Current Status of ITER Neutron Activation System Measurement Uncertainty Characterization

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1. Introduction

The ITER Korea domestic agency (KO-DA) developed a Neutron Activation System (NAS) for KSTAR with the objectives of developing a prototype for the ITER NAS, and accumulating operational experience in a fusion device. The KSTAR NAS has been in operation since the 2011 KSTAR experimental campaign [1].

In the early stage of development, the total D-D fusion neutron yield per plasma discharge was measured using the activation of indium sample [1]. Subsequently, candidate activation samples applicable to KSTAR were selected and successfully tested for the measurement of secondary D-T neutrons produced by triton burnup in deuterium plasmas [2, 3]. In addition, for the reconstruction of the neutron energy spectrum at the KSTAR NAS irradiation end, several types of activation samples suitable for the KSTAR environment were selected. Gamma-ray peaks from the activated samples were successfully measured, and the neutron energy spectrum was reconstructed based on these measurements [4]. Through these studies, the initial objectives of prototype development and the accumulation of operational experience in a fusion device were successfully achieved.

For the ITER NAS, a measurement uncertainty of less than 10% is required [5]. Quantification of this uncertainty is important for accurately assessing fusion power, enabling quantitative comparison with computational simulation results, and providing reliable technical justification to regulatory authorities. To quantify the overall measurement uncertainty, fundamental studies are currently underway to identify and classify the sources of uncertainty and to establish appropriate evaluation criteria for each contribution.

2. Characterization of uncertainty sources

2.1 Neutron yield determination

Currently, the relationship used in the NAS to determine the neutron yield from the activation of a sample is given by Eq. (1).

$$(1)\quad Y_n = \frac{R \cdot t_0}{(\#\ of\ target\ nuclei)\cdot \int \sigma(E)\phi'(E)dE}$$

In equation (1), constant reaction rate is assumed. Here, R is the reaction rate, t_0 is neutron irradiation time, $\sigma(E)$ is the target reaction cross-section, and $\phi'(E)$ is the neutron fluence per source neutron at the irradiation position.

The reaction rate is determined from the gamma-ray peak counts measured from the activated sample using the following equation.

$$(2)\quad R = \frac{\lambda C}{\alpha_\gamma \varepsilon e^{-\lambda t_1}(1-e^{-\lambda \Delta t})(1-e^{-\lambda t_0})}$$

In Eq. (2), λ is decay constant, C is the number of counts in the target gamma-ray peak, α_γ is the gamma-ray emission probability, ε is detection efficiency for the target gamma-ray, t_1 is the cooling time between the end of irradiation and the start of measurement, Δt is the gamma ray counting time, and t_0 is the neutron irradiation time.

The number of target nuclei can be determined from the measured mass of the sample. The integral term in Eq. (1), which represents the neutronics contribution, is determined through a combination of in-situ calibration and neutronics calculations. Therefore, once the reaction rate R is determined from the measured gamma-ray peak counts, the total number of fusion neutrons produced during a plasma discharge can be determined.

2.2 Classification of uncertainty sources

As described in the previous section, the neutron yield is determined from three main components: the gamma-ray measurement, the number of target nuclei, and the neutronics term. The combined uncertainty in the neutron yield is obtained by propagating the uncertainties associated with these three components.

The reaction rate is determined based on the constant reaction assumption and the parameters λ, C, α_γ, ε, t_0, t_1 and Δt. Each of these parameters, together with the constant reaction rate assumption, represents a potential source of uncertainty in the determined reaction rate. For the sample mass term, uncertainties associated with the sample purity and mass contribute to the uncertainty in the number of target nuclei. For the neutronics term, uncertainties in the reaction cross-section and the energy dependent neutron fluence are propagated through the integral term and contribute to the overall uncertainty.

2.3 Preliminary plan for characterization and quantification of uncertainty sources

For detailed characterization of the uncertainty sources, overall analysis procedure will be reviewed based on relevant ASTM standards. ASTM has established a number of standards related to neutron activation analysis. The following table lists the ASTM standards that are potentially applicable to the characterization of uncertainty in the NAS. These standards also provide guidance for activation sample selection and gamma-ray detector characterization.

Table I: ASTM standards applicable to ITER NAS uncertainty characterization

ASTM	Title
E181	Standard Guide for Detector Calibration and Analysis of Radionuclides in Radiation Metrology for Reactor Dosimetry
E261	Standard Practice for Determining Neutron Fluence, Fluence Rate, and Spectra by Radioactivation Techniques
E496	Standard Test Method for Measuring Neutron Fluence and Average Energy from d-t Neutron Generators by Radioactivation Techniques
E844	Standard Guide for Sensor Set Design and Irradiation for Reactor Surveillance
E1018	Standard Guide for Application of ASTM Recommended Cross Section and Associated Nuclear Data File

In detail, ASTM E181 can be applied to the characterization of uncertainty sources with gamma-ray measurements. ASTM E261 and E496 can be used for a more detailed evaluation of the overall neutron activation analysis process. ASTM E844 can provide guidance for selecting appropriate activation reactions that may minimize measurement uncertainty and provide the nuclear data required for uncertainty characterization. In addition, IRDFF-II and IAEA Neutron Metrology File (NMF), which provides dosimetry reaction cross-section data, can serve as useful references for this purpose. ASTM E1018 can be applied to the characterization of uncertainty associated with the reaction cross-section data.

The quantification of the characterized uncertainty sources will be carried out through the following process. First, candidate target reactions will be selected based on the ASTM E844 and dosimetry cross-section libraries and data files, such as IRDFF-II and IAEA NMF. Second, once the list of candidate reactions has been established, the expected activation levels and gamma-ray spectra will be simulated. Based on these simulations, the target and potentially interfering gamma-ray peaks will be identified, and the required cooling time will be determined. Third, candidate gamma-ray detectors will be characterized to determine the required counting time and the expected net peak counts, which are directly related to counting statistics. High-purity germanium (HPGe), NaI(Tl), $LaBr_3$(Ce), $CeBr_3$ and CZT detectors are available for this purpose (Fig. 1). Finally, once the preceding steps have been completed, an overall uncertainty evaluation will be performed in an appropriately characterized testbed.

Up to this point, the uncertainty quantification framework for all terms in Eq. (1), except for the neutronics term, has been established. Quantification of the uncertainty associated with the neutronics term is relatively challenging because it involves multiple uncertainty contributions from both the reaction cross-section data and the energy-dependent neutron fluence, including systematic components that are difficult to quantify. At the present stage, the energy dependent neutron fluence calculated using MCNP will be used. For the uncertainty in the energy dependent neutron fluence, only the statistical uncertainty from the MCNP calculation will initially be considered.

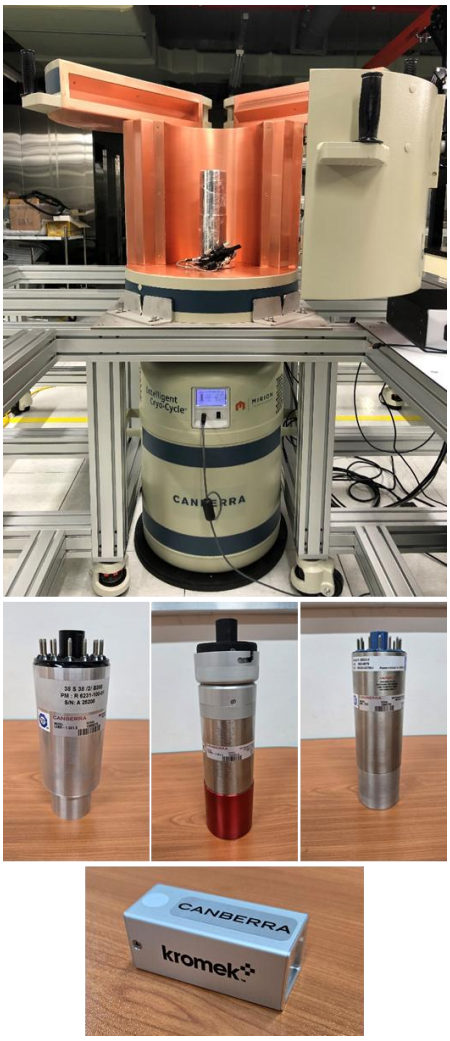


Fig. 1. Candidate detectors: from the top left, HPGe detector system, $LaBr_3$(Ce), $CeBr_3$, NaI(Tl) and CZT detectors.

3. Summary

To quantify overall uncertainty in the neutron yield determined by the ITER NAS, characterization of the uncertainty sources is currently underway. A plan for uncertainty quantification has been established. Preliminary uncertainty estimates will be evaluated according to this plan, and appropriate improvement measures will be considered if the evaluated uncertainty exceed 10%. The use of a Compton-suppression detector system is one potential approach for reducing the measurement uncertainty.

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