Nuclear Heating in Fusion Reactors

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In fusion reactors neutrons produced by DT or DD reaction interact and make various types of reactions such as (n, g), (n, n), etc. with materials constructing the first wall, blankets and divertors, etc. In these reactions secondary neutrons, gamma-rays and/or charged particles are created and target nuclides are knocked on. The charged particles and the knocked nuclides move in the materials in short range and lose their kinetic energy by exchanging into thermal energy. The neutrons and gamma-rays travel in the materials in farther longer range than the charged particles and also exchange their energy into thermal energy. The thermal energies exchanged from kinetic energies are so called nuclear heat. In the first wall, blanket and divertor, etc. the nuclear heating rates are restricted in a certain range since their temperatures are controlled. In superconductive magnets nuclear heating rate is also restricted in order to prevent the magnets from quenching. Since estimated nuclear heating rates have uncertainties, we must allow for design margin in thermal and nuclear design. The design margin should be restricted as small as possible from the view point of reactor cost. Nuclear data used in calculating nuclear heating rates are required for high accuracy as wall as that in neutron and gamma-ray flux calculation codes. Nuclear heating rates are estimated with multiplying neutron and gamma-ray fluxes by nuclear heating constants in neutron and gamma-ray, respectively, (so called "neutron KERMA and gamma KERMA factors") in the case of using ANISN, DOT, DORT, TORT, etc. The gamma-ray KERMA factors can be given exactly by the value of gamma-ray energy deposition of (incident gamma-ray energy) - (outgoing gamma-ray energy). There are two methods to calculating the neutron KERMA factors. One is a direct method and the other an energy balance method. In the direct method the neutron KERMA factors are given by following equation.

$$K(E_n)=S^{x}_{\mathrm{reaction}}(E_c + E_p)\cdot s_x(E_R)\ .$$

Where E_n, E_c and E_p are incident neutron energy, charged particle energy and knocked on energy in the laboratory system, respectively, s_x is a cross section of reaction x and E_R is relative kinetic energy. The values of E_c and E_p are estimated by kinematics and energy conservation in collision. In the energy balance method the neutron KERMA factors are calculated by following equation.

$$K(E_n)=S^{x}_{\mathrm{reaction}}(E_n + Q_{n,x})\cdot s_x(E_n) - (e_n \cdot s_{n\text{-}prod}(E_n) + e_g \cdot s_{g\text{-}prod}(E_n)).$$

Where $Q_{n,x}$ is Q-value of reaction x, $s_{n\text{-}prod}$ and $s_{g\text{-}prod}$ are secondary neutron production cross section and gamma-ray production cross section, respectively, and e_n and e_g are outgoing neutron and gamma-ray energies in the center of mass system. In MCNP code, nuclear heat is given by the value of (incident neutron energy + Q-values in all reactions) - (outgoing neutron and gamma-ray energies). In MCNP code nuclear heating rates can be estimated easily without the KERMA factor set. In the energy balance method and method in MCNP code, if nuclear data of the secondary neutron and the outgoing gamma-ray energies, and the Q-values in all reactions are consistent with each other, the nuclear heating rates can be given as exact values. But if not so, KERMA factor by energy balance method or nuclear heating rates in MCNP cannot be estimated as exact values, because of deduction of large values each other. The uncertainties in KERAM factors calculated by the direct method are considered the same as those in nuclear data of 10-20%. On the other hand, if we restrict the uncertainties in KREAM factors estimated by the energy balance method or in nuclear heating rates in MCNP to the same as those by the direct method, nuclear data must be required to highly accurate of several % in addition to consistency in nuclear data of the secondary neutron and the outgoing gamma-ray energies, and the Q-values in all reactions. In fact since all nuclear data are not always consistent each other and have uncertainties, we had better apply a direct method avoiding deduction of large values each other.