Probabilistic Assessment of Severe Accident Consequence in West Bangka

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Abstract. Probabilistic dose assessment for severe accident condition is performed for West Bangka area. Source-term from WASH-1400 reactor analysis is used as a conservative release scenario for 1000 MWe PWR. Seven groups of isotopes are used in the simulation based on core inventory and release fraction. Population distribution for Muntok district and the area within a 100 km radius is obtained from 2014 data. Meteorological data is provided through cyclic sampling from a database containing two-year site-specific hourly records in 2014-2015 periods. PC-COSYMA segmented plume dispersion code is used to investigate the assumed the consequence of the accident scenario. The result indicates that early or deterministic effect is important for areas close the release point while long-term or stochastic effect is related to population distribution and covers area of up to 100 km from the release point. The mean annual expected values for early mortality and late mortality for the population within 100 km radius from Muntok site are $2.38 \times 10^{-4}$ yr\textsuperscript{-1} and $1.33 \times 10^{-3}$ yr\textsuperscript{-1} respectively.

1. Introduction

Spatial distribution of radioactive pollutant concentration and its probability is predicted using a single source-term and a set of meteorological data. The resulted distribution can aid emergency response officials to prepare evacuation route and the areas to be evacuated during an accident. The recent example from Fukushima Daiichi nuclear accident has demonstrated that timely evacuation has prevented catastrophic radioactive exposure to the public.

Dose analysis can be performed using both deterministic and probabilistic methods. Probabilistic Risk Assessment (PRA) or Accident Consequences Assessment (ACA) is a process where potential consequence of radionuclide release is analyzed, taking into consideration a number of conditions that may persist during the sequence of the accident. Consequence is analyzed for a range of conditions. A pair of condition under consideration is a probable occurrence and this pair is related to a certain probability.

Generally, it is not reasonable to adopt any single specific accident scenario as the basis for the establishment of nuclear emergency planning. The spectrum of the source terms of the nuclear facility in question and the whole scope of local weather conditions should all be taken into consideration. The consequences of most common nuclear accidents are negligible, including the rare occurrence accidents included in the Design Basis Accidents (DBA). It is only in the case of Beyond Design Basis
Accidents (BDBA), which occurs with extremely low probabilities that any problem of relocation can appear[1]. In this paper, the postulated accident is a BDBA using core inventory and release fraction from WASH-1400 data, which were obtained from probabilistic safety analyses based on the operation experience of the PWRs in USA[2][3]. The source terms were more conservative and the calculated doses and risks are relatively large.

Site feasibility study performed in Bangka Island of Bangka Belitung Islands Province had identified several possible locations for future nuclear power plants. One of the candidate sites is located in Muntok district in western tip of Bangka Island. The candidate site is located relatively far from population centers however it is necessary to prepare for emergency planning actions in case of an accident. This paper aims to evaluate health effects and risks based on a hypothetical and conservative source-term and on site-specific meteorological database providing a range of possible weather condition.

2. PC-COSYMA accident analysis code

The description provided in this section is referenced from Jones et al. (1996) and PC-COSYMA User’s Manual[4][5] unless otherwise stated.

PC-COSYMA was developed by NRPB and FZJ to evaluate radioactive dispersion across Europe in the framework of MARIA program. COSYMA (Code SYstem from MAria) is a software package for assessing the offsite consequences of accidental releases of radioactive material to the atmosphere. It was developed as part of the European Communities program Methods for Assessing the Radiological Impact of Accidents (MARIA). The code contains three different accident consequence codes, designed for application in different time periods and distance regimes. The Near Early (NE) program calculates early health effects and the influence of emergency actions to mitigate the consequences, and is used in the near-field. The Near Late (NL) program considers only late health effects and the associated mitigating countermeasures, and is also used in the near-field. The Far Late (FL) subsystem is concerned with late health effects at distances far from the site, together with the appropriate countermeasures. The NE and NL subsystems use the MUSEMET program, a segmented Gaussian plume model, allowing incorporation of temporal changes in the meteorological conditions. The FL subsystem uses the MESOS model intended to address transport and dispersion over large distances. The NL subsystem can also be used with ISOLA, a model for very long duration releases which are sufficiently small that no countermeasures will be expected. External irradiation pathways are considered with a variety of countermeasures to be considered. Doses, early and latent health effects are calculated based on models from United Kingdom, United States, and Federal Republic of Germany.

The input for the code includes user-specified deposition velocities for five different isotope classes: noble gases, vapor, aerosols as well as iodine in elemental, organic or aerosol-type phase. Meteorological data input includes hourly wind speed, wind direction, rainfall rate and atmospheric stability class. The output of the code includes doses, health effects and risks at specific grid points and associated probability distributions.

The wind speed at the height $z$ is calculated using $U(z) = U_0(z/z_0)^p$ where $z_0$ is wind measurement height and $p$ is the wind profile index. Surface roughness of $\geq 1$m is assumed and the values for $p$ in Table 1 is used.

| Atmospheric stability category | A  | B  | C  | D  | E  | F  |
|-------------------------------|----|----|----|----|----|----|
| $p$                           | 0.07 | 0.13 | 0.21 | 0.34 | 0.44 | 0.44 |

Health effects in PC COSYMA include early morbidity for lung function impairment, hyperthyroidism, skin burns, cataracts and mental retardation. The early mortality effects include pulmonary syndrome, hematopoietic syndrome, gastrointestinal syndrome, pre- and neonatal death...
and death from skin burns. The risk $R$ of early effects to an individual is calculated using the hazard function $H$:

$$R = 1 - e^{-H}$$

where

$$H = \ln 2 \times \left( \frac{D}{D_{50}} \right)^S$$

$D$ (Gy) is the dose received by a certain organ in a certain period, $D_{50}$ (Gy) is the dose causing the effect in 50% of the exposed population, and $S$ is the shape parameter characterizing the slope of the dose-risk relationship. For the same dose, a higher dose rate is more effective in causing early health effects. PC COSYMA divided the irradiation into several periods and replaced the ratio $(D/D_{50})$ by:

$$\frac{D}{D_{50}} = \sum_i \frac{D_i}{D_{50}}$$

where $i$ specified the $i$th period and:

$$D_{50} = D_{\infty} + \frac{D_0}{X_i}$$

Where $X_i$ is the average dose rate in the $i$th period, $D_{\infty}$ is the value for $D_{50}$ at high dose rate and $D_0$ is a parameter. There is no threshold for early effects but when the value for $R$ is less than 1%, the corresponding dose was assumed to be below the threshold and $R$ is reset to zero.

The late effects considered in PC COSYMA include 11 types of cancers and hereditary effects. The cancers are leukemia and cancers to the bone surface, breast, lung, stomach, colon, liver, pancreas, thyroid, skin and the remainder of human body. The absolute risk (additive model) is applied for leukemia and bone surface cancer and the relative risk (multiplicative model) is applied for the rest. Additive risk assumes that the excess mortality from cancer caused by a given dose of radiation is expressed as a constant number of extra cancer deaths per year, irrespective of the underlying spontaneous rate in the population while multiplicative risk assumes that excess mortality is expressed as a constant percentage of the underlying rate. The incidence of late effects is calculated in PC COSYMA using no-threshold linear dose-risk relationship. As an example, the risk of a certain late health effect caused by external irradiation from material deposited on the ground could simply be expressed as:

$$r = SF \times \sum_k (AG(k) \times ARC(k))$$

Where $k$ specifies a particular radionuclide, $SF$ is the mean shielding factor for external irradiation from materials deposited on the ground, $AG$ is the radionuclide concentration deposited on the ground ($Bq \cdot m^{-2}$). The risks of other late health effects caused by other exposure pathways are calculated with formulas similar to the above equation. The coefficients used in this paper are given in ICRP-60[6].

3. Methodology
The meteorological data for the modeling is obtained from an on-site monitoring in west Bangka area. The duration of the data is approximately 2 years (2014-2015) with a completeness of more than 90% in each year[7]. The required parameters by PC-COSYMA are wind speed and direction, atmospheric stability condition, rainfall rate and boundary layer height. Atmospheric stability condition is determined by lapse-rate method using temperature difference at the heights of 80 and 10 meters.

Probabilistic dispersion modeling is performed using cyclic sampling for meteorology data. In the cyclic sampling, a period of 61 hours is selected as the interval and therefore for one year data of about 8760 hours there are 144 sample hours.

Simulation is performed for west Bangka area, centered at the meteorological station location. This is located at the westernmost tip of Bangka Island in Bangka-Belitung Province. Flat topography with rough surface is assumed considering various palm oil and rubber plantations exist in the neighboring
areas. The reactor is assumed to be a 40×40 m building and the stack height is 25 m. The actual duration of the release is 0.5 hours but because of the requirement in the model it is changed to 1 hour as the minimum duration of release.

![Division of sector and radial distance from release point](image)

Figure 1. Division of sector and radial distance from release point (20 km radius intervals are shown)

The investigated area in Muntok area, West Bangka is included in a 100 km radius and is being divided into 20 concentric stripes and 16 sectors each having 22.5 degree angle provided in Figure 1. The assumed release point is located at the center of the concentric circles. The distances of the circles are 0.8, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90 and 100 km. the sectors are numbered in clockwise direction starting from the north direction in the middle of the 1st sector.

Deposition velocities are set as provided in PC COSYMA as follows; aerosols: $0.001 \text{ ms}^{-1}$; elemental iodine: $0.01 \text{ ms}^{-1}$; organic iodine: $5 \times 10^{-4} \text{ ms}^{-1}$. Washout coefficient is provided as $\lambda = a \times i^b$ where $i$ is the rainfall intensity in mm h$^{-1}$. The coefficient $a$ and index $b$ is provided as the default by PC COSYMA as in Table 2.

| Category         | Aerosol   | Elemental iodine | Organic iodine |
|------------------|-----------|------------------|----------------|
| $a$              | $8 \times 10^{-5}$ | $8 \times 10^{-5}$ | $8 \times 10^{-7}$ |
| $b$              | 0.8       | 0.6              | 0.6            |

The source term data of WASH-1400 were obtained from probabilistic safety analyses based on the operation experience of the PWRs in USA. The source terms were more conservative and the calculated doses relatively large. The model itself contains nine release scenarios for Pressurized Water Reactor (PWR) and seven radionuclide groups. Scenario PWR1, with annual probability of $9 \times 10^{-9}$, is selected since it offers the most conservative amount of release. The details on radionuclides, their groups and release fractions can be seen in detail in the WASH-1400 report. PWR1 accident can be described as a condition after an accident involving core uncovery and followed by core melt. In the next phase, early total containment failure occurred with early major containment leakage and later containment melt-through. The spray or suppression pool failure occurred and radioactive materials are released to the environment.

Source term is one of the determining factors affecting accident consequences. It is defined as the amount and form of radioactive release, duration of release, release energy, release height, etc. At the moment, the reactor type and power have not been decided yet. In this paper, a pressurized water
reactor of 1000 MWe class is assumed and correspondingly WASH-1400 data for PWR1 type of accident is used as the most conservative scenario.

PWR1 scenario is further divided into PWR1A and PWR1B each having annual probability and released energy of $4 \times 10^{-7}$ yr$^{-1}$ and 5.86 MW for PWR1A, respectively, and $5 \times 10^{-7}$ yr$^{-1}$ and 152 MW for PWR1B, respectively. The release fractions relative to core inventory for 7 nuclide groups are provided in the following Table. The fraction of organic iodine is 1% of all types of iodine.

No further retention or reduction is performed and the fraction is directly released to the environment. No countermeasures are taken.

| Category | Group 1 | Group 2 | Group 3 | Group 4 | Group 5 | Group 6 | Group 7 |
|----------|--------|--------|--------|--------|--------|--------|--------|
| PWR1     | 0.9    | 0.7    | 0.4    | 0.4    | 0.05   | 0.4    | 3.00E-03 |

Notes:
(a) includes Mo, Rh, Tc, Co, Ru
(b) includes Nd, Y, Ce, Pr, La, Nb, Am, Cm, Pu, Np, Zr

In this model, the stack height was taken to be 25.0 m, the height and width of the reactor building were set at 40 and 40 m, respectively, to include consideration of building wake effect. The calculations assumed no countermeasures. The other input parameters were based on those from Cao (2000)[8] or default values in the COSYMA code. Other adopted parameters included the following: fraction of contaminated skin: 10%; integration time for late skin dose: 10,000 d; integration time for early individual dose: 7 d; half life of radioactivity deposited on skin: 30 d; radioactivity concentration deposited on skin is equal to that deposited on the ground.

The population distribution around the release point is obtained from the field survey during the site study using the 2014 data in Bangka Island and South Sumatra province located to the south of Bangka Island on the other side of Bangka Strait. The data is also provided 20 concentric stripes and 16 sectors as shown in Table 4. The calculated population density is provided in Figure 2.
Table 4. Population distribution within 100 km radius from release point[7].

| Sector | Outer radius |
|--------|--------------|
|        | 0.8 | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
| 1 N    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   |
| 2 NNE  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   |
| 3 NE   | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   |
| 4 ENE  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   |
| 5 E    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   |
| 6 ESE  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 982  | 699  | 1119 |
| 7 SE   | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 406  | 1119 | 2118 |
| 8 SSW  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 1439 | 2159 | 0    |
| 9 S    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 406  |
| 10 SSW | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| 11 SW  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| 12 WSW | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| 13 W   | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| 14 WNW | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| 15 NW  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
| 16 NNW | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |

| Sector | Outer radius |
|--------|--------------|
|        | 15  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  | 100 |
| 1 N    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   |
| 2 NNE  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   |
| 3 NE   | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   |
| 4 ENE  | 0    | 0    | 0    | 5610 | 7155 | 5090 | 22230 | 33500 | 89601 | 283749 |
| 5 E    | 0    | 0    | 0    | 2541 | 0    | 0    | 11983 | 41700 | 109517 | 335845 |
| 6 ESE  | 3718 | 11415 | 3586 | 9508 | 0    | 816  | 0    | 0    | 0    | 0   |
| 7 SE   | 5213 | 3151 | 5342 | 13687 | 0    | 0    | 0    | 0    | 9607 | 1931 |
| 8 SSW  | 1625 | 0    | 0    | 0    | 0    | 0    | 14246 | 21464 | 32774 | 11582 |
| 9 S    | 406  | 0    | 0    | 0    | 0    | 0    | 23821 | 32893 | 62470 | 50650 |
| 10 SSW | 0    | 0    | 0    | 0    | 0    | 0    | 48726 | 79079 | 154802 | 0    |
| 11 SW  | 0    | 0    | 0    | 0    | 0    | 0    | 40733 | 88762 | 154802 | 0    |
| 12 WSW | 0    | 0    | 0    | 0    | 0    | 0    | 4202  | 78285 | 129161 | 0    |
| 13 W   | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   |
| 14 WNW | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   |
| 15 NW  | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   |
| 16 NNW | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0   |
4. Result and Discussion

Meteorological data record from monitoring height of 10 meter shows that wind is distributed into all 16 sectors with the highest frequency of 14.7% from the South-Southeast direction for 2014 and 20.9% from the Southeast direction for 2015. Wind speed is dominated by 2.1-3.6 m/s class with a frequency of 58% and 62.8% for 2014 and 2015 respectively. There is no occurrence of calm wind condition for both years. Average wind speed at 10 meter level are 2.43 m/s and 2.35 m/s for 2014 and 2015 respectively. Wind condition can be summarized by the windrose plot for the monitoring period for 2014 and 2015 in Figure 3. The colors in the windrose plot signify the classes of wind speed while the bars represent the direction from which the wind is blowing. Zero degree is to the North direction and rotates clockwise in 16 directions classes.

![Windrose in Bangka station at 10 m height](image_url)

**Figure 3.** Windrose in Bangka station at 10 m height

The average individual effective dose at a certain radius from release point is presented in Figure 4. The maximum and minimum doses for the first 24 hours after the release was initiated (early effect) are 4.1 Sv at radius 0.4 km and 0.64 mSv at radius 95 km respectively. The late effect maximum and minimum doses are 37.7 Sv at radius 0.4 km and 14.1 mSv at radius 95 km respectively.

![Early and late average individual effective dose by distance](image_url)

**Figure 4.** Early and late average individual effective dose by distance
The predicted numbers of early morbidity, early mortality and fatal cancers for general public within 80 km radius from release point for PWR1A accident scenario is provided in Figure 5. It can be observed that the early (deterministic) effect is different from late (stochastic) effect. Most of the early effect occurred in closer proximity of about 10 km from the site which includes population center in the city of Muntok and surrounding area. The effect does not transgress to over 40 km radius. On the other hand, late mortality affect mostly areas far from the site causing almost 500 deaths per year at a distance of 100 km, almost five times the number for the population within 40 km radius. Cao et al. (2000)[8] stated that this is caused by the threshold value effect for close distance which cannot be exceeded at larger distances. Late effect is calculated using linear relationship between dose and risk and there are finite probabilities at larger distances although the actual dose values are small. The number of cancer fatality is obtained from the product of cancer probabilities and the number of population in the area and therefore it is in close relation with population density. Taking into consideration the dominant wind direction in the area, most of the early effect will be incurred by the population in the South East to South sector within the 40 km radius around the city of Muntok.

Figure 5. Total number of early morbidity, early mortality and late mortality (fatal cancers) within 80 km radius (yr⁻¹) for PWR1A accident

Figure 6 provides the complementary cumulative distribution functions (CCDFs) for early morbidity and early mortality. Each point the graphs can be interpreted as the probability of having results larger than or equal to the value in the horizontal axis. The number of early morbidity is dominated by skin burns, followed by hematopoietic and gastrointestinal (GI) syndromes. The frequencies for other types of morbidity are very small in this case. Early mortalities are caused mostly by pre- and neo-natal syndromes while other causes have lower frequencies of occurrence.

Figure 6. Complementary Cumulative Distribution Function (CCDF) for early morbidity and early mortality (yr⁻¹) within 80 km radius for PWR1A accident
Figure 7 provides the CCDFs for fatal cancers (late effect) for PWR1A release scenario. The effect is dominated by lung cancer from inhalation of radioactive substance in extended period of time, followed by remaining internal organs. Smallest effects are incurred by the skin and bone surface. In comparison to the early health effects, where skin effect is dominant, in the late effect skin effect is the least dominant because of larger distance and concentration factor due to dispersion effect. Most of the effect will be felt by the South Sumatran population across the Bangka Strait in the Southeast to West Southwest sectors at radius 60 km and more where there are densely populated areas. Although there are increasingly heavier populations to Northeastern to Eastern sectors, they are less likely to be affected due to the small probability of wind blow to this direction.

Figure 7. CCDF for fatal cancers ($yr^{-1}$) for PWR1A release

Using the CCDFs for early and late effects as well as the annual probability of PWR1A of $4 \times 10^{-7} yr^{-1}$ the annual averaged expected values for early morbidity, early mortality and late mortality for population within 100 km radius from the release point are $4.51 \times 10^{-3} yr^{-1}$, $2.38 \times 10^{-4} yr^{-1}$ and $1.33 \times 10^{-3} yr^{-1}$ respectively. In comparison to traffic accidents deaths of 13 people in 2014\[9\], the expected values for early and late mortality from PWR1A severe accident is about four to five degrees of magnitude smaller.

The Nuclear Energy Regulatory Agency of Indonesia (BAPETEN) Chairman Decree No. 1 (2010)\[10\] stipulates that reactor with a capacity of more than 100 MWt and installation or facility with very high potential risk able to generate radioactive releases causing severe deterministic effects offsite is included in the Radiological threat Category 1. Emergency Zones and radius for installation/facility with radiological threat Category 1 are defined as follows: 3 – 5 km radius for Precautionary Action (PAZ), 25 km radius for Urgent Protective Zone (UPZ), and 300 km radius for Food Restriction Planning. In UPZ, preparations are made to promptly take urgent protective measures based on environmental monitoring. In this zone, sheltering is recommended when the effective dose exceed 10 mSv. However, considering the early effect which includes areas within 40 km boundary, it is recommended that UPZ is extended to 40 km for West Bangka site.

5. Conclusion

Probabilistic analysis for severe accident consequence in West Bangka NPP candidate site has shown that early health effect is an important consideration for areas surrounding the site to a radius of 40 km. late health effect affects farther areas due to the linear relationship between dose and risk and also higher population density beyond 40 km up to 100 km to the South of the site in South Sumatra Province. Average yearly probability for early and late mortalities are $2.38 \times 10^{-4} yr^{-1}$ and $1.33 \times 10^{-3} yr^{-1}$ respectively. In comparison to the fatalities from traffic accident in West Bangka in 2015, the late and early mortality risks from a severe nuclear accident are between 4 and 5 order of magnitude smaller respectively. In relation to emergency planning zones, it is suggested that the
Urgent Protective Zone being extended from 25 km to 40 km from the proposed plant considering the early effects due to existing population and meteorological factors.

Acknowledgement
The authors acknowledge the Ministry of Research and Technology for funding this research and Nuclear Physics and Biophysics Laboratory in Institute Teknologi Bandung for the computation facility.

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