



Analysis of tritium behaviors on VHTR and forward osmosis integration system

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ABSTRACT

Recently, a novel concept of integrating Very High Temperature Reactor (VHTR) waste heat to Forward Osmosis (FO) system has been proposed. The proposed nuclear desalination system possesses a significantly higher energy utilization rate, however at the same time introduces a tritium exposure issue. This is especially critical as the VHTR integrated FO system produces potable water since tritium is especially hazardous when ingested. In this study, a numerical code named BOTANIC is developed using a chemical process analysis code, gProms, in order to understand tritium behaviors in the VHTR-FO system and migration of tritium to downstream processes. The code involves tritium generation, sorption, leakage, purification, recombination, dissociation, permeation, trapping, release models. The developed code is verified using the analytical solutions and the benchmark code in stepwise approach. Using the developed BOTANIC code, tritium behavior in the proposed VHTR-FO system is analyzed and sensitivity analysis is extensively conducted in order to figure out the effective measures for reducing tritium level in the final product. Based on the sensitivity analysis results, two mitigation concepts are suggested and investigated; (1) protective barrier in PHX and (2) ceramic PHX.

1. Introduction

Water scarcity and energy depletion are the two major global issues which are only intensifying due to global population growth. Nuclear desalination concepts have been suggested and studied in order to tackle the mentioned issues. The concept of integrating desalination technology to nuclear power plant has gained attention due to its cost competitive feature. The feasibility of the integrated nuclear desalination plants has been proven with over 100 accumulated reactor years of experience in Kazakhstan, India and Japan (IAEA, 2007). The concept of nuclear desalination technology has evolved in terms of energy utilization rate as seen in Table 1. Improvement in energy utilization rate was possible due to the concept of integrating VHTR to desalination technology. As VHTR has a very high operating temperature and employs gas turbine power conversion cycle, high quality waste heat is discharged from the reactor. Concept of utilizing this waste heat has enabled the enhancement of the energy utilization efficiency.

Although the integration of VHTR and desalination process produces an effective electricity and water cogeneration system (Park and Kim, 2014), it also intensifies the tritium migration issue from VHTR to integrated desalination system. And this safety issue must be treated more severely as the integrated desalination system produces drinking

water. Tritium, a radioactive hydrogen isotope with two additional neutrons than the typical hydrogen, goes through beta decay and releases at maximum 18.6 keV of energy during this process. The emitted low energy beta particles can only penetrate about 6.0 mm of air and are unable to penetrate human skin. The low-energy beta particle emitted by tritium has a maximum range in water or tissue of 6 mm, thus, it can be said as non-hazardous externally (Glasstone and Jordan, 1980). However, beta radiation is a type of ionizing radiation which can cause cell damage and further cause cancer or genetic disorder when exposed inside the body. Given its low energy beta emission and the short range in air, tritium poses a health risk only when ingested, inhaled or absorbed through skin. The biological half-life of tritium depends on the form and the method of intake. Only about 0.004 percent of inhaled tritium gas is retained more than a minute or so, the rest is eliminated almost immediately through respiration (Fairlie, 2007). When tritium is ingested in tritiated water form it immediately mixes with the body fluids and has a half-life of 10 days. And as tritiated water act as water in the body, tritium is distributed through all biological fluids within 1–2 h. In other words, tritium is hazardous when ingested in the body. And as a result, regulatory limits have been set for tritium in drinking water. The EPA standard for drinking water is set as $2 \times 10^{-5} \mu\text{Ci/mL}$ (EPA, 1976). Thus, tritium must be treated more

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Nomenclatures and Abbreviations

A	Area (m^2)	S_e	Energy source term (J s^{-1})
C	Concentration (mol m^{-3})	S_m	Mass source term (kg s^{-1})
$C_{1,s}$	Constant used in Myers isotherm ($\text{cm}^3 \text{m}^{-2} \text{mmHg}^{-1}$)	t	Time (s)
$C_{2,s}$	Constant used in Myers isotherm ($\text{m}^2 \text{n}$)	T	Temperature (K)
$C_{s,2}$	Constant used in Myers isotherm (K^{-1})	v	Vertical distance between PCHE channel (m)
C_H	Annealing factor used in Myers isotherm	x	Mass fraction
d	Diameter (m), grain size (m)	y	Mole fraction
D	Diffusivity, Permeability ($\text{mol m}^{-1} \text{s}^{-1} \text{Pa}^{-0.5}$)	Y	Average yield per fission (fission^{-1})
E_a	Activation energy (J mol^{-1})	W	Reactor power (MW)
F	Flowrate (kg s^{-1})	f	Fraction of helium supply rate (s^{-1})
Fi	Fission rate per thermal megawatt ($\text{fissions W}^{-1} \text{s}^{-1}$)	λ	Tritium decay constant (s^{-1})
h	Specific enthalpy (J kg^{-1}), convection heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$), horizontal distance between PCHE channel (m)	σ	Cross section (cm^2)
L	Length, Thickness (m)	φ_f	Average fast neutron flux ($\text{n/cm}^2/\text{s}$)
L_R	Leakage rate (kg s^{-1})	φ_{He}	Average thermal neutron flux experienced by the helium inventory ($\text{n/cm}^2/\text{s}$)
M	Mass (kg)	φ_{th}	Average thermal neutron flux ($\text{n/cm}^2/\text{s}$)
M_T	Total mass holdup (kg)	ρ	Density (kg m^{-3})
N	Number of atoms	η	Efficiency
o	Offset distance of PCHE channel (m)	<i>BOTANIC</i>	Behavior of Tritium Analytic Code
P	Pressure (Pa), Partial Pressure (Pa)	<i>FO</i>	Forward Osmosis
R	Universal gas constant ($\text{J mol}^{-1} \text{K}^{-1}$), Permeation rate (mol s^{-1})	<i>IHX</i>	Intermediate Heat Exchanger
S	Source term (kg s^{-1}), (J s^{-1})	<i>MED</i>	Multi Effect Distillation
S_0	Sievert's pre-factor	<i>MSF</i>	Multi Stage
S_1	Shape factor 1	<i>PCHE</i>	Printed Circuit Heat Exchanger
S_2	Shape factor 2	<i>PHX</i>	Process Heat Exchanger
		<i>RO</i>	Reverse Osmosis
		<i>TRF</i>	Tritium Reduction Factor
		<i>VHTR</i>	Very High Temperature Gas-Cooled Reactor

seriously in the suggested integration system as the product of the VHTR integrated system is drinking water.

Tritium is involved in various phenomena in the VHTR integrated system as can be seen in Fig. 1. Tritium is generated and lost through various processes. The processes include tritium production, sorption, leakage, purification and permeation. In VHTR, tritium is mainly produced as a byproduct in ternary fission reaction. Tritium is also generated in neutron capture reactions with the core and coolant materials such as ^6Li , ^3He , ^{10}B and ^7Li . Most of the tritium generated in the core is retained or sorbed in the reactor core and some are released into the coolant. Some of the tritium in the system is removed through purification, portion of tritium is leaked out of the system and some permeate into secondary and even to the integration loop. As seen here, tritium produced in the core can migrate down into the secondary system, into the industrial process and into the final product of that process through permeation in the heat exchanger. Therefore, understanding and predicting tritium behavior, migration of tritium to downstream processes is important in terms of safety, licensing and public acceptance.

In this study, tritium analysis code named Behavior of Tritium

Analytic Code (BOTANIC) is developed based on a commercial chemical process analysis code called gPROMS. The code incorporates physical/chemical models for analyzing tritium generation, sorption, leakage, purification, recombination, dissociation, permeation, trapping, release mechanisms. BOTANIC possesses several distinctive features such as non-diluted assumption and capacity to perform system dynamics calculation. The developed code is then verified using the analytical solution and benchmark calculation results generated based on the Peach bottom reactor core II data. With the verified code, the tritium behavior in the VHTR and FO integrated system is analyzed and tritium mitigation approaches have been suggested based on the sensitivity analysis.

2. Physical models

2.1. Conservation equations

In order to solve the transport of the species in the system, mass and energy conservation equations are solved as shown below. Generation or loss of each species is reflected using the source terms; S_m and S_e .

Table 1
Nuclear desalination advances (IAEA, 2007).

Desalination technology	LWR-Multi Stage Flash (MSF)	LWR-Multi Effect Distillation (MED)	LWR-Reverse Osmosis (RO)	VHTR-Multi Stage Flash (MSF)	VHTR-Multi Effect Distillation (MED)	VHTR-Forward Osmosis (FO)
Electricity consumption [kWh/m^3]	3.5	1.5	6	3.5	1.5	0.84
Thermal energy consumption [kWh/m^3]	25–200	25–200	0	25–200	25–200	26–150
Top brine temperature [$^{\circ}\text{C}$]	110	65	N/A	110	65	N/A
Energy utilization rate [%]	33.0	33.0	33.0	51.1	76.8	89.6
Disadvantage	Energy intensive (thermal)	Energy intensive (thermal)	Low quality product	Energy intensive (thermal)	Energy intensive (thermal)	Requires post-process: draw solute recovery process

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