Current status and prospects of an activation analysis system development for nuclear fusion facilities

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1. Introduction

The activation analysis system comprises an activation analysis codes and a nuclear data library, designed to improve the precision of the Shut-Down Dose Rate (SDDR) calculations in complex nuclear fusion facilities. SDDR denotes the gamma dose rate resulting from activation according to the cooling time after a nuclear fusion facility has shut down. Accurate calculation of the SDDR necessitates using both radiation transport and activation inventory calculation codes to ensure the post-shutdown dose rate remains below the radiation safety limit.

Activation analysis and gamma dose rate evaluation are crucial for various aspects of nuclear fusion facility management, including shielding design, material selection, licensing, maintenance, and waste management. A verified analysis system is vital not only during the design phase but also for obtaining facility licenses. Given this importance, having a secure and reliable analysis system is essential. Such a system plays a key role in determining the economic feasibility of a project by influencing decisions related to waste management, shielding, material selection, and associated construction costs due to activation.

Unlike nuclear fission reactors, which typically have symmetrical and relatively simple structures, nuclear fusion facilities are characterized by their complex shapes, structures, and diverse materials. This complexity necessitates a fast and straightforward calculation system, distinct from existing methods.

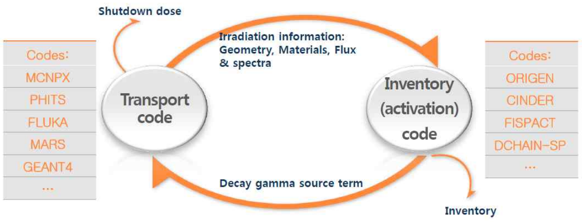

Fig. 1 General activation analysis system and tools used

2. Activation analysis method

The Rigorous 2-Step (R2S) method is widely employed for activation analysis in nuclear and radiation facilities because it can utilize existing radiation transport and activation nuclide calculation codes without requiring modifications. The R2S method involves two Monte Carlo radiation transport calculations and one activation nuclide calculation as follows:

Monte Carlo Calculation (I) + Activation Nuclide Calculation: This step generates a decay gamma-ray source within a given geometry, based on radiation distribution and nuclear reaction product information obtained through neutron/gamma transport calculations.

Monte Carlo Calculation (II): Here, the decay gamma-ray source term is input for each region, and a gamma transport calculation is performed to assess activation over time.

In the R2S method, the decay gamma-ray source term is calculated as the cell average for a given geometry, meaning that the distribution of the gamma-ray source term within the cell is not considered. To address this limitation, multi-cell structure calculations are being performed (as illustrated in the accompanying figure), but these are difficult to apply to the activation analysis of large nuclear/radiation facilities.

The Direct 1-Step (D1S) method was developed as an alternative to the R2S method through the ITER project. It aims to enhance the accuracy of activation analysis in complex, large-scale facilities and is used for various analyses, such as stationary dose rate calculations. The D1S method streamlines the process by requiring only one Monte Carlo calculation. This method directly uses the decay gamma-ray source at the point where the activated nuclide is generated, accurately considering the distribution of the gamma-ray source term within the cell.

For example, at the point where Co-59 undergoes a capture reaction and Co-60 is generated, the D1S method uses the decay gamma-ray of Co-60 rather than the immediate gamma-ray of Co-59 for gamma transport and activation analysis. Utilizing the D1S method necessitates modifying the Monte Carlo code and developing a D1S-specific nuclear data library, where the immediate gamma spectrum is replaced with the decay gamma spectrum.

3. ITER status

Public protection, worker exposure dose, electronic component/device protection, environmental impact limitation, waste leakage minimization, and prediction are all essential considerations in nuclear fusion facilities. However, complex shapes often require substantial time and resources for accurate calculations.

To address licensing issues related to SDDR for maintenance and worker dose, the ITER Director General requested the EU in August 2020 to develop a code for source analysis in complex nuclear fusion facilities like ITER. Consequently, various codes have been developed by entities such as F4E, ENEA, and UNED.

The SDDR standard at ITER is set at 100 μSv/h. Until recently, this requirement was not met after a 10^6 second (11.6 day) shutdown. To address this, various shielding materials were introduced, shielding structures amended, and neutron streaming reanalysis conducted. This remains one of the biggest issues at ITER.

Since design changes are not always feasible and the standard cannot be lowered, there is consideration to modify the ITER operation plan to reduce the neutron flux, which is the source of the radiation. This situation underscores the critical importance of developing accurate activation codes to ensure safety and economic feasibility in future demonstration reactors and nuclear fusion reactors.

A more precise D1S method appears likely to be applied over the existing conservative R2S method. Ensuring the accuracy of continuous D1S calculations and applying relevant libraries for new materials will be essential challenges.

Activation evaluation cases at the ITER facility include:

- Evaluation of Radiation Dose On and Off Site.
- Evaluation of Operator Exposure Dose (ORE).

Optimal Shielding Design for In-Situ Maintenance at the Port: Activation analysis is performed for various options such as vacuum vessel port extension (VVPE), stainless steel (SS), borated stainless steel, B4C, and additional port duct.

SDDR Evaluation for Port Plug (PP): The current design criteria are challenging to meet, so structural changes and the introduction of various shields are being considered. If unresolved, remote maintenance may be necessary.

4. EU status

As developers commissioned by the ITER Organization, they are not only tasked with developing and verifying codes but are also transitioning their own programs from the existing R2S method to the D1S method. They performed an SDDR evaluation for ITER Port 16 (EU solid/liquid TBM test). According to the Korea-EU joint development agreement, the solid type of the port is being co-developed with Korea, which is also tracking the associated technology.

For the SDDR evaluation following a 10^6 second (11.6 day) shutdown under the SA2 scenario, we used the R2S method until 2016. However, since the official development and distribution of the D1S-UNED code at ITER, we have adopted it for recent reinterpretations and licensing processes. Beyond just using the D1S method, we also incorporate our own nuclear fusion neutron source for verification and TBM mock-up tests during code development.

The EU has been conducting a variety of research and development projects related to nuclear fusion reactors since 1992. This includes the development of various neutron sources for nuclear fusion research. For instance, the Frascati neutron source, which utilizes the D-T reaction, has been constructed and is employed for verification during the development of the D1S-UNED code.

Following verification, research is being carried out on tritium production, radiation shielding, and dose assessment of ITER materials. Given the importance of these research activities, it is crucial to build similar facilities in Korea to support code development and nuclear fusion research. The Frascati neutron source has the capability to produce up to 10^{11} n/s 14 MeV neutrons through nuclear fusion reactions by accelerating deuterium ions up to 1 mA and colliding them with a tritium target.

5. KO status and KAERI strategy

The Korea Fusion Energy Research Institute (KFE) conducted an R2S-based activation analysis in 2018 and is now using the ITER-supplied D1S-UNED system for recent analyses but has not developed its own activation system. In 2020, SDDR evaluation for K-DEMO used the R2S method with MCNP-5 and FISPACT. For the ITER TBM, the D1S-UNED code is currently being requested for further analysis.

Korea lacks a unique fusion nuclear analysis tool, relying instead on manual calculations and verified overseas codes for TBM design and evaluations. While other ITER TBM participating countries have developed their own tools, Korea needs to develop its own for securing core technologies for DEMO and future fusion reactors.

For ITER projects, Korea has modified the MCNP code with the D1S methodology and used ITER-provided D1S libraries. Approval for the new D1S-UNED code has been requested, but creating a D1S library is challenging without an approved program.

Thus, Korea must develop an independent D1S activation analysis system, including a D1S library production program. The conceptual design of K-DEMO currently uses 1-D array calculations with ANISN, highlighting the need for improved system analysis to optimize reactor performance, size, and cost.

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