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Calculation of Radioactive Source Term Release from Flexblue SMR

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One of the National Research Programs (PRN) in the energy sector of the Indonesian Ministry of Research and Technology for the period of 2020-2024 is the assessment of small modular reactor (SMR) nuclear power plant (NPP). French-designed Flexblue is a PWR-based submerged SMR with a power of 160 MWe. The Flexblue reactor module was built on the ocean site and easily provided the supply of reactor modules, in accordance with the conditions of Indonesia as an archipelagic country. As a part of safety aspect, it is necessary to know the release of fission products (source term), for the study of the radiation safety of a nuclear reactor. This paper aims to examine the source term in normal and abnormal operating conditions, as well as postulated accidents. Based on the Flexblue reactor core parameter data, the calculation of the reactor core inventory using the ORIGEN2 software is evaluated. The source term calculation uses mechanistic and graded approach. The normal source term is calculated assuming the presence of impurities on the fuel plate, due to fabrication limitations. Meanwhile, the abnormal source term is postulated in the LOCA event. The highest source term activity of Flexblue both under normal and abnormal conditions is that of the noble gas group radionuclides. In the normal operation, the maximum source term is 2.14E+04 Ci. In the small-LOCA event, the maximum source term activity is 4.86E+03 Ci, while the maximum activity of the source term under large-LOCA event is 9.73E+05 Ci.

1. INTRODUCTION

Flexblue is an SMR (small modular reactor) type NPP with the power of 160 MWe submerged on the seabed. It is measuring a hundred meter long and about 14 meters in diameter. The reactor was adapted from the submarine nuclear reactor technology. Flexblue is designed to be installed at a depth of 100 meters below the ocean surface[1, 2]. This reactor is a moveable and subsea-based nuclear power unit operating up to 100 m depth and a few kilometers away from the shore. Flexblue uses typical pressurized water reactor (PWR) technology. The concept is based on existing technologies and experience from the oil and gas, civil nuclear and shipbuilding industries[2]. The Flexblue reactor module was assembled on the ocean site and easily provided by the supply of reactor modules. This is suitable with the conditions of Indonesia as an archipelagic country.

Flexblue and similar SMR of PWR-type have a safety design equivalent to that of a Generation III+ nuclear power plant. Compared to large nuclear power plants, it has comparably high safety features. With a smaller reactor power combined with passive and immersion systems, permanently available heat sink, very low CDF (core damage frequency), long grace period, and claimed to have a low source term. Since the calculation of the

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Flexblue source term is not yet officially available, this paper aims to examine and calculate the Flexblue source term using a mechanistic source term calculation approach and a graded approach. The mechanistic source term calculation and the graded approach of the large PWR were taken, since the detailed data for the SMR were still limited[3-4]. By using parameters from NUREG (US Nuclear Regulatory Commission) and EUR (European European Utility Requirements for LWR NPP) references[5-7] and parameters generated from deterministic and probabilistic studies, calculations are performed.

Source term calculation under normal operation is done by assuming the presence of uranium impurities on the cladding surface due to fabrication limitations. In addition, the assumption of pinholes on the fuel cladding is irradiated during the operating cycle [8-9]. Meanwhile, for postulation, LOCA (lost of coolant accident), is assumed to be the abnormal event[10-11]. Source term calculations using a mechanistic source term approach for large and SMR HTR and PWR-types have been carried out using similar methods in several studies[12-14]. The calculation of the LOCA accident conditions for the PWR-1000 MWe using the NUREG and EUR reference parameters[7-11], as well as the experimental, deterministic, and probabilistic process combination parameters have also been carried out[12-15].

2. METHODOLOGY

2.1. Core Inventory Calculation

The core inventory is calculated using ORIGEN-2[16-18], based on the reactor data of the PWR-160 MWe[1]. Calculated done based on the parameter of Flexblue core geometry (see Figure 1)[1]. The reactor is made up of 77 fuel bundles. Each fuel bundle is composed of 17x17 fuel pins containing 112 fuel pins of UO_2 with enrichment of 4.95%, 32 Gd_2O_3 burnable poison (BP) with 9% enrichment, 24 control channels, and 1 instrumentation channel. The reactor runs for 38 months with a fuel reshuffle pattern of around 50% (37 fresh fuel bundles)[1, 2].

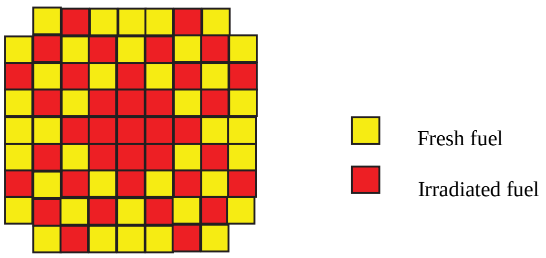

Fig. 1. Reactor core fuel bundle configuration

2.2. Source term Calculation

Calculation of the source term of the Flexblue reactor under normal operating conditions used the assumption for discharge radionuclides from the fuel subsystem due to the presence of pinholes on cladding will result in about 0.1% of radionuclides release from inventory to the reactor coolant [3, 7]. Approximately, electricity production stops every 3 years for refueling. The module is disassembled and returned to a coastal facility, which hosts the spent fuel storage. Major overhaul occurs every 10 years, i.e., every three fuel cycles. Several Flexblue units can operate on the same site and hence share the same support systems [8]. Radionuclide release factor from the core to the reactor coolant, containment, chimney, and to the environment, used already existing parameters[3, 7, 8]. The normal operating source term calculation mechanism is shown in Figure 2.

2.3. Postulated abnormal event

The postulated abnormal event for the Flexblue reactor was a LOCA. The assumption of failed cores is 3% for small-LOCA and 30% for large-LOCA. Release parameters for each safety system were using the parameters of the similar reactor (PWR-100 MWe) which have been calculated [2, 7]. The source term calculation mechanism in LOCA accident conditions is shown in Figure 2.

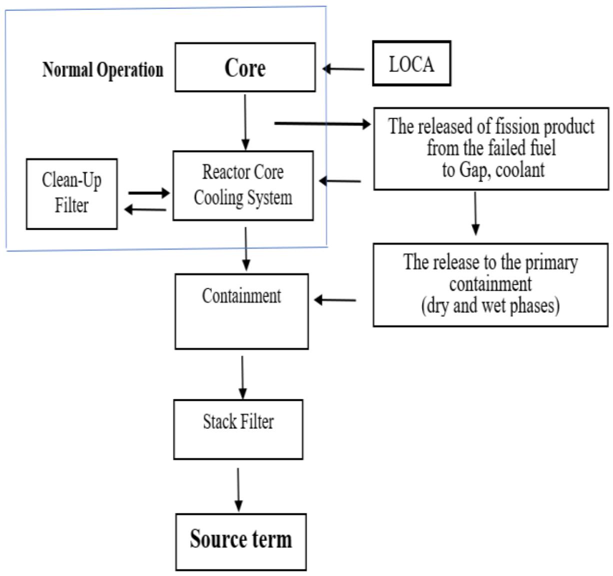

Fig. 2. Transport mechanism of source term at normal operation and LOCA of Flexblue SMR

3. RESULTS AND DISCUSSION

3.1. Core Inventory

ORIGEN-2 was used to obtain an inventory of fission products and some nuclear characteristics materials, such as mass of nuclides, radioactivity, radiotoxicity, neutron, and photon emission[19-20].

The results of the calculations in Table 1 are grouped based on the characteristics and types of radionuclides such as the noble gas group (Xe, Kr); halogen (I); alkali metal (Cs, Rb); tellurium (Te, Sb, Sc); barium-strontium (Ba, Sr); noble metals (Ru, Rh, Pd, Mo, Tc, Co); lanthanide (La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am) and the cerium group (Ce, Pu, Np)[1].

Table 1. Radioactivity of Flexblue radionuclide inventory

No.	Radionuclides Group	Radioactivity (Ci)
1.	Noble Gas	6.48E+07
2.	Halogen	1.16E+08
3.	Alkali Metal	2.01E+06
4.	Tellurium	1.93E+07
5.	Strontium, Barium	3.42E+07
6.	Noble Metal	4.19E+07
7.	Lanthanide	5.63E+07
8.	Cerium	3.45E+07

The fission product inventory is influenced by the type of fuel, the amount and composition of uranium, fuel fraction, reactor power, core configuration, and duration of irradiation, among others. This parameter will affect the amount of fission product activity confined in the fuel cladding.

Inventory activity for the core Flexblue was highest from the halogen group, as much as 1.16E+08 Ci, followed by the noble gas group at 6.48E+07 Ci. The inventory activity of Flexblue (PWR-160 MWe) was higher than that of PWR-100 MWe (SMART) for each of the radionuclide groups such as halogen (8.04E+07 Ci) and noble gases (2.85E+07 Ci)[3]. The larger thermal power and core size, the higher the core inventory activity of Flexblue.

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3.2. Source term of Normal Operation

Fission products are in volatile fuels such as those of the halogen (I) group, and alkaline metals (Cs). The fission product passes to the fuel gap due to the pellet diffusion process. The diffusion process is influenced by the diffusion coefficient, temperature, and fuel fraction. Pinholes that occur due to porosity in the fuel cladding, caused the fission products in the fuel gap released from primary coolant[3, 7, 8]. The release of fission products from the pinhole reaches 0.1-1%. The release of fission products from the cladding is also due to the assumed impurity of uranium on the fuel surface due to fabrication limitations. Uranium contaminants on the surface can be up to 10 microns by weight of uranium[3, 7, 8].

Source term activity for the fission and activation products of Flexblue under normal operation is shown in Figure 3. The highest source term activity of the noble gas groups (Xe, Kr), and followed by the halogen groups (I, Br) and the alkali metal groups (Cs and Rb).

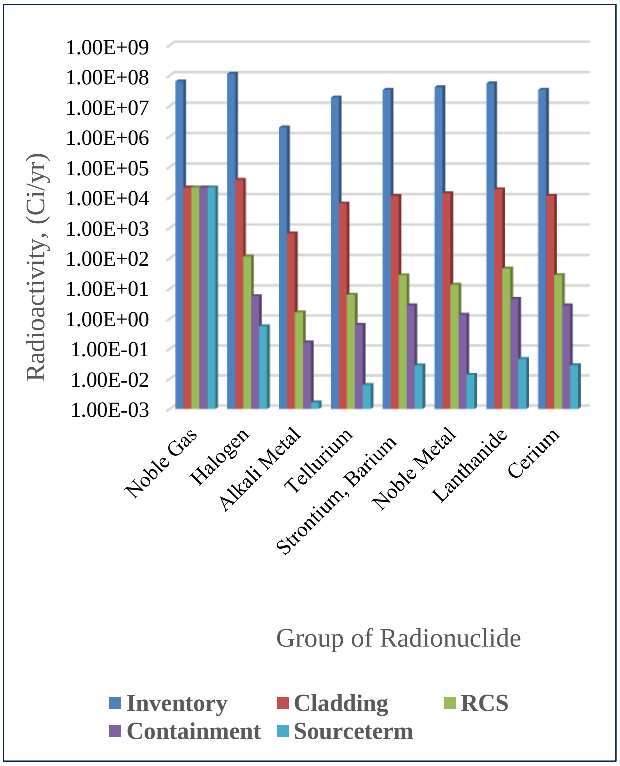

Fig. 3. Source term activity of the Flexblue at normal operation

Maximum source term activity for Flexblue under normal operating conditions is that of the noble gas group radionuclides, around 2.14E+04 Ci. This condition is due to the noble gas is an inert gas that does not react with the material, so that the safety barrier in the reactor, such as filters, does not prevent the discharge of the noble gases.

3.3. Source term of LOCA

In an abnormal condition or accident caused by LOCA, core cooling and integrity containment is not maintained, resulting in fuel failure and fission product confined in the core are released into the cooling system through the intermediate gap cladding and fuel, and finally to the containment. Displacement conditions of the radionuclides from the inventory to the cladding occur based on postulation of core and system damage reactor safety such as ECCS (emergency core cooling system). If the ECCS still works, then the accidents that occur are still at the basic accident level of the DBA (design basis accident) or DBC (design basis condition). Included in the DBC are small LOCA and large LOCA[3].

During the reactor operation, fission products are formed in the fuel, confined by cladding, so that they do not escape into the environment through the cooling system, containment, and filter. If the fuel integrity fails due to LOCA, a source term will be formed. If LOCA occurs due to valve failure, small LOCA will occur. However, if there is a total failure of the cooling system and it is not covered by the ECCS, large LOCA will consequently occur.

The activity of the small-LOCA source term is depicted in Figure 4. Maximum source term for small LOCA on Flexblue reactor is from the Noble gas group, with the activity of 4.86E+03 Ci.

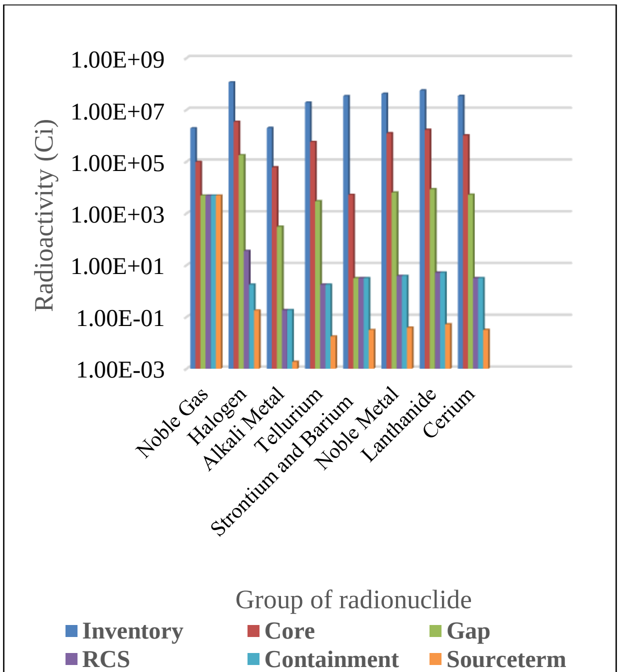

Fig. 4. Source term activity of the Flexblue at small-LOCA postulation

If the fuel cladding cracks or breaks, fission products are released into the system. The coolant temperature increases in proportion to the increase in core temperature. In general, the phenomenon of nuclide transfer in LOCA accidents is almost the same if the reactor has safety features that are not significantly different, such as ECCS (cold, hot, or cold and hot leg types) and other safety systems. The fission product activity and the release fraction of small and large LOCA accidents are different due to the severity of core damage, fuel failure fraction, as well as the completeness of the safety features. The maximum activity of the source term under large LOCA conditions is 9.73E+05 Ci from the Noble gas group, as shown in Figure 5.

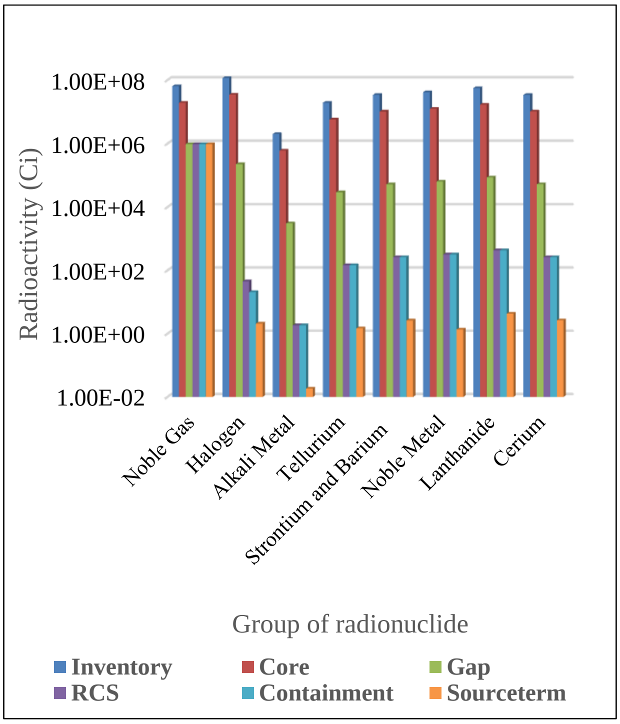

Fig. 5. Source term activity of the components and sub-systems on the PWR-100MWe at large-LOCA

4. CONCLUSION

Source term calculations for normal operation and abnormal LOCA conditions postulated from Flexblue-160 MWe were obtained. The core reactor inventory and source term are divided into radionuclide groups which are noble gases group (Xe, Kr); halogen (I); alkali metal (Cs, Rb); tellurium group (Te, Sb, Sc); barium-strontium group (Ba, Sr); noble metals (Ru, Rh, Pd, Mo, Tc, Co); lanthanides group (La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am) and cerium group (Ce, Pu, Np). The highest source activity for Flexblue under normal operating conditions is that of the noble gas group radionuclides, which is 2.14E+04 Ci. In the small-LOCA event, the maximum source term is also from the noble gas group with the activity of 4.86E+03 Ci. The maximum activity of the source term under large-LOCA event is 9.73E+05 Ci from the noble gas group.

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AUTHOR CONTRIBUTION

M. Budi Setiawan and P. Made Udiyani equally contributed as the main contributors of this paper. All authors read and approved the final version of the paper.

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