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Validation of a Tritium Behavior Analysis Code for a VHTR

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1. Introduction

Tritium is a radioactive isotope of hydrogen with the half life of 12.32 years. Effect of radiation from tritium on health is relatively small and hazard only if it is taken into the body, because tritium decays by emitting a low-energy(18.6 keV) beta particle with no gamma radiation. However, it has been proven that an internal exposure by the tritium through inhalation or drinking water can cause serious damage to human bodies and that the effectiveness of tritiated water (HTO or T_2O) is 25000-times the effectivity of tritium (HT or T_2).

In a Very High Temperature Gas-Cooled Reactor (VHTR), neutron interactions with boron in control rods, impurities in the graphite core and ^{3}He isotopes in helium coolant gas as well as ternary fissions produce tritium under reactor operating conditions. Compared to the pressurized heavy or light water reactors, tritium in VHTR circulates and diffuses more readily because of the gaseous coolant. Since tritium can penetrate the structure barriers with its high diffusion coefficients even in intact material conditions, tritium should be treated as an important part of the regulation of a VHTR.

Recently, the code developments to evaluate quantitatively tritium behavior in high temperature gas-cooled reactors has been performed; for examples, TRITGO code (General Atomics)[1], THYTAN code (JAEA)[2], TPAC code (Idaho National Laboratory)[3], etc. Efforts to develop the mechanistic models and to increase the reliability of the analysis results have also been made in world-leading countries in the field of gas-cooled nuclear reactors such as USA and Japan. In KAERI, a tritium behavior analysis code (TRIBAC)[4] for a VHTR is under development, which will be verified and validated in this series of studies.

2. Implementation and Verification

2.1 Tritium Sources

The tritium generation mechanism in VHTRs is well described by Ohashi and Sherman[5]. The primary tritium birth mechanism is ternary fission of fuel (e.g., ^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu) by the thermal neutrons. The secondary birth mechanisms are from ^{6}Li, ^{7}Li, ^{3}He, and ^{10}B by neutron capture reactions. ^{6}Li and ^{7}Li are impurities in the core graphite material such as the sleeve, spine, reflector, and fuel matrix. ^{3}He is an impurity in the reactor coolant helium. ^{10}B exists in control rods, burnable poisons, and reflectors. Table I summarizes various tritium birth reactions and their microscopic neutron cross sections.

Table I: Tritium birth reactions and effective neutron cross sections

Reaction	Neutron group	Effective cross-section[cm^2]
^{6}Li(n, α)^{3}H	Thermal	4.0764×10^{-22}
^{7}Li(n, nα)^{3}H	Fast	7.1800×10^{-27}
^{10}B(n, 2α)^{3}H	Fast	1.3520×10^{-26}
^{10}B(n, 2α)^{7}Li	Thermal	1.6306×10^{-21}
^{12}C(n, α)^{9}Be	Fast	1.4680×10^{-28}
^{9}Be(n, α)^{6}Li	Fast	1.6520×10^{-26}
^{3}He(n, p)^{3}H	Thermal	2.2803×10^{-21}

With considerations on various tritium sources, the total tritium production rate is expressed as a summation of all possible tritium production rates.

$$\left[\frac{d(N_T)_r}{dt}\right]_{Prod} = \left[\frac{d(N_T)_r}{dt}\right]_{Fuel} + \sum_{TS}\left[\frac{d(N_T)_r}{dt}\right]_{TS}$$

Here, subscript *r* represents the region in a core so that the left hand side means total production rate of tritium particles at the region *r*. The first term of the right hand side is the production rate of tritium particles by ternary fission in the fuel region. Subscript *TS* represents tritium production sources such as ^{6}Li, ^{7}Li, ^{9}Be, ^{12}C, ^{10}B, ^{3}He. The governing equations for each tritium source are addressed as follows:

Ternary fission: $\left[\frac{d(N_T(t))_r}{dt}\right]_{Fuel} = kP_rY - \lambda(N_T(t))_r$

^{6}Li(n,α)T:

$$\left[\frac{d(N_6(t))_r}{dt}\right]_{Li6} = -\pi\Phi_{th}\sigma_6\left[(N_6(t))_r\right]_{Li6}$$

$$\left[\frac{d(N_T(t))_r}{dt}\right]_{Li6} = \pi\Phi_{th}\sigma_6\left[(N_6(t))_r\right]_{Li6} - \lambda\left[(N_T(t))_r\right]_{Li6}$$

^{9}Be(n,α)^{6}Li(n,α)T:

$$\left[\frac{d(N_9(t))_r}{dt}\right]_{Be9} = -\pi\Phi_f\sigma_9\left[(N_9(t))_r\right]_{Be9}$$

$$\left[\frac{d(N_6(t))_r}{dt}\right]_{Be9} = \pi\Phi_f\sigma_9\left[(N_9(t))_r\right]_{Be9} - \pi\Phi_{th}\sigma_6\left[(N_6(t))_r\right]_{Be9}$$

$$\left[\frac{d(N_T(t))_r}{dt}\right]_{Be9} = \pi\Phi_f\sigma_6\left[(N_6(t))_r\right]_{Be9} - \lambda\left[(N_T(t))_r\right]_{Be9}$$

^{12}C(n,α)^{9}Be(n,α)^{6}Li(n,α)T:

$$(N_{12}(t))_r = \text{constant}$$

$$\left[\frac{d(N_9(t))_r}{dt}\right]_{C12} = \pi\Phi_f\sigma_{12}(N_{12}(t))_r - \pi\Phi_f\sigma_9\left[(N_9(t))_r\right]_{C12}$$

$$\left[\frac{d(N_6(t))_r}{dt}\right]_{C12} = \pi\Phi_f\sigma_9\left[(N_9(t))_r\right]_{C12} - \pi\Phi_{th}\sigma_6\left[(N_6(t))_r\right]_{C12}$$

$$\left[\frac{d(N_T(t))_r}{dt}\right]_{C12} = \pi\Phi_{th}\sigma_6\left[(N_6(t))_r\right]_{C12} - \lambda\left[(N_T(t))_r\right]_{C12}$$

Here, k is the fission rate per thermal megawatt, P_r is the regional reactor power in MW, Y is the average yield per fission, λ is the decay constant of tritium in sec^{-1}, σ is the microscopic neutron cross section in cm^2, and Φ is the neutron flux in $cm^{-2}sec^{-1}$. The similar equation set can be composed for the following reactions.

$^7Li(n,n'\alpha)T$:
$^{10}B(n,2\alpha)T$ with fast neutron:
$^{10}B(n,\alpha)^7Li(n,n'\alpha)T$ with thermal neutron:
$^3He(n,p)T$:

In the TRIBAC code[4], the governing equation sets for the decay chains with or without continuous production are solved by the Bateman equation[6]. Except the tritium source model, models for tritium permeation, chemi-sorption, diffusion, leakage, and purification are implemented into the TRIBAC code along with the models for tritium recoil and tritium behavior in SI systems. The detailed description is provided in Yoo et al.[4]

2.2 Validation of the source term calculations

The measure data from the Peach Bottom Power Station Unit No. 1 is utilized and compared with the calculated results. The Peach Bottom HTGR was a helium-cooled, graphite-moderated, 115 MWt reactor, which operated from 1967 to 1974.[7] The total helium flow of 210,000 kg/h was divided equally between the two primary loops each containing a helium compressor and steam generator. Coolant temperatures at the core inlet and outlet of the reactor vessel were 345 and 714°C, respectively, and the primary loop pressure was approximately 2.4 MPa (335 psig).

As a first step of V&V, the core model is verified by comparing the calculated tritium production rates with the measured and analytical solutions[5]. Table II through V shows the results. Present calculation results by using TRIBAC match with the analytic solutions with less than 2% differences for all cases.

Table II: Tritium production by ternary fission

Reported Value [Bq]	Analytic	THYTAN	TPAC	TRIBAC
4.43E+13	4.43E+13	4.42E+13	4.42E+13	4.43E+13

Table III: Tritium production from Li-6

Component	Reported Value [Bq]	Analytic [Bq]	THYTAN [Bq]	TRIBAC [Bq]
Sleeve	5.13E+11	5.11E+11	5.12E+11	5.12E+11
Spine	3.66E+10	3.78E+10	3.78E+10	3.79E+10
RRR*	6.01E+11	5.77E+11	5.75E+11	5.73E+11
PRR**	6.89E+11	6.78E+11	6.69E+11	6.68E+11
Axial reflector	3.37E+11	3.42E+11	3.42E+11	3.43E+11
Fuel matrix	4.80E+11	5.67E+11	5.68E+11	5.69E+11

* RRR = Removable Radial Reflector,
** PRR = Permanent Removable Reflector

Table IV: Tritium production from B-10

Reported Value [Bq]	Analytic	THYTAN	TRIBAC
3.17E+12	3.19E+12	3.18E+12	3.186E+12

Table V: Tritium permeation and purification

	Analytic [atoms]	TRIBAC [atoms]
Purification	1.19E+19	1.18E+19
Leakage	1.37E+19	1.36E+19

3. Conclusions

The tritium behavior analysis code (TRIBAC) for a VHTR is under development in KAERI. As the first step of verification and validation of the developed computer software, the purified and leaked tritium and the tritium production rates of the Peach Bottom HTGR were calculated and compared with the analytic solutions. It has been proven that the developed TRIBAC code predicts tritium sources in a reasonable accuracy, compared to other tritium analysis codes. The next step will be the development of the containment model and simulation of tritium behavior in overall system of the Peach Bottom plant. The developed computer software can be used for the purposes of designing and the safety analysis for licensing and approval of the demonstration plant.

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