Comparison of Tritium Generation Amounts between Pebble and Block Type Reactor for VHTR

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1. Introduction

In 2004, the Korea Atomic Energy Research Institute (KAERI) launched a nuclear hydrogen program in which it aimed to develop and demonstrate by 2019 a mass producing hydrogen. Preconceptual designs for both pebble and block-type HTGR cores are being performed [1]. Because the main purpose of these reactors is to produce heat-induced hydrogen, none of the radioactive nuclide must contain in any generated hydrogen. Furthermore, because tritium is the only radionuclide that can permeate from the primary circuit through the heat exchanger walls into the secondary circuits where it causes unwanted contamination. This study is based on the conceptual design parameters of a gas turbine-modular helium rector (GT-MHR) and a PBMR because these types of reactors are reference reactors of the nuclear hydrogen program [2]

2. Methods and Results

Tritium is produced in the HTGR by ternary fission and by activation reactions between trace impurities and control materials that contain boron. In addition, a HTGR-specific tritium source is given by the helium coolant itself in the form of the neutron-absorbing nuclide ^{3}He, which has an abundance of extremely low isotopes. Compared with these sources, the contributions of other tritium-producing reactions with nuclides such as ^{9}Be or ^{12}C are negligible [3]. A detailed estimation of the amounts of tritium in relation to each source is as followed.

2.1 production of tritium in fuel

If the average yield of tritium atoms per fission is assumed to be approximately 1×10^{-4}(Y) and the fission rate per MW_{th}(K) is assumed to be 3.12×10^{-4} fission·sec^{-1}·MW_{th}^{-1}, the rate at which tritium is produced from fission may be obtained by using a simple differential equation [4]. Furthermore, no significant error is introduced by using the average power $\overline{P}$ rather than the complex power history P(t), given $\overline{P}$ is assumed to be constant over the life of the core. The result equation is as followed.

$$N_T(t) = K\overline{P}Y\left(\frac{1-\exp(-\lambda t)}{\lambda}\right) \qquad (1)$$

Where
$N_T(t)$: numbers of tritium
λ : decay constant

2.2 Production from ^{3}He in the coolant

Helium obtained from natural gas deposits is used as a reactor coolant. The level of ^{3}He contamination in commercially available helium has been shown to vary with the source. In general, helium derived from natural-gas wells contains approximately 0.1 ppm to 0.2 ppm ^{3}He, whereas the ^{3}He levels in atmospheric helium are about ten times higher [1,3]. Hence, it was assumed that the ^{3}He level is about 0.16 ppm in this study. The result equation is as followed.

$$N_{T1} = \frac{(V_1+V_7)\overline{\phi_{th}}\sigma_3 N_3}{Q+\lambda V} \qquad (2)$$

$$N_{Ti} = \frac{V_{i+1}}{V}\overline{\phi}_{th}\sigma_3 N_3\left[\frac{1-\exp(-\lambda t)}{\lambda}\right], i = 2\sim5 \qquad (3)$$

Where
$(V_1+V_6)/V$: the fraction of N_3 that exists in the coolant(V_1) and purge flow passages(V_6) of the core
Q: The helium loss flow rate is the sum of the chemical cleanup system flow and the helium leakage flow rate
N_{Ti} : tritium atoms in sleeve graphite (i=2), removal radial reflector(i=3), permanent radial reflector(i=4), and axial reflector(i=5)

2.3 Production from ^{6}Li in graphite

The production rate of tritium from the ^{6}Li contained in graphite can be easily evaluated by using a simple differential equation [4]. However, the Li levels in graphite can be so low that determining of an appropriate average concentration for a large graphite mass is difficult from the perspective of analytical chemistry and the sampling procedure. Furthermore, the Li content in graphite varies with the production region and company. In the case of an AVR, the Li content is assumed to be 0.5 ppm for the core graphite and 1.0 ppm for the reflector graphite [3]. In addition, the Li content is assumed to be 10 ppb for a HTR. The lithium concentration is around 5 ppb in ATR-2E block graphite and less than 0.8 ppb in spherical graphite fuel elements. This shows the technical possibility of manufacturing graphite qualities whose lithium content is significantly below the design value of 50 ppb. The Li concentrations for Peach Bottom were measured in the selected samples of Peach Bottom graphite, and the average of these values yields a ^{7}Li concentration of 7.0

ppb, this value was assumed to be representative of the graphite in this study. The result equation is as followed.

$$N_T(t) = \left(\frac{\bar{\phi}_{th}\sigma_6 N_6(0)}{\lambda - \bar{\phi}_{th}\sigma_6} \right) \left[e^{-\bar{\phi}_{th}\sigma_6 t} - e^{-\lambda t} \right] \quad (4)$$

where

$\bar{\phi}_{th}$: thermal flux in core and in removal radial reflector

σ_6: effective cross section ^{6}Li(n,α)T

$N_6(0)$: the initial amounts of ^{6}Li

2.4 Production from ^{10}B in the burnable poison and control rods

The amount of burnable poison is determined by reactivity control requirements, which may vary with each core reload. The diameter of the lumped burnable poison (LBP) rods is specified according to the self-shielding requirements of the absorber material for controlling the burnout rate relative to the fissile fuel burnout rate. The mass of the boron is not specified, so it can be surmised only from the amount of excess reactivity. The excess reactivity of 600 MW_{th} block-type reactor was calculated about 1.22 at BOC by using VSOP. In case of the Pebble type reactor, burnable poison is not used so it doesn't need to consider. The result equation is as followed.

$$\frac{N_T(t)}{N_{10}(0)} = \frac{ba}{(b-a)(\lambda-a)}(e^{-at} - e^{-\lambda t}) - \frac{ba}{(b-a)(\lambda-b)}(e^{-bt} - e^{-\lambda t}) + \frac{c}{\lambda-a}(e^{-at} - e^{-\lambda t}) \quad (5)$$

where

$$a = \beta\bar{\phi}_{th}\sigma_{10}, b = \bar{\phi}_{th}\sigma_7', c = \bar{\phi}_{th}\sigma_{10}'$$

And the result equation for evaluation of tritium by control rods is as followed.

$$N_T(t) = 5.184\times10^{-8} \times \frac{\sigma_{10}'\bar{\phi}_f}{\beta\sigma_{10}\bar{\phi}_{th}} \times \frac{\bar{P}}{f}\left(\frac{\sigma_a}{\sigma_f}\right)_{fuel}\left[\frac{1-\exp(-\lambda t)}{\lambda}\right] \quad (6)$$

where

β : self-shielding factor

$\bar{\phi}_f$: average flux in excess of 0.18 MeV

σ_{10}: cross section for ^{10}B(n,α)^{7}Li

σ_{10}' : cross section for ^{10}B(n,2α)T

3. Conclusion

In this study, tritium generation in high temperature gas-cooled reactors was performed. To evaluate tritium generation and diffusion, both pebble and block type HTGR core were referred. Tritium source and evaluated amounts was summarized in table 1. As anticipated, ternary fission produced the largest source and the boron is only major source term in case of block type reactor because the Pebble type reactor is not used the burnable poison. These results of tritium production amounts can be used for evaluation of tritium diffusion from where it was generated to primary He coolant.

ACKNOWLDEGMENTS

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Table 1. Comparison of the tritium production rate according to the reactor type (unit : Ci/yr)

Reactor type	Thermal Power (MW_{th})	Units	Tritium Source					Reference
			Ternary fission	^{3}He	^{6}Li	^{10}B	Total	
Pebble	500	Ci/yr	3200	200	150	260	3810	[3]
		%	84.0	5.3	3.9	6.8	100	
Block	115	Ci/yr	303	11	73	219	606	[4]
		%	50.0	1.8	12.0	36.2	100	
Pebble	300	Ci/yr	1196.8	67.9	82.6	12.4	1359.6	This study
		%	88.0	5.0	6.1	0.9	100	
Block	600	Ci/yr	2183.3	39.8	169.5	941.3	3333.9	This study
		%	65.5	1.2	5.1	28.2	100	