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Radiological risk assessment of a proposed site for a generic VVER-1000 using HotSpot and InterRas codes

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ABSTRACT

An assessment of radiological risk of a proposed site for a generic VVER 1000 MW nuclear power plant has been conducted using international radiological assessment system (InterRAS) code and HotSpot Health Physics Code in view of Ghana's plan to add nuclear energy to her energy mix. The radiological risk assessment was estimated by considering a hypothetical accident event for a generic VVER 1000 MW at the proposed site. The kind of radionuclides to be release from the fuel meat to the gap between the meat and the clad defined the intervention measures and countermeasures. The available radionuclide for the hottest fuel rod was determined by depleting the core, a method sometimes termed as "source term estimation". The direction of trajectory and Total Effective Dose Equivalent (TEDE) received with the corresponding ground deposition of the released radionuclides were estimated. The right protective actions were determined by estimating the appropriate intervention distances. The maximum TEDE calculated were 3.7×10^{-1} Sv at 0.1 km and 3.7×10^{-1} Sv at 0.18 km for InterRAS and HotSpot codes respectively towards the north-east of the release point. Radiological doses of 10 mSv and above was limited to 1.0 km from the point of release. The intervention level for evacuation (50 mSv) ends at 0.5 km for InterRAS code and 0.7 km for HotSpot code. The intervention level for sheltering (10 mSv) also ended at 1.5 km for both InterRAS and HotSpot code. The highest total radionuclide ground deposition was estimated to be approximately 4.0×10^{6} kBq m^{-2} at 0.1 km and 3.8×10^{6} kBq m^{-2} at 0.18 km for InterRAS and HotSpot respectively. Beyond 5.0 km distance, the ground deposition was in the range of 0.1–1 kBq m^{-2}. Generally, the estimated annual effective dose for the public was less than the 1 mSv limit, which is the annual allowable limit for the public. Therefore, with respect to the outcome of the estimated results, there wouldn't be any radiological risk above the allowable limit, hence the site can be considered as the candidate site for the construction of the proposed nuclear power plant.

1. Introduction

For developing nations like Ghana, the need for reliable, cost effective, and environmentally friendly source of energy is more fundamental. Such kind of energy system can boost the economic indexes and even save lives. The country needs reliable energy to expand its industry, mechanise agriculture, increase trade and improve transportation system. These have been the core ideas of the country, as such Ghana has decided to add nuclear energy to its energy mix (Adu-Gyamfi et al., 2017; Birikorang et al., 2012). A stable energy resource like nuclear energy plays a very significant role as a major contributor to energy sustainability being the key for the development of every country. The total generation of electricity from nuclear energy worldwide keeps increasing yearly and more countries are showing the interest to become nuclear countries (WNA, 2018: Shamsuddin et al., 2017).

With all the benefits of nuclear power and it role in decarbonizing energy mix that helps in limiting global warming there are other challenges that are very critical. Some of the major challenges facing the nuclear industry include dealing with public acceptance, ensuring environmental safety against radiation, protecting reactors from natural disasters and external aggression and finding effective solutions for long-term waste management. Construction of new nuclear power plant

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demands critical and cautious assessment before siting the plant due to its complexity. The environment and the atmosphere could adversely be affected by the emission of fission products as a result of radiological releases from nuclear power plant (NPP) accident. (Van Dorsselaere et al., 2011). Nuclear energy acceptance will depend on how these challenges are met.

Safety is a critical feature during NPP's sitting to ensure that the public and the environment will be in a safe condition in case of accidents. It is a requirement by law in Ghana that a detailed radiological and environmental assessment be carried out regarding site selection preceding the construction. This requirement aims to avoid any unjustifiable exposure during any accident. (Nuclear Regulatory Authority, 2015). In assessing the radiological risk in NPP's operations, one critical issue is to estimate radiation dose and means of demonstrating how radiation dispersion of released radionuclides during radiological accident can be addressed. This is done mostly to fulfil the nuclear safety objective (IAEA, 2003). This assessment which needs to be done to aid site selection and the subsequent construction is the main research objective of this study.

As Ghana is making all the needed effort to include nuclear energy in its energy generation mix, it is important to evaluate the impact NPP will have on the environment before the start of construction. It is also a way of identifying the candidate site for the construction. Assessment of possible environmental impact using design-basis (DB) accident approach is therefore essential. The design-basis accident assessment scenario adopted in this study is based on hypothesis. The hypothetical accident scenarios used was based on the prediction of loss of coolant accident as a result of break in one of the primary cold leg pipelines as shown in Fig. 1.

To evaluate the radiological risk associated with the proposed site, the direction of trajectory of the released radionuclides is determined, total effective dose equivalent (TEDE) received from the released radionuclides is calculated, the activity of the deposited radionuclides is calculated and the intervention distances are also estimated for the determination of the right protective actions.

This paper presents an assessment of the radiological risk associated with generic VVER-1000 reactor at the proposed site. The VVER-1000 design is a 3000 MWth pressure vessel type reactor with four-loop system. It has gross electric output of 1000 MW. The Russian word Voda Voda Energo Reactor, abbreviated VVER or WWER stands for 'water-water energy reactor', thus water-cooled water-moderated energy reactor. The VVER plants have proven to be highly reliable over more than 1300 reactor-years of operation. The VVER is a pressurized water reactor (PWR), the commonest type of nuclear reactor worldwide, employing light water as coolant and moderator similar to PWR. The plant design and materials used has characterized the significant differences between the VVER and other PWR. (Sangiorgi, 2015). Table 1 shows the various parameters of the generic VVER reactor under study.

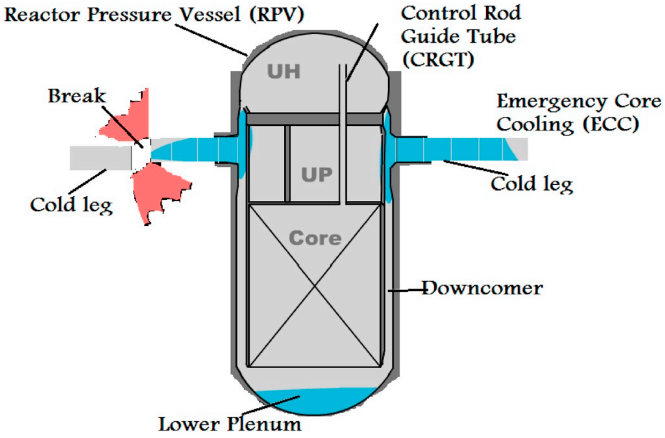

Fig. 1. Schematic diagram depicting the break in the Cold leg.

2. Materials and methods

HotSpot Health Physics Code and International Radiological Assessment System (InterRAS) are the two main codes used in this study. The codes are field-portable set of software tools for evaluating incidents involving radioactive material. They are simple model codes which are run on personal computers covering the entire path through the environment, including the food and water pathway, and covering essentially a lifetime of exposure to a contaminated environment. The codes are used by health physics personnel, emergency response personnel and emergency planners. This makes HotSpot and InterRAS codes appropriate codes for estimation of radiological consequence assessments for the propose site for nuclear power plant construction in Ghana.

2.1. HotSpot Health Physics Codes

The HotSpot Health Physics Code or HotSpot program, provides a first-order approximation of the radiation effects associated with the atmospheric release of radioactive materials. The HotSpot program was created to equip emergency response personnel and planners with a fast, field-portable set of software tools for evaluating incidents involving radioactive material. The software is also used for safety-analysis of facilities handling radioactive material. This program is designed for short-range (less than 10 km), and short-term (less than a few hours) predictions. (Homann and Aluzzi, 2013). HotSpot includes atmospheric dispersion models, the module calculates the 95th percentile of the dose distribution for up to 20 radial centerline distances in each of 16 wind direction sectors (direction dependent), and all 16 sectors (direction independent).

2.2. The International Radiological Assessment System (InterRAS) code

The International Radiological Assessment System (InterRAS) was developed by the International Atomic Energy Agency (IAEA). It is designed to be used in the independent assessment of dose projections during response to radiological emergencies. The system supplements assessments based on plant conditions and quick estimates based on hand-calculation methods. InterRAS code is mainly used by response personnel to conduct an independent evaluation of dose and consequence projections. The model was developed to allow consideration of the dominant aspects of source term, transport, dose, and consequences (IAEA, 1997; Sehgal, 2011).

2.3. The HotSpot and InterRAS algorithms

The HotSpot and InterRAS codes use the Gaussian dispersion model for all assessments, the model has been widely used and verified in the scientific community and is still the basic workhorse for initial atmospheric dispersion calculations. The Gaussian model generally produces results that agree well with experimental data in simple meteorological and terrain conditions, and as a result, has found its way into most governmental guidebooks, and is also used and accepted by the US

Table 1
Generic VVER-1000 reactor parameters.

Reactor parameter	Quantity
Reactor power	3000 MW(t)
Averaged fuel burn-up	40000 MWD/MTU
Containment type	VVER 1000
Design pressure	414 kPa
Coolant mass	2.60×10^5 kg
Assemblies in core	151
Containment volume	7.08×10^4 m^3
Design leak rate	0.25%/d

Environmental Protection Agency.

Plume shape and spread vary in response to meteorological conditions. The general Gaussian dispersion equation that calculate the steady state concentration of air contaminant in the ambient air resulting from a point source is given by:

$$\chi(x,y,z;H)=\frac{Q}{2\pi\mu\sigma_y\sigma_z}\left[\exp-\left(\frac{y^2}{2\sigma_y^2}\right)\right]\left\{\exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right]+\exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right]\right\}$$

where,

H - is the Height of the plume $[m]$,

σ_y and σ_z - are respectively horizontal and vertical deviations of plume concentration distribution $[m]$,

Q - is the uniform emission rate of pollutants $\left[\frac{kg}{s}\right]$,

x - Along-wind coordinate measured in wind direction from the source $[m]$,

y- Cross-wind coordinates direction $[m]$,

z - Vertical coordinate measured from the ground $[m]$,

$\chi(x,y,z)$ - Mean concentration of diffusing substance at a point (x,y,z) $\left[\frac{kg}{m^3}\right]$ and

μ - Mean wind velocity affecting the plume along the x - axis $\left[\frac{m}{s}\right]$

2.4. *Site meteorological conditions*

The proposed site chosen for this study is Axim which is a coastal area located in the western Region of Ghana with an elevation of 38 m, lying on Latitude 4.86992 north and Longitude −2.24046 west. A 10 year period (2008–2017) meteorological data was used for this study. The meteorological data of Axim indicate annual average wind speed of 1.5 m s^{-1} with an annual average temperature of 27.3 °C with no precipitation. The wind direction is mostly south-western. The principal atmospheric stability class that pertains in Axim is stability class A. The atmospheric stability class defines the terms of tendency of a parcel of air that moves upward or downward after it has been displaced vertically by a small amount. Essentially, unstable atmospheres of stability class A tend to develop vertical updrafts which increase boundary-layer turbulence intensity (Zoras et al., 2006; Arya, 1999; Wart et al., 1998).

2.5. *Source term and accidental release scenario*

The InterRAS code has the capability of calculating the source term for the type of reactor selected for the analysis. The InterRAS code source term estimations for nuclear reactor accidents analysis are dependent largely on the source term estimation methods as discussed by McKenna and Glitter (1988) in US Nuclear Regulation Commission Guide-1228 (NUREG-1228). The method selected for the simulation of the InterRAS code was based on the assumption that the release was started when there was stop of flow of coolant to the reactor vessel exposing the fuel, thus 'the time the core was uncovered'. This method could be the most powerful and important source term type that InterRAS uses. The hottest fuel rods was assumed to contain nearly all of the radioactivity at an NPP. Mostly a large release is possible when many fuel rods are substantially damaged. The surest way this can realistically occur is by loss of water from the primary coolant system, thus rendering the core of the reactor uncovered by water. Most of the parameters used in the simulation are described in Table 1.

When one inputs the duration that a reactor core is left uncovered with water, the InterRAS code quantify the amount of core damage that is likely to occur and as a result estimate the activity of each fission product nuclide that will be released from the core. The core damage estimation is based on the damage timings for PWRs (McGuirea et al., 2007). The source term calculated by the InterRAS code was used in developing a source term input deck for the HotSpot code to allow for good comparison between the results of the two codes under the similar condition for the source term used.

The activity of each radionuclide present in the source term as estimated by the InterRAS code is presented in Table 2. The total activity of the source term was 1.11 × 10^{16} Bq.

The release fraction adopted was based on PWR core inventory fraction released into containment as recommended in Regulatory Guide 1.183 (2000). This was applied to radionuclides assumed to have adverse health consequences.

3. Results and discussion

3.1. *Release trajectory of radionuclides*

The simulation of InterRAS and HotSpot computer codes was carried out by using the site specific meteorological conditions, the generic VVER 1000 plant parameters and the source term generated. Most trajectory models produce uncertainty results with regard to starting phase and the height of the tracer. With the help of atmospheric dispersion model most of these uncertainties has been reduced by improving on the accuracy of detective technology. The simulated results generated by the codes show that the radionuclide emission moves towards the north-east direction as depicted in Figs. 2 and 3.

The areas that falls within the plume of the radionuclide emission include parts of the Western region of Ghana, which is from Axim towards Isakro Township as shown in Fig. 4.

3.2. *Calculation of TEDE doses*

The HotSpot and InterRAS codes were able to calculate the doses (TEDE) within different stability classes as shown in Figs. 5 and 6. The doses decreases with increasing wind speed and vice versa due to inverse relationship between the estimated dose/concentration and the mean wind velocity in the Gaussian equation.

More so, at constant wind speed, the maximum dose (TEDE) decreases as one transitions from an unstable stability class to a more stable stability class, thus from Stability class A to Stability class F.

Table 2
Accident source term for the generic VVER-1000.

Nuclide	Activity (Bq)	Nuclide	Activity (Bq)	Nuclide	Activity (Bq)
Ba-137m	5.98E+13	Mo-99	7.15E+12	Te-127	7.56E+12
Ba-140	2.25E+14	Np-239	1.03E+14	Te-127m	7.72E+09
Ce-144	5.78E+12	Pr-144	5.74E+12	Te-129	4.76E+13
Cs-134	1.06E+14	Pr-144m	1.03E+11	Te-129m	1.94E+13
Cs-136	1.89E+13	Pu-239	2.77E+06	Te-131	8.11E+12
Cs-137	6.82E+13	Rb-88	2.76E+14	Te-131m	3.60E+13
Cs-138	5.28E+11	Rh-103m	5.32E+12	Te-132	4.03E+14
I-131	4.69E+14	Rh-106	2.60E+12	Xe-131m	2.67E+13
I-132	6.18E+14	Ru-103	5.38E+12	Xe-133	4.58E+15
I-133	7.66E+14	Ru-106	2.60E+12	Xe-133m	1.56E+14
I-134	8.88E+12	Sb-127	2.04E+13	Xe-135	1.51E+15
I-135	4.03E+14	Sb-129	3.46E+13	Xe-135m	1.91E+14
Kr-85	3.42E+13	Sr-89	1.33E+14	Xe-138	3.39E+09
Kr-85m	2.13E+14	Sr-90	1.15E+13	Y-90	3.01E+11
Kr-87	3.79E+13	Sr-91	9.05E+13	Y-91	8.10E+12
Kr-88	3.36E+14	Tc-99m	7.02E+12	Y-91m	3.75E+13
La-140	1.85E+13				

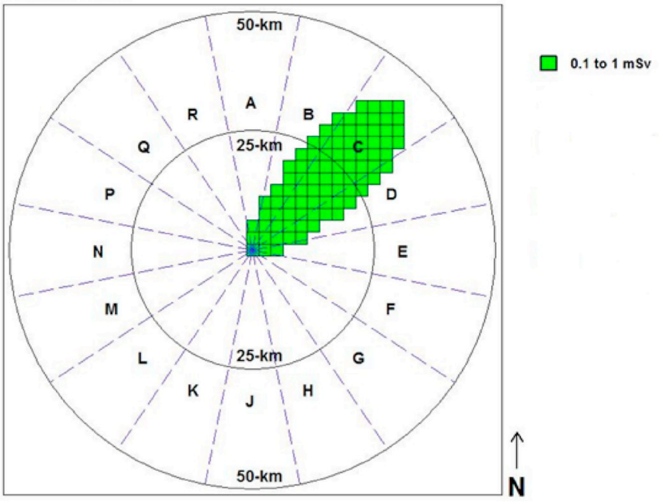

Fig. 2. Coordinate system showing Gaussian distributions in the vertical and horizontal direction.

The maximum TEDEs and the downwind distances where they were recorded by both codes were very comparable though varied slightly due to difference in sigma values coded in both codes. Unstable stability class recorded higher doses than more stable stability class due to the fact that there are better atmospheric mixing within unstable stability class than more stable stability class.

The fundamental factor which yielded the greatest radiological impact (worst case scenario) with respect to the prevailing meteorological condition was identified to be stability class A at lower wind speed. The site meteorological condition coincidentally follows the worst case scenario, therefore narrowing the research work findings on stability class A with a corresponding wind speed of 1.5 m s^{-1}.

It was observed that the TEDE increases till it peaks, after which it decreases as one moves farther away from the point of release for both codes as can be seen from Fig. 7. Notwithstanding, the maximum dose was estimated to be within 0.2 km from the release point for both codes.

The estimated maximum TEDE were 3.70×10^{-1} Sv at 0.1 km and 3.69×10^{-1} Sv at 0.18 km for InterRAS and HotSpot respectively. The doses decreases sharply along the downwind distance after the maximum dose point. The TEDE levels beyond 4.0 km from the release point are less than 1 mSv. Based on the levels of doses shown by the results of this study and the ICRP 103 guidelines (ICRP, 2008), the following analyses were made:

a. The dose level within the region of release as a result of the accident were less than 1 mSv, especially areas that are 4.0 km away from the release point within the path of the emission;
b. Moreover some areas will be exposed to dose level of less than 0.1 mSv and within the ranges of 0.1 mSv–1 mSv, 1 mSv–10 mSv and 10 mSv–100 mSv as presented in Fig. 8;
c. Since dose less than 1 mSv can hardly have a detrimental effect on human health and the environment, such levels are not considered in most assessment and do not need any countermeasures;
d. In such cases, the operators determines the best countermeasures basing the measures on the site regulation documents and seeking approval from the competent State authority

Doses of 10 mSv and above will be limited to 1.0 km from the point of release which is expected to be within the vicinity of the power plant or the buffer zone where public occupation is restricted. More so, for dose levels above 10 mSv, there exist a link between radiation and cancer risk according to ICRP 96 (Valentin, 2005). Considering the level of exposure likely to be received by staff and emergency workers within the 1.0 km distance and their risk to cancer, much effort will be needed in reducing

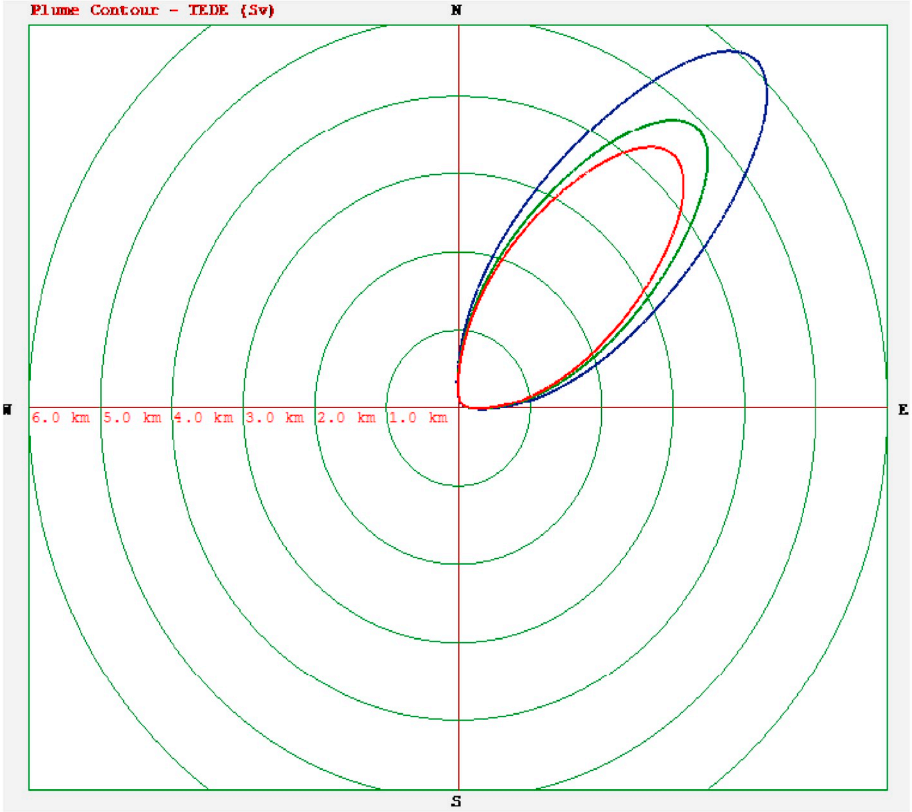

Fig. 3. Dose footprint of TEDE from the release of radionuclides showing the direction of the propagation (InterRAS code).

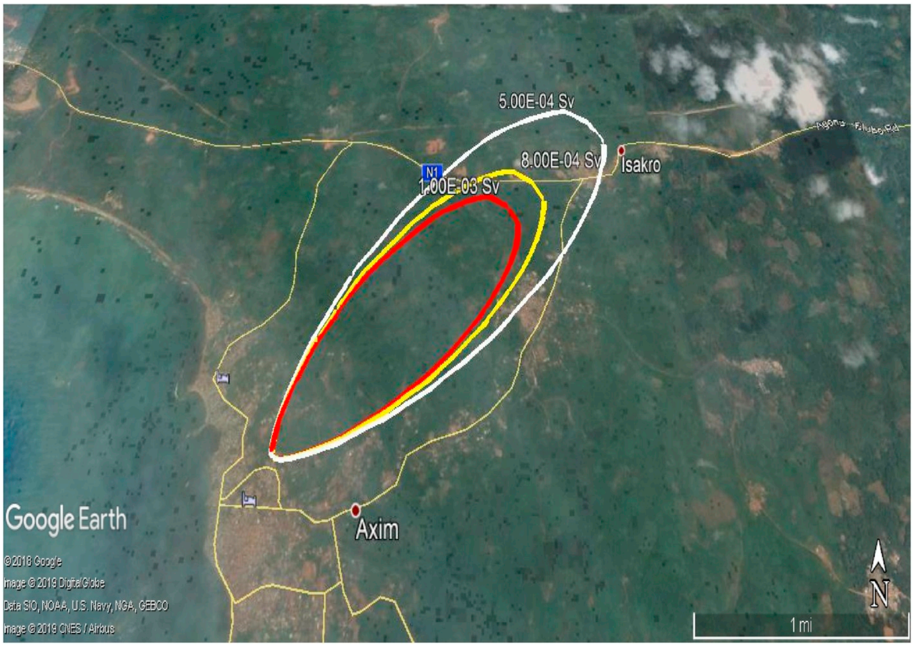

Fig. 4. Plume contour TEDE from the release of radionuclides showing the direction of the propagation (HotSpot).

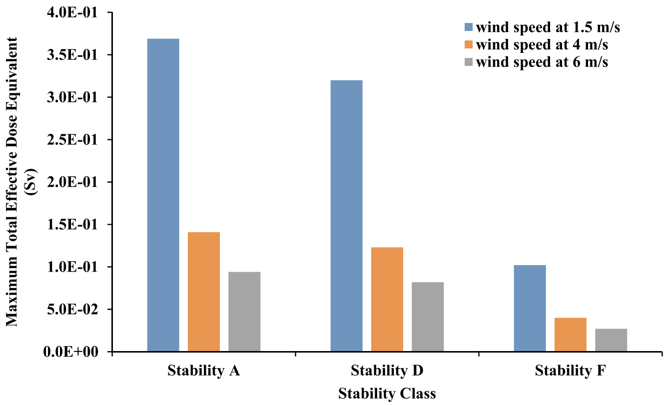

Fig. 5. Plume contour showing areas that falls within the path of the radionuclide emission.

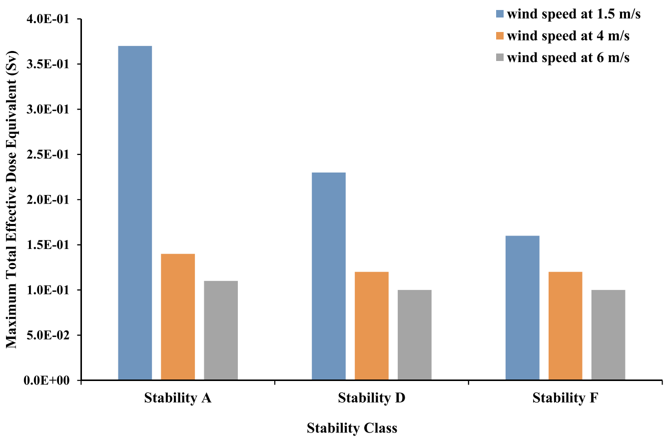

Fig. 6. Maximum TEDE for Stability Classes at varying wind speed (HotSpot).

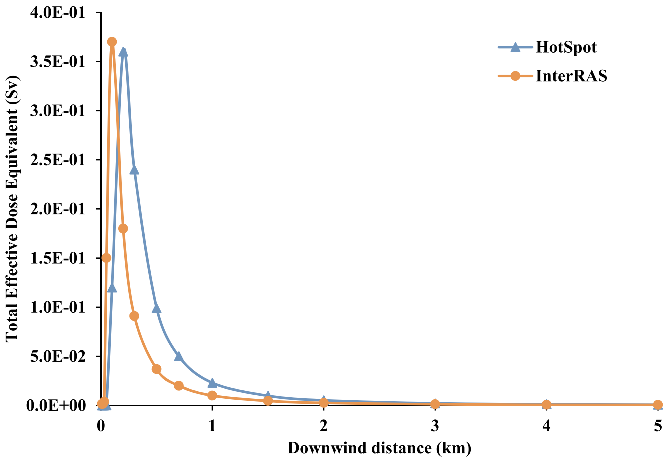

Fig. 7. Maximum TEDE for Stability Classes at varying wind speed (InterRAS).

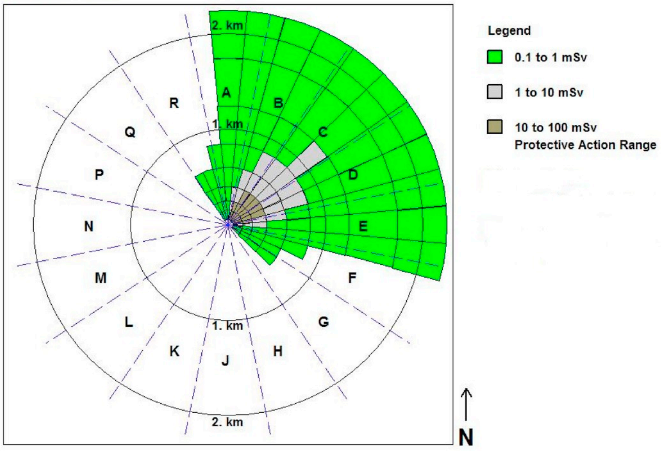

Fig. 8. TEDE (Sv) as a function of downwind distance from the release point in stability class A.

the exposure. In such cases all forms of principles of radiation protection methods should be employed. In this study, there is a conservation assumption of 1% probability of risk to cancer for dose levels above 100 mSv. Therefore real numbers could possibly be higher than as presented.

Even though, the levels of dose to the public is expected to be insignificant, the total affected area is likely to cover a sizeable area which would predominantly be occupied by facility workers. Measures should be put in place to reduce the level of exposure as low as reasonably achievable. Monitoring and assessment of individual exposure should periodically be performed and made available for radiological emergency planning coupled with regular training in radiation measures.

3.3. Ground deposition of released radionuclide

The ground deposition of the released radionuclide impacted greatly within 1.0 km from the release point. The highest total radionuclide ground deposition was estimated to be 4.0×10^6 kBq m^{-2} at 0.1 km and 3.8×10^6 kBq m^{-2} at 0.18 km for InterRAS and HotSpot code respectively on the north-east direction along the plume trajectory. The activity decreases along the downwind distance. For both codes, the activity values rises and peaks then starts a sharp decrease till it reaches very low levels as shown in Figs. 9 and 10. From 2.0 km onwards, the activity values for both codes are almost the same as illustrated in Fig. 10.

The top ten radionuclide according to activity contribution for the highest ground deposition of 4.0×10^6 kBq m^{-2} at 0.1 km from the release point is shown in Fig. 11. Iodine-131 (I-131) has the highest contribution of 2.8×10^5 kBq m^{-2} in terms of activity. Beyond 5.0 km, the activities decrease significantly.

Based on the outcome of results, surrounding water bodies, plantation and other terrestrial environment within the 5.0 km distance will experience minimal effects from the accident since the highest contributor, thus, I-131 has a half-life of 8 days. Thus, in 8 days, half the initial activity of I-131 will decay. It will decay from the ground after few half-lives within a short period. Cs-137 isotope with half-life of 30.17 years which is also potentially harmful when it enters the human body has less activity that will only have negligible effect on the environment. Beyond the 5.0 km distance, the ground deposition is in the range of 0.1–1 kBq m^{-2}. Though these levels of concentration do not pose much harmful effect, putting in place measures to monitor radiation of the water bodies, plantation and soil in the areas that are within the ground deposition plume contour line is very important.

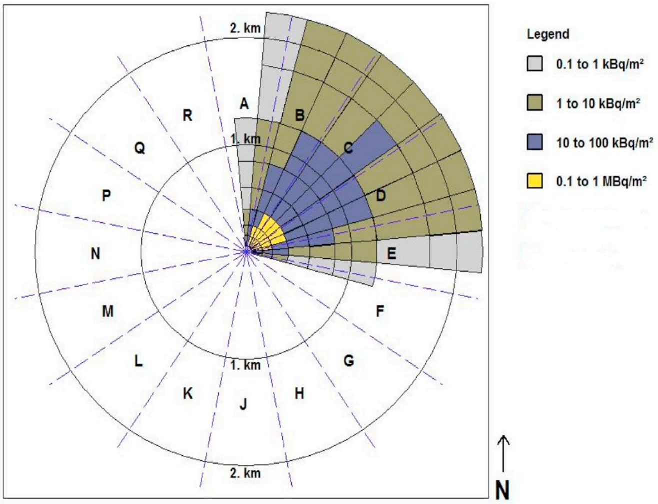

Fig. 9. Dose footprint of TEDE from the release of radionuclides showing the levels of doses at different points (InterRAS code).

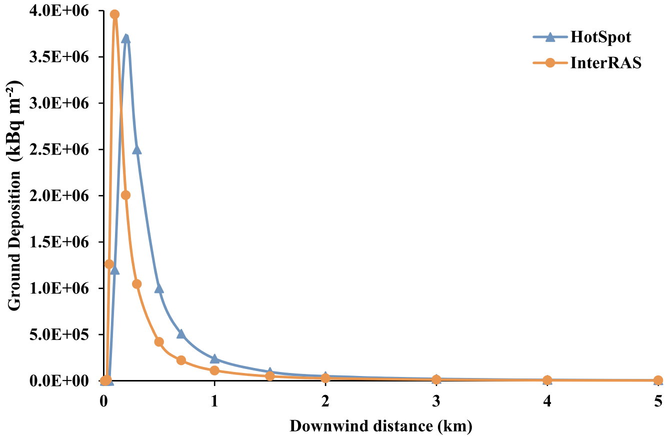

Fig. 10. Activity footprint of Surface concentration from the release of radionuclides (InterRAS).

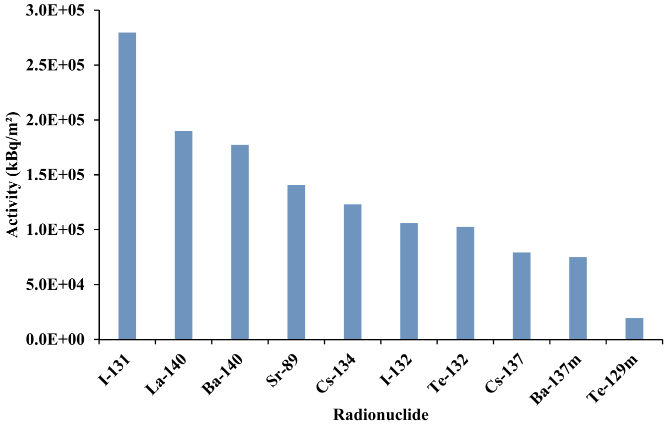

Fig. 11. Surface Deposition concentration as a function of downwind distance from the release of radionuclides.

3.4. Estimation of intervention distances

In accordance with IAEA Safety Standards GS-R-2 (IAEA, 2011), sizes of emergency planning zones which are dependent on the estimated intervention distances are to be defined in the course of site assessment of NPP. The intervention level for evacuation (50 mSv) and sheltering (10 mSv) were achieved at slightly varied distances for both code as seen in Fig. 8. The intervention level for evacuation (50 mSv) ended at 0.5 km for InterRAS and 0.7 km for HotSpot code. Again, the intervention level for sheltering (10 mSv) ended at 1.5 km for both InterRAS and HotSpot code. The outcome can be a way of helping in the determination of the emergency planning zones without any trans-boundary issues. It can also lessen the cost that may be incurred during possible evacuation process.

4. Conclusion

The radiological risk assessment for a proposed site for a generic VVER 1000 MW is conducted using HotSpot and InterRAS codes. The direction of trajectory was observed to be towards the north-east from the point of release. Doses were estimated at various distances and it was realised that the doses decreases significantly with increasing distance from the point of release. The maximum TEDE calculated were 3.7×10^{-1} at 0.1 km and 3.7×10^{-1} at 0.18 km for InterRAS and HotSpot codes respectively. Radiological doses of 10 mSv and above was limited to 1.0 km within the vicinity of the plant or the buffer zone where no public occupation is allowed. The radionuclide concentration beyond

4.0 km within the path of the emission was less than 1 mSv. Therefore the public will not receive dose level more than 1 mSv which is the annual allowable dose limit for the public. It was realised that the intervention level for evacuation (50 mSv) and sheltering (10 mSv) were achieved at slightly varied distances for the two codes. The intervention level for evacuation (50 mSv) ends at 0.5 km for InterRAS and 0.7 km for HotSpot code. The intervention level for sheltering (10 mSv) also ends at 1.5 km for both InterRAS and HotSpot. The highest total radionuclide ground deposition was 4.0×10^6 kBq m^{-2} at 0.1 km and 3.8×10^6 kBq m^{-2} at 0.18 km for InterRAS and HotSpot code respectively along the north-east direction. The ground deposition of the radionuclide is shown to have insignificant radiological impact on the water bodies, plantation and other terrestrial environment within the 5.0 km distance from the release point. Beyond the 5.0 km distance, the ground deposition is in the range of 0.1–1 kBq m^{-2}. The results of the two codes proves to be comparable. The analytical result of the study is suited as the start of the development of a baseline document to help in the assessment for the identification of a candidate site for the nuclear power programme in Ghana and also could assist in the development of an emergency plan for the candidate site.

Author contribution statement

Kwame Gyamfi: Data curation, software, writing – original draft, investigation, visualization, S. A. Birikorang: Resource, conceptualization, validation, software, writing – review and editing, visualization, E. Ampomah-Amoako: writing – review and editing, visualization, J. J. Fletcher: Supervision, visualization, writing – review and editing

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pnucene.2019.103239.

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