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Source Term Atmospheric Release and Core Inventory Analysis for the PUSPATI TRIGA Reactor under Severe Accident Conditions

(Pengeluaran Atmosfera *Source Term* dan Analisis Inventori Teras bagi Reaktor PUSPATI TRIGA di bawah Keadaan Kemalangan yang Teruk)

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ABSTRACT

The estimation of core inventory and source term of nuclear reactor is a part of procedures for conducting a Level 2 Probabilistic Safety Assessment (PSA). Currently, there are not many studies in this area for nuclear research reactors, as it is yet to be made compulsory in the regulatory licensing process among the nuclear-powered countries. This assessment is important to be done in order to be informed about the severity of a nuclear accident. In this study, the type of radionuclides and their activities when unintentionally released to the atmosphere were calculated using the ORIGEN2 code. This work was carried out for PUSPATI TRIGA Reactor (RTP) under a hypothetical severe accident. The core inventory for RTP was determined by assuming the reactor to be operated continuously for 365 days at full power (1 MWt). 42 radionuclides were chosen due to their dominant effects in source term. The atmospheric release of radionuclides is not the same as another depending on the physical condition of the reactor after the accident. The effects of these radionuclides when exposed to the public may cause serious health concern.

Keywords: Atmospheric dispersion; core inventory; ORIGEN2; severe accident; source term

ABSTRAK

Anggaran inventori teras dan source term *untuk reaktor nuklear merupakan sebahagian daripada prosedur dalam menjalankan Penilaian Kebarangkalian Keselamatan (PSA) Tahap 2. Pada masa ini, tidak banyak kajian sebegini dilakukan ke atas reaktor nuklear penyelidikan, memandangkan ia belum lagi diwajibkan dalam peraturan proses perlesenan dalam kalangan negara yang menggunakan tenaga nuklear. Penilaian sebegini adalah penting untuk dijalankan untuk mengetahui tahap keterukan situasi apabila berlakunya kemalangan nuklear. Dalam kajian ini, jenis radionuklid dan aktivitinya apabila berlaku perlepasan tidak sengaja dikenal pasti dengan menggunakan kod ORIGEN2. Kajian ini dilakukan ke atas Reaktor TRIGA PUSPATI (RTP) yang dianggap berada dalam keadaan kemalangan teruk hipotetik. Inventori teras untuk RTP ditentukan dengan andaian bahawa reaktor beroperasi selama 365 hari tanpa henti dengan kuasa penuh (1 MWt). 42 radionuklid dipilih berdasarkan kesan dominan dalam* source term. *Bergantung kepada keadaan fizikal reaktor selepas kemalangan terjadi, situasi perlepasan radionuklid ke atmosfera adalah tidak sama mengikut kes. Kesan daripada dedahan radionuklid ini kepada orang awam juga boleh menyebabkan masalah kesihatan yang serius.*

Kata kunci: Inventori teras; kemalangan teruk; ORIGEN2; perlepasan atmosfera; source term

INTRODUCTION

The 9/11 attacks have triggered many countries to revise the safety requirement of high-rise building from terrorism (Gandhi & Kang 2013). Nuclear power plant is no exception; it is similarly vulnerable to terrorist threat which may lead to a large-scale nuclear accident. Previous studies reported that major nuclear power plants (NPP) accidents have resulted in adverse health effects due to radiation exposure (Hasegawa et al. 2015). As such, a comprehensive research on the consequences of a nuclear accident is necessary.

In 2011, a nuclear accident at the Fukushima Daiichi Nuclear Power Station resulted in a huge emission of radioactive material into the atmosphere (Kadowaki et al. 2017). The release of radioactive materials produced in the reactor core to atmosphere is defined as source term. A list of estimated radionuclides in core inventory is required prior to the source term study. Accident source term is an important discipline of nuclear safety studies which articulates the details of the magnitude, composition, form (physical and chemical) and mode of release (puff, intermittent or continuous) of radioactive elements (fission and/or activation products) released during a reactor accident (Obaidurrahman & Gupta 2013).

One approach commonly used in the conduct of safety analysis of research reactors is to assume a hypothetical accident that results in a limiting source term atmospheric release producing the most severe consequences (IAEA 2008). Accidents are further subdivided into a design basis accident (DBA), beyond design basis accident (BDBA) and severe accidents (IAEA 2003). Simulations of accident scenarios are important to assess the possible hazards in case of an accident at any nuclear facility (Villa et al. 2010). There are some hypothetical accident scenarios for TRIGA reactors which have been reported previously (Glumac et al. 1997; Margeanu et al. 2015). In this paper, the chosen possible accident scenario is a plane crash that caused either a total destruction or partial damage of the reactor building (Haydn 2009).

The aim of this study was to calculate the core inventory of RTP to determine the source term with the maximum possible activity released to atmosphere under a hypothetical severe nuclear accident. To date, there is still no thorough study on the aforementioned RTP source term analysis. In the previous source term study (Usang et al. 2014), the irradiation time of the fuel was similar to this work which is 365 days, but the purpose was to determine which set of library in the ORIGEN2 code (PWR and BWR library) that will closely match the TRIGA fuel. In addition, it may also be mentioned here that the source term calculation reported in the RTP Safety Analysis Report 2017 only covered noble gases and halogens group (PUSPATI 2017). Thereby, this paper is the first such detailed study on the source term atmospheric release for a full power-operated RTP and the consequences towards the environment and public health.

RTP RESEARCH REACTORS AND ITS CHARACTERISTICS

PUSPATI TRIGA Reactor (RTP) is a 1 MW thermal, pool-type research reactor fueled with uranium-zirconium hydride (UZrH1.6) containing about 8.5% by weight of uranium enriched to 19.99% of U-235. The main specifications of RTP are presented in Table 1. RTP incorporates facilities for advanced neutron and gamma radiation studies as well as for isotope production, sample activation, and student training. The core is surrounded by graphite which acts as the neutron reflector. Shielding above the core is provided by water. Four control rods are used to control the power level of the reactor. The cross section of the RTP facility is shown in Figure 1. RTP belongs to Nuklear Malaysia (Malaysian Nuclear Agency) and is the only nuclear research reactor in Malaysia. The reactor achieved its first criticality on 28th June 1982 (Usang et al. 2014).

PROBABILISTIC SAFETY ASSESSMENT (PSA)

Probabilistic Safety Assessment (PSA) is used to evaluate the safety aspects of NPP by analyzing the potential risks

TABLE 1. Main specifications of RTP

Parameter	Value
Reactor type	Pool-type
Coolant	Light water
Moderator	Light water
Reactor power (MWth)	1
Fuel material	$UZrH_{1.6}$
Uranium content	8.5%
Uranium enrichment	19.99 %
Fuel meat dimension	
• Length	1.5 inch
• Diameter	1.43 inch
No. of control rods	4
Control rod material	Boron carbide
Cladding material	Stainless steel-304

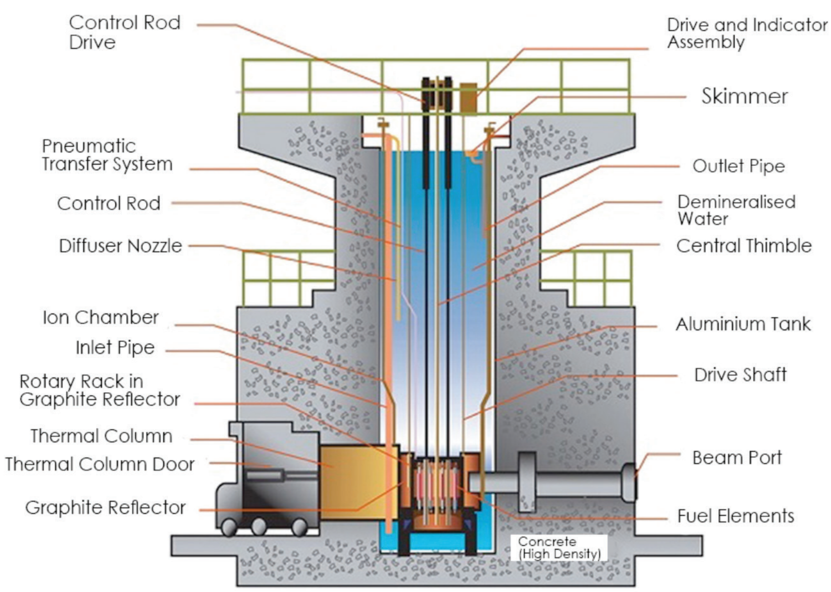

FIGURE 1. Cross section of the RTP facility

Source: (Rozainiee et al. 2008)

resulted from an abnormal situation or accident (IAEA 1996). There are three levels of PSA: Level 1, Level 2 and Level 3 as shown in Figure 2. All these levels of assessments are to be done sequentially, in which results from lower level assessments are used as start-up for the subsequent higher-level assessment. The core inventory and source term analysis is part of the results obtained from PSA Level 2 and thus, is used in PSA Level 3. However, as RTP is built without a containment dome, a complete PSA Level 2 is irrelevant.

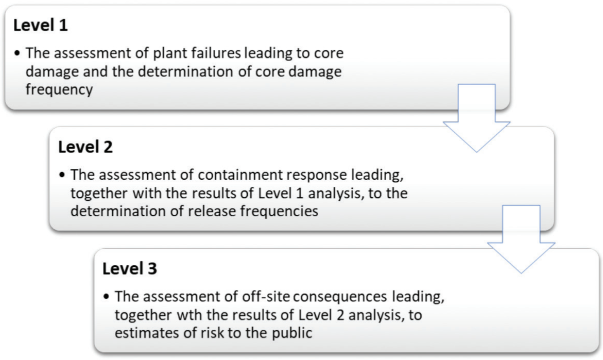

FIGURE 2. Summary for each level and work flow in PSA

Source: IAEA (1996)

METHODS

In this study, the International Atomic Energy Agency (IAEA) guidelines are used as reference to ensure result that meets international standard is produced. First, accident scenario that may cause the release of source term must be selected. All safety and emergency features of the reactor building were assumed to be not functioning. Then, the calculation of core inventory was done and followed by determination of source term.

SELECTION OF ACCIDENT SCENARIO

Initiating event is defined as an incident which creates a disruption in the plant which may potentially leads to reactor core damage, whether or not the safety system successfully operates (IAEA 1993). All possible accident sequences from the initiating events can be used to establish event trees to determine the accident that leads to a source term (IAEA 2008). When selecting an accident scenario, foreseeable events with potentially serious consequences together with significant frequency of occurrence must be considered (IAEA 2016). Two accident scenarios caused by a plane crash have been selected: total destruction of reactor building, and reactor building is partially damaged.

Total destruction of reactor building To demonstrate this accident, a large plane was assumed to crash at the reactor building. During the impact, all fuel rods were totally damaged and the reactor building was completely destroyed. This resulted in full release of radionuclides from the fuel meat to the atmosphere (Muswema et al. 2015). It was also assumed that radionuclides were released at the ground level through cracks and collapsed building structures.

Reactor building is partially damaged In this case, the building was assumed to not completely be destroyed, it was assumed to be damaged severely. Several fuel rods were destructed but most remained inside the water tank. Hence, only fraction of fission products in the reactor core were released to the atmosphere. The release height was assumed to be the same as the height of reactor which is 6.5 m. Only radionuclides with high level of mobility were assumed to cause radiological doses outside the reactor facility (Malek et al. 2012).

CALCULATION OF CORE INVENTORY

Radionuclide inventory in a nuclear reactor core is a complex function of fission nuclide compositions (U-235, U-238, Pu-239), power history, operating power, burnup, neutron flux level and neutron absorption (Obaidurrahman & Gupta 2013). This calculation will list down all radionuclides together with their activity resulted from the fission reactions in the reactor core. The isotopic inventory of the nuclear fuels evolve throughout the operating life time of a nuclear reactor (Foudil et al. 2017). It is a primary requirement to have a radionuclide inventory prior to determination of source term in order to describe the release of radioactive materials.

ORIGEN2 is a computer code widely used for calculating the buildup, decay and processing of radioactive materials developed by Oak Ridge National Laboratory (ORNL 1999). The primary function of this code is to compute time-dependent concentrations and source terms of a large number of nuclides that are simultaneously generated or depleted through neutronic transmutation, fission, radioactive decay, input feed rates, and physical or chemical removal rates (Parks 1992). The core inventory for RTP was calculated with an assumption that the reactor is operated at full power for 365 days continuously and no decay factor.

DETERMINATION OF SOURCE TERM

For research reactors, the fission products normally dominate the list of source terms as actinides and transuranic elements are often excluded due to their smaller scale of effects (Mirza et al. 2010). In most cases, the dominant radionuclides constituting the source term also include noble gases, volatile and semi-volatile groups (Ullah et al. 2010). The source term is directly proportional to core inventory which in turn depends on the core fissile content, reactor power, fuel burn-up, spatial neutron flux profile and operating schedule (Ullah et al. 2010). An accident with severe core damage may cause the release of radionuclide with significant fraction from the core to the atmosphere (Raza & Iqbal 2005).

The release fraction depends primarily on the physical and chemical properties of the radionuclides. These release fractions used in safety analysis vary widely depending on the level of conservatism assumed and the severity of the nuclear accident scenario being considered (IAEA 1992). The use of conservative release fractions is preferred to avoid complex calculations (Obaidurrahman & Gupta 2013). The release fractions from US-NRC regulatory guide was used to calculate the source term (NRC 2000) as shown in Table 2.

TABLE 2. Release fractions value

Group	Release fraction
Noble gases	1
Halogens	0.4
Alkali metals	0.3
Tellurium group	0.05
Ba, Sr	0.02
Lanthanide	0.0002

RESULTS AND DISCUSSION

In this study, RTP was simulated to be operated at full power for 365 days continuously to obtain the maximum possible activity in the core. The core inventory data in Table 3 is the reflection of activity possessed by radionuclides inside the fuel elements. Radionuclides of interest were grouped as noble gases, halogens, alkali metals, tellurium group, Ba-Sr group and lanthanide as shown in the following table. While some nuclides could take years to decay, there are

TABLE 3. Radionuclide inventory for the RTP core after 365 days of continuous operation at full power (1MW)

Nuclide	Half-life (hour)	Group	Activity (Bq)
Br-83	2.374	Halogen	1.61E+14
Br-84	0.53	Halogen	3.02E+14
Br-85	0.048	Halogen	3.75E+14
I-131	192.6	Halogen	8.77E+14
I-132	2.295	Halogen	1.31E+15
I-133	20.83	Halogen	2.03E+15
I-134	0.875	Halogen	2.29E+15
I-135	6.58	Halogen	1.89E+15
I-136	0.023	Halogen	9.24E+14
Kr-83m	1.83	Noble gas	1.61E+14
Kr-85m	4.48	Noble gas	3.79E+14
Kr-85	94073.64	Noble gas	5.20E+12
Kr-87	1.27	Noble gas	7.65E+14
Kr-88	2.83	Noble gas	1.08E+15
Kr-89	0.053	Noble gas	1.37E+15
Kr-90	0.009	Noble gas	1.36E+15
Kr-91	0.0024	Noble gas	1.01E+15
Xe-131m	284.16	Noble gas	9.73E+12
Xe-133m	52.75	Noble gas	5.96E+13
Xe-133	125.94	Noble gas	2.03E+15
Xe-135m	0.2548	Noble gas	3.45E+14
Xe-135	9.14	Noble gas	1.07E+15
Xe-138	0.23	Noble gas	1.87E+15
Xe-139	0.011	Noble gas	1.52E+15
Xe-140	0.0038	Noble gas	1.06E+15
Ba-140	306	Ba-Sr group	1.87E+15
Sr-89	1213.68	Ba-Sr group	1.44E+15
Sr-90	253164	Ba-Sr group	4.13E+12
Y-91	64.8	Lanthanide	1.75E+15
Zr-95	1536.77	Lanthanide	1.92E+15
Zr-97	16.74	Lanthanide	1.76E+15
Nb-95	840	Lanthanide	1.89E+15
Pr-143	6360	Lanthanide	1.77E+15
Nd-147	263.52	Lanthanide	6.86E+14
Te-127m	2616	Tellurium group	6.49E+12
Te-129m	806.4	Tellurium group	3.20E+13
Te-131m	0.42	Tellurium group	1.12E+14
Te-132	3.204	Tellurium group	1.30E+15
Ru-103	3	Alkali Metal	9.87E+14
Ru-106	8966.16	Alkali metal	7.31E+13
Rh-105	35.36	Alkali metal	3.38E+14
Cs-137	264289.2	Alkali metal	4.31E+13
		Total	4.03E+16

also many short-lived radionuclides present in the core as the result from the fission reaction.

The results in Figure 3(a)-3(g) shows the core inventory of fission products according to their group at various nuclear fuel burnup. Most of the fission products in Figure 3(a)-3(c) follows the same trend: it plateaued out after 5 MWd/kg burnup. For Ba-Sr group, lanthanides, alkali metals and tellurium group in Figure 3(d)-3(g), the radionuclides show mixed trends. Sr-89, Sr-90 (Figure 3(d)), Nb-95, Y-91, Zr-95 (Figure 3(e)), Ru-103, Ru-106, Cs-137 (Figure 3(f)) and Te-127 m (Figure 3(g)) shows increasing trend, in which the plateau level of most fission products increase with fuel burnup. These are due to the variation of the fission products with nuclear parameters such as fission yield, cross section and decay constant (Foudil et al. 2017).

SOURCE TERM

Total destruction of the reactor building A plane crash which caused a total destruction of the reactor building

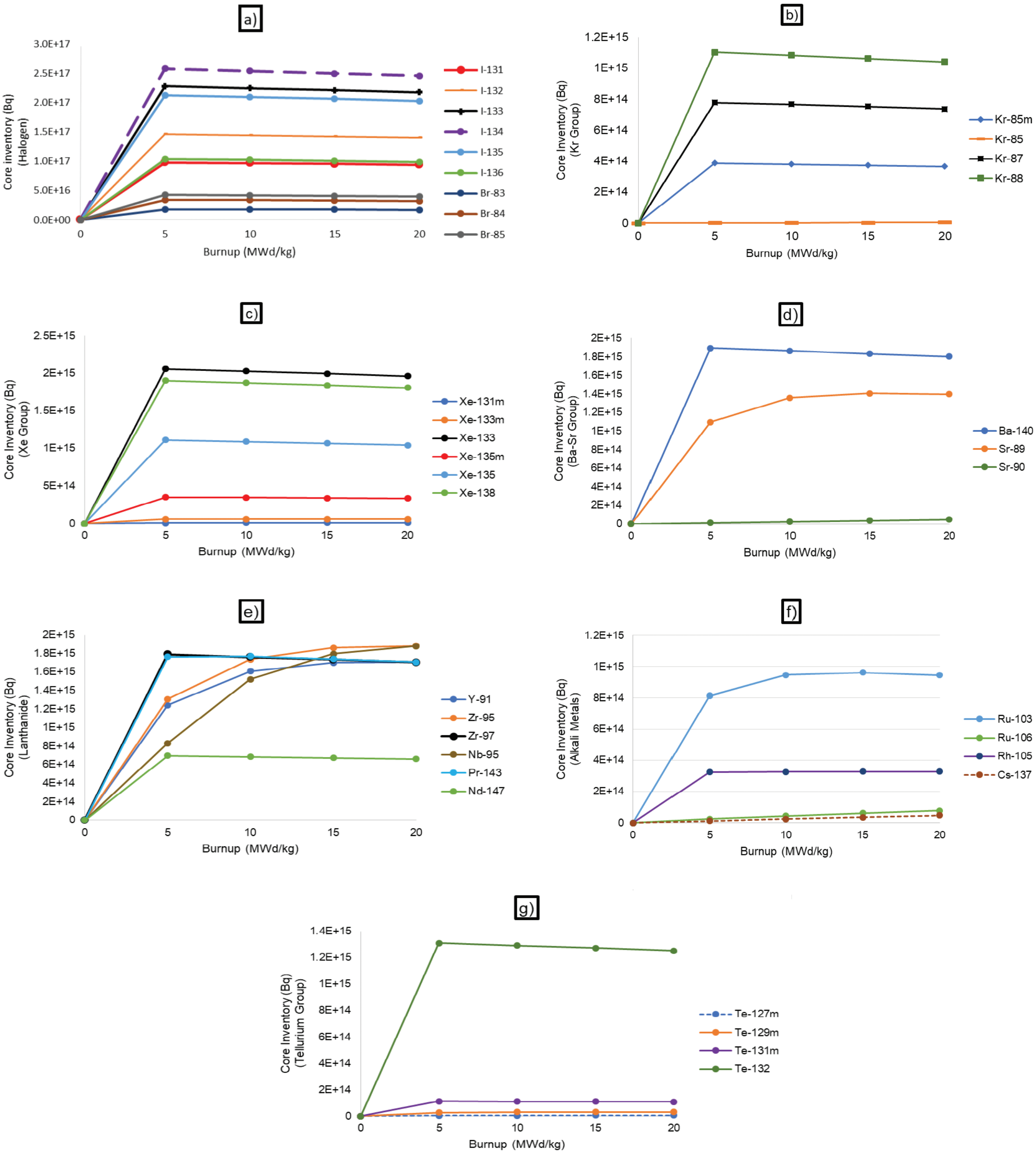

FIGURE 3. RTP core inventory in (Bq) for radionuclides in group (a) Halogen, (b) Noble gas: Kr group, (c) Noble gas: Xe group, (d) Ba-Sr group, (e) Lanthanide, (f) Alkali metals, and (g) Tellurium group versus burnup in megawatt day/kg (MWd/kg)

was assumed, resulting in all fuel elements to have been compromised and the reactor core was uncovered which allows direct release of radionuclides to the atmosphere. In worst-case scenario, all nuclides in Table 3 were assumed to be released to the atmosphere.

Partially damaged reactor 42 radionuclides were chosen and grouped as the source terms in the form of noble gas, halogens, Ba-Sr group, lanthanide, alkali metals and tellurium group. Figure 4(a) shows that noble gas group resulted in the most significant contribution to the source term, where Xe-133 has the highest activity released since xenon is passive chemically and does not settle in the body (Foudil et al. 2017). However, xenon is also known as asphyxiant gas which may diminish oxygen in the air. Consequently, excess inhalation of xenon may result in dizziness, loss of consciousness and death. Noble gas is assumed to be released completely from the core because of its inert nature and thus may easily escape from the core. Hence, they are considered as important contributors to the whole body dose (Malek et al. 2012).

Figure 4(b) shows the halogen source term, with I-134 was recorded to have the highest activity released. The released was followed by I-133, I-135, I-132, I-136 and I-131. Bromine group only recorded a significantly lower activity released compared to that of iodine. In nuclear reactor safety, the iodine retention in an accident is a primary concern. Different radioisotopes of iodine may affect both thyroid and lung dose causing radiological hazards. For instance, I-131 is mobile and volatile, and once deposited into the ecosystem, it is readily taken up in the food chain and accumulated in the thyroid gland where it would produce tumors (Apostoaei et al. 1999).

In Figure 4(c), the activity released by Ba-140, Sr-89 and Sr-90 in Ba-Sr group are also likely to enter the biological systems. Of these, Ba-140 and Sr-89 are less important because of their short half-lives. On the other hand, Sr-90 has a long half-life and may pose a significant biological effect, recorded the lowest activity released in the group. However, as the atomic radius of barium, strontium and calcium are of similar dimensions, atomic exchanges of these elements are very likely to occur, leading to the possibility of bone cancers when radioactive strontium or barium change places with calcium (Marques 2012). These radionuclides give the greatest impact on children, since they are subjected to growth and cell production.

Figure 4(d) shows the lanthanide group with a focus on Y-91, Zr-95, Zr-97, Nb-95, Pr-143 and Nd-147. All radionuclides in this group have half-life of less than one year, with Pr-143 and Zr-97 have half-lives of 265 days and 16.74 h, respectively. Little is known about

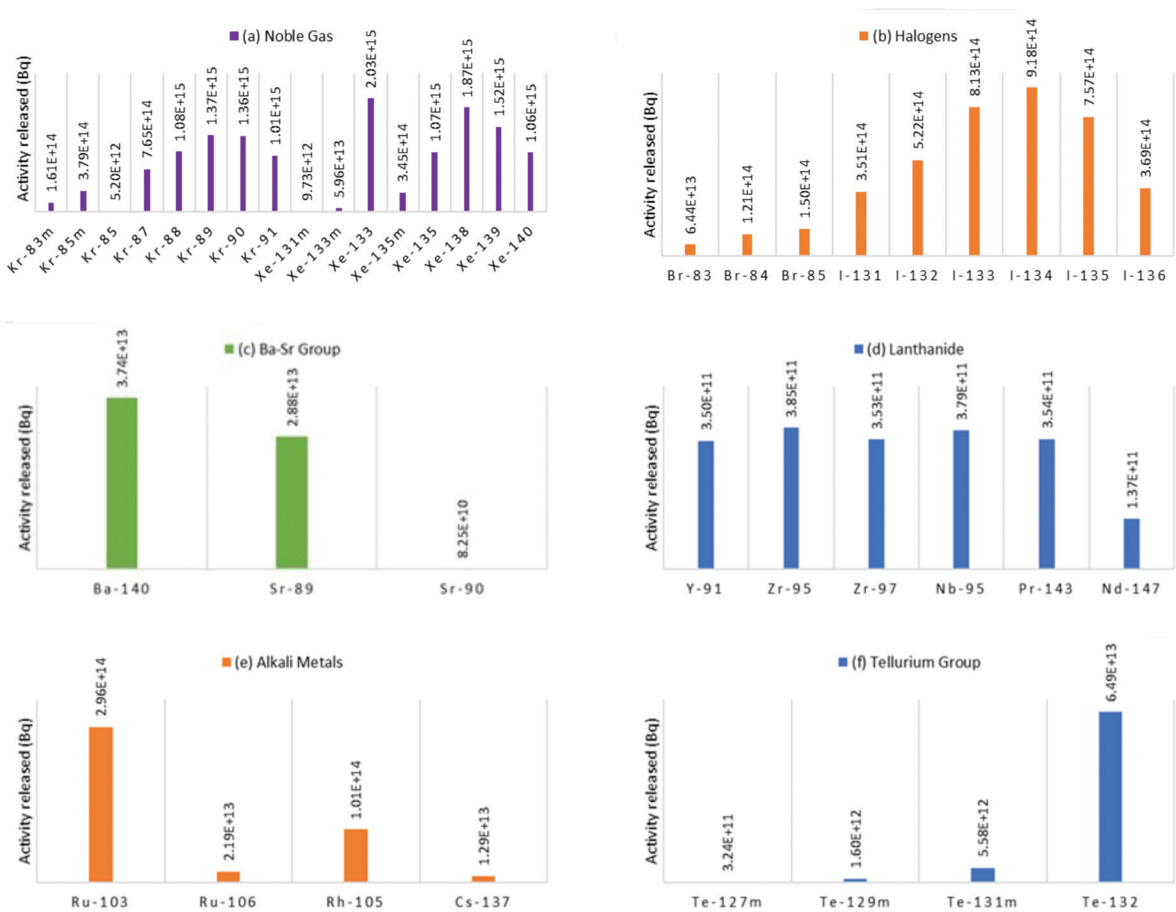

FIGURE 4. Source term (according to group) after a hypothetical severe accident at the partially damaged RTP

the biological effects of occupational exposure to the lanthanides (Rim et al. 2013). Lanthanide group is among the lowest contributor in source term with relatively low activity released and it should not be compared with the activity released for the case of rare earth mining.

For alkali metals and tellurium group, both may exist as an aerosol source term. Aerosols are a critical factor in the atmospheric hydrological cycle and radiation budget (Tao Wei-Kao 2012). This means that human can be exposed to these radionuclides and easily absorbed into the body through inhalation. Hence, aerosols source term can also cause health effects depending on their nature. Based from Figure 4(e) and 4(f), Ru-103 and Te-132 from respective groups show notable value of activity released. Despite Cs-137 was recorded to have one of the lowest activity released, its long half live is still a major concern as it easily moves and spreads in nature due to its high water solubility in its own form of salt.

Conclusion

A hypothetical severe accident such as a plane crash was considered as the worst case scenario to occur at the RTP. In this study, ORIGEN2 was used to calculate the core inventory with an assumption that the reactor has been operated for 365 days at full power continuously. This calculation is necessary to ascertain the fission products together with their activity in the reactor core. It is observed throughout this work that in a severe nuclear accident, various radionuclides have potential to be released to the environment. This situation may potentially lead to a serious health effects among the public in the surrounding. The results in this work can be a precursor to study the exposure pathways and dose assessments as well as drafting a proper and detailed countermeasures plan for such emergency.

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