Radiological dose in Muria peninsula from SB-LOCA event

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Abstract. Dose assessment for accident condition is performed for Muria Peninsula region using source-term from Three-Mile Island unit 2 SB-LOCA accident. Xe-133, Kr-88, I-131 and Cs-137 isotopes are considered in the calculation. The effluent is assumed to be released from a 50 m stack. Lagrangian particle dispersion method (LPDM) employing non-Gaussian dispersion coefficient in 3-dimensional mass-consistent wind-field is employed to obtain periodic surface-level concentration which is then time-integrated to obtain spatial distribution of ground-level dose. In 1-hour simulation, segmented plumes with 60 seconds duration with a total of 18,000 particles involved. Simulations using 6-hour worst-case meteorological data from Muria peninsula results in a peak external dose of around 1.668 mSv for low scenario and 6.892 mSv for high scenario in dry condition. In wet condition with 5 mm/hour and 10 mm/hour rain for the whole duration of the simulation provides only minor effect to dose. The peak external dose is below the regulatory limit of 50 mSv for effective skin dose from external gamma exposure.

1. Introduction
The capability to estimate radioactive dose dispersion in a course of an accident in a nuclear facility is important to support emergency planning activities and ensure public safety from ionizing radiation exposure. In nuclear power plant site study stage, the information contained in this analysis can be used as an input in emergency response planning, radiation protection activities, and nuclear power plant siting and design.

A computer code named MODAL has been developed based on Lagrangian Particle Dispersion Method[2][12]. The code is capable of handling spatial and temporal variation in topography, wind and source-term. The inputs for this code include topography, surface wind station data and source-term which are usually available during the site study phase through survey, monitoring or other means of data collection.

The Three-Mile Island unit 2 (TMI-2) nuclear accident occurred in March 28, 1979. It was a scale-5 in International Nuclear Event Scale which resulted in some damage to the reactor core and release of radioactive substance to the environment. According to the US-Nuclear Regulatory Committee, this is the most serious accident in the U.S. commercial nuclear power plant operating history. A number of literatures have discussed and reconstructed the amount of radioactive released to the atmosphere for several isotopes such as I-131, Cs-137, Kr-88 and Xe-133. Haste et.al.[5] through simulation with MELCOR/MACCS proposed a total mass of about 0.1 kg of noble gasses and $2.5\times10^{-7}$ kg of CsI. The radionuclide is assumed to be released in a 6-hour period from seconds 8.500 to 30.000 after the accident started. Meteorological data in the model[5] was taken from Surry PWR which is about 200
miles away from TMI-2 site. The result of probabilistic analysis showed that average total calculated individual dose is less than 0.2 mSv at 95% probability and 0.4 mSv at 99% probability. Peak average individual dose are 0.5 and 1.1 mSv for 60 m and surface release height respectively. Jaffe (USNRC) is quoted to have estimated a peak of 0.7 mSv with a release of 2.5 million Ci of noble gasses and 15 Ci of I-131. Gudiksen and Dickerson [6] found about 2.4-10 million Curies of noble gasses with a majority of Xe-133 and 14 Curie of I-131 and 2.6 Curie of I-133. McColl and Prosser [7] found about 62 thousand Curie of Kr-88, 13.5 Ci of I-131, and 8.38 million Curie of Xe-133. The source term used in this paper is summarized in Table 1.

| Radionuclide | Haste et al. | McColl et al. | Gudiksen and Dickerson | NRC | Max. |
|--------------|-------------|---------------|------------------------|-----|------|
| Cs-137       | 2.27E+04    | -             | -                      | -   | 2.27E+04 |
| I-131        | 3.12E+07    | 2.31E+07      | 2.40E+07               | -   | 3.12E+07 |
| Kr-88        | -           | 1.06E+08      | -                      | -   | 1.06E+08 |
| Xe-133 (low) | -           | 1.44E+10      | 4.11E+12               | 4.28E+12 | 4.28E+12 |
| Xe-133 (high)| -           | -             | 1.71E+13               | -   | 1.71E+13 |

This paper aims to assess radioactive dose imposed to the Ujung Lemahabang area in Muria Peninsula by a small-break loss-of-coolant accident (SB-LOCA) such as the Three-Mile Island unit 2 in the USA. Deterministic analysis is performed to obtain spatial distribution of dose in the case of sustained wind condition or in the worst-case meteorological condition.

2. Theory/calculation

Lagrangian Particle Dispersion Method (LPDM) is run by tracking a number of particles in a flow field. LPDM uses stochastic differential equation to explain the similar process as the advection-diffusion equation in Lagrangian framework[9].

Atmospheric turbulence is inherently stochastic and many researchers proposed an approach based on the statistical nature of turbulence. In stochastic representation, marked particles undergo advection process by wind at a certain speed and at the same time experiencing random movement simulating turbulent fluctuation. Average distribution of particles is determined by averaging particle paths. Since every particle moves independently, simultaneous handling of particles is unnecessary and therefore requires small computer memory [1]. The accuracy of this method increases with smaller computational volume.

The advection process of particles is provided by a diagnostic 3-dimensional wind field based on the Mass consistent method (MCM) proposed by Sasaki in 1958 and implemented by Sherman[10]. MCM employs minimization of functional in equation (1).

\[
E(u, v, w, \lambda) = \int_{V} \left[ \alpha_1^2 (u - u^0)^2 + \alpha_2^2 (v - v^0)^2 + \alpha_3^2 (w - w^0)^2 + \lambda \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) \right] dx dy dz
\]

In this model, it is assumed that release rate, wind speed and wind direction are constant during the hour. Topography and meteorological data are used to construct a 3-dimensional wind field using mass-consistent method[10]. The wind field takes part in the advection process of the fictitious particles. The dispersion part is run using spatially variable empirical dispersion coefficient constructed based on the atmospheric stability condition and depth of boundary layer. These data are assumed because literature data is not available. Radioactive decay and wet deposition in case of rain is accommodated in the model.
Wet deposition of radioactive material, or tropospheric particles in general, is primarily accomplished by two mechanisms, namely ‘rainout’ and ‘washout’. Rainout is the process of particles becoming entrained into cloud droplets, either by nucleation or by scavenging, and are subsequently removed from the atmosphere along with cloud water during precipitation. Washout is particle scavenging by falling precipitation. The scavenging process of washout consists of repeated exposures of particles and gases to cloud or precipitation elements with some chance of accretion by the elements for each exposure[8]. In the simulation, wet deposition is caused by washout because the radioactive plume is below cloud.

Wet deposition can be assumed as the decrease of radioactivity level in the atmosphere from the presence of rain. The decrease can be estimated using exponential form in equation (2) and coefficients provided in Table 2 [11]:

\[
\frac{dq_n}{dt} = -\Lambda q_n \quad (\Lambda = \alpha \gamma^\beta)
\]

\( q_n \) is particle radioactivity, \( \Lambda \) (sec-1) is washout coefficient, \( \alpha \) and \( \beta \) are factors for washout coefficient for a certain radionuclide and \( \gamma \) is the rainfall rate (mm/hour).

| Isotope | \( \alpha \) | \( \beta \) |
|---------|-------------|-------------|
| I-131 (p) | 7 \pm 5 \times 10^{-5} | 0.69 \pm 0.12 |
| I-133 (p) | 1.6 \pm 3 \times 10^{-5} | 0.5 \pm 0.2 |
| Cs-134 (p) | 2.8 \pm 0.6 \times 10^{-5} | 0.51 \pm 0.07 |
| Cs-137 (p) | 3.4 \pm 0.9 \times 10^{-5} | 0.59 \pm 0.08 |

After each puff step (60 seconds), time-integrated air concentration (TIAC) is obtained by calculating concentration in one time-step and taking summation throughout simulation time. Plumes of particles released in the first hour are followed for the next 5 hours. Concentration is calculated using kernel approximation method for surface layer (0-5 m layer). Dose at gridpoints are then calculated using dose conversion factors from Lam et.al. [8].

Meteorological data for worst-case condition is obtained from site feasibility study monitoring program performed in the 1994-1995 period[11]. Frequency analysis was done to determine worst-case example in which there is high frequency of wind-direction consistently blowing to the land and populated area as well as calm or low wind-speed condition. A 12-hour duration of consistent wind direction from NW to N sectors in November 14, 1994 was identified. Five rain conditions were simulated: no rain, 5, 10, 15, and 20 mm/hr rain for the whole duration of simulation. These values are selected because rain analysis data shows that rain occurred in 10 mm/hour or less almost 90% of the time. Larger values are added to see the effect of larger rates to the dose distribution and peak. In rain condition, at the end of every puff integration step, probability deposition of each particle is calculated and deposited particle height will be set to terrain height or at surface level.

During the worst-case situation, the Pasquill stability class varies between D and E (neutral and slightly stable).
3. Methodology
MODAL will be used to calculate external gamma exposure from I-131, Cs-137, Kr-88 and Xe-133 isotopes emitted through a 50 meter high stack in 6-hour duration. The modeled area is 100 km × 100 km with Cartesian grid size of \( \Delta x = 1 \) km, \( \Delta y = 1 \) km and \( \Delta z = 0.05 \) km. Total height of the model is 1500 meters. The air is incompressible and has uniform density anywhere in the grid.

Simulations are performed using isotopes of Cs-137, I-131, Kr-88, and Xe-133 each with a total strength of 0.011, 15.04, 62.000, and 8.37 million Curies respectively. The plume is released from a 50 m high stack at a constant rate from second 8.500 to 30.000 after the actual accident happens. Two scenarios are prepared each containing different amount of Xe-133 release provided in Table 1. For each isotope, maximum value is taken from available data for conservative assumption.

A number of simulations are performed representing dry and rain condition with 5, 10, 15 and 20 mm/hr rain intensities. Worst-case meteorological condition is picked from meteorological database from on-site monitoring program performed during site feasibility study in 1994-1995 periods. Worst-case condition in this paper is defined as condition where wind is blowing to a consistent sector during the entire duration of radioactive release. This type of atmospheric condition will tend to produce higher TIAC for locations in the downwind direction from the source emission. Frequency analysis is performed to pick a period in the database where wind blow consistency is found.

4. Results and discussion
Simulations performed using TMI-2 source-term and worst-case meteorological data produce the peak doses for low-case and high-case scenarios are provided in Table 3.

| Table 3. Peak dose | Peak dose (mSv) |
|-------------------|-----------------|
|                   | Low-case | High-case |
| Dry condition     | 1.668    | 6.892     |
| Rain (5 mm/hr)    | 1.687    | 7.914     |
| Rain (10 mm/hr)   | 1.861    | 7.621     |
| Rain (15 mm/hr)   | 1.600    | 6.828     |
| Rain (20 mm/hr)   | 1.705    | 7.798     |

As a comparison, the average peak dose from field monitoring after the accident in areas around TMI-2 was found to be around 0.2-1.1 mSv in different literatures. Due to the sparse location of monitoring stations, the measurement result may not resolve the actual peak dose in the area. Nevertheless, the measured peak dose is within one order of magnitude with the result of the simulation although the low-case source-term provide better representation to the actual source-term emitted during the accident. Peak dose gridpoint is located about 2.5 km from the point of emission. From the simulation, there is no apparent increase in maximum dose due to rain.
Dose distributions are provided in Figure 3 and 4, representing the dry condition and wet condition with 10 mm/hour rain respectively. High-dose areas are located a few kilometers away from the release point because the radioactive plume is released from a 50 m stack. The difference in dispersion pattern between dry and wet condition is not very noticeable in high dose area but is more visible in low dose area.

When doses at grid points are compared, slightly noticeable shift can be identified as described for 5 mm and 10 mm rains as given in Figure 5 and 6. In the event of rain, doses are generally higher at majority of grid points, especially at lower dose values below 0.15 mSv as indicated by the values of offsets and multipliers of the linear fit. Similar increases in dose are also observed for 15 mm and 20 mm rains.
5. Conclusion
In a consistent wind direction, dose accumulation is concentrated in areas downwind the release point. Fluctuation in wind direction may enhance the dispersion process and thus reduce the peak dose. Wind speed also induces more dispersion and will reduce peak dose but the location of the peak dose in this case will be farther from the source.

Simulation using approximation for source-term and meteorological condition for TMI-2 reactor accident with assumed worst-condition for Muria peninsula has resulted in 1.668 mSv peak dose for low scenario and 6.892 mSv for the high scenario in dry condition. The peak dose is located in the radius between 3 to 5 kms in the direction of 12-hour consistent wind direction covering the middle part of Balong village. In the presence of rain during the simulation period has increased the dose at grid points but does not alter the distribution pattern significantly. At the dominant rainfall rate level of 5 mm/hr and 10 mm/hr for Ujung Lemahabang area, the increase in dose from wet deposition is considered to provide minor effect. In this simulation, the peak external dose is well below the regulatory limit of 50 mSv/year set by the Indonesian nuclear regulatory agency (BAPETEN) for equivalent dose for skin for general public.

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