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Development of radionuclide dispersion modeling software based on Gaussian plume model

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Abstract It has come to attention that Malaysia have been aiming to build its own nuclear power plant (NPP) for electricity generation in 2030 to diversify the national energy supply and resources. As part of the regulation to build a NPP, environmental risk assessment analysis which includes the atmospheric dispersion assessment has to be performed as required by the Malaysian Atomic Energy Licensing Board (AELB) prior to the commissioning process. The assessment is to investigate the dispersion of radioactive effluent from the NPP in the event of nuclear accident. This article will focus on current development of locally developed atmospheric dispersion modeling code based on Gaussian Plume model. The code is written in Fortran computer language and has been benchmarked to a readily available HotSpot software. The radionuclide release rate entering the Gaussian equation is approximated to the value found in the Fukushima NPP accident in 2011. Meteorological data of Mersing District, Johor of year 2013 is utilized for the calculations. The results show that the dispersion of radionuclide effluent can potentially affect areas around Johor Bahru district, Singapore and some parts of Riau when the wind direction blows from the North-northeast direction. The results from our code was found to be in good agreement with the one obtained from HotSpot, with less than 1% discrepancy between the two.

Keywords Gaussian plume model, atmospheric dispersion, nuclear power plant accident, emergency respond plan

AMS mathematics subject classification 82D75, 00A71

1 Introduction

Tenaga National Berhad (TNB), Malaysia has generated more than 130kWh of electricity in 2011 and with increase of 3% per annum towards 2030 [1, 2] shows the increasing demand of electricity usage within Malaysia. However, as reported by PETRONAS in 2010, our natural gas reserve used to for electricity generation will be depleted rapidly starting 2022. To address this issue, Malaysian Government has formally decided in the New Energy Policy in 2010 to include nuclear energy as one of the choice of renewable energy [3]. In reciprocal to the interest shown by the government of Malaysia in building its pioneer nuclear power plants for electricity generation, local researchers are gearing their researches towards the implementation of nuclear power program. One example of such research work is the investigations of suitable candidate locations for the nuclear power plants [4].In performing this study, many aspects have to be considered especially with regards to the environmental and radiological impacts to the neighboring areas [5, 6]. In these impact assessments, an atmospheric dispersion model is usually used to estimate the impact on the surrounding areas should there be an accidental release of radionuclide from the nuclear power plant, or in the case of a major accident. Information from the dispersion analysis as well as the development of such code are important for real-time emergency response plan during the operation of nuclear power plant in the future [7–9].

Atmospheric dispersion model is a study of mathematical model that is used to describe the dispersion of particle or substance from a source. It was originally used to study pollution hazard caused by the released from factory's chimneys [10,11]. In any atmospheric dispersion assessment, its results depends on the wind speed at the time of occureance, wind direction, rainout and the atmospheric stability. Developed back in 1961 by Pasquill [10], Gaussian plume model (GPM) is one of the oldest mathematical model in atmospheric dispersion analysis and have been widely used due to its simplicity and limited amout of data needed for calculations. GPM have been used in many emergency events, such as in the work of refs. [12–14]. Other than that, GPM has also been used to assess the dispersion of radioactive effluent from a hypothetical nuclear accident [11, 15–20].

In preparation for the country's first nuclear power plant, we are working towards producing our very own dispersion computer code to assess the radioactive effluent dispersion released in an emergency situation such as in the Fukushima accident. The code has been applied herein to a case of a hypothetical nuclear accident in Mersing, Johor. Our GPM dispersion code is benchmarked to the HotSpot Health Physics code (hereafter referred as HotSpot) developed by Steven G.Homann and Fernando Aluzzi in Lawrence Livemore National Laboratory's National Atmospheric Release Advisory Center (NARAC) [21]. The HotSpot code is meant for short-range dispersion with radius less then 10 km and for a short-term prediction (less than a few hours).

This paper is organized as follows. Section 2 provides a general information regarding the Gaussian plume model while the technical details of the calculations using our present code will be discuss in section 3. The results will be presented in Section 4 and finally the conclusion for the current progress of the work is given in Section 5.

2 Gaussian Plume model approach

The governing equation to describe the transport of effluent is given by the expression [22, 23]

$$\frac{\partial C}{\partial t} + \nabla \cdot \vec{J} = S \tag{1}$$

where C refers to the mass $[kg/m^3]$, S the source function $[kg/m^3 s]$ and J being the mass flux $[kg/m^2 s]$ with the combinations of diffusion and advection effects. Following the Fick's law, the three dimension advection-diffusion equation to be solved is of the form

$$\frac{\partial C}{\partial t} + \nabla.(\ C\vec{u}) - \nabla.(\ -\mathbf{K}\nabla C) - S = 0 \tag{2}$$

whereby $\mathbf{K}$ is the diffusion coefficients $[m^2/s]$ and $\vec{u}$ is the wind velocity $[m/s]$.

In the Gaussian approach, assumptions are taken in order to solve equation (2) namely:

- The wind velocity in the y-direction or also known as cross wind direction is negligible.
- The wind velocity in the z-direction is negligible.
- Radioactive effluent is released at a constant rate, Q from a single point source which located at height, H from the ground. The source term may be written as

$$S(\vec{x}) \;=\; Q\;\delta(x)\;\delta(y)\;\delta(z-H) \tag{3}$$

- The solution takes place in a steady state conditions.
- The diffusion due to advection in x-direction is overwhelming large compared to the diffusion because of turbulent in the x-direction.
- The radioactive effluent does not penetrate the ground.

Following these approximation, the activity of air concentration at a certain mesh point in the Cartesian coordinate system $C(x, y, z)$ $[Bq/m^3]$ is given by;

$$C(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z\; u}\exp(\frac{-y^2}{2\sigma_y^2})\Big\{\exp(\frac{-(z-H)^2}{2\sigma_z^2}) + \exp(\frac{-(z+H)^2}{2\sigma_z^2})\Big\} \tag{4}$$

where x is the downwind distance, y is the crosswind distance from the center line of the plume and z is the height above the ground for which the concentration is calculated (all in units of m). Figure 1 shows a sketch of the Gaussian plume and the relation between the quantities just mentioned. The parameters Q, u and h are the release rate $[Bq/s]$, mean wind speed $[m/s]$ and the effective release height $[m]$, respectively.

The standard deviation of the horizontal Gaussian distribution, σ_y and vertical Gaussian distribution, σ_z are calculated using expression in the form;

$$\sigma_y = \chi_y \cdot x \quad ; \quad \sigma_z = \chi_z \cdot x \tag{5}$$

where χ_y and χ_z are the turbulent wind speed fluctuations on the $y-$ and $z-$ directions. Under neutral atmospheric conditions, these parameters can be estimated as

$$\chi_y = \frac{0.88}{\ln(\frac{h}{z_o}) - 1} \tag{6}$$

$$\chi_z = \frac{0.50}{\ln(\frac{h}{z_o}) - 1} \tag{7}$$

3 Calculation details

3.1 Information on study area - Mersing, Johor

Mersing district is located in east coast of Johor with a total area of 2838.6 km^2 with total population of 69,028 people. This location was selected due to it having small population size per area as compared to other site in Johor [24]. According to IAEA siting regulation [5], the population at the selected candidate location need to be as low as reasonable achievable. Due to this reason, Mersing is a potential site for building of a nuclear power plant. Generally, the wind speed in Mersing ranges from 1.6 to 3.3 m/s and the wind direction varies due to monsoon season. Atmospheric dispersion analysis in this study utilizes meteorological data in 2013 of Mersing district (2.15 N, 104.0 E). All the meteorological data was obtained from the Malaysian Meteorological Department. Figure 2 shows the wind rose of Mersing district in 2013.

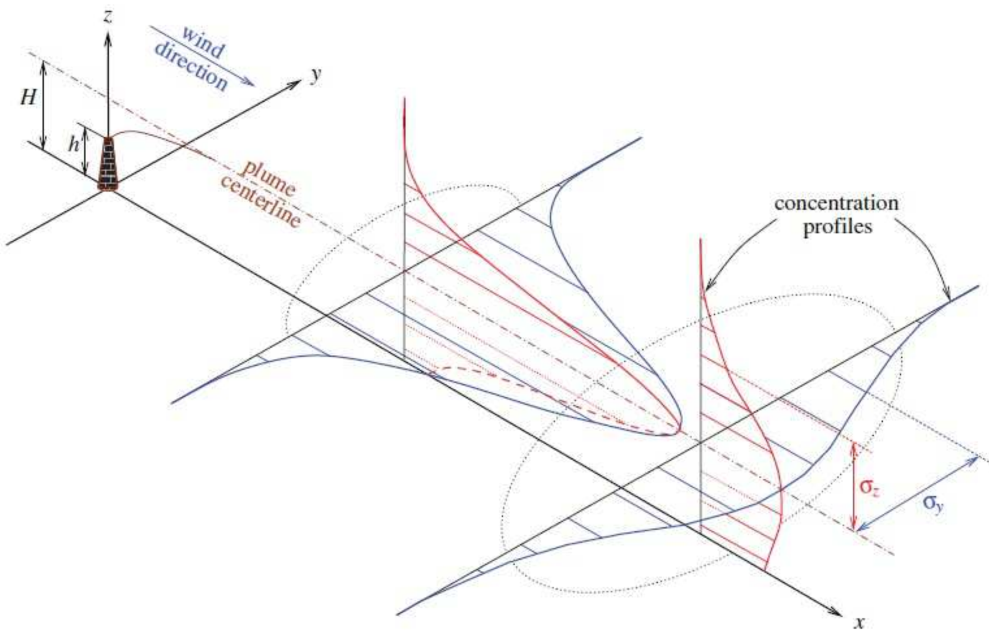

Figure 1: A schematic diagram of the Gaussian plume model extracted from Stockie [22]. The bell shape in each plume represent the movement of radioactive effluence in the atmosphere

3.2 Input parameters

Fortran computer langague were used in this studies and various input parameters are needed for the calculations using the Gaussian plume model. The types of input parameters as well as the flow of the calculations using our present code are reflected in Figure 3. Data such as Ambient Temperature and Stack Effluent Temperature are needed to determine either the movement of radioactive effluent in the atmosphere is due to momentum or buoyancy. In this calculations, we have chose a stack temperature which is higher than the ambient temperature. In this situation the release of the radioactive effluent from the stack is dominated by momentum factor. Then the activity of air concentration is then calculated using equation (4) up to a point where the concentration drop belows the minimum threshold set here to 0.1 Bq-sec/m^3. However for the purpose of comparing the results between the two codes, we have performed calculations only up to 80 km from the release point.

For this paper, we have utilized the data obtained from the Fukushima Dai-ichi accident in 2011 rated at Level 7 by the International Nuclear and Radiological Event Scale (INES). The input data used for both our current code and the HotSpot software are tabulated in Table 1. According to [25–27] in the event of Fukushima accident, apart from Cs-137, another radioactive substance namely I-131 was also released. However, we chose to focus on the dispersion of Cs-137 due to its longer half-life (30 years) as compared to I-131 (8 days).

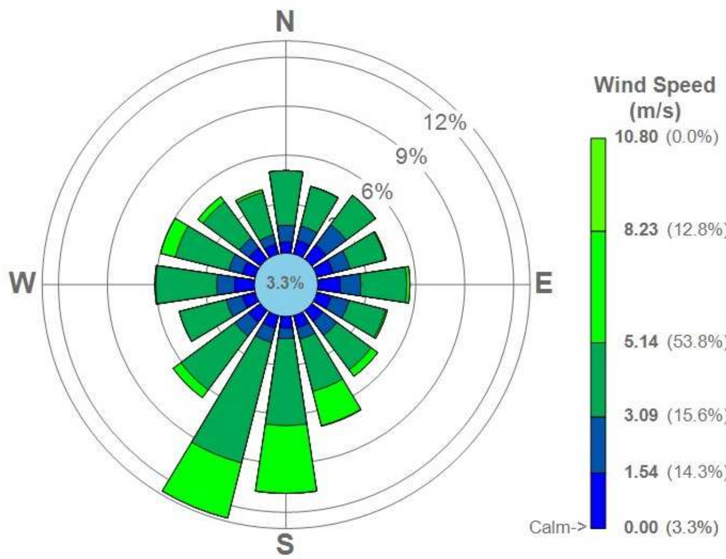

Figure 2: Wind rose showing the frequency distributions of wind speeds and wind directions throughout 2013. The wind blowing from North-Northeast to South-Southwest is predominant.

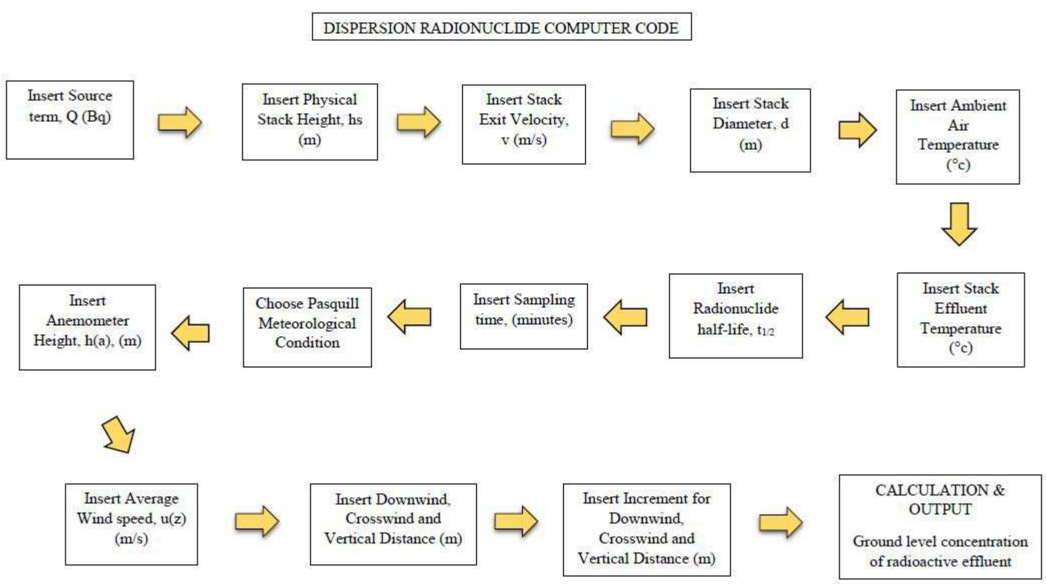

Figure 3: Flowchart showing a sequence of input parameters to be provided by users into the current GPM code before the start of the calculations.

Table 1: Input parameters used in the HotSpot and the current GPM dispersion code

Parameters	**Input Data**	**References**
Radionuclide	Cs-137	[25–27]
Deposition Velocity	0.20 cm·sec	[26]
Material at Risk	2.06×10^{16} Bq	[26]
Sample Time	60 minutes	[26, 27]
Average Wind Speed	3.22 m/s	Average Malaysian meteorological conditions
Frequency Wind Direction	North-northeast to South-southwest	Average Malaysian meteorological conditions
Source Height	20 m height	[26, 27]
Meteorological Condition	Stability Class B	Average Malaysian meteorological condition
Atmospheric Temperature	30 degree Celcius	-
Stack Temperature	60 degree Celcius	-

4 Results and Discussions

The results from our calculations are tabulated in Table 2 together with the results obtained from HotSpot code. These values correspond to the radionuclide effluent concentration at the ground level along the downwind direction. The highest value (3.6×10^{10} Bq-sec/m^3) of Cs-137 concentration is predicted at 1.0 km from the suggested nuclear power plant site. From the results we found that the values obtained from the two codes to match except for only one point which is at 40 km distance. The results shows that the values at 1 km distance is higher compared to 500 m due to the shortcoming of the Gaussian plume model. The simplicity in the input parameters and straight-line nature of the Gaussian Plume Model makes it unsuitable to be employed for calculation in the near wake distance from the point of radioactive effluence release [14, 16, 28].

By considering the effluent concentrations at 80 km away from the release point, it would appear that major parts of Johor Bahru district, Singapore and some parts of Riau will be affected in the case of a nuclear accident at the level which was experienced during Fukushima accident. However, a word of caution is warranted here. The dispersion pattern obtained here is due to the fact that we have employed a unidirectional wind for the whole year. An actual analysis would need a specific set of wind speed and direction for that particular month. The results for such calculations will differ greatly from the one obtained herein. This has not been performed here since it is beyond the scope of the current work which was mainly to serve an initial test of the GPM code that has been developed. A total time taken to complete this set of calculations is about 100 seconds using our GPM dispersion code which we believe could be enhanced in the future.

Table 2: Concentration of Cs-137 Results by using our dispersion computer code and HotSpot software.

Distances in x-direction (km)	Computer Code (Bq-sec/m^3)	HotSpot (Bq-sec/m^3)
0.50	2.3X10^{10}	2.3X10^{10}
1.00	3.6X10^{10}	3.6X10^{10}
2.00	1.5X10^{9}	1.5X10^{9}
4.00	4.5X10^{9}	4.5X10^{9}
6.00	2.2X10^{9}	2.2X10^{9}
8.00	1.3X10^{9}	1.3X10^{9}
10.00	8.8X10^{8}	8.8X10^{8}
20.00	2.7X10^{8}	2.7X10^{8}
40.00	8.8X10^{7}	8.7X10^{7}
60.00	4.6X10^{7}	4.6X10^{7}
80.00	2.9X10^{7}	2.9X10^{7}

5 Conclusion

In this paper, we discussed the current progress of our Gaussian plume model code that has been benchmarked with the usually used HotSpot software for a hypothetical nuclear accident in Mersing, Johor. From our choice of input data, in particular when using the average wind speed and most frequenct wind direction in 2013, and assuming a rather unstable atmospheric condition, we found that the potential affected areas cover a major part of Johor Bahru district, Singapore and a small part of Riau, Indonesia. This was deduced from the high radioactive concentrations even at 80 km from the supposed nuclear reactor site. A visual radioactive effluent distribution over a global map is currently in progress. Comparison with the HotSpot code shows a variation of about 1% disprepancy at only one spot at 40 km along the downwind direction. This provides us with condence in the code and to follow-up with the next part of our work. In particular, we are working on incorporating the building washout eect as an extension to the basic GPM used herein.

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References

[1] Ibrahim, N. TENAGAL1NK Towards renewable energy *Tenaga Nasional Berhad*. 2011. 01/10

[2] Basri,N. A., Ramli, A. T., Aliyu, A. S., Malaysia energy strategy towards sustainability: a panoramic overview of the benefits and challenges. *Renewable and Sustainable Energy Review*. 2015. 42: 1094–1105

[3] PEMANDU Chapter 6: Powering the Malaysian economy with oil, gas and energy economic transformation programme: a road map for Malaysia. *Jabatan Perdana Menteri*. 2010. 183–221

[4] Basri, N. A., Ramli, A. T., Selection of possible candidate area for nuclear power plant in Johor, Malaysia. *Journal of Nuclear and Related Technologies*. 2012. 9(1).

[5] International Atomic Energy Agency (IAEA). *Site Survey and Site Selection For Nuclear Installations.* IAEA Safety Standard Series, No.SSG-35. 2015.

[6] Atomic Energy Licensing Board. *Guideline For Site Selection For Nuclear Power Plant* Atomic Energy Licensing Board. 2011.

[7] Benamrane, Y., Boustras, G., Atmospheric dispersion and impact modeling system: how are they perceived as support tools for nuclear crises management?. *Safety Science*. 2015. 71: 48–55

[8] Benamrane, Y., Wybo, J. L., Armand, P., Cherbobyl and Fukushima nuclear accidents: what has changed in the use of atmospheric dispersion modeling?. *Journal of Environmental Radioactivity*. 2013. 126: 239–252.

[9] Rentai, Y., Atmospheric dispersion of radioactive material in radiological risk assessment and emergency response. *Progress In NUCLEAR SCIENCE and TECHNOLOGY*. 2011. 1: 7–13

[10] Turner. D. B., *Atmospheric Dispersion Estimates: An Introduction to Dispersion Modeling*. 2nd. Edition. CRC Press. 1994

[11] Birikorang, S. A., Abrefah, R. G., Sogbadji, R.B. M., Nyarko, B.J. B., Fletcher, J. J., Akaho, E.H. K., Ground Deposition Assessment of Radionuclides Following A Hypothetical Release From Ghana Research Reactor-1 (GHARR-1) Using Atmospheric Dispersion Model. *Progress in Nuclear Energy*. 2015. 79: 96-103

[12] Man. C. K., Kwok, Y. H., Assessment Of Risk To Hong Kong Due To Accidental Release Of Radionuclides From A Nearby Nuclear Power Plant. *Journal of Radioanalytical and Nuclear Chemistry*. 2001. 250(3): 485-490

[13] Pirouzmand, A., Dehghani, P., Hadad, K., Nematollahi, M., Dose Assessment Of Radionuclides Dispersion From Bushehr Nuclear Power Plant Stack Under Normal Operation And Accident Conditions. *International Journal of Hydrogram Energy*. 2015. 40: 15198-15205

[14] Sahin, S., Ali, M., Emergency Planning Zone Estimation For Karachi-2 And Karachi-3 Nuclear Power Plant Using Gaussian Puff Model. *Hindawi Publishing Corporation Science Technology of Nuclear Installation*. 2016

[15] Cheng, Y. H., Shih, C., Chiang, S. C., Weng, T. L., Atmospheric Puff Model Development In PCTRAN. *15th International Conference On Nuclear Engineering*. 2007.

[16] Tseng,C. C., Chang, N. B., Environmental Exposure Assessment For Emergency Respond In a Nuclear Power Plant Using An Intergrated Source Term And 3D Numerical Model. *Environ Model Assess*. 2009. 14: 661-675

[17] Sohrabi, M., Ghasemi, M., Amrollahi, R., Khamooshi, C., Parsouzi, Z., Assessment Of Environmental Public Exposure From A Hypothetical Nuclear Accident For Unit-1 Bushehr Nuclear Power Plant. *Radiat Environ Biophys*. 2013. 52: 235-244

[18] Sohrabi, M., Parsouzi, Z., Amrollahi, R., Khamooshy, C., Ghasemi, M., Public Exposure From Environmental Release Of Radioactive Material Under Normal Operation Of Unit-1 Bushehr Nuclear Power Plant. *Annals of Nuclear Energy*. 2013. 55: 351-358

[19] Aliyu, A. S., Ramli, A. T., Saleh, M. A., Environmental Impact Assessment Of A New Nuclear Power Plant (NPP) Based On Atmospheric Dispersion Modeling. *Stoch Environ Res Risk Assess*. 2014 28: 1897-1911

[20] Aliyu, A. S., Ramli, A. T., Saleh, M. A., Assessment Of Potential Human Health And Environmental Impact Of A Nuclear Power Plant (NPP) Based On Atmospheric Dispersion Modeling. *Atmosphera*. 2015. 28(1): 13-26

[21] Homann, S. G., Aluzzi, F., HotSpot Health Physics Codes Version 3.0 User's Guide *National Atmospheric Release Advisory Center*. 2013. 3

[22] Stockie, J. M The Mathematical Of Atmospheric Dispersion Modelling. *SIAM REVIEW*. 2011. 53(2): 349-372

[23] Veigele, Wm. J., Head, J. H., Derivation Of The Gaussian Plume Model. *Journal of the Air Pollution Control Association*. 1978. 28(11): 1139-1141

[24] Jabatan Perangkaraan Malaysia *Laporan Bancian Penduduk 2010*. 2010. 1

[25] Hirose, K. Fukushima Dai-ichi Nuclear Power Plant Accident: Summary of Regional Radioactivity Deposition Monitoring Results. *Journal of Environmental Radioactivity*. 2012. 111. 13-17

[26] Korsakissok, I., Mathieu, A., Didier. D., Atmospheric Dispersion and Ground Deposition Induced by the Fukushima Nuclear Power Plant Accident: A local Scale Simulation and Sensitivity Study *Atmospheric Environment*. 2013. 70. 267-279

[27] Katata, G., Ota. M., Terada. H., Chino. M., Nagai. H., Atmospheric Discharge and Dispersion of Radionuclides During the Fukushima Dai-ichi Nuclear Power Plant Accident. Part 1: Source Term Estimation and Local-scale Atmospheric Dispersion in Early Phase of the Accident *Journal of Environmental Radioactivity*. 2012. 109. 103-113

[28] Venkatesan, R., Mathiyarasu, R., Somayaji, K.M A Study of Atmospheric Dispersion of Radionuclides At A Coastal Site Using A Modified Gaussian Model and A Mesoscale Sea Breeze Model *Atmospheric Environment*. 2002. 36. 2933-2942