Study of the quantitative measurement of fuel assemblies with improved efficiency

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1. Introduction

The International Atomic Energy Agency (IAEA) carried out quantitative measurement of the fraction of ^{235}U in fresh nuclear fuel assemblies using Uranium Neutron Coincidence Collar (UNCL) for safeguards and inspection.

According to the agreement between Korea and IAEA for the application of safeguards in connection with the treaty on the non-proliferation of nuclear weapons in 1975, all nuclear materials, related devices and techniques in Korea should be verified by an IAEA safeguard inspector. Therefore, nuclear fuel assemblies, manufactured by the Korea Nuclear Fuel (KNF) company, have been inspected by the IAEA.

The inspection device which IAEA has used in Korea is the UNCL but it showed high uncertainty due to the effect of burnable poisons such as gadolinium oxide (gadolinia, Gd_2O_3). To improve the accuracy of the UNCL, therefore, present authors have tried to figure out the reason of the high uncertainty and find alternative technologies, available to replace the UNCL.

2. Methods and Results

2.1 Detecting principle of UNCL

The UNCL detector mainly consists of AmLi neutron source, JSR-12 neutron coincidence analyzer, and ^{3}He detector tubes embedded in a box-shaped polyethylene [Figure 1].

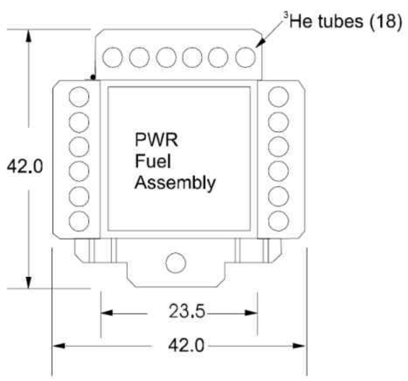

Fig. 1. UNCL-I shown in PWR Configuration [1]

The measurement process of the UNCL is: a PWR fuel assembly is placed at the center of UNCL and irradiated by a source, AmLi. Induce fission neutrons are then emitted from ^{235}U in a fuel assembly and measured by the ^{3}He neutron detector bundle. This system relies on the neutron coincidence counting technique, which can separate time-uncorrelated neutrons from fission events from the time-correlated fission neutrons from accidental events such as spontaneous fission or (α,n) reactions.

Coincidence counting method is based on the concept of Rossi-alpha distribution. It distinguishes the fission neutron signals (coincidence) from other noise signals (accidental) by using a shift register which detects neutrons by time. As we can see in Figure 2, the real coincidence (R) gate value can be calculated by subtracting the accident (A) gate value from the sum gate value (R+A). The real coincidence value can be then converted into the total mass of ^{235}U in a fuel assembly by using conversion factors.

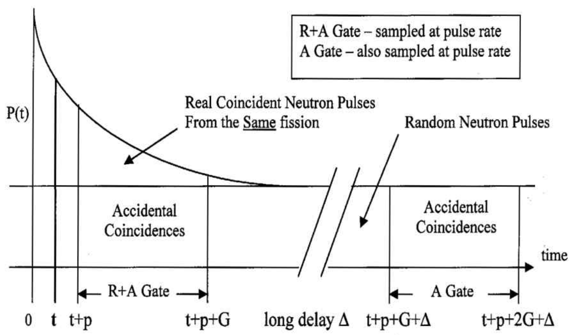

Fig. 2. Coincidence counting method [2]

For the UNCL, AmLi is employed as a fission source since its every energy is lower than the threshold value of ^{238}U. The contribution to the total fission neutron counts from ^{238}U is negligible with the AmLi so the mass of ^{235}U can be estimated. However, the AmLi source becomes no longer available in the market[3].

2.2 Limitation of UNCL

As mentioned before, the measured total coincidence neutron counts can be converted into ^{235}U by using the conversion factors. Other factors such as a burnable poison and geometrical conditions should be also considered. For that, IAEA developed 6 correction factors and the equation of the standard calibration curve for those correction factors is:

$$kR = (k_0 + k_1 + k_2 + k_3 + k_4 + k_5) \cdot R \quad (1)$$

- k_0: AmLi Source Strength
- k_1: Electronics Change and Geometric Variations
- k_2: Detector Cross-Calibration
- k_3: Burnable poison, Gd_2O_3
- k_4: Heavy metal loading, gU/cm
- k_5: Other conditions

To date, most correction factors have shown a good agreement in the verification process but only k_3 factor is limited by the numerical and geometrical problems of a burnable poison, Gd_2O_3, in a fuel assembly. The correction factor k_3 can be calculated via [1]:

$$k_3 = 1 + \frac{n_{poison}\ N_{ref}}{N_{assay}} A_c\left[1 - e^{-\lambda_a G}\right](B_c - C_c E_{enr}) \quad (2)$$

- n_{poison} = number of poison rods in the assay fuel assembly
- N_{ref} = total number of rods in the reference fuel assembly
- N_{assay} = total number of rods in the assay fuel assembly
- A_c, B_c, C_c = calibration constants
- λ_a = poison absorption factor (also a calibration constant)
- G = weight percent gadolinium in the poison rods
- E_{enr} = weight percent ^{235}U enrichment of the fuel

IAEA has tried to experimentally modify the k_3 correction factor, showing linearly related to the number of BP rods in an assembly. However, the k_3 correction factor still shows inaccurate results since the number of neutrons absorbed by a gadolinia cannot be numerically counted.

Thus, other techniques, measuring epi-cadmium neutrons or fast neutrons, have been suggested and developed by IAEA. Those new techniques are introduced and compared with the original UNCL in the following subchapters

2.3 Time Correlated Induced Fission (TCIF)

Since an AmLi source becomes no longer available in a market and eventually its price has increased, another technique using a ^{252}Cf source was developed. This numerous advantages of the TCIF method compared with the AmLi neutron source follow:

- Doubles rate (coincidence count rates) increases within the same time.
- Uncertainties can be minimized by a large calibration curve slope when the total counts convert into the mass of ^{235}U.
- The higher source strength eliminates the need for the passive(no source) measurement and facilitates unattended mode operation

2.4 Fast Mode High-Efficiency UNCL

The composition of the fast mode UNCL is basically same with the original UNCL but one more cadmium layer (a Cd-liner) was installed inside. That Cd-liner can absorb all of the thermal neutrons and allow to only measure epi-cadimium neutrons in the system. Consequently, the fast mode UNCL showed a lower uncertainty for burnable poison Gd_2O_3 rods but the longer measurement time was required due to the lower count rates. To increase the total neutron count rates in the system of the fast mode UNCL, some ways to increase ^{3}He pressure or the number of tubes have been considered. However, these modified fast mode high-efficiency UNCLs showed some limitations like:

- ^{3}He detector embedded nearby an AmLi source contributes to increase the doubles rates. It means the final experimental results are possibly inaccurate due to a high uncertainty caused by those detectors. To minimize that uncertainty, it is necessary to optimize the design of the Fast UNCL.
- Considering cost-effectiveness, it should be challenge to increase ^{3}He gas pressure in the fast mode UNCL.

Therefore, the IAEA starts considering a technique based on the liquid scintillation fast neutron detection which has higher sensitivity than the thermal neutrons.

2.5 Liquid Scintillator-Based Fast Mode Collar

Recently, many countries are interested in fast neutron detection due to some reasons, mainly; 1) high count rates and 2) the incredible price of ^{3}He gas. A fast neutron detector using liquid scintillators are also being studied to replace the thermal neutron measurement technique using ^{3}He tubes. This technique is featured by a higher count rates (higher efficiency), lower gamma sensitivity, a fast response time, and relatively lower sensitivity to thermal neutrons. Only one concern on this technique is a larger volume of a detector.

The Fast mode UNCL with liquid scintillator has a fast die away time, less than 1us. It makes the system become more sensitive and eventually have low measurement errors.

2.6 Comparison of Improved UNCL Technique

All techniques, newly developed and mentioned before, are compared in terms of a die-away time setup, cost, stability, and others [Table 1].

Table 1: Comparison of Improved UNCL Technique

	Time Correlated Induced fission(TCIF)	Fast Mode High-Efficiency UNCL	Liquid Scintillator-Based Fast Mode Collar

measurement time for less than 1% measurement error in fast mode	Thermal mode : about 5 min Fast mode: about 1 hour	about 20 min	about 10 min
System price	$50,000	$150,000	$150,000
System stability	stable	stable	unstable (Flammable liquid scintillator, Gain change in the photomultiplier tube)
Easiness of operating system	System set-up, operation, etc. Easy	System set-up, operation, etc. Easy	System set-up, operation, etc. difficulty
weight	about 40 kg	about 60 kg	about 80 kg
Usefulness of Fast mode	Fast mode requires long time measurement likewise UNCL, Low usefulness	Requires relatively short measurement time, High usefulness	Requires very short measurement time because of the short time neutron die-away time, Very high usefulness

3. Conclusions

The UNCL is definitely a useful device for verifying the fraction of ^{235}U in fresh nuclear fuel assemblies but originally shows high uncertainties for impure samples such as mixed-oxide (MOX) fuels or burnable poison rods. Gadolinium oxide (gadolinia, Gd_2O_3) is currently used as burnable poison for PWR fuel in order to 1) decrease the excess of reactivity, 2) increase core lifetime, 3) reduce the amount of mechanical control required, and 4) improve core power distributions. However, it also causes the other problem, a high uncertainty, in terms of safeguards inspection. For instance, if poison rods are loaded with fuel assemblies, the intensity of signals coming from the UNCL is dramatically decreased, more than 20%, since poison materials absorbs thermal induced and spontaneous neutrons from the ^{235}U and a source (AmLi). In order to minimize this problem, IAEA developed the k_3 correction factor, showing linearly related to the number of BP rods in an assembly. However, the k_3 correction factor still shows inaccurate results since the number of neutrons absorbed by a gadolinia cannot be numerically counted.

In this paper, with the purpose of improving the original UNCL, the Time Correlated Induced Fission (TCIF), the fast mode high-efficiency UNCL, and the liquid scintillator-based fast mode collar were compared. Consequently, the fast mode UNCL using liquid scintillator can be a solution to overcome the limitation of k_3 poison correction factor in the original UNCL system since it has very short measurement time (10 minutes) in fast mode and shows lower uncertainty.

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