Evaluation of tungsten activation by neutrons generated during D+D nuclear fusion reactions

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The KSTAR device is a superconducting nuclear fusion research facility that conducts deuterium + deuterium fusion experiments. The reaction occurs in a 50:50 ratio, as shown below:

- D + D → He-3 (0.82 MeV) + n (2.45 MeV)
- D + D → T-3 (1.01 MeV) + p (3.02 MeV)

The 2.45 MeV neutrons generated during this process irradiate surrounding devices, which then decay according to their physical half-life.
The radiation generated during this decay serves as a source of radiation exposure for radiation workers during maintenance.
The KSTAR device is equipped with a PFC (Plasma Facing Component) to protect the vacuum vessel from plasma. Plans are underway to coat the PFC's surface with tungsten for operation. We will conduct an evaluation to identify regulatory issues and the extent of increased radiation exposure to workers, and present the results to develop an operational plan. The KSTAR device's design requirement of 1.2 x 10^{20} neutrons per year will be used as the basis for the evaluation.
The general reaction equation for the stable isotope tungsten (W) capturing a neutron to produce a heavier isotope (W*) is as follows, and gamma rays (r) are generated:

$$Z^{A}W + n \rightarrow Z^{A+1}W + r$$

Isotopes such as ^{181}W, ^{185}W, and ^{187}W, produced through this neutron capture reaction, are radioactive nuclides with relatively long half-lives, and are expected to contribute to increased radiation exposure for workers.

Structure of the KSTAR device

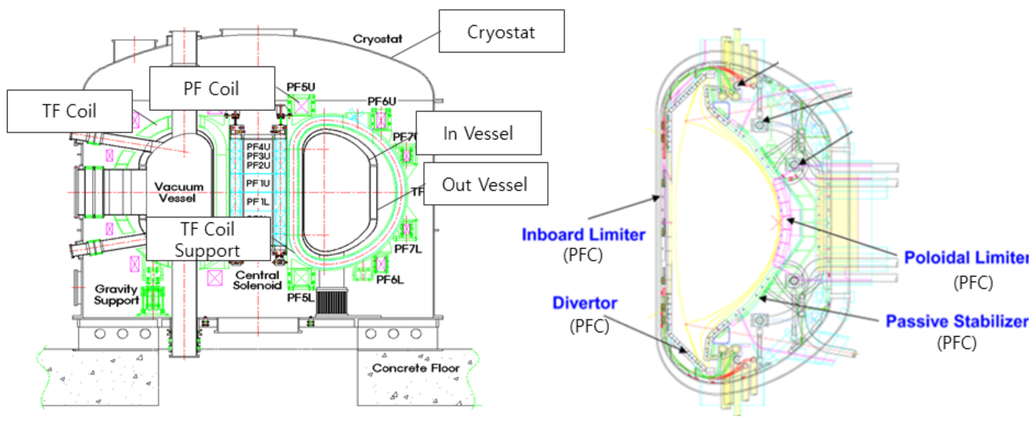

Figure 1 Structure of the KSTAR device

The interior of the KSTAR vacuum vessel is covered with graphite tiles as plasma contact components (PFCs). The vacuum vessel and cryogenic vessel are made of SS316 stainless steel, and the superconducting coils are made of Nb3Sn and NbTi, both containing copper stabilized conductors. The Nb3Sn coil contains Inconel 908. This evaluation aims to assess the radiation dose resulting from coating all PFCs, excluding the lower diverter, with tungsten.

Radiation properties of tungsten

The neutron distribution of the KSTAR device is shown in Figure 2.

Although tungsten is evaluated as a material with low radioactivity in a fusion environment, some isotopes (180W–186W) capture neutrons to become radioactive isotopes.

Considering the half-life and cooling period (approximately one month), the major nuclides that could affect exposure are 181W, 185W, 187W, and 182Ta.

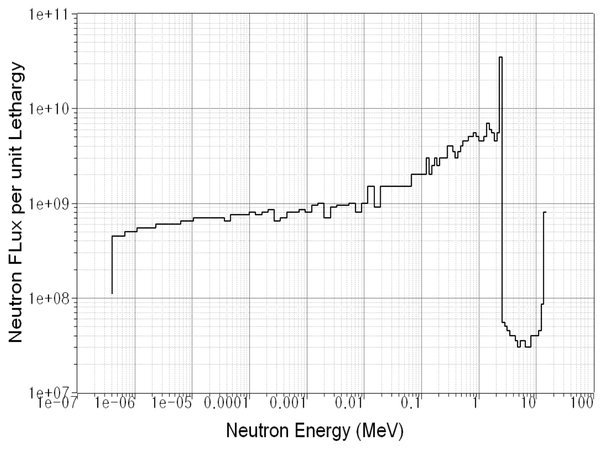

Figure2 Neutron energy distribution of the KSTAR device

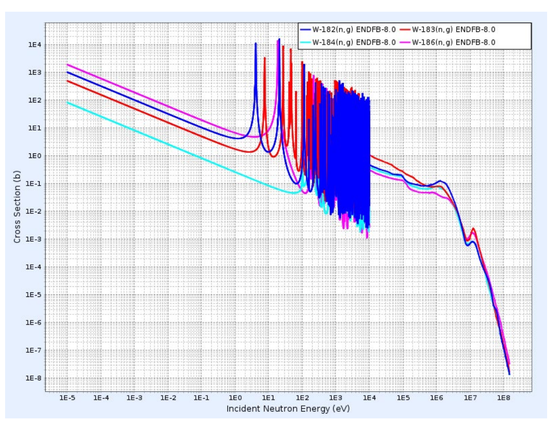

Figure3 Activation cross-section of tungsten

Interpretation and Computation Methodologies

The neutron source term (0–14.06 MeV) data from the KSTAR device is used as the source term for MCNP calculations.

MCNP: Calculates the neutron flux (F14 Tally) and reaction cross-section (F24 Tally) to produce the 1-group microscopic reaction cross-section.

ORIGEN-2: Calculates the generation and extinction of nuclides and changes in radioactivity over time based on the Bateman equation.

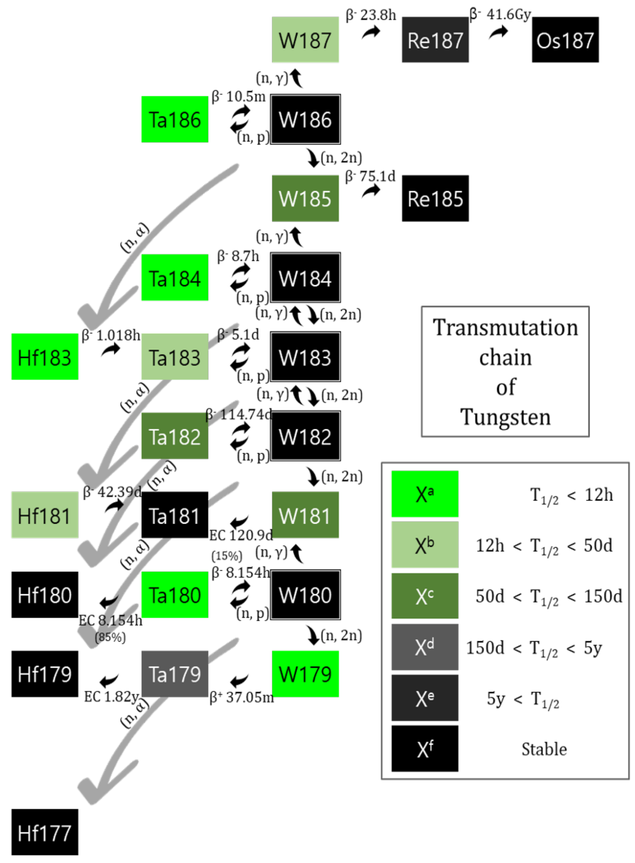

Figure 4 Tungsten nuclear reaction chain

Analysis Results and Evaluation

Changes in radioactivity: Upon 30 days of cooling following one year of continuous operation (20,000 seconds), 185W and 181W exhibited the most dominant radioactivity (Bq/m²).

Gamma radiation emission: Gamma radiation with average energies of 10 keV and 57.5 keV accounted for more than 90% of the total, making them highly dominant.

Dose Assessment: The estimated radiation exposure for workers was calculated using ICRP-74 dose conversion factors. Internal access will be restricted for one month after the work is completed, and managers will be required to wear protective equipment as necessary.

The radiation exposure dose from the activation of tungsten was estimated at 4.48 × 10^{-3} μSv/h, which is an insignificant level in terms of exposure.

Conclusion

Safety Management: The calculated radiation dose satisfies the dose limits under the Atomic Energy Safety Act, and worker exposure is minimized in accordance with the ALARA principle.

Additional Measures: We plan to control internal exposure by conducting monitoring using air samplers and providing appropriate protective masks if radioactive tungsten particles are detected.