manuscript) to the cooling times, irradiation history and the burnup value of a spent fuel.

2 Material and methods

The TRR is an open pool, MTR type light water-moderated and cooled reactor with a thermal power of 5 MW. The TRR is operated under critical mode. The reactor core is composed of two types of fuel assembly: standard fuel elements (SFE) and control fuel elements (CFE). The first considered core (No. 83) consists of 28 SFEs containing 19 fuel plates and 5 CFEs containing 14 fuel plates. The core is fueled with 20% enriched U_3O_8-Al MTR fuels. The TRR core is cooled with the mass flow rate of 500 m^3h^{-1}. Two types of control rods are used in the TRR: one made of Ag-In-Cd alloy, and the other of stainless steel. Both have a set of two control plates as a fork type shape (Mirvakili et al., 2012). A schematic view of TRR core is shown in Fig. 1. MCNPX 2.6.0 code is used to calculate the fuel assembly dose rates in the air and water instead of lead cask (Pelowitz et al., 2013; Fensin, 2008). ENDF.VI library was used for the MCNPX calculations. A TRR fuel assembly was modeled using the MCNPX code (Fig. 2) and some proportional counter dosimeters were placed around the modeled fuel at different positions to calculate the gamma dose rate consequence of the spent fuel assembly. ORIGEN code was used to calculate the uranium oxide fuel assembly gamma emission rates on different burnup values and cooling times (NRC et al., 1997). Libraries of delayed gamma and No. 204, 205 and 206 containing neutron cross sections of light nuclides, fission products and minor actinides were used by the ORIGEN code input. The gamma source extracted from the ORIGEN code was used in MCNPX code input as a gamma source for the gamma dose rate calculations.

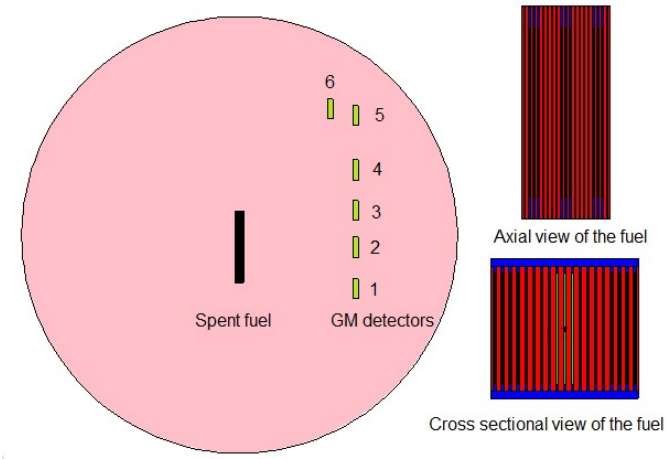

Figure 2: Cross sectional view of a TRR fuel assembly and Geiger Mller dosimeters around it.

TRR core involves 33 fuel assemblies which maximum received power of the fuel assemblies is 0.15 MW at 5 MW operational power of the research reactor. The value is used to calculate different burnups of the spent fuels using ORIGEN code.

To calculate the gamma dose rates, LB 1236 gamma dosimeter is used in TRR, which is a kind of proportional counter detectors (Berthold Technologies, 2020). Hence, the detector dimension (4.5×18 cm^2) was used in the computational simulations. To calculate the gamma dose rates, F4 tally of the MCNPX code was used and the DE/DF flux to dose conversion factors were applied to calculate the gamma dose rates in the detector volume. The gamma source spatial distribution in any dimension was considered as Gaussian function by means of -41 *a b* function card of MCNPX which the a factor is center of the distribution and the b factor is FWHM of the distribution. By experimental measurements of the axial gamma dose rates along a TRR spent fuel, the b factor was determined.

First, the spent fuel dose rates were calculated in the air at different cooling times for the highest burnup, which is 64%. The dose rates in air were calculated at 100 cm distance of the fuel surface. Then the gamma dose rates were calculated at the same distance in water environment. The obtained values were used to calculate air to water gamma dose rate ratios. The ratio is to be used as a conversion factor, because most of the candidate fuels have high gamma dose rate so that their dose rate measurement in the air is impossible in view of high exposure of the operators. Dependency of the air to water dose rate ratios or conversion factors to burnup, irradiation history and cooling times were investigated when the detector positions in the air and water are the same (100 cm than the fuel surface). The calculations were reported for detector No. 2 that is shown in Fig. 2 at the hottest point because the detector is located in front of the spent fuel middle. To obtain an optimum position for detector in air and water that could result in an approximately fixed ratio or conversion factor, it is mandatory the received gamma spectra in the detectors be analyzed. In TRR, the water measurements are carried out when the detector is placed at 20 cm interval than the fuel surface and the air measurements are carried out when the detector is placed at 100 cm than the spent fuel surface. Hence the gamma spectra received by the detector at 20 cm of water and the 100 cm of air were investigated for the different cooling times of a 64% burnup spent fuel. The conversion factor dependency to cooling time, irradiation history and the burnup values were investigated for the routine measurement arrangement in TRR (20 cm water, 100 air).

3 Results and discussion

3.1 Calculation of the conversion ratio at 100 cm air and water

First, the 64%-burnup spent fuel dose rates were calculated in the air and water environment separately at 100 cm distance of the fuel assembly surface. The conversion factor of air to water is presented in Fig. 3 for different cooling times up to 3 months. The figure investigates the conversion factor dependency to the spent fuel irradiation history. The investigation was carried out by considering two continuous or discontinuous irradiation procedures for obtaining 64% burnup, also in continuous mode, both 3 MW and 5 MW powers were investigated that means the fuel irradiation at 3 MW power by using longer irradiation times could obtain the 64% burnup than irradiation at 5 MW power. For the discontinuous option, the spent fuel experiences the alternatively irradiation and cooling times to obtain 64% burnup. The achieved results showed that the conversion factor is completely dependent to the irradiation history that means at any cooling time the irradiation history of the spent fuel should be clear so that measurement at water could obtain the gamma dose rate in 100 cm of air by using the conversion factor curve.

By increasing the cooling times, the gamma spectra is being softened and high-energy gamma sections are vanishing so for the remained low energy spectra, water is more absorber than air that causes the air to water gamma dose rate ratio is ascending.

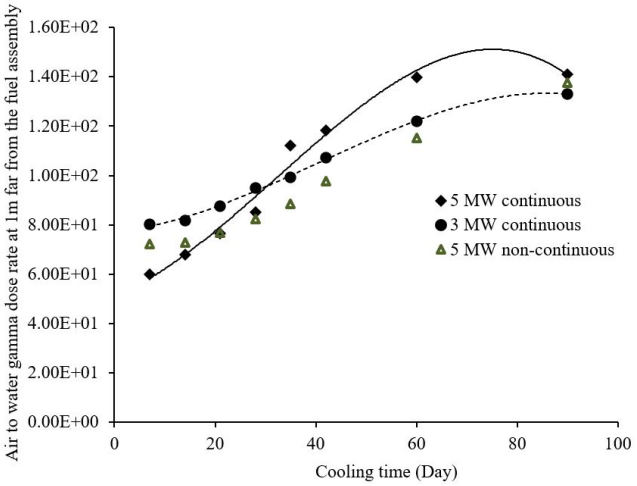

Figure 3: Investigation of the conversion factor dependency to the spent fuel irradiation history at low cooling times for 64%-burnup spent fuel.

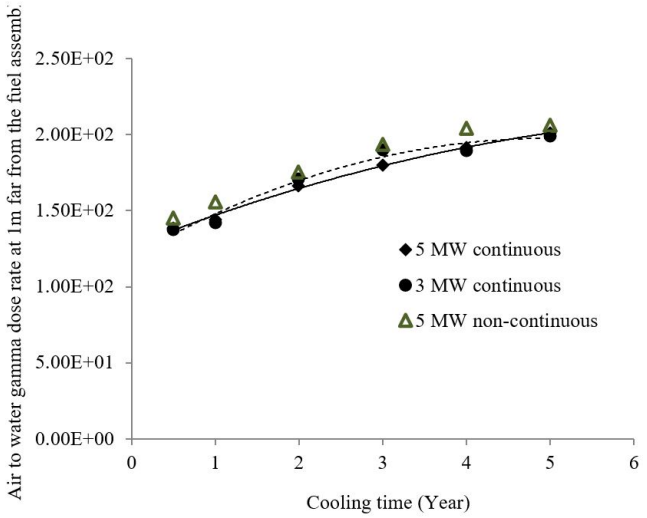

Figure 4: Investigation of the conversion factor dependency to the spent fuel irradiation history at long cooling times for 64%-burnup spent fuel.

The same investigation was carried out for long cooling times, more than 6 months. The obtained results showed that the conversion factor has less dependency to the irradiation history, but the cooling time of the spent fuel after its final irradiation should be clear. Therefore, by measuring the gamma dose rate and using the curve, the gamma dose rate at 100 cm of the air would be estimated (Fig. 4).

As it is seen in the figure 4, in long cooling times, the gamma spectra softening rate is slower so the ascending behavior of the air to water gamma dose rate ratio is less dependent to cooling times than the that of Fig. 3 (short cooling times).

3.2 Calculation of the gamma spectra received by detector at 100 cm air and 20 cm water

The gamma detector receives gamma spectra in water or air environments which every environment has itself attenuation coefficient for the emerged gamma spectra from the spent fuel. The following equation is used to investigate the detector position in the air and water environments:

$$\frac{I}{I_0} = \mathrm{e}^{-\mu x} \qquad (1)$$

where I is the gamma intensity at the detector position, I_0 is the gamma intensity at the fuel position, μ is the environment attenuation coefficient, and x is the environment thickness (distance) between the fuel and the detector.

It should be noticed that when I (the received intensity) at the detector position is approximately identical for the air and water environments at different cooling times, the conversion factor would be independent to the cooling time. If the average energy received by the detectors in air and water is different, both intensity and average energy determine the gamma dose rates as well as their ratio. Hence, the further investigations shows the gamma spectra variations and average energy received by the proportional detector in any environment at different cooling times. For this step, the same routine measurements of the TRR was modeled *i.e.* 20 cm water and 100 cm air.

Figure 5 compares the gamma spectra variation for a 64%-burnup spent fuel at 7-days of the cooling time when the detectors at 20 cm water and 100 cm of air receive the gamma spectra. As the figure shows, at this cooling time, the gamma intensity is higher at 20 cm of water than 100 cm of air as well the spectra shapes is a little different at low energies while after 1 MeV the spectra shape is approximately identical in both air and water environments. The average gamma energy is received by the proportional detector in air and water are about 77 keV and 21 keV, respectively.

The same investigation was carried out for a 64%-burnup 90-days cooled spent fuel. The investigation showed at this cooling time the gamma intensity is higher at 20 cm of water than 100 cm of air as well the spectra shapes is a little different at low energies while after 1 MeV the spectra shape is approximately identical in both air and water environments. The average gamma energy is received by the proportional detector at air is about 75 keV and in the water the value is about 30 keV (Fig. 6).

In addition, the investigations for 64%-burnup 5-years cooled spent fuel showed that the same behavior is observable at this cooling time. The average gamma energy is received by the Proportional detector at air is about 42 keV and in the water the value is about 23 keV (Fig. 7).

The average gamma energy during the different cooling times in the air is about 65 keV and the value is about 25 keV in the water. Figure 8 shows if the detector is placed at 20 cm water, regarding average energy of 25 keV the detector at water should be placed at ∼100 cm of air regarding the average energy of 65 keV.

Hence, the conversion factors at different cooling times were investigated by this measurement arrangement (20 cm water, 100 cm air).

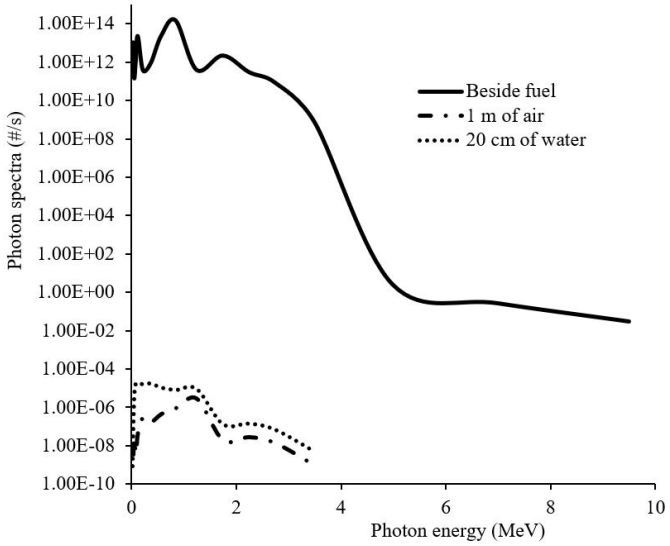

Figure 5: Comparison of the gamma spectra at 20 cm water and 100 cm air for a 64%-burnup 7-days cooled spent fuel.

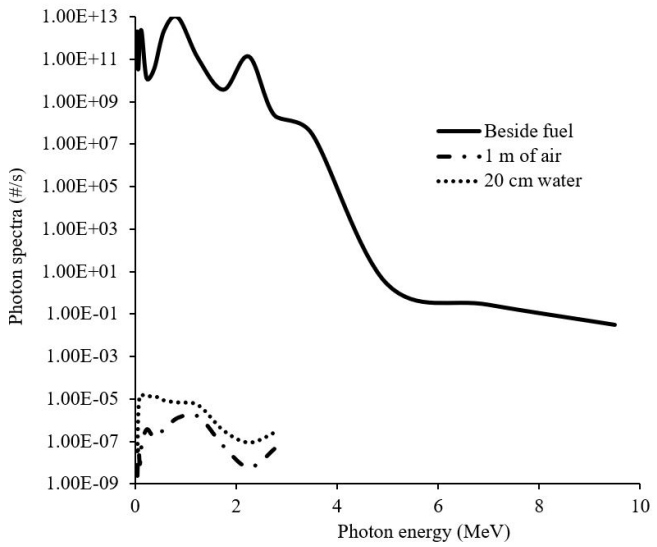

Figure 6: Comparison of the gamma spectra at 20 cm water and 100 cm air for a 64%-burnup 90-days cooled spent fuel.

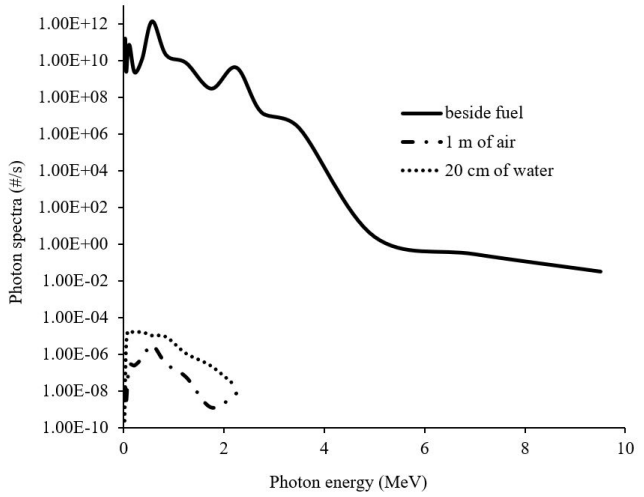

Figure 7: Comparison of the gamma spectra at 20 cm water and 100 cm air for a 64%-burnup 5-year cooled spent fuel.

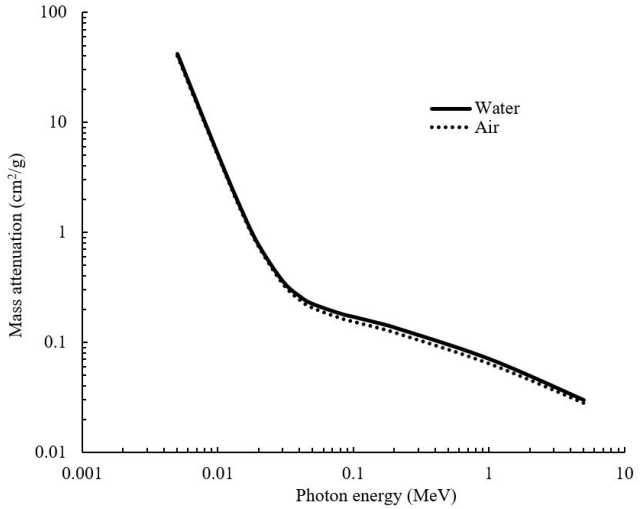

Figure 8: Comparison of mass attenuation of average gamma energies in air and water.

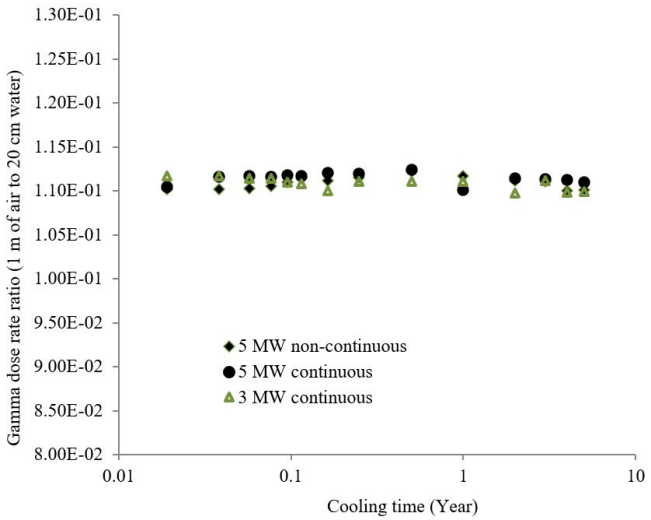

Figure 9: Investigation of the conversion factor dependency to the spent fuel irradiation history and cooling times for 64%-burnup spent fuel for the 20 cm water and 100 cm air arrangement.

It should be taken in attention finding a conversion factor is very important because measurement of the spent fuel gamma dose rate inside the air is impossible in view of the personnel high exposure. For example, the gamma dose rate of a 64% burnup 4-month cooled spent fuel at 1 m of the spent fuel surface at air is 984 $mSv.h^{-1}$.

The first selected position (20 cm of water) will assure unsaturation of the gamma dosimeter. Also from the ORIGEN code output, it can be found some low-energy gamma emitter radioisotopes (57 keV $< E_\gamma$) have long half-life and the highest weight in the gamma spectra. Therefore, integral on the energy of the spent fuel volume source can obtain the equivalent interval of 100 cm air so that during the different cooling times the ratio of the received gamma intensity at the positions is always constant.

3.3 Calculation of the conversion ratio at 100 cm air and 20 cm water

According to Fig. 9, for a 64% burnup spent fuel, the conversion factor has not any dependency to irradiation history because all the investigated spent fuels which were reached to 64% burnup via different histories of continuous and non-continuous resulted in identical conversion factor values at different cooling times. As the calculations showed, the conversion factor is independent to the cooling time for a 64%-burnup spent fuel when the value is obtained for the 20 cm water and 100 cm air arrangement. The relative discrepancy between the values is less than 2%. Hence, by this arrangement a constant conversion factor is used to convert the measured gamma dose rate at 20 cm of water to 100 cm of air which the value is approximately 0.11.

The next step is the investigation of the conversion factor to the TRR spent fuel burnup values. At this stage, the conversion factors were compared for the 5%-burnup, 30%-burnup and 64%-burnup at different cooling times.

As Fig. 10 shows, there is not significant dependency for the different burnups. The relative discrepancy between the values is less than 2%.

Displacement of the Proportional detector from 20 cm of water and 100 cm of air were investigated. As Fig. 11 shows, when the Proportional detector has a shift ±1, 2, or 3 cm in water the conversion factor would have about ±11% up to ±38% deviation respectively for the least and highest displacements from 20 cm position.

Figure 12 shows, when the Proportional detector has a shift ±1, 2, or 3 cm in air the conversion factor would have about ±2% up to ±6% deviation respectively for the least and highest displacements from 100 cm position. All of the calculation errors were less than 0.2%.

At final step, a benchmark study was carried out for a spent fuel assembly of TRR. The gamma dose rates of the spent fuel were measured in the air and water. The dose rate measured by IAEA experts at 100 cm of air was 21.9 mSv.h^{-1} and the value was 94 mSv.h^{-1} at 20 cm water. The ratio is 0.23 according to the IAEA measurements. Another fuel assembly measurement data by IAEA experts reveals the conversion factor is 0.22 ($5.27E+03$ mSv.h^{-1} at air and $2.34E+04$ mSv.h^{-1} at water). IAEA uses CZT detector, which its efficiency curve is linear for average of 65 keV than 25 keV (Redus, 2002).

Therefore, the trend of the measurements and the present work is identical that means the conversion factor has independency to the burnup, cooling time and irradiation history but the simulated conversion factor is half of the measured value by IAEA.

A benchmark study was carried out in the present work by means of TLD dosimeter. A spent fuel assembly was selected and the gamma dose rate at 20 cm of water and 100 cm of air was measured. The results showed the water-placed TLD dose rate is 97.09 mSv.h^{-1} and the value is 10.26 mSv.h^{-1} for the air-placed TLD. Our measurement showed the air to water ratio is 0.106, which has 3.6% relative discrepancy with MCNPX computational value.

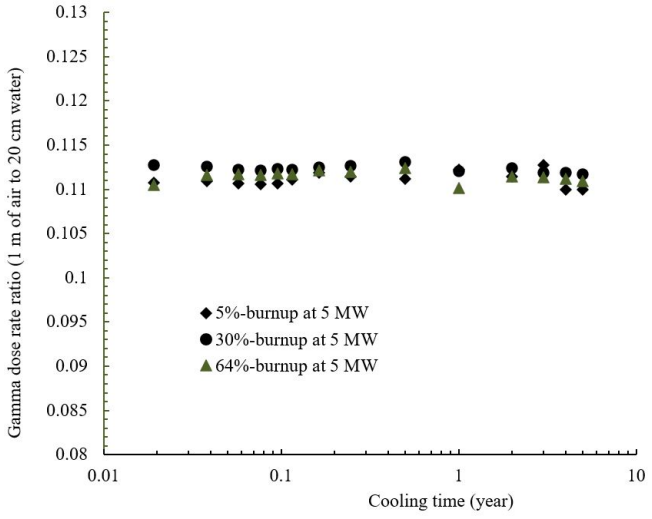

Figure 10: Investigation of the conversion factor dependency to the spent fuel burnups and cooling times for the 20 cm water and 100 cm air arrangement.

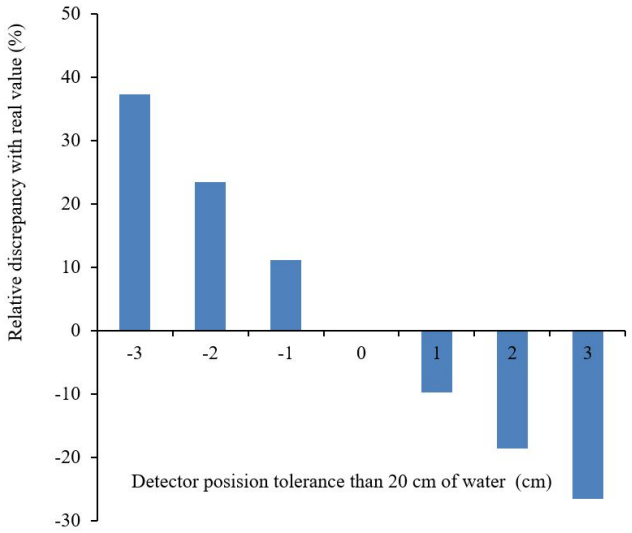

Figure 11: Investigation of the detector shift than its position in 20 cm of water effects on the calculation errors.

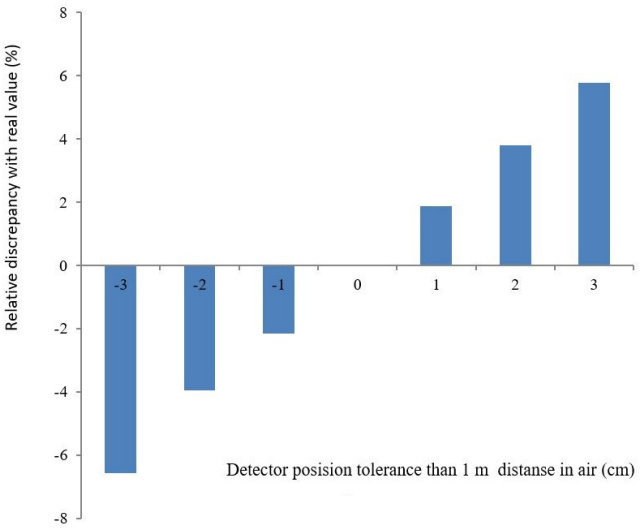

Figure 12: Investigation of the detector shift than its position in 100 cm of air effects on the calculation errors.

4 Conclusion

Gamma dose rate of the nuclear spent fuels in an important issue in regard of shield designs or storage sites. Measurement of the spent fuel gamma dose rate in the air is approximately impossible especially during short cooling times (less than 10 year). Hence, a correct procedure to convert the measured gamma dose rates in water to its real value in air has been needed. The present study investigated the conversion factor dependency to the spent fuel irradiation history, cooling time and burnup value. The obtained results showed by selection of the measurement position of 20 cm of water and its conversion to 100 cm of air the as much as reliable value could be obtained if a conversion factor of 0.11 is applied. The value is independent to the spent fuel irradiation history, cooling time and burnup values. Displacement detector in water would result

in ±11% up ±38% when the detector has ±1 or ±3 cm displacement from 20 cm. Comparison of simulation conversion factor with the measured values by IAEA showed the used conversion factor by IAEA is two times than the simulation data by this work and the TLD measurements showed more conformity with the simulation data in this work.

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