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Source Term Analysis of Small Long-Life without Refueling 420 MWt PWR during Loss of Coolant Accident (LOCA)

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Abstract

Source term analysis of a small long-life 420 MWt PWR has been performed. The analysis includes calculation of fission products inventory in the core, the core activity, source term activity and toxicity, and also dose calculation on various situations during LOCA. Diffussion calculation conducted during the Beginning of Life (BOL) of the reactor. LOCA scheme calculated when the reactor has been operated for 10080 full power days. Fission products activities in the core have a total of 3.2E+08 Ci. Fission product activity that are released to the environment with assumption that 100% of noble gas, 50% of halogens and 1% of other source term groups are released resulting in a total activity of 6.71E+05 Ci, or about 0.21% of total activity in the core. Toxicity analysis show that there are 200 nuclides released to the atmosphere categorized as dangerous. Calculation of thyroid dose in the boundary of exclusion zone (350 m) gives result of 0.57593 rem, while in low population zone resulted in 0.23013 rem. Whole body dose calculation in exclusion zone resulted in 0.14583 rem and in low population zone, the whole body dose is 0.05107 rem.

Keywords: *Long-live PWR, LOCA, Source term, Activity, Toxicity, Thyroid dose, Whole body dose, Exclusion zone, Low population zone*

1. Introduction

The need for electricity in Indonesia is increasing year after year. Up to now, Indonesia still depends on fossil fuels especially oil to generate the electricity. The fluctuation of oil price and the diminution of oil reserve in Indonesia has become a big concern. Asides from that, about 35% areas of Indonesia hasn't yet reached by electricity. To answer the challenge, Indonesia has released a regulation on energy policy which includes nuclear energy as one of the alternative energy to generate electricity.

Few studies of small long-live PWR, of which can be operated more than 20 years without refueling nor fuel shuffling. This PWR uses thorium cycle as fuel with addition of Protactinium-231 as burnable poison.

Chernobyl and Three-Mile Island events has become a lesson-learned that the operation of a nuclear reactor needs multi-disciplinary studies in safety including the probability of radioactive source release or source term to environment in case that an accident happened in a nuclear reactor.

The analysis of radioactive sources released from a nuclear power plant to the atmosphere during normal operation and accident is one of the requirements in design licensing in Indonesia. This research discuss about analysis of source term on a 420 MWt small long-live without refueling PWR during loss of coolant accident (LOCA)

2. Source Term Analysis

If an accident happened, a sum of fission products and actinides, also known as source terms, could be released from a nuclear facility to the atmosphere. Source term is one of the basic parameters to estimate the consequence of an accident for human and environment.

On Regulatory Guide 1.183, US-NRC grouped source term into eight groups to be calculated on design basis analysis.

Table 1. Source term groups[1)]

Group	Element(s)
Nobel Gas	Xe, Kr
Halogen	I, Br
Alkali	Cs, Rb
Tellurium	Te, Sb, Se
Barium	Ba, Sr
Nobel Metal	Ru, Rh, Pd, Mo, Tc, Co
Lanthanide	La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am
Cerium	Ce, Pu, Np

Process of radionuclides release and its distribution are relatively complex problems. Thus, several assumptions need to be made in order to perform source term analysis:

- Inventory of radionuclides in the reactor core depends on the type of reactor, power level and reactor operation period. When an accident happen, it is assumed that the reactor has been operated for a long time full power days so that the inventory of radioactive sources in reactor core have reached an asymptotic value.

- Source term release from the reactor building to the atmosphere via air occurs with a constant velocity according to the design basis of the reactor.
- Immediately after release, radioactive materials will form a radioactive cloud of which it grows and widespread depending on meteorological factors such as velocity and direction of wind, stability of atmosphere, and diffusion parameter.
- During radioactive sources transport process, it is assumed that there is no deposit process of solid particulates.
- The effect of radionuclides decay is only calculated as long as the radionuclides are still contained in reactor building. It will be omitted after the release of source terms to the atmosphere.

The reactor specifications used in this research are printed in Table 2.

Table 2. PWR specification[2)]

Parameter	Specification
Power	420 MWt
Refueling period	28 years
Coolant	Water (H_20)
Fuel	$(Th,U)O_2$
Burnable poison	Pa-231
U-233 enrichment	6%-7%-9%
Percentage of Pa-231	4.3%-7%-9%
Cladding	Zircalloy-4
Volume fraction of fuel-cladding-moderator	60 %-10%-30%
Pin diameter	1.224 cm
Pitch	1.4 cm
Core geometry	2-D cylinder (R-Z)
Fuel cell geometry	Square Cell
Core active volume	130 cm x 280 cm
Reflector width	30 cm

3 Calculation Method

Generally, this research includes three calculation processes: Fuel cell calculation; Core neutronic calculation; and Source term analysis.

SRAC is used to calculate macroscopic cross section and fuel burn-up process. The resulted macroscopic cross section data then used to calculate the neutron flux and power density distribution in the reactor core. MATLAB program is used to solve 2 dimensional multigroup diffusion equation, source term calculation, and dose calculation. Fission yield data were adopted from JNDC data, ALI data from 10 CFR 20 part B.

As mentioned before, the analysis of source term is performed only for LOCA accident case, in which the reactor is assumed to has been operated for 10080 days (28 years).

The activity of source term can be calculated with the following formula[3)]:

$$C_0 = 8.46\times10^5 F_p F_b P Y_i (1-e^{-\lambda_i t})Ci$$

with the value of F_p is taken from US-NRC Regulatory Guide 1.183 and value of F_b is assumed according to the behavior of the elements. The values of F_p and F_b during LOCA accident are shown in Table 3.

Table 3. Value of F_p and F_b during LOCA accident

Group	F_p	F_b
Nobel Gas	1.0	1.0
Halogen	0.4	0.5
Alkali	0.3	0.01
Tellurium	0.05	0.01
Barium	0.02	0.01
Nobel Metal	0.0025	0.01
Lanthanide	0.0005	0.01
Cerium	0.0002	0.01

Dose calculation is calculated for two zones, exclusion zone and low population zone (LPZ). Parameter for dose calculation can be seen in Table IV.

Table IV Parameter for dose calculation

Zone	Body Parts	Distance (m)	Exposure Time
Exclusion zone	Thyroid	$100 \le d \le 350$	2 hours
	Whole Body		
LPZ	Thyroid	$400 \le d \le 1500$	30 days
	Whole Body		

The assumptions used in calculation of radiation dose are:

- Direction of the wind is not changing during the release and transport process of the radioactive materials.
- The most stable of atmosphere turbulence (type F on Pasquill classification) is used.
- For the calculation of direct gamma radiation, the reactor is assumed as a source point where the effect of buildings and topography as shieldings of gamma radiation are not taken into account.

The total external dose of gamma radiation received by a person who stands on the radioactive cloud path for t_0 time can be calculated by the following formula[3)]:

$$H = \frac{0.262\overline{E_\gamma}\lambda_l C_0}{\pi\overline{\upsilon}\sigma_y\sigma_z M\lambda_c\lambda_e}(1-e^{-\lambda_c t_0}) \text{ rem}$$

While internal dose for a specific body part for a person who stands on the radioactive cloud for t_0 times can be calculated by the following formula[3]:

$$H = \frac{592B\xi q\lambda_l C_0}{\pi\bar{\upsilon}\sigma_y\sigma_z M\lambda_c\lambda_e}(1 - e^{-\lambda_c t_0})\ \text{rem}$$

4. Results and Discussions

4.1 Neutron Flux and Power Distribution in the Core

Calculation of neutron flux and power density distribution in core performed by making discreet of core into meshes. The radial axis (R) consists of 50 meshes, and the axial axis (Z) consists of 50 meshes, with the coordinate 0,0 is placed right in the middle of reactor core.

Figs. 2 and 3 show two dimensional graph of flux distribution for radial and axial direction respectively. Near the reflector there are jumps in the thermal and epithermal neutron distributions.

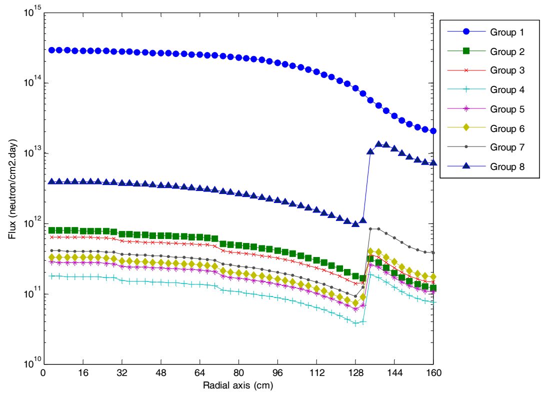

Figure 2. Neutron flux distribution radial axis

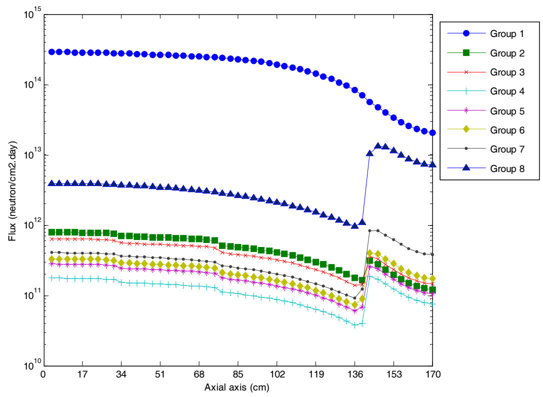

Figure 3. Neutron flux distribution axial axis

Amplification of neutron flux distribution in reflector region is caused by neutron moderation by the reflector materials.

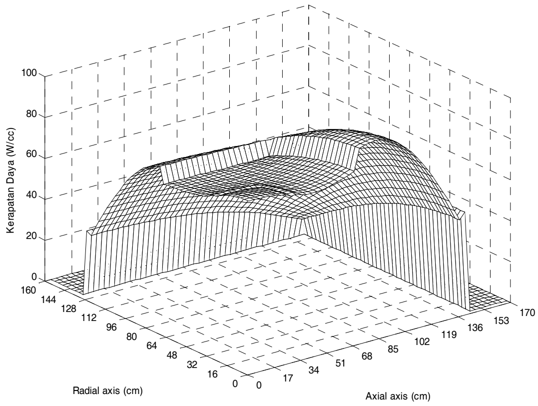

Figure 4. Power density distribution in core

Fig. 4 shows that there are a relatively flat power density distribution in region 1 and region 2, but there are a trend of decrease in the edge of region 3. There are no power generate in region 4 because of no fissile material in the region despite there are neutron flux distribution in region 4.

4.2 Source Term Analysis and Dose Calculation

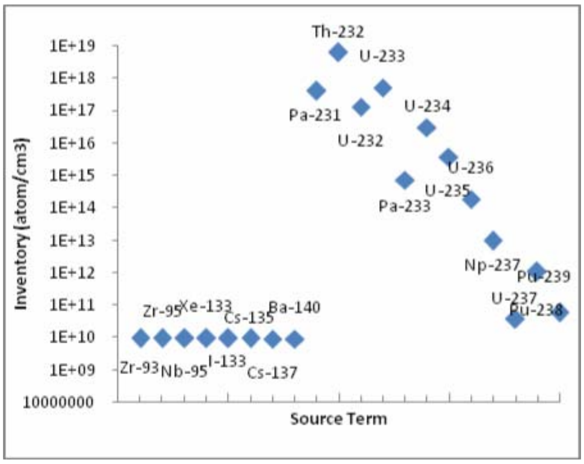

Figure 4. Radionuclides inventory in core (top 20)

Fig. 4 shown that transuranium elements are dominating the inventory in core. While fission product has relatively low inventory compared to the transuranium elements. Inventory of a single fission product is not more than 1.00E+10 atom/cm^3.

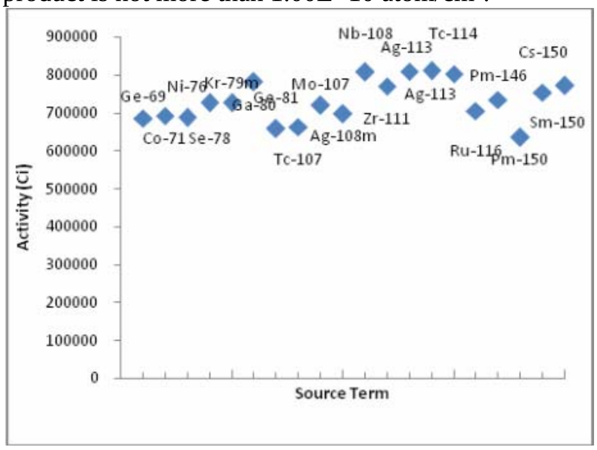

Figure 5. Radionuclides activity in core (top 20)

From Fig. 5, it can be seen that radionuclide with the highest activity is Mn-68, then Cr-67. Total activities of fission products and transuranium elements in core is 3.2E+08 Ci. Clearance time required if an accident happened so that the core can be considered as safe is about 1.49E+19 seconds.

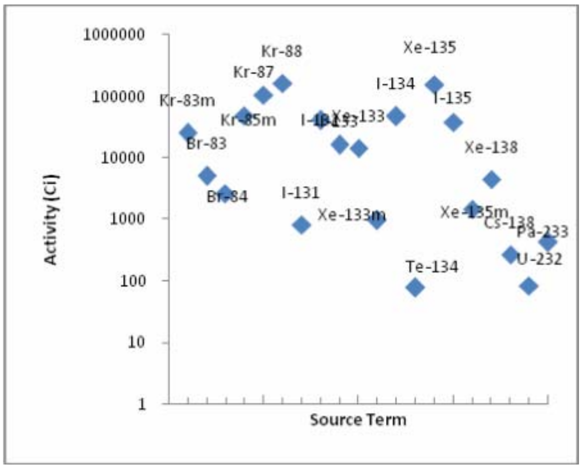

Figure 6. Source term activity (top 20)

The calculation of source term performed with assumptions that there are no damage to the containment. It is assumed that all of noble gases are released to the atmosphere, while only 50% of halogen can be disposed by the safety system. For the remaining source term groups, it is assumed that only 1% release to the atmosphere because these groups are usually formed as solid particulates that can be disposed by safety system. With these assumptions, the total activities that released to the environment is about sekitar 0.21% of total activitied in core or about 6.71E+05 Ci. The top 20 source terms activities are shown in Fig. 6.

Toxicity degree of source terms released to the environment are dominated by noble gases (Kr and Xe), followed by halogen (especially Iodine). There are about 200 radionuclides that are considered toxic released to the environment, the remaining are within the limit value allowed in environment.

This research shows that the maximum dose received by a person who stands on a distance of 100 m from reactor for two hours is 1.53129 rem for whole body and 6.04725 for thyroid gland.

As a comparison, on the boundary of exclusion zone (d = 350 m), for a conventional PWR reactor, US-NRC sets maximum dose value 189 rem for thyroid gland, and 9.74 rem for whole body with two hours exposure time. For LPZ, with distance 0,5 miles, US-NRC sets maximum dose value 130 rem for thyroid gland, and 8.54 rem for whole body with 30 days exposure time[4)]. With the same parameter used, the dose calculation in this research resulted a value of 0.57593 rem for thyroid gland and 0.14583 rem for whole body. For the LPZ the results are 0.23013 rem for the thyroid gland and 0.05107 rem for the whole body. It can be said that the dose received by a person at the exclusion zone or LPZ are still below the maximum dose allowed if an accident occurred on a PWR according to *Regulatory Guide* 1.4 US-NRC.

4. Conclusion

Lost of Cooling Accident has been assumed to be occurred when reactor has been operated for 10080 full power days of 420 MWt.

Total activities of fission product in the core just before the accident is 3.2E+08 Ci.

Total activities of fission product released to the atmosphere with assumption of all noble gases, 50% of halogen and 1% of the other source term groups released is about 6.71E+05 Ci, or about 0,21% of total activities in core.

There are about 200 radionuclides that are considered toxic released to the environment, the remaining are within the limit value allowed in environment.

Calculation of dose received for thyroid gland at the boundary of exclusion zone is 0.57593 rem and in LPZ is 0.23013 rem below the requirement for PWR which are 180 rem and 130 rem respectively. Dose calculation for whole body at the boundary of exclusion zone is 0.14583 rem and at LPZ is 0.05107 rem, which also below the requirement of 9.74 rem dan 8.54 rem. It can be concluded that if a LOCA accident occurs then the dose received by human population will be still below the dose limit.

References

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