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NEAR-RANGE GAUSSIAN PLUME MODELLING FOR GAMMA DOSE RATE RECONSTRUCTION

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Abstract: In the context of nuclear facilities, atmospheric dispersion modelling is often used for emergency planning and during accidents. Gamma dose rate stations, that are installed in the vicinity of many nuclear facilities as part of an early warning network, are often the first source of information when radioactivity is released to the atmosphere. Moreover, at some installations these stations are also able to pick up emissions during routine operation. In this work, we perform near-range atmospheric transport and dispersion simulations at three nuclear installations (of which two were operating normally and one during an incident) under varying meteorological conditions. The purpose of this modelling is to check consistency between the various components of several unexplored datasets. Source terms are estimated based on stack monitoring and/or calculations, and meteorological data were obtained on-site. A Gaussian plume model is used for the dispersion calculations, and gamma dose rates are calculated through volumetric integration over the full cloud and all different photon energies rather than using dose coefficients. Modelling results are subsequently compared with gamma dose rates that were observed using both fixed and mobile measurement stations. Largely consistent results were obtained between observed dose rates and modelling results.

Key words: *Near-range, atmospheric dispersion, Gaussian plume, gamma dose rate, radionuclides*

INTRODUCTION

In this study, we performed calculations for the near-range atmospheric dispersion of several types of gamma-emitting radionuclides at different facilities in Belgium. Such calculations are of critical importance to determine the impact of radiological contamination in the event of a radiological or nuclear emergency but also in preparing for such emergencies. Using concentration fields obtained by a Gaussian plume model (Bultynck and Malet, 1972), we calculated ambient dose equivalent rates (Healy and Baker, 1968) and compared those to real measurements from TELERAD stations (Sonck et al, 2008). The aim is to check the consistency between meteorological and source term data on the one hand and ambient dose equivalent rates on the other. To this end, we present three case studies. For case I, we reproduced results from a 2017 campaign at the National Institute for Radioelements (IRE) in Fleurus (Camps et al, 2019). For case II, we simulated the 2019 anomalous release of Se-75 from the Belgian Reactor 2 (BR2) at SCK CEN in Mol (De Meutter and Hoffman, 2020). For case III, we simulated the continuous release of Ar-41 over the course of a day's routine operation of the Belgian Reactor 1 (BR1) at SCK CEN (Bijloos et al, 2020).

MODEL

In this study, we used a Gaussian plume model (GPM) including ground surface reflection and a dispersion parametrisation that was specifically developed for the SCK CEN site in Mol (Bultynck and Malet, 1972), which is characterised by its flat terrain and many trees. The horizontal and vertical dispersion coefficients are a function of the atmospheric stability and the downwind distance. Moreover, they are multiplied by a correction factor to account for variations in the meteorological sampling periods (Beychock, 1994). The model further accounts for plume rise (Briggs, 1971) and dispersion is constrained to the height of the mixing length of the boundary layer, which also depends on the atmospheric stability (Kretzschmar, Mertens and Vanderborght, 1984). In a given time window, the meteorological conditions enter through the wind speed and direction, the ambient temperature and the atmospheric stability class. Meanwhile, the source is defined by a radiological emission rate (Bq s^{-1}), the emission height and the total gas outflow and temperature out of the stack. Plume profiles are calculated for consecutive time windows and then projected onto a three-dimensional domain in the correct wind direction.

This spatially resolved concentration field $\chi(\boldsymbol{r}')$ can be used to calculate the ambient dose equivalent rate at a detector in location $\boldsymbol{r}$. However, a single radionuclide can have many different decay pathways and all of these need to be taken into account separately. For example, Se-75 emits 21 γ-rays with different energies E_γ and intensities I_γ. We describe the ambient dose equivalent rate as (Healy and Baker, 1968)

$$\frac{\partial}{\partial t}H^*(10,\boldsymbol{r}) = \sum_{\gamma} C_\gamma I_\gamma \left[\frac{\mu_{\mathrm{en}} K E_\gamma}{4\pi\rho} \iiint \frac{B(\mu\mathscr{r})\exp[-\mu\mathscr{r}]}{\mathscr{r}^2}\chi(\boldsymbol{r}')\mathrm{d}\boldsymbol{r}'\right] \qquad (1)$$

where $[\dots]$ is the dose rate integral over all point sources $\chi(\boldsymbol{r}')\mathrm{d}\boldsymbol{r}'$ that form the plume. Here, $\mathscr{r} = \|\boldsymbol{r}' - \boldsymbol{r}\|$ is the source–detector distance. The mass attenuation coefficients μ/ρ and mass energy absorption coefficients μ_{en}/ρ (with ρ the air density) depend on E_γ (Martin, 2013) as does the build-up factor $B(\mu\mathscr{r})$ (Trubey et al, 1991). $K = 1.6 \times 10^{-13}$ is a proportionality constant. The factors C_γ are γ-dependent conversion factors (ICRP, 1996) to go from Gy s^{-1} to Sv s^{-1}. Taking $\sum C_\gamma I_\gamma [\dots]_\gamma$ finally yields the total ambient dose equivalent rate in a point $\boldsymbol{r}$ due to a radionuclide concentration field $\chi(\boldsymbol{r}')$. The Python source code – Atmospheric Dispersion and Dose Equivalent Rates (ADDER) – has been made publicly available at https://gitlab.com/jpfr95/adder.

CASE I: ROUTINE RELEASE AT IRE IN 2017

A three-day measurement campaign was conducted at the National Institute for Radioelements (IRE) on 12, 13 and 15 September 2017. The object of that campaign was to measure a plume consisting of Xe-133, Xe-133m, Xe-135 and Xe-135m that is routinely emitted at IRE (Camps et al, 2019). On-site wind data were available each ten minutes at a height of 30 m, the same as the stack height. To determine the atmospheric stability, data from a meteorological mast in Mol were used. Source term data were available each fifteen minutes for all four separate isotopes. Finally, dose rates were available from eight TELERAD stations (Sonck et al, 2008). Three of these were fixed while five others could be moved around (Figure 1).

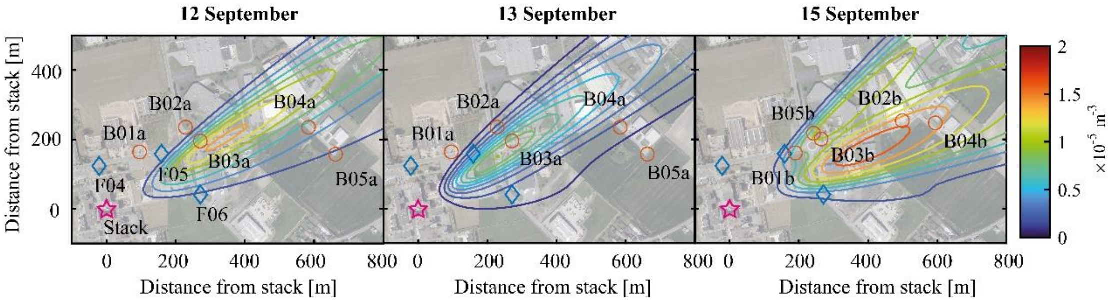

Figure 1. Average concentration profiles for a unit release superimposed on an aerial photograph of the IRE site in Fleurus dated 2018 (https://geoportail.wallonie.be). Also plotted are the locations of the stack (pink stars), the fixed TELERAD stations (blue diamonds) and the mobile TELERAD stations (red circles).

Simulations were performed on a 2.4-km-by-2.4-km-by-0.2-km grid with a 10-meter spacing in all dimensions. Briggs' buoyant plume rise formula was switched off while the stack height was artificially increased to 35 m to account for momentum plume rise, which is not included in the model. The GPM was used to simulate unit releases because the isotope ratios varied over time. The time-averaged results are shown in Figure 1. Contributions to the dose rate were then separately calculated for each of the isotopes in each of the detectors at each point in time. The total simulated dose rates are shown in Figure 2 and compared to TELERAD measurements. Limited data were available to cleanly subtract the background radiation level, so the assumption was made that the first timestamp of a detector in the morning was indicative of the background. Overall, the match between GPM and TELERAD is good, but results are better for 12 and 13 September than for 15 September. This might be related to the combination of a more variable wind (as evidenced by Figure 1) and a much lower average wind speed. The wind speed averaged 6.1 m s^{-1} on 12 September and 10.3 m s^{-1} on 13 September, while it was only 2.9 m s^{-1} on 15 September.

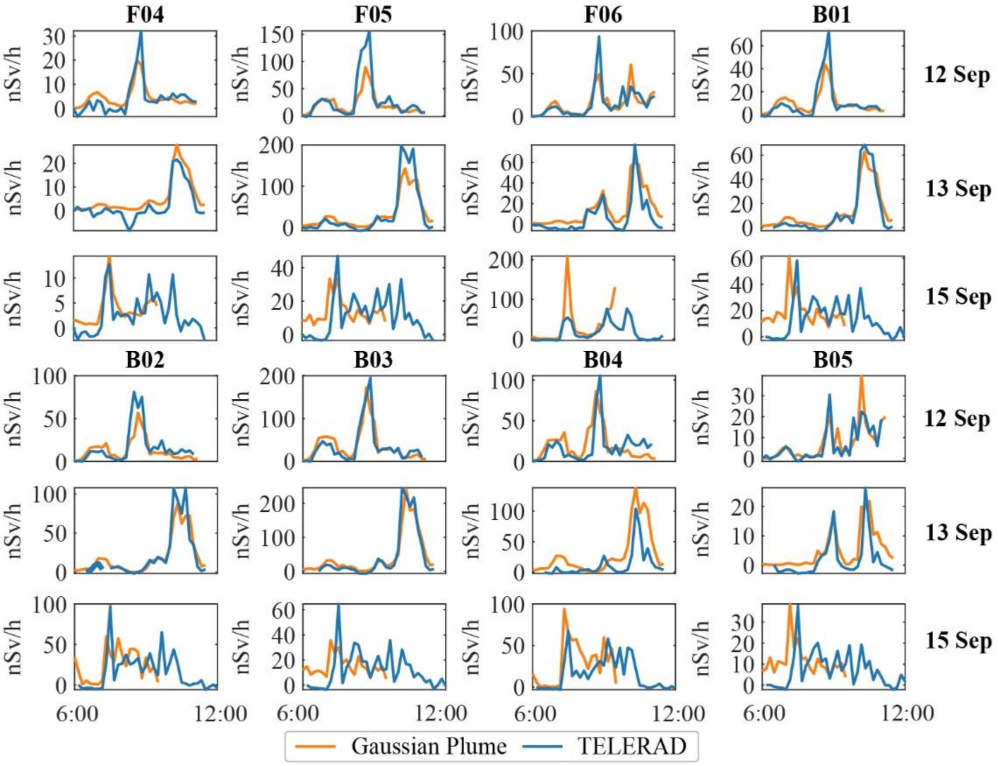

Figure 2. Results of GPM compared to TELERAD data for the IRE case. F04–F06 are fixed stations while B01–B05 are mobile stations. The background radiation is subtracted from the TELERAD signals (see text).

CASE II: ANOMALOUS RELEASE AT BR2 IN 2019

A small but measurable puff of radioactive Se-75 was released to the atmosphere during an incident in one of the hot cells at the Belgian Reactor 2 (BR2) of the Belgian Nuclear Research Centre (SCK CEN) in Mol on 15 May 2019 (De Meutter and Hoffman, 2020). This release was picked up by three TELERAD stations downwind of the BR2 stack (Figure 3). However, the release was so small that the increase in dose rate was only slightly bigger than the fluctuations in the radiation background (Figure 4). On-site wind data were available at a height of 69 m each ten minutes. Additionally, measurements of the ambient temperature at 8 m and 114 m were available each ten minutes to determine the stability class and account for plume rise. There was an ENE wind averaging 6.3 m s^{-1} and a slightly unstable atmosphere of class four. Additionally, the integrated source term of the puff was available. Under the assumption of a constant release for half an hour between 15:10–15:40 CEST (UTC+2), this allowed for the formulation of an emission rate. The BR2 stack has a height of 60 m, a gas outflow of 41.7 m^3 s^{-1} and an (assumed) gas temperature of 15°C.

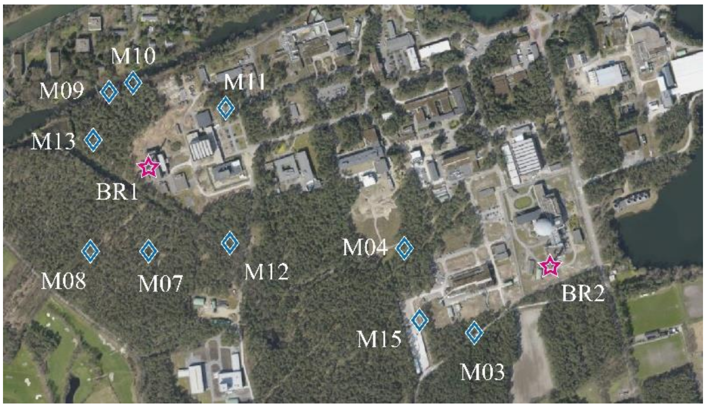

Figure 3. Aerial photograph of the SCK CEN site in Mol dated 2013–2015 (https://www.geopunt.be/). Locations of the BR1 and BR2 stacks (purple stars) along with several TELERAD stations (blue diamonds) are indicated.

A manuscript (Frankemölle et al, 2022) is under preparation that will cover the near-range dispersion of this anomalous release more fully in the future including deposition and concentration measurements. Here, we focus on the three TELERAD detectors. Since these detectors are close to the BR2, the release was simulated on a small grid of only 500-m-by-500-m-by-200-m with a 10-meter spacing in all dimensions. Plume rise was enabled. Simulations results are shown in Figure 4 together with TELERAD data. Based on the available meteorological and source term data, the GPM matches the TELERAD data quite well.

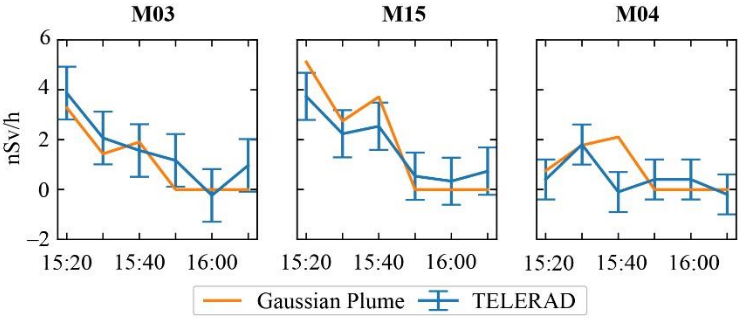

Figure 4. Results of GPM versus TELERAD measurements for the BR2 case. The mean background radiation is calculated based on the period 12:00–15:00. Error bars denote the 95% confidence intervals of that mean background.

CASE III: ROUTINE RELEASE AT BR1 IN 2019

The Belgian Reactor 1 (BR1) at SCK CEN in Mol is an air-cooled reactor that emits Ar-41 during routine operation. Seven TELERAD stations that surround the reactor (Figure 3) routinely pick up increased dose rates during operation (Bijloos et al, 2020). The same meteorological data were available here as in case II and the BR1 stack is also 60 m high. Plume rise is neglected. As the source term, we used ten-minute averaged data from an uncalibrated detector in the BR1 stack that monitors the relative release rate of Ar-41 and we scaled it so that its mean release rate during stable operation amounted to 57 GBq h^{-1} (Bijloos et al, 2020) initially. The release was simulated on an 500-m-by-500-m-by-200-m grid with a 10-meter grid spacing in all dimensions. Results are shown in Figure 5.

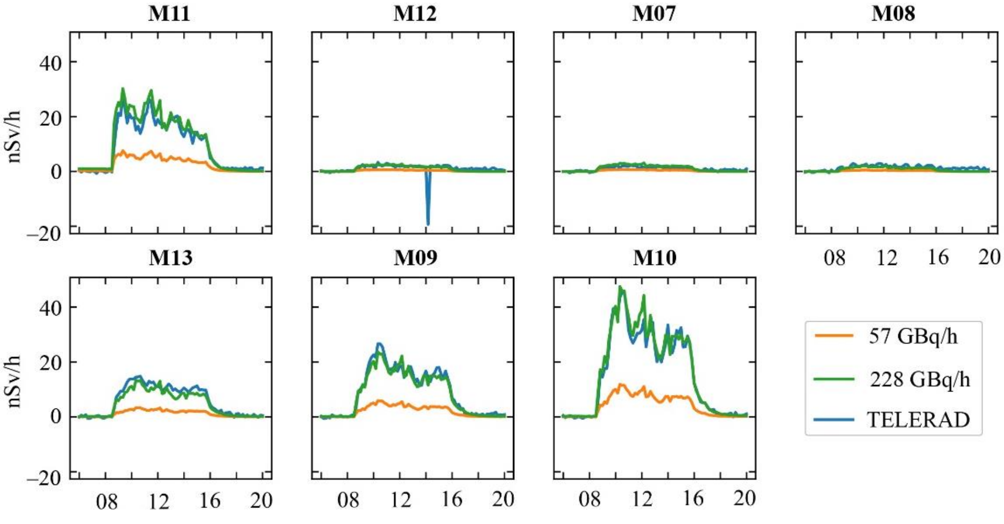

Figure 5. Simulations of the ambient dose equivalent rates in seven TELERAD stations around the BR1 compared to actual measurements. Two source term estimates, 57 GBq h^{-1} and 228 GBq h^{-1}, were compared.

We find that using a source term of 57 GBq h^{-1} leads to around a factor of 4 underestimation of the ambient dose equivalent rates at all TELERAD stations. This is in line with Bijloos et al (2020), who found a factor of 3.5 to 4 underestimation using various dispersion models for the BR1. They found that an alternative estimate for the BR1 source term of 150 GBq h^{-1} (Rojas-Palma et al, 2004) yielded better results that were, however, still off by a factor of 1.2 to 1.5. Motivated by our and their findings, we also tested a fourfold increased source term of 228 GBq h^{-1}. In this case, we observe that the data match very well.

DISCUSSION AND CONCLUSION

In this study, we set out to confirm the consistency between meteorological and source term data on the one hand and measurements of ambient dose equivalent rates by TELERAD stations on the other using a Gaussian plume model (GPM). Routine and anomalous releases from three different nuclear facilities were analysed. Largely consistent results were obtained for IRE and BR2. For BR1, consistent results could only be obtained with a four times larger source term than the current accepted value. That results for IRE and BR2 – more complex situations with multiple emission lines and/or very small detections – should yield considerably better results begs the question whether the values quoted (Bijloos et al, 2020; Rojas-Palma et al, 2004) adequately describe the true source term. This was previously pointed out by Bijloos et al (2020). Overall, GPM seems well-suited to simulating ambient dose equivalent rates. Envisaged next steps are to combine GPM with Bayesian inference or data assimilation approaches to yield even closer matches. In the future, GPM might even be used estimate the source term of the BR1 directly from TELERAD data.

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