p ISSN 0852−4777; e ISSN 2528 - 0473

ESTIMATION OF ROUTINE DISCHARGE OF RADIONUCLIDES ON POWER REACTOR EXPERIMENTAL RDE

Pande Made Udiyani, Sri Kuntjoro
Center for Nuclear Reactor Technology and Safety – BATAN
Kawasan Puspiptek, Serpong, Tangerang Selatan, 15314
e-mail : pmade-u@batan.go.id
(Naskah diterima: 19-12-2016, Naskah direvisi: 30-01-2017, Naskah disetujui: 06-02-2017)

ABSTRACT

ESTIMATION OF ROUTINE DISCHARGE OF RADIONUCLIDES ON POWER REACTOR EXPERIMENTAL RDE. Experimental power reactor (RDE), which is planned to be constructed by BATAN, is a kind of High Temperature Gas Cooled Reactor (HTGR) with 10 MWth power. HTGR is a helium gas-cooled reactor with TRISO-coated fuel that is able to confine fission products to be remained in the core. To ensure the safety for workers and public surroundings of the RDE site and to meet the regulatory body requirements for construction and operation, research is needed for environmental radiation in normal and abnormal condition. This study is focused on normal operating condition, while for the accident condition study will be carried out after the final design has been completed. Estimation of radiology in the environment involves the source term released into the environment under routine operation condition. The purpose of this study is to estimate the source terms released into the environment based on postulation of normal or routine operation of the RDE-10 MWth. The research approach starts with an assumption that there are defects and impurities in the TRISO fuel because of limitations during the fabrication. Mechanisms of fission products release from the fuel to the environment were created based on the safety features design of RDE. Radionuclides inventories in the reactor were calculated by the use of ORIGEN-2 whose library has been modified for HTGR type, while assumptions on TRISO fuel defects and release fraction for each compartment of the RDE safety systems are defined by a reference parameter. The results show that the important source terms of RDE are group of noble gases (Kr and Xe), halogen (I), Sr, Cs, H-3, and Ag. Activities of RDE source terms for routine operations have no significant difference with the HTR-10 source terms with the same power.

Keywords: Routine discharge, radionuclide, source terms, RDE, HTGR.

p ISSN 0852−4777; e ISSN 2528 - 0473

ABSTRAK

ESTIMASI LEPASAN RADIONUKLIDA PADA KONDISI OPERASI RUTIN REAKTOR DAYA ESKPERIMENTAL*. Reaktor daya eksperimental (RDE) yang akan dibangun BATAN adalah jenis High Temperature Gas Cooled Reactor (HTGR) dengan daya 10 MWth. HTGR merupakan reaktor berpendingin gas helium dengan bahan bakar TRISO dengan pelapis yang mampu mengungkung produk fisi tidak lepas ke luar teras. Untuk menjamin keselamatan pekerja dan masyarakat sekitar reaktor RDE serta untuk memenuhi persyaratan dari badan pengawas pada tahap pembangunan dan operasi perlu dilakukan penelitian radioaktivitas lingkungan untuk reaktor RDE pada kondisi operasi normal maupun kecelakaan. Pada makalah ini dilakukan penelitian untuk kondisi operasi normal, sedangkan untuk kondisi kecelakaan akan dilakukan bila disain final telah lengkap. Estimasi radiologi di lingkungan melibatkan suku sumber nuklida yang lepas ke lingkungan pada kondisi operasi rutin. Tujuan dari penelitian ini adalah untuk estimasi suku sumber lepas ke lingkungan berdasarkan postulasi operasi rutin atau normal RDE. Metodologi penelitian dimulai dengan asumsi adanya cacat dan pengotor pada bahan bakar TRISO karena keterbatasan fabrikasi. Mekanisme lepasan produk fisi dari bahan bakar TRISO ke lingkungan dibuat berdasarkan desain fitur keselamatan RDE. Inventori reaktor dihitung menggunakan ORIGEN-2 yang sudah dimodifikasi untuk suhu tinggi HTGR, dan asumsi TRISO cacat serta fraksi lepasan untuk setiap kompartemen sistem keselamatan RDE menggunakan parameter acuan. Estimasi menghasilkan untuk radionuklida suku sumber yang berperan di RDE-10 MWth adalah kelompok gas mulia (Kr dan Xe), halogen (I), Sr, Cs, H-3, dan Ag. Aktivitas suku sumber RDE untuk kondisi operasi rutin tidak ada perbedaan yang berarti dengan suku sumber HTR-10 dengan daya yang sama.*

Kata Kunci*: Operasi rutin, radionuklida, suku sumber, RDE, HTGR.*

INTRODUCTION

BATAN has set the priority activities in a focused area of energy for the period 2015-2019, namely development of an experimental power reactor (RDE). Batan is planning to build an experimental power reactor RDE of HTGR (High Temperature Gas Cooled Reactor) type with 10 MWth power. The HTGR is an advance reactor concept. It has advantages in the design, where it includes passive heat removal, fuel capable of confining radioactive fission products and thus serving as additional barriers to fission products and radioactive releases. Passive heat removal occurs when a reactor shutdowns and the decay heat removal is achievable through conduction, natural convection and radiation heat transfer. All the achievable concept may occur due to the core geometry, low power density of the core and high thermal capacity of the core structures. Fuel that is capable of confining fission products is characterized by the fuel element design with multi coated layers of silicon carbide fuel particles for optimum retention of fission products. The silicon carbide layer has the ability to confine fission products and it can also withstand very high temperature. Barrier of fission products release of RDE-10 MWth consists of the pressure boundary, building, suppression pool and filters[1-8].

To ensure the safety of workers and public around the reactor site from radionuclides release from the RDE-10 MWth reactor and to meet the criteria required by the regulatory body for the construction and operation of the reactor, it is necessary to analyse the distribution of radionuclides into the environment on normal operation and accident conditions. These analyses are also required for public guarantee that the reactor is built to operate safely. Public acceptance on the radioactivity in the environment is one of the key factors on the construction phase of the Nuclear Power Plant (NPP). Estimation on the fission products released from RDE-10 MWth under normal operating condition is needed to estimate radiological environment caused by the reactor operation. This research was conducted to analyse the source terms of RDE-10 MWth reactor under normal operating condition, which will be used to estimate the environment dose in Serpong Nuclear Area (KNS).

Fission products are released from a reactor in accordance with radionuclides transport mechanisms. Release mechanism includes fuel, core, building ventilation, helium purification, gaseous radioactive waste system, and neutron activation of circulating air through the Reactor Cavity of Cooling System (RCCS)[2-5, 6-7]. Mechanistic approach for a source term development is required to setup technical basis and to take appropriate benefit of radionuclide retention capabilities of each of the multiple barriers in radionuclides transport. The radionuclide transport mechanism from reactor core to environment is consistent to the HTGR safety design approach. Unlike the LWR reactors, the HTGR safety features rely on TRISO fuel conditions. Defence in depth in HTGR reactor fuel starts from TRISO, which consists of several layers, for prevention of fission products escape into the cooling system. The most important consideration in analysing of fission products release rate from an HTGR core is to predict the in-service performance of the TRISO-coated fuel particles. The TRISO particle properties are ones of the most important factors in determining the radiological safety of HTGR. This is because retained fission products in the fuel, fuel burnup and temperature that can be tolerated in the reactor core are mainly determined by the properties of the TRISO fuel particles[1,7-12].

The methodology to estimate the source rate is by examining the diffusion mechanisms of fission products from the TRISO fuel into the environment. This

p ISSN 0852−4777; e ISSN 2528 - 0473

activity involves estimating reactor inventory, primary coolant condition, condition of confinement of the reactor building, filters in the cooling system, the reactor building and other systems in reactor operation. Reactor inventory will be calculated with ORIGEN-2 software that has been modified for high temperature HTGR. Release fraction of TRISO fuel to cooling system circulation is assumed as defective particles due to limitations in fabrication. Mechanisms of transport of the released fraction from fuel to the cooling circulation, reactor building and the environment are adopted from reference parameters.

THEORY

The fuel element consists of TRISO fuel particles containing fissile and fertile materials confined in the SiC layer, which serves to hold the fission products. The buffer layer or a layer of porous carbon, serves as an empty volume for fission products, accommodating swelling if there is swelling in the kernel, and diluting fission recoils. Inner Pyrocarbon (IPyC) prevents CI attack to the kernel during fabrication, reduces the tensile stress in SiC, and holds fission product gases. Silicon Carbide (SiC) fucntions as part of the main bearings, that retain fission products gases and metals. Outer Pyrocarbon (OPyC) reduces the tensile stress in the SiC, holds fission product gases, serves as chemicals to protect SiC from rift, and provides bonding surface for compacting[2-4, 8-9,13].

Source term is an expression used to denote information about the actual or potential release of radioactive material from a given source, which may include specifcation of the composition. The amount, rate and mode of the release of a source term depend on core inventory, reactor type, postulations of accident, safety system, operation history of a nuclear reactor. Source terms refer to the quantities, half life, physical and chemical forms, and thermal energy of radionuclides (used here interchangeably with fission products) released from reactor building to the environment during postulated events/accidents. In HTGRs the core does not “melt”, and high temperature capability of the core materials is not limiting. For HTGRs, the comparable events are those in which there is limited, incremental degradation or failure of fuel particle coatings, but such events do not result in loss of callable geometry. The HTGR definition is judged properly for fuel use application rather than the reactor building as primary barrier to fission products release.

The expected fission product sources associated with a graphite core containing tristructural-isotropic (TRISO)-coated particle fuel (including transport through the various fuel particle layers) and other sources of circulating activity, such as contaminated dust. The various mechanisms of holdup for fission products within the fuel element, core graphite, helium pressure boundary, and reactor building and the influence that the reactor building design would have on atmospheric releases. Radionuclide (RN) transport in HTGRs occurs within fuel kernels, particle coatings, fuel matrix/graphite, primary coolant circuit, and reactor building. These multiple RN barriers provide defense-in-Depth[1,7]. The four coating layers of a TRISO particle have specialized purposes as shown in composite, by which they join a high-integrity pressure vessel that is extremely retentive of fission products. Coating layer purposes on Figure 1 are:

1. Fuel Kernel[13]
   - Contains fissile and fertile material
   - Retains fission products
2. Buffer layer (Porous Carbon layer)
   - Void volume for fission gases
   - Accommodates Kernel swelling
   - Attenuates fission recoils

3. Inner Pyrocarbon (IPyC)
   - Prevents Cl attach Kernel during manufacture
   - Reduces tensile stress in SiC
   - Retains gaseous fission products
4. Silicon Carbide (SiC)
   - Primary load bearing member
   - Retains fission products gases and metals
5. Outer Pyrocarbon (OPyC)
   - Reduces tensile stress in SiC
   - Retains fission product gases
   - Protects SiC from core chemical environment
   - Provides bonding surface for compacting.

The following five barriers to fission product radionuclides release are reviewed:

1. Fuel particle kernel
2. Silicon carbide and pyrocarbon coatings of the fuel particle
3. Fuel matrix and graphite fuel element
4. Helium pressure boundary (primary circuit)
5. Reactor building

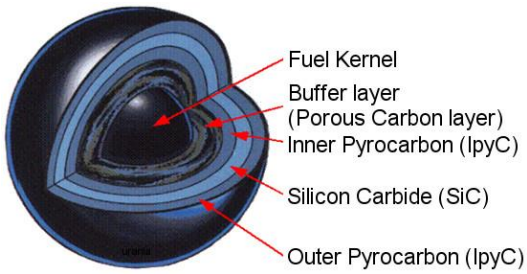

Figure 1. TRISO fuel particle configuration[1,7]

From Fig 1, four coating layers of TRISO particle act as pressure vessel with high integrity that is very strong against fission products. The main purpose of the high density IPyC coating, on which SiC coating is deposited, is to have high integrity and prevent chlorine (Cl_2) and hydrogen chloride (HCl) againts being absorbed by fuel kernels during the deposition process of SiC[2-4,7,9,13]. Therefore, IPyC plays an important role during the fabrication. IPyC coating is tightly bound to the SiC layer keep the SiC layer firm during compression time of irradiation and dimensionally stable.

SiC coating layer is the most important in TRISO particles because it provides most of the structural strength and dimensional stability as well as serves as a major barrier to the release of fission products, especially some of the metal volatile fission products such as cesium. As upholstery, high density OPyC shrinks during irradiation time, which also produces compressive stress in SiC dimension, and is partly compensating for the components of the tensile stress caused by the internal gas pressure. OPyC coatings are also effective in maintaining the fission gas in the fuel particles in case of SiC fabrication defect that fails to work up to about 1800 °C[2-4,7,12-14].

Transport mechanism of fuel nuclides of TRISO fuel into the environment under normal condition shows that there is a relationship between some elements affecting the behavior and distribution of radionuclides in the primary circuit and elements influencing the behavior of radionuclides in the reactor building. After some period of normal operation, distribution of most of the radionuclides produced by fission products (as well as long-lived radionuclides such as Cs-137 and Sr-90) will be formed in the primary circuit. The quantity of each species in the cooling system depends on the detachment of radionuclides from the fuel, half-life of radionuclides, adsorption of certain radionuclides in the fuel by core graphite and graphite dust[1,7]. Deposition on certain components of the primary circuit, including falling dust, may result in lowering the speed of the helium purification system performance (HPS). Release rate of each radionuclide during normal operation depends mainly on initial fuel quality and fuel service condition.

The particles of the first fuel are assumed to fail to keep it self intact in

p ISSN 0852−4777; e ISSN 2528 - 0473

service. Despite very limited number of failures in service is anticipated during normal operation, there is a statistical limit of fuel failures in a service established for design purposes because only a limited population can be irradiated for the qualification of fuel. Initial particle defects and assumed failures in a service would release gases and metals of fission products. Detachment from defective particles is a function of the nature of the defect, temperature, fuel level, and time. Fission product gas of iodine and a small part of the metal fission products penetrate through the graphite and then off to the reactor coolant system.

Helium purification system, which attracts a fraction of the cooler on each pass in a reactor, will reduce the concentration of some fission products. Deposition of fission products is condensed on the surface of the primary system, and it is also expected when the temperature is low enough. Design of HTGR with higher inlet and outlet cooling (such as the outlet temperature of 900-950 °C) will have precipitation of iodine less than in that with lower temperature (such as, the outlet temperature of 700-800 °C). Lower temperature design produces higher iodine circulation inventory, which will be separated at the time of reduction in pressure (depressurization) accident. Deposition is a function of partial pressure of fission products, local temperature, cooling chemical and surface condition of metal alloys used in the cooling system[1,6-7].

Graphite dust in the primary circuit will also absorb certain fission products. Dust can accumulate in areas that have a low speed, and it will contribute to worker doses and potential sources of activity in helium. Finally, during reactor operation, quasi-steady condition model will be developed for the inventory in the purification system, inventory deposition in the cooling system, and circulatory activity. Radionuclides concentration at steady state in the primary circuit and radionuclides deposited on the primary circuit components will accumulate in the dust in the system to form the first source of radionuclides release into the reactor building in case of pressure reduction in depressurization accident[1,6-7].

METHODOLOGY

The RDE-10 MWth source terms are calculated based on HTGR inventory models[15]. The reactor inventory is calculated using ORIGEN-2 with cross-section modified for high temperature. The reactor source terms are determined from its inventories and radionuclide fractions released from the fuel to the cooling system and other reactor systems until stack. The released fractions used were obtained from a reference parameter[1,6-7, 16].

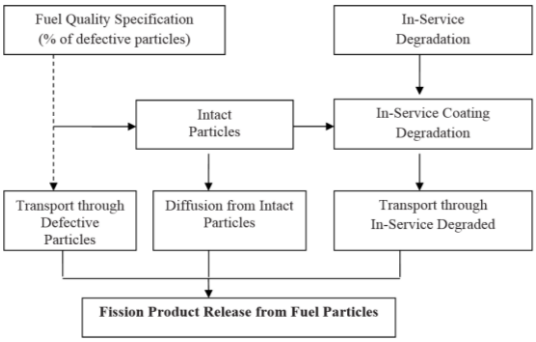

Figure 2. Mechanistic nuclide transport nuclides of TRISO[6-7]

Removable fission products parameters from pebble and the four layers to the environment are calculated using removable fractions and diffusion processes in the scheme of Fig. 2-3 and assumptions of parameters[1,6-7,16]. Defective particles and fuel diffusion from the kernel to the outside part of the pebble in Fig. 2 are assumed by fuel quality and irradiation temperature. The process of fission products release from the kernel to the outside part of the pebble is strongly influenced by the diffusion process of fission products such as diffusion in UO_2 kernel, diffusion in layers, and diffusion in graphite crystals. Based on Fig. 2, it is

assumed that the Removable Fraction (FL) through defective particles is $8x10^{-4}$, diffusion through intact coatings is $5x10^{-4}$, transport through degraded coatings In-service is $5x10^{-5}$, and release of fission products from fuel particles is $5x10^{-3}$[1,6-7,16].

Figure 3 shows the transport mechanism of fuel nuclides into the environment. Assumptions for fission products release from fuel particles is 5 x 10^{-3}; fission products release from fuel quality specification on contamination is 6 x 10^{-5}; and fission product release from Heavy metal contamination is 5 x 10^{-5}[1,6-7,16]. On the circulating system, activity in primary coolant is assumed to be 1 % for the nuclides of I and H-3, and 10 % for other nuclides. Removable fraction to the primary coolant of reactor building is 2.3 x 10^{-3}, and efficiency of filters in cleanup section in helium purification system is 99 % for (I, H-3) and 90% for other nuclides. The efficiency of the filter to the outside of reactor building is 99% for I and H-3 and 90% for other nuclides[8-9].

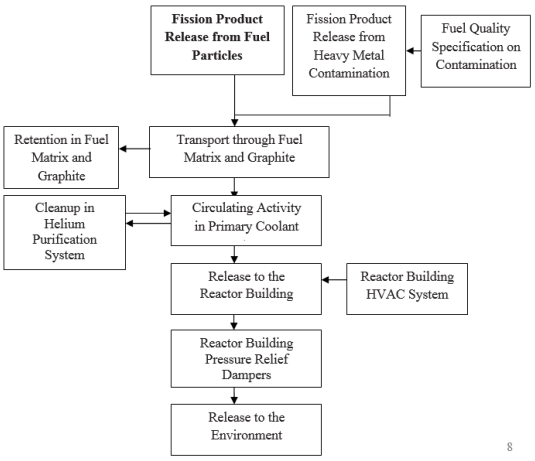

Figure 3. HTGR mechanistic nuclide transport to environment[1,6-7]

RESULT AND DISCUSSION

The results of inventory calculation for the RDE-10 MWth are presented in Table 1 and the source terms are presented in Table 2 – 3. The calculated results in Table 1[15] used Origen-2 that has been modified based on core parameters of HTGR such as burn up fraction, irradiation time, reactor power, neutron flux, the number of fissile elements (uranium or mix), and geometry of the core.

Table 1 describes the fission products formed in the fuel pebble, which depend on the parameters of irradiation. Dominant nuclides in the inventories of the RDE-10 MWth can be grouped into noble gases (Kr and Xe), Halogen (I), Cs, Sr, H-3 and Ag. Table 2 displays fission products release from fuel particles of the RDE-10 MWth, and Table 3 shows fission products release from the core to the environment. The fission products release from fuel particles of the RDE-10 MWth was calculated based on the mechanism of routine release in Figure 2 and the results are shown in Table 1.

Table 1. Inventory activity of HTGR 10 MWth[15]

Nuclide	Activity (Bq)	Nuclide	Activity (Bq)
H-3	3.81E+12	I-131	9.75E+15
Kr-83m	1.41E+15	I-132	1.46E+16
Kr-85	8.75E+13	I-133	2.11E+16
Kr-85m	3.59E+15	I-134	2.47E+16
Kr-87	7.10E+17	I-135	1.70E+16
Kr-88	1.03E+16	Sr-89	1.30E+16
Xe-131m	1.07E+14	Sr-90	5.35E+14
Xe-133	2.05E+16	Cs-134	3.11E+14
Xe-133m	5.90E+14	Cs-137	6.90E+14
Xe-135	7.95E+15	Ag-110m	2.16E+12
Xe-135m	2.64E+15		

The TRISO fuel of HTGR is resistant to high temperatures, so that under normal operating condition the calculation of source terms depend on assumptions on fuel conditions and uranium impurities on the TRISO surface. The initial defective particles and those assumed to fail in service will release gases and metals fission products. Releases from defective particles are strong function of the nature of the defect, temperature, burnup, and time. The rate of release of each species of the radionuclides from the fuel particles during normal operation is primarily dependent on the initial fuel quality

p ISSN 0852−4777; e ISSN 2528 - 0473

and the fuel service conditions. Assumptions for particle defects that occur in fuel TRISO are taken conservatively.

The most important consideration in predicting the radionuclides release rate from the RDE-10 MWth reactor is the prediction of the in-service performance of the TRISO-coated fuel particles. There is a significant retention of the fission products in the kernel itself. The fuel kernel and the SiC coating are the major barriers for fission products release from the fuel particle[6,13-14,16]. The graphitic materials do not retain fission gases and iodine, but operation experience indicates that fission metals like strontium and cesium are strongly retained in these materials. Retention in the graphitic materials are a strong function of temperature and fast fluence[6-9,12,14].

Table 2. Fission product release from fuel particles RDE-10 MWth.

Nuclide	Activity of inventory (Bq)	Transport through defective particles	Diffusion from Intact particles	Transport through in-service degraded	Fission product to fuel particles	Fission product release from fuel particles
H-3	3.81E+12	3.05E+09	1.91E+09	1.91E+08	5.14E+09	2.57E+07
Kr-83m	1.41E+15	1.13E+12	7.05E+11	7.05E+10	1.90E+12	9.52E+09
Kr-85	8.75E+13	7.00E+10	4.38E+10	4.38E+09	1.18E+11	5.91E+08
Kr-85m	3.59E+15	2.87E+12	1.80E+12	1.80E+11	4.85E+12	2.42E+10
Kr-87	7.10E+17	5.68E+14	3.55E+14	3.55E+13	9.59E+14	4.79E+12
Kr-88	1.03E+16	8.24E+12	5.15E+12	5.15E+11	1.39E+13	6.95E+10
Xe-131m	1.07E+14	8.56E+10	5.35E+10	5.35E+09	1.44E+11	7.22E+08
Xe-133	2.05E+16	1.64E+13	1.03E+13	1.03E+12	2.77E+13	1.38E+11
Xe-133m	5.90E+14	4.72E+11	2.95E+11	2.95E+10	7.97E+11	3.98E+09
Xe-135	7.95E+15	6.36E+12	3.98E+12	3.98E+11	1.07E+13	5.37E+10
Xe-135m	2.64E+15	2.11E+12	1.32E+12	1.32E+11	3.56E+12	1.78E+10
I-131	9.75E+15	7.80E+12	4.88E+12	4.88E+11	1.32E+13	6.58E+10
I-132	1.46E+16	1.17E+13	7.30E+12	7.30E+11	1.97E+13	9.86E+10
I-133	2.11E+16	1.69E+13	1.06E+13	1.06E+12	2.85E+13	1.42E+11
I-134	2.47E+16	1.98E+13	1.24E+13	1.24E+12	3.33E+13	1.67E+11
I-135	1.70E+16	1.36E+13	8.50E+12	8.50E+11	2.30E+13	1.15E+11
Sr-89	1.30E+16	1.04E+13	6.50E+12	6.50E+11	1.76E+13	8.78E+10
Sr-90	5.35E+14	4.28E+11	2.68E+11	2.68E+10	7.22E+11	3.61E+09
Cs-134	3.11E+14	2.49E+11	1.56E+11	1.56E+10	4.20E+11	2.10E+09
Cs-137	6.90E+14	5.52E+11	3.45E+11	3.45E+10	9.32E+11	4.66E+09
Ag-110m	2.16E+12	1.73E+09	1.08E+09	1.08E+08	2.92E+09	1.46E+07

Figure 3 is the basis for calculation of the process of fission products release from pebble fuel to the environment. Table 3. is the results of fission products release from the core to the environment during normal operation. The most species of radionuclides released into the primary circuit will reach a steady-state concentration, which is governed by radionuclides half-life.

After some period of normal operation, steady-state distributions of most of the species of radionuclides generated by fission (other than long-lived radionuclides

such as Cs-137 and Sr-90) will be established in the primary circuit. The primary circuit inventory of long-lived condensable radionuclides such as Cs-137 and Sr-90 continues to increase during the lifetime of the facility. The amount of each nuclide present in the coolant depends on the release of that nuclide from the fuel, radionuclide half-life, adsorption of certain species of radionuclides in the fuel, in core graphite and on graphite dust, plate out of certain species on primary circuit components, drop out of dust in areas of low velocity, and performance of the helium purification system (HPS)[8-9,13-14].

Table 3. Fission product release from core to the environment

Nuclide	Activity (Bq)						
	Release from fuel particles	Release from heavy metal contamination	Fuel quality specification on contamination	Transport through fuel matrix and graphite	Circulating activity in primary coolant	Release to the reactor building	Release to the environment
H-3	2.57E+07	1.91E+08	2.29E+08	4.45E+08	4.45E+06	1.02E+04	1.02E+03
Kr-83m	9.52E+09	7.05E+10	8.46E+10	1.65E+11	1.65E+11	1.65E+11	1.65E+11
Kr-85	5.91E+08	4.38E+09	5.25E+09	1.02E+10	1.02E+10	1.02E+10	1.02E+10
Kr-85m	2.42E+10	1.80E+11	2.15E+11	4.19E+11	4.19E+11	4.19E+11	4.19E+11
Kr-87	4.79E+12	3.55E+13	4.26E+13	8.29E+13	8.29E+13	8.29E+13	8.29E+13
Kr-88	6.95E+10	5.15E+11	6.18E+11	1.20E+12	1.20E+12	1.20E+12	1.20E+12
Xe-131m	7.22E+08	5.35E+09	6.42E+09	1.25E+10	1.25E+10	1.25E+10	1.25E+10
Xe-133	1.38E+11	1.03E+12	1.23E+12	2.39E+12	2.39E+12	2.39E+12	2.39E+12
Xe-133m	3.98E+09	2.95E+10	3.54E+10	6.89E+10	6.89E+10	6.89E+10	6.89E+10
Xe-135	5.37E+10	3.98E+11	4.77E+11	9.28E+11	9.28E+11	9.28E+11	9.28E+11
Xe-135m	1.78E+10	1.32E+11	1.58E+11	3.08E+11	3.08E+11	3.08E+11	3.08E+11
I-131	6.58E+10	4.88E+11	5.85E+11	1.14E+12	1.14E+10	2.62E+06	2.62E+05
I-132	9.86E+10	7.30E+11	8.76E+11	1.70E+12	1.70E+10	3.92E+06	3.92E+05
I-133	1.42E+11	1.06E+12	1.27E+12	2.46E+12	2.46E+10	5.67E+06	5.67E+05
I-134	1.67E+11	1.24E+12	1.48E+12	2.88E+12	2.88E+10	6.63E+06	6.63E+05
I-135	1.15E+11	8.50E+11	1.02E+12	1.98E+12	1.98E+10	4.56E+06	4.56E+05
Rb-88	6.95E+10	5.15E+11	6.18E+11	1.20E+12	1.20E+11	2.77E+07	2.77E+05
Sr-89	8.78E+10	6.50E+11	7.80E+11	1.52E+12	1.52E+11	3.49E+07	3.49E+05
Sr-90	3.61E+09	2.68E+10	3.21E+10	6.25E+10	6.25E+09	1.44E+06	1.44E+04
Cs-134	2.10E+09	1.56E+10	1.87E+10	3.63E+10	3.63E+09	8.35E+05	8.35E+03
Cs-137	4.66E+09	3.45E+10	4.14E+10	8.06E+10	8.06E+09	1.85E+06	1.85E+04
Ag-110m	1.46E+07	1.08E+08	1.30E+08	2.52E+08	2.52E+07	5.80E+04	5.80E+02

Table 3 shows that the dominant fission products in source terms on routine operating appear to be noble gases because they are inert, which means that they do not interact with matters. Noble gases due to their nature as inert gases are released from the existing barriers. Other nuclides are H-3, Sr, Cs, and Ag. Source terms on routine operation (normal operation) is limited by a

p ISSN 0852−4777; e ISSN 2528 - 0473

multi-barrier system that functions as fission product confinement of radionuclides against being released into the environment. The barriers start with the four layers in TRISO fuel, graphite in core matrix, purification systems in primary cooling system, filters and safety features in reactor building and filters in venting system. Each of these barriers restricts and reduces fission products release into the environment. The fuel kernel and fuel particle coatings are the first principle barriers against fission product release. The release fraction was calculated with factoring the effects of particle production quality (amount of new particles are assumed to have defective coatings), heavy metal contamination, incremental in-service, coatings failure rate in accident condition, and diffusion of fission products through the particle coatings under normal operation. As a comparison is the source terms activity of noble gases and other main nuclides in HTR-10 reactor[6]. The noble gases are Kr-88 and Xe-133, while the other main nuclides are I-131 and Cs-137 with their activities of 3.2E09 Bq, 8.5E09 Bq, 4.0E07 Bq and 6.9E03 respectively[6]. The comparison result of the other main nuclides of the RDE and the HTR-10 shows no significant differences. For noble gases, however, activity values have significant differences because the calculation adopted a conservative model related to the HTR-10 model. This conservative model is related by the characteristics of the fact that noble gases do not react with materials.

CONCLUSION

Estimation of source terms in the RDE-10 MWth routine discharge was calculated by following fission products release mechanisms of an HTGR model with its initial postulation of fuel TRISO defects and impurities as surface contamination. Estimated result that the RDE-10 MWth radionuclides for routine discharge (source terms) can be divided into groups of noble gases (Kr and Xe), halogen (I), Sr, Cs, H-3, and Ag. Activities of the RDE-10 MWth source terms for routine operation, especially radionuclides, shows no significant differences with the pebble HTR-10 source terms for the same reactor power.

REFERENCES

[1] Hales J.D., Williamson R.L., Novascone S.R., (2013), “Multidimensional Multiphysics simulation of TRISO particle fuel”. J.Nuc. Mat.; 443: 531-2

[2] Katoh Y., Vasudevamurthy G., Nozawa. T., (2013), *“*Properties Of Zirconium Carbide For Nuclear Fuel Applications*”*, J.Nuc. Mat; 441: 718-9

[3] Phillips J.A., Nagley S.G., Shaber E. L., (2012), “Fabrication Of Uranium Oxycarbide Kernels And Compacts For *HTR* Fuel*”*, J. Nuc. Eng. Des.; 251: 261-5

[4] Katoh Y., Snead L.L., Henager Jr C.H., (2014), “Current Status And Recent Research Achievements In *SiC/SiC* Composites*”*, J. Nuc. Mat.; 455: 387,394

[5] Katoh Y., Ozawa K., Shih, (2014), “Continuous SiC fiber, CVI SiC Matrix Composites For Nuclear Applications: Properties And Irradiation Effects*”*, J. Nuc. Mat.; 448: 448-450

[6] Yuanzhog Li and Jianzhu Cao, (2002), “Fission product release and its environment impact for normal reactor operation*”*, Nuclear Engineering and Design.; 218: 81-90

[7] INL, (2010), “*HTGR Mechanistic Source Term White paper”*, Idaho National Laboratory.

[8] Zhang L.Q., Zhang C.H., Han L.H., (2014), “Surface Damage on 6H–SiC by Highly-Charged Xeq+ Ions Irra-

diation", Journal of Nuclear Materials 455:; 704-6

[9] Katoha Y., Ozawa K., Shih C., (2014), "Continuous SiC Fiber, CVI SiC Matrix Composites for Nuclear Applications": Properties and irradiation effects, Journal of Nuclear Materials. ; 448: 448–9

[10] Cromarty R.D., Van Rooyen G.T, De Villiers J.P.R., (2014), "Crush Strength of Silicon Carbide Coated TRISO Particles: Influence of test method and process variables", Journal of Nuclear Materials.; 445: 30–6

[11] Liu R., Liu B., Zhang K., (2014), "High Temperature Oxidation Behaviour of SiC Coating in TRISO Coated Particles", Journal of Nuclear Materials.; 453: 107-9

[12] Carter L.M., Brockman J.D., Loyalka S.K., Robertson J.D., (2015), "Measurement Of Cesium Diffusion Coefficients In Graphite IG-110", Journal of Nuclear Materials.; 460: 30-1.

[13] Liu R., Liu M., Chang J., Shao Y., Liu B., (2015), "An Improved Design of TRISO Particle With Porous SiC Inner Layer by Fluidized Bed-Chemical Vapour Deposition", Journal of Nuclear Materials.; 467: 917-26

[14] Gerczak T.J., Hunn J.D., Lowden R. A., Allen T. R., (2016), "SiC Layer Microstructure in AGR-1 and AGR-2 TRISO Fuel Particles and The Influence of Its Variation on The Effective Diffusion of Key Fission Products', Journal of Nuclear Materials.; 480: 257-70

[15] Kuntjoro S. and Udiyani P.M., (2016), "The Analysis Of Inventory For 10 MWt, 20MWt and 30MWt Experimental Reactor", Jurnal Urania. ; 22: 55-9.

[16] Carter L.M., Brockman J.D., Robertson J.D., Loyalka S.K., (2016), "ICP-MS Measurement of Iodine Diffusion in IG-110 Graphite for HTGR/VHTR", Journal of Nuclear Materials.; 473: 218-22.

p ISSN 0852−4777; e ISSN 2528 - 0473