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Ahmed G. Mostafa[1], Sayed A. Makhlouf[2], Elham El-Hakim[3], Morsy S. El-Tahawy[4], Abdel Fatah A. Hamed[4], Atef El-Taher[2,*]

[1] *Physics Department, Faculty of Science, Al-Azhar University, Cairo, Egypt*
[2] *Physics Department, Faculty of Science, Al-Azhar University, Assiut, Egypt*
[3] *Nuclear Fuel Research Laboratory, Nuclear Research Center, Atomic Energy Authority, Inshas, Egypt*
[4] *Nuclear Safeguards and Physical Protection Department, Egyptian Nuclear and Radiological Regulatory Authority, Cairo, Egypt*

*Corresponding author: atef.eltaher@gmail.com

VERIFICATION OF ^{235}U MASS CONTENT IN SOME NUCLEAR FUEL FABRICATION FOR CANDU REACTORS BY AN ABSOLUTE METHOD

In this paper, the physical inventory taking of nuclear materials (NM) (under safeguards application) at the nuclear fuel research laboratory at Inshas, Egypt has been considered. NM with different forms and sizes were verified. The verification method based on non-destructive measurements of gamma radiation emitted from NM was tested. Monte Carlo method (MCNP5) and Multi-Group Analysis software (MGAU Genie 2000, version 3.2) were used to estimate ^{235}U mass content in the studied forms. Some of the parameters which affect NM mass estimation were also investigated. The proposed procedure covers different forms found at the nuclear fuel research laboratory such as pellets, sludge, and rods. The average accuracies for the estimated ^{235}U masses ranged between –0.351 and –1.005 %, while the precision was about 2.065 and 7.45 % for MCNP5 and MGAU respectively. These results are found to be acceptable within the limits of the International Target Values.

Keywords: fuel fabrication, physical inventory taking, Monte Carlo method.

1. Introduction

In order to fulfill its national and international safeguards commitments, a state should establish and maintain a State System of Accounting for and Control of nuclear materials (NM) [1]. The main function of that system is to verify all NM in such a state. Verification activities are achieved via two main steps.

First, the facility operators are obliged to provide the inspectors with all information relevant to NM inventory and inventory changes, as well as the NM quantities received, produced, shipped, lost or otherwise removed from the inventory. The NM quantities in an inventory must be stored within a certain limited area using different measuring techniques and accounting procedures. Also, an essential requirement is to evaluate the precision and accuracy of the measurements and estimate the overall uncertainty [2].

Second, the measured NM quantities are compared with those declared by the facility operators. The acceptance of the operator's declarations (operator–inspector differences) depends on some criteria which are related to the accuracy and precision of the obtained measurements for both inspectors and operators [3].

Many years ago, the MCNP (Monte Carlo N-Particle) simulation technique, has become progressively popular and it has been used by many authors to simulate the process of gamma-ray detection [4 - 14]. It was used to calculate the response characteristics of different types of germanium detectors at different gamma-ray energy ranges [15 - 21]. Also, it was used for efficiency calibration of detectors either directly or through combination with experimental measurements [4]. Relative efficiency curves determination and simulation of energy spectra were also performed by the aid of the MCNP program [22 - 23].

The present work aims to verify ^{235}U mass content in nuclear fuel fabrication for CANDU reactors with different forms using an absolute MCNP code to fulfill the safeguard commitments.

2. NM with different forms and standard NM verification

^{235}U mass content in some NM with different shapes (pellet, sludge, and rod) has been studied. These NM were verified based on passive absolute non-destructive assay methods by using HPGe detector and the Monte Carlo program (MCNP5).

An assayed sample must be located at distance "D" in front of the detector such that the axis of symmetry of the detector is perpendicular to the surface of the NM sample facing its center. Accordingly, the net count rate (C_R) for the assayed NM sample can be obtained by applying the following equation:

$$C_R = M_{235} \cdot S_{185} \cdot A_t \cdot \Omega_f \cdot \varepsilon_i \cdot F_e \cdot F_c, \quad (1)$$

where M_{235} is the mass of ^{235}U isotope in the material in grams; S_{185} is the concentration activity of the line energy 185.7 keV for gamma rays (disintegrations/second/gram) obtained from "the ^{235}U activity" calculated by using its 185.72 keV gamma line; A_t is the total attenuation correction factor for material configuration setup; Ω_f is the fractional solid angle of the material subtended by the detector; ε_i is the intrinsic full energy peak efficiency of the detector at 185.7 keV gamma energy; F_e is a correction factor for electronic losses (due to pileup and dead time); F_c is a correction factor for ambient background and coincidence summing.

If the measuring system is optimized to minimize the effects of electronic losses, background and coincidence summing, then, Eq. (1) can be simplified to become

$$C_R = M_{235} \cdot S_{185} \cdot A_t \cdot \Omega_f \cdot \varepsilon_i. \quad (2)$$

Since the equation that relates the absolute full-energy peak efficiency to the intrinsic full energy peak efficiency is

$$\varepsilon_{ab} = A_t \cdot \Omega_f \cdot \varepsilon_i. \quad (3)$$

Therefore, the net C_R becomes

$$C_R = M_{235} \cdot S_{185} \cdot \varepsilon_{ab}. \quad (4)$$

Using Eq. (4), a calibration curve that relates the C_R and the mass content of ^{235}U for each NM sample with definite geometry can be constructed. The calculations were performed using the multi-purpose MCNP5 code.

In addition to the used method, the verification by non-destructive method based on the Multi-Group Analysis software (MGAU) was also employed. The MGAU is used to analyse the spectrum obtained for the verified NM samples, and then ^{235}U enrichment independent of the verified NM samples can be also calculated. The estimated ^{235}U mass based on MGAU measurements can be calculated by applying the following equation:

$$M_{U\text{-}235} = E_{U\text{-}235} \cdot M_T, \quad (5)$$

where $E_{U\text{-}235}$ is the enrichment by ^{235}U; M_T is the total mass of uranium.

3. Experimental work

3.1. Enrichment measurement

The ^{235}U enrichment was measured using a HPGe detector with MGAU analysis software. The allowable time for measurements was limited to the field requirements. Consequently, the measurements represent a state of practice ones, which met the inspection working conditions. However, standard NM (SNM) was measured for a long time just to investigate the effect of time on the estimated errors.

3.2. C_R measurement

C_R due to ^{235}U were measured using the HPGe detector. The sample was placed in front of the detector. The sample to detector distance (DIST) was chosen such that counting losses due to electronics were minimized. The detector dead time did not exceed 1 %. Three runs were taken for each sample and the mean value of the measured C_R was used in calculations.

3.3. Measurements setup of natural NM sample

The C_R of each NM sample was located so that the axis of symmetry of the detector passes through the central point of the material and the measurements were carried out at three different DIST. The mass of ^{235}U was estimated for each NM sample using the absolute method and compared with the declared value. Special holders were designed to fix the measured samples precisely in front of the detector to minimize the contribution of the systematic error component to the overall accuracy. The distances between the sample and detector were selected and varied taking into consideration that errors due to electronic losses are always kept as low as possible and could be neglected.

The fuel manufacturing purpose requires that the circular bases of the pellet have to be slightly concaved. Such a factor was ignored in the simulation where it was expected to be of negligible contribution to the results of Monte Carlo calculations. The extended axes of symmetry of the pellet and the HPGe crystal detector are the same. The experimental setup configuration for sludge is approximately identical to that of the pellet. The specifications of the pellet and sludge are given in Table 1.

Table 1. **Specifications of the used pellet and sludge**

Sample	Density, g/cm^3	Height, cm	Diameter, cm	Material
Pellet	10.7	1.5	1.2	UO_2
Sludge	5.2	2.55	2.55	

The sintered UO_2 pellets are contained in a zirconium tube (rod) welded from both ends. The specifications of the zirconium tube are given in Table 2.

The fuel rod was placed in front of the detector so that the extended axis of symmetry of the detector must cut that of the rod perpendicular to its midpoint.

Table 2. **Specifications of zirconium tube used in the manufacturing fuel rod**

Height, cm	Top and bottom thicknesses, cm	Outer radius, cm	Wall thickness, cm	Density, g/cm^3	Material
49.5	0.25	0.66	0.05	7.30	Zr

All measurements were performed at Inshas. This location belongs to the Egyptian Atomic Energy Authority during the measurement time.

4. Results and discussion

4.1. Fuel pellet

The used UO_2 was weighted and then the total mass of uranium (M_T) in the pellet was calculated. Then the declared value of U-enrichment was multiplied by M_T to obtain the ^{235}U declared mass (M_D). On the other hand, ^{235}U was also obtained by multiplying M_T by the enrichment value obtained using MGAU software (in this case the ^{235}U mass is denoted by M_G).

Table 3 shows the estimated average mass of ^{235}U in the fuel pellet based on MGAU results in comparison with the declared ones. Table lists the pellet location, the sample to DIST, M_T, M_D with the estimated percentage relative standard deviation (RSD %), the measured enrichment based on MGAU software (E_G) with the associated RSD %, the estimated ^{235}U mass (M_G) (based on E_G) with the estimated RSD % and the percentage relative accuracy (R_{DG} %) R_{DG} % [= $((M_D - M_G)/M_D)\cdot 100$].

Table 3. **The estimated ^{235}U mass contents in pellet based on MGAU measurements in comparison with the declared value**

Pellet	DIST, cm	U Mass, g ± RSD %			$E_G \cdot 10^{-3}$ ± RSD %	Lifetime, min	R_{DG} %
		M_T	M_D	M_G			
L1	5.4	17.37 ± 0.01	0.125 ± 0.01	0.127 ± 9.7	7.297 ± 9.7	81.27	–1.34
L2	4.4			0.126 ± 5.9	7.27 ± 5.9	62.97	–0.97
L3	1.35			0.123 ± 7.0	7.11 ± 7.0	32.82	1.26

It is clear from Table that the declared ^{235}U masses agree with the values estimated based on MGAU software with a maximum deviation value of –1.344 %. The uncertainties RSD % in M_G range between 5.9 and 9.7 %. Although RSD % is relatively large, it was expected that this trend for all current in-field measurements is due to high statistical errors which in turn may be due to the measurement's lifetime. In the present work for pellet the found uncertainty values of the mass were found to be large, but it still near to that found in the literature [14] which ranged from 3.6 to 6.7 %.

The estimated ^{235}U mass contents in pellets based on Monte Carlo calculations are given in Table 4, in addition to the sample locations (DIST), M_D and estimated ^{235}U mass (M_M), the measured C_R and absolute full-energy peak efficiency (ε_{ab}) calculated using MCNP. Both C_R and ε_{ab} are provided with the estimated uncertainties to reflect the random error effect on the overall error. It is clear from Table that the statistical components due to C_R measurements and ε_{ab} calculations affect the overall uncertainties by a value of less than 2 %. The calculated percentage relative accuracy R_{DM} % [= $((M_D - M_M)/M_D)\cdot 100$] (ranges between –1.63 and –0.66) is comparable with that for MGAU-based values.

Table 4. **The estimated ^{235}U mass contents in pellet based on MCNP calculations in comparison with the declared value**

Pellet	DIST, cm	U Mass, g ± RSD %		$C_R(S^{-1})$ ± RSD %	$\varepsilon_{ab} \cdot 10^{-4}$ ± RSD %	Time of ε_{ab} calculation, min	R_{DM} %
		M_D	M_M				
L1	5.4	0.125 ± 0.01	0.126 ± 2.1	1.032 ± 1.1	1.727 ± 0.67	6.77	–1.05
L2	4.4		0.127 ± 1.8	1.345 ± 0.8	2.323 ± 0.69	7.20	–1.63
L3	1.35		0.126 ± 2.0	5.318 ± 1.3	9.441 ± 0.40	7.55	–0.66

The estimated average ^{235}U masses are 0.1254 g and 0.1263 g for MGAU and MCNP-based methods, respectively. The average accuracies for both methods are –0.35 and –1.11 %.

Fig. 1 summarises the obtained results for M_G and M_M with associated uncertainties concerning M_D (solid line). The figure illustrates the agreement of the estimated masses with the M_D within the associated uncertainties. The two methods for estimation of ^{235}U mass are both accurate, however, the accuracy in the method based on MGAU was found to be better than that based on MCNP. But the precision of the MCNP-based method is better.

It is expected that the positively biased values for M_M are due to a systematic error that could appear as a result of the position uncertainty.

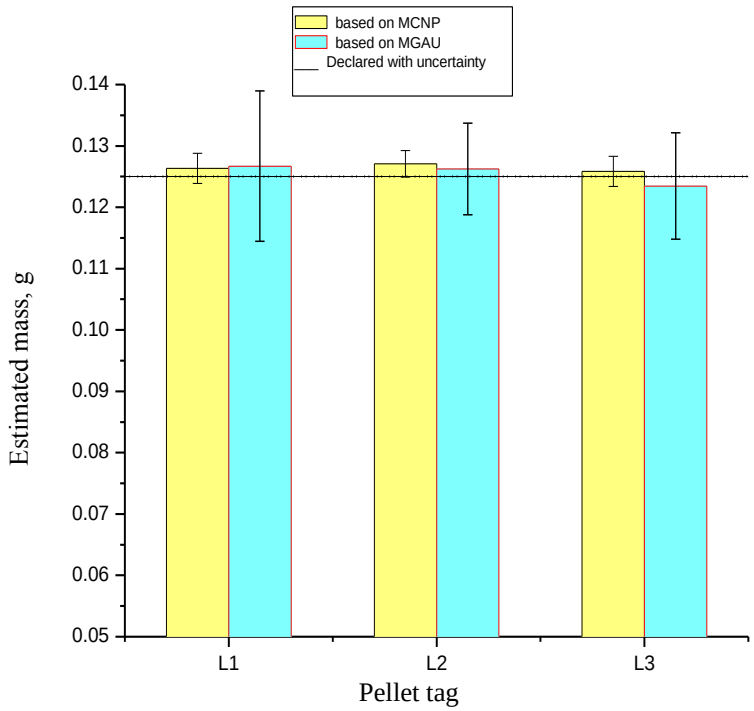

Fig. 1. The estimated ^{235}U masses based on MCNP and MGAU methods and the declared value for the pellet sample. (See color Figure on the journal website.)

4.2. Sludge

The ^{235}U mass content in sludge was also estimated and the obtained results based on MGAU and MCNP methods are given in Tables 5 and 6 respectively. The sludge sample was measured at three different locations concerning the detector. The average accuracies for M_G and M_M are –0.84 and 0.21 % respectively. It can be seen that both the accuracy and precision of the MCNP-based method are better than those for MGAU.

Table 5. **The estimated ^{235}U mass content in sludge based on MGAU measurements in comparison with the declared value**

Sludge	DIST, cm	U Mass, g ± RSD %			$E_G \cdot 10^{-3}$ ± RSD %	Lifetime, min	R_{DG} %
		M_T	M_D	M_G			
L1	3.5	34.37 ± 0.01	0.24725 ± 0.01	0.248 ± 6.2	7.226 ± 6.22	21.86	–0.368
L2	4.5			0.247 ± 4.4	7.200 ± 4.44	33.11	0.002
L3	5			0.253 ± 6.9	7.356 ± 6.93	36.24	–2.150

Table 6. **The estimated ^{235}U mass content in sludge based on MCNP calculations in comparison with the declared value**

Sludge	DIST, cm	U Mass, g ± RSD %		$C_R(S^{-1})$ ± RSD %	$\varepsilon_{ab} \cdot 10^{-4}$ ± RSD %	Time of ε_{ab} calculation, min	R_{DM} %
		M_D	M_M				
L1	3.5	0.247 ± 0.01	0.250 ± 1.7	7.378 ± 0.83	6.654 ± 0.43	6.89	–0.95
L2	4.5		0.249 ± 1.5	5.561 ± 0.67	5.515 ± 0.43	6.78	–0.53
L3	5		0.242 ± 1.8	4.556 ± 0.86	4.005 ± 0.43	6.77	2.11

Fig. 2 shows the estimated ^{235}U masses using MCNP and MGAU-based methods in comparison with the M_D. As mentioned previously, the precision of MGAU results could be improved through extending the time of measurement. While more accurate results could also be obtained by reducing systematic errors duo to sample position in case of MCNP-based method.

4.3. Fuel rod

The fuel rod was measured at three different locations concerning the detector. Table 7 lists the results obtained for ^{235}U mass of the fuel rod sample at three locations based on the MGAU method.

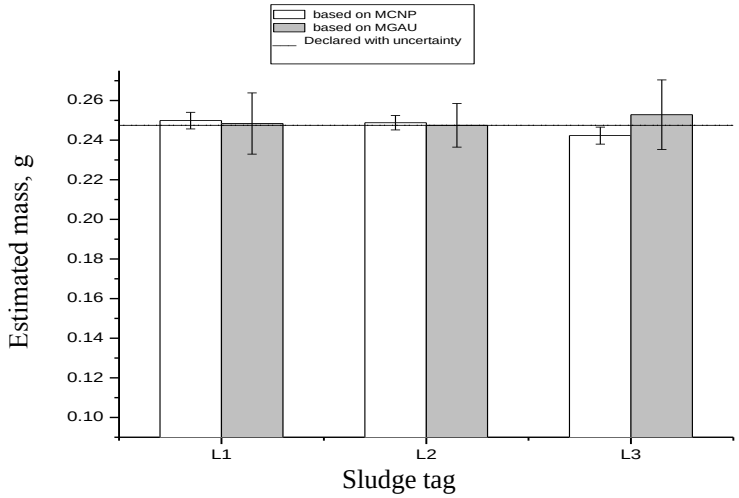

Fig. 2. The estimated ^{235}U masses based on MCNP and MGAU methods and the declared value for sludge sample. (See color Figure on the journal website.)

Table 7. **The estimated ^{235}U mass content in fuel rod based on MGAU measurements in comparison with the declared value**

Rod	DIST, cm	U Mass, g ± RSD %			$E_G \cdot 10^{-3}$ ± RSD %	Lifetime, min	R_{DG} %
		M_T	M_D	M_G			
L1	23.7	493.307 ± 0.01	3.552 ± 0.01	3.417 ± 10.5	6.928 ± 10.5	15.79	3.8
L2	17.75			3.589 ± 10.0	7.275 ± 10.0	19.19	–1.0
L3	11			3.655 ± 6.3	7.410 ± 6.3	26.78	–2.9

It can be shown from this Table that the average estimated mass is 3.554 with average relative accuracy from the declared one of about –0.06 %. Table 8 gives the ^{235}U mass results based on MCNP calculations, where the average relative percentage accuracy, in this case, is about –0.27 %. The accuracies due to both methods are still comparable. Fig. 3 illustrates the results obtained from MGAU and MCNP calculations.

Table 8. **The estimated ^{235}U mass content in fuel rod based on MCNP calculations in comparison with the declared value**

Rod	DIST, cm	U Mass, g ± RSD %		$C_R(S^{-1})$ ± RSD %	$\varepsilon_{ab} \cdot 10^{-5}$ ± RSD %	Time of ε_{ab} calculation, min	R_{DM} %
		M_D	M_M				
L1	23.7	3.55 ± 0.01	3.473 ± 2.7	2.35 ± 1.2	1.43 ± 1.83	38.62	2.2
L2	17.75		3.520 ± 2.7	3.49 ± 1.3	2.12 ± 1.82	35.50	0.89
L3	11		3.691 ± 2.2	5.79 ± 1.2	3.52 ± 1.21	36.37	–3.9

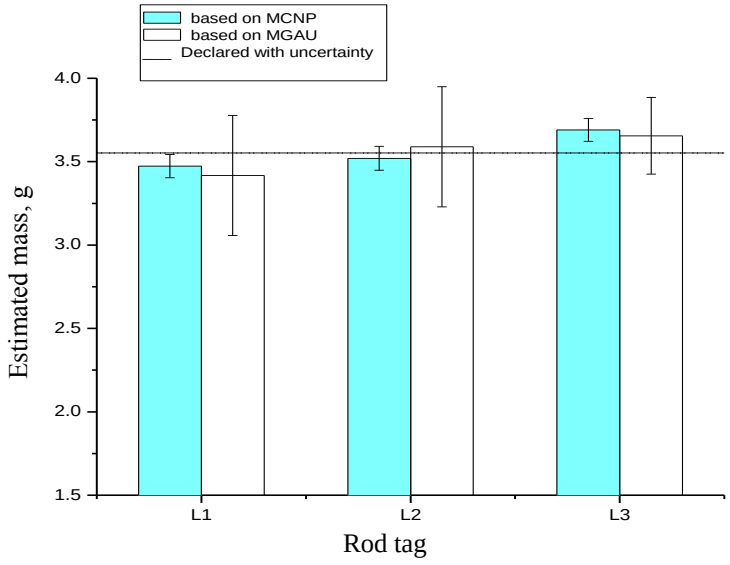

Fig. 3. The estimated ^{235}U masses based on MCNP and MGAU methods together with the declared value for rod sample. (See color Figure on the journal website.)

It is noticed from Fig. 3, that the uncertainty in the estimated ^{235}U mass using MCNP calculations at the third location (L3) is relatively high when compared with the M_D value within the calculated uncertainty. It is expected that this may be because of position-related uncertainty, especially when the sample dimensions are larger in comparison with the dimensions of the experimental setup. Such effect was also expected for other samples with relatively large dimensions.

4.4. Effect of measuring time factor on the precision of MGAU results

In all the obtained results it was noticed that the precision of ^{235}U mass estimation using MGAU was relatively high (about 7.32 % on average). It was expected that the main source of such higher values may be due to the limited measuring time available in a nuclear facility. To evaluate the effect of measuring time on the precision of the obtained results, a SNM was used. The measurement has been performed taking into consideration all conditions at a facility except a relatively longer measuring lifetime was taken. While the measuring time for different measured NM samples was ranging between 15 and 81 min, the SNM sample was measured for 205.9 min. As it was expected, the long measuring time results are found of better precision values.

Table 9 shows the obtained ^{235}U mass content in the SNM with the associated precision. The obtained precision values are improved by about 2.09 % due to the applied longer time of measurements. The maximum value for the precision is about 2.5 % while it ranges between 6.3 and 10.5 % for the measurements described previously as the fuel rod due to the applied longer time of measurements in the case of the SNM. Comparable values for the relative accuracy and precision of ^{235}U mass content in the SNM were obtained using the MGAU-based method. Consequently, under certain conditions (relatively large measuring time), acceptable results could be obtained using MGAU. On the other hand, Table 10 gives the relative accuracy and precision based on MCNP calculations, where the results appeared also acceptable. Consequently, this method is independent of the measuring time. Fig. 4 shows the estimated ^{235}U mass using MCNP and MGAU-based methods in comparison with the M_D.

Table 9. **The estimated ^{235}U mass content in SNM based on MGAU measurements in comparison with the declared value**

SNM	DIST, cm	U Mass, g ± RSD %			$E_G \cdot 10^{-3}$ ± RSD %	Lifetime, min	R_{DG} %
		M_T	M_D	M_G			
L1	10	56.5603 ± 0.01	0.4072 ± 0.01	0.4123 ± 2.0	7.290 ± 2.0	205.93	–1.3
L2	14.4			0.4096 ± 1.7	7.242 ± 1.7	174.27	–0.59
L3	18.8			0.4153 ± 2.5	7.343 ± 2.5	161.24	–2.0

Table 10. **The estimated ^{235}U mass content in SNM based on MCNP calculations in comparison with the declared value**

SNM	DIST, cm	U Mass, g ± RSD %		$C_R(S^{-1})$ ± RSD %	$\varepsilon_{ab} \cdot 10^{-4}$ ± RSD %	Time of ε_{ab} calculation, min	R_{DM} %
		M_D	M_M				
L1	10	0.4072 ± 0.01	0.3998 ± 2.0	9.540 ± 1.3	5.226 ± 0.35	7.30	1.8
L2	14.4		0.4092 ± 2.0	5.354 ± 1.3	2.844 ± 0.35	6.94	–0.49
L3	18.8		0.3990 ± 2.1	3.374 ± 1.4	1.838 ± 0.36	6.95	2.0

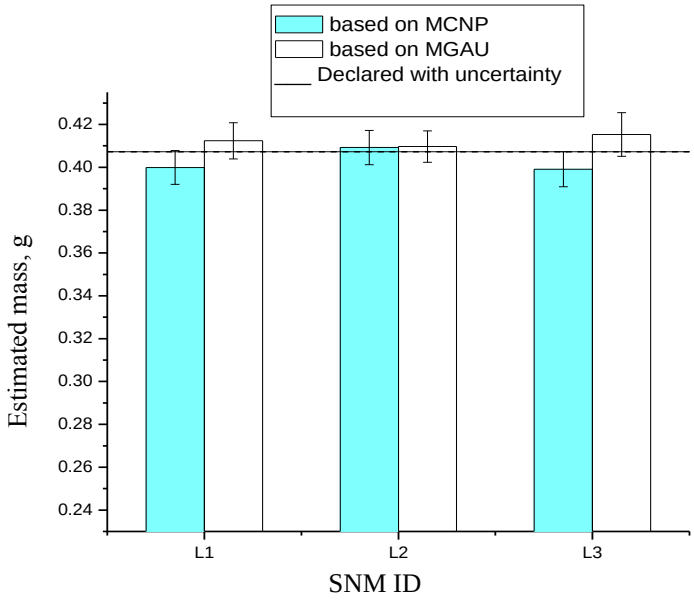

Fig. 4. The estimated ^{235}U mass based on MCNP and MGAU methods together with the declared value for the SNM. (See color Figure on the journal website.)

4.5. The origin of Monte Carlo based results biasing

In most cases, the obtained results agreed with the declared values within the estimated accuracy and precision. Further investigation of the origin of such discrepancies is required. In all the obtained results for the estimated ^{235}U mass content in different samples and different configurations, the accuracy of the estimated mass was found to be ranged between –3.9 and 2.2 %.

The obtained accuracies indicated that the biasing effect is not of the same systematic value in all cases, but it could be considered as such for every single configuration set up. Consequently, it was thought that the origin of biasing could be due to the position-related errors. To investigate this assumption, Monte Carlo calculations were repeated for some cases that showed some discrepancies. Relatively very minor changes in sample locations were considered in Monte Carlo calculations to clarify the effect of position-related errors.

Table 11 shows the effect of changing sample to DIST on the overall estimated accuracy. It is clear from this Table that any slight change (few millimeters or even less) results in considerable biasing. This may explain the discrepancies found in some cases such as those obtained for rod (L1, L3) and sludge (L3).

Table 11. **Change inaccuracy due to the change in efficiency as a result of distance uncertainty**

Sample tag	Change in the distance, mm	Efficiency		Accuracy	
		Obtained result	After changing of distance	Obtained result	After changing of distance
Pellet-1	0.278	$1.77668 \cdot 10^{-4}$	$1.79 \cdot 10^{-4}$	–1.049	$-2.22 \cdot 10^{-16}$
Sludge-3	0.625	$4.08892 \cdot 10^{-4}$	$3.99 \cdot 10^{-4}$	2.106	0
Rod-1	0.195	$1.47000 \cdot 10^{-5}$	$1.43 \cdot 10^{-5}$	2.213	$-1.25 \cdot 10^{-16}$

The obtained overall uncertainty results for the present work were found to have a maximum value of less than 2.8 %, which could be accepted in comparison with nearly similar cases of International Target Values [24].

5. Conclusion

It could be finally concluded that, with some precise data regarding the assayed samples (the specifications of the samples and the position of the samples related to the detector), the detector characteristics and the experimental setup configuration, the MCNP method can be used to verify NM in different forms with acceptable accuracy and precision.

The obtained results based on MCNP5 are in agreement with the declared values within the estimated relative average accuracy –1.11, 0.21 and –0.27 % for pellet, sludge, and rod respectively and relative precision (< ±2.75 %) are in agreements except for some cases such those obtained for rod (L1, L3) and sludge (L3).

The obtained uncertainty results are found comparable with those published by the International Atomic Energy Agency (IAEA) as International Target Values. The relative average accuracy obtained from MGAU is –1.06, –1.78 and –0.18 % for pellet, sludge and rod respectively but the relative average precision is relatively large (7.45 %), which may be due to the short lifetime of measurements.

The application of MCNP in ^{235}U mass estimation can be effectively used to control NM in fuel fabrication facilities and perform physical inventory taking activities. This technique can also provide the essential basis for physical inventory taking activities in a fuel fabrication facility of CANDU reactor fuel.

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Ахмед Г. Мостафа[1], Саєд А. Махлуф[2], Ельхам Ель-Хакім[3], Морсі С. Ель-Тахаві[4], Абдель Фатах А. Хамед[4], Атеф Ель-Тахер[2,*]

[1] Кафедра фізики, факультет науки, університет Аль-Азхар, Каїр, Єгипет
[2] Кафедра фізики, факультет науки, університет Аль-Азхар, Ассіут, Єгипет
[3] Лабораторія досліджень ядерного палива, Центр ядерних досліджень, Управління з атомної енергії, Іншас, Єгипет
[4] Відділ ядерної безпеки та фізичного захисту, Державна адміністрація ядерного та радіологічного регулювання, Каїр, Єгипет

*Відповідальний автор: atef.eltaher@gmail.com

ВЕРИФІКАЦІЯ ВМІСТУ ^{235}U В ДЕЯКИХ ВИДАХ ЯДЕРНОГО ПАЛИВА ДЛЯ РЕАКТОРІВ КАНДУ АБСОЛЮТНИМ МЕТОДОМ

Розглянуто фізичну верифікацію ядерних матеріалів (ЯМ) (при дотриманні гарантій безпеки) в лабораторії дослідження ядерного палива в Іншасі, Єгипет. Були верифіковані ЯМ різних форм та розмірів. Метод верифікації заснований на неруйнівних вимірюваннях гамма-квантів, випромінюваних з ЯМ. Метод Монте-Карло (MCNP5) та програмне забезпечення для багатогрупового аналізу (MGAU Genie 2000, версія 3.2) були використані для оцінки масового вмісту ^{235}U у досліджуваних зразках. Були також вивчені деякі параметри, що впливають на оцінку маси ЯМ. Запропонована процедура охоплює різні форми, що є в лабораторії дослідження ядерного палива, такі як гранули, шлам та стержні. Середня точність для оцінених мас ^{235}U становила від –0,351 до –1,005 %, тоді як прецизійність становила приблизно 2,065 та 7,45 % для MCNP5 та MGAU відповідно. Ці результати вважаються прийнятними в межах міжнародних рекомендацій.

Ключові слова: виготовлення палива, фізичний облік ядерних матеріалів, метод Монте-Карло.

Ахмед Г. Мостафа[1], Сайед А. Махлуф[2], Эльхам Эль-Хаким[3], Морси С. Эль-Тахави[4], Абдель Фатах А. Хамед[4], Атеф Эль-Тахер[2,*]

[1] Кафедра физики, факультет науки, университет Аль-Азхар, Каир, Египет
[2] Кафедра физики, факультет науки, университет Аль-Азхар, Ассиут, Египет
[3] Лаборатория исследований ядерного топлива, Центр ядерных исследований, Управление по атомной энергии, Иншас, Египет
[4] Отдел ядерной безопасности и физической защиты, Государственная администрация ядерного и радиологического регулирования, Каир, Египет

*Ответственный автор: atef.eltaher@gmail.com

ВЕРИФИКАЦИЯ СОДЕРЖАНИЯ ^{235}U В НЕКОТОРЫХ ВИДАХ ЯДЕРНОГО ТОПЛИВА ДЛЯ РЕАКТОРОВ КАНДУ АБСОЛЮТНЫМ МЕТОДОМ

Рассмотрена физическая верификация ядерных материалов (ЯМ) (при соблюдении гарантий безопасности) в лаборатории исследования ядерного топлива в Иншасе, Египет. Были верифицированы ЯМ различных форм и размеров. Метод верификации основан на неразрушающих измерениях гамма-квантов, излучаемых ЯМ. Метод Монте-Карло (MCNP5) и программное обеспечение для многогруппового анализа (MGAU Genie 2000, версия 3.2) были использованы для оценки массового содержания ^{235}U в исследуемых образцах. Были также изучены некоторые параметры, влияющие на оценку массы ЯМ. Предложенная процедура охватывает различные формы в лаборатории исследования ядерного топлива, такие как гранулы, шлам и стержни. Средняя точность для оцененных масс ^{235}U составляла от –0,351 до –1,005 %, тогда как прецизионность составляла примерно 2,065 и 7,45 % для MCNP5 и MGAU соответственно. Эти результаты считаются приемлемыми в рамках международных рекомендаций.

Ключевые слова: изготовление топлива, физический учет ядерных материалов, метод Монте-Карло.

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