Atmospheric Dispersion and dose Evaluation Due to the Fall of a Radioactive Package at a LILW Facility

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Abstract This work aimed to calculate the concentration of the radioactive plume due to the fall of a low and intermediate level waste (LILW) package in the Monitoring Building of the Waste Management Center (CGR), which will be built in Angra dos Reis, Brazil, and is currently under licensing. To calculate the plume concentration two models were used: the Pasquill-Gifford Gaussian model and the one using the ANSYS CFX 14.0 software, which uses Reynolds Averaged Navier-Stokes (RANS) equations and is based on the finite volume method. After evaluating plume concentration, doses for six age ranges were also calculated due to the fall of four different kinds of packages. Doses were evaluated at critical points where an individual could be immersed in the plume. The highest dose found was $7.32 \times 10^{-5}$ Sv for 7 to 12 year old children due to the fall of a drum containing resin from Angra 1 nuclear power plant primary circuit. This dose represents only 0.03% of the one stipulated for the exclusion area due to an accident.

Keywords LILW, Atmospheric Dispersion, Radionuclides, Computational Fluid Dynamics

1. Introduction

The low and intermediate level waste (LILW) produced by Angra 1 and 2 and Angra 3 in the near future, are deposited in the Waste Management Center (CGR, in Portuguese), and located at Almirante Álvaro Alberto Nuclear Power Station in Angra dos Reis, Brazil. The CGR consists of three deposits capable of storing drums, liners and metal boxes containing solid LILW compacted or immobilized in cement or bitumen matrix. As stated in [1], "In order to provide the tailing deposit complex of a more specific package control and stored volume reduction, Eletronuclear decided to implement a Monitoring Building, to monitor and promote the isotopic accounting of radioactive waste packages, as well as to create facilities that allow segregation of industrial wastes contained in conventional compressible packages, thereby reducing the volume of stored packages. The gathering of the isotopic inventory of packaged waste (isotope accounting) meets basic safety requirements for acceptance of radioactive waste for disposal purposes, presenting evidence of its compliance with authorized limits."

The isotopic accounting and segregation of these materials is of fundamental importance for the final disposal of these wastes.

Nowadays, the CGR monitoring building is in the licensing process at the National Nuclear Energy Commission (CNEN). One of the postulated accidents in this building is the free drop of drums with radioactivity release through the ventilation system, leading to a radioactive plume. This paper aims to discuss this scenario, evaluate the atmospheric dispersion and public individual dose due to the inhalation and exposure to a radioactive plume.

An overview of the monitoring building is presented in section 2, which also contains a bibliographic analysis of accidents at LILW facilities, dispersion models used in the nuclear industry and standards and technical specifications involving LILW packages. Site features that were considered, such as wind speed profile in the region, terrain, places of individual exposure, release times and package characterization, radionuclides and project activities considered are discussed in the third section. Section 4 describes the Gaussian approach and also the computational fluid dynamics (CFD) approach used to simulate atmospheric dispersion. Numerical simulations were performed by means of the CFX 14.0 code, which uses Reynolds Averaged Navier-Stokes (RANS) equations and is based on the finite volume method. The dose calculation is briefly described in section 5, following the recommendations of the International Atomic Energy Agency (IAEA)[2] and the dose coefficients for different age groups recommended by...
2. Site Description and Dispersion Features

The CGR Monitoring building will be built between deposits 1 and 2 (Figure 1). Packages will move into the building via an overhead crane and electrical hoist and, according to their classification and analysis throughout the building, go through package reception rooms, for isotopic and radiometric measurements, package opening and contaminated material segregation, radioactive waste recompression, reusable material handling, and measurement and disposal of conventional industrial waste[1]. The building is also equipped with ventilation system, air conditioning system, fire protection, radiation monitoring, P-10 gas, compressed air, communication, physical protection, drainage and drainage collection.

There will be five routes of package displacement inside the building, where packages will be hoisted up to a maximum height of 6.5 meters for their displacement. According to a preliminary analysis of these routes, the fall of a package can lead to the release of radioactive material that could undergo suspension and be released from the building by a failure of the ventilation system, thus creating a radioactive plume. This scenario of a package freefall is one of the main predicted accidents at LILW facilities, and it is revised in the following subsections, as well as current models and standards concerning it.

2.2. Atmospheric Dispersion Models

The atmospheric dispersion model used today in the process of licensing of radioactive facilities is the Gaussian plume model, which uses the Pasquill-Gifford atmospheric stability classes to determine the dispersion coefficients[10, 11]. These models give results consistent with experimental measurements on flat land and some adjustments can be made to take into account the release height, boundary layer, deposition and other factors. Reference[7] is an American standard where the Gaussian model is conservatively used.

Some atmospheric dispersion computer codes that have been used for regulatory purposes are ISCST3[12], ARTM, CALLPUFF, AERMOD[13] and XOQDOC[14], which are advanced Gaussian plume air dispersion models. AERMOD uses a Gaussian treatment just in horizontal and vertical for stable conditions and the non-Gaussian probability density function in vertical for unstable conditions. All these packages have pre-processors for atmospheric and ground conditions. A comparison of dispersion model features between AERMOD and ISCST3 can be seen in[13] for types of sources modeled, plume rise, urban treatment, boundary layer parameters, mixed layer height and others features.

The CFD approach has been used to evaluate atmospheric dispersion in a wide number of cases. In the chemical process industry, there exists already computer codes for CFD calculation of pollutant dispersion such as, for example, Local ARIA, MISKAM and MICRO-CALGRID[13]. Further studies are being published in order to exploit the full power of this tool to model dispersion scenarios[16-18].

2.3. Package: Specifications and Standards

The classification of packages containing radioactive materials is in IAEA[19], NRC[20] and CNEN[21] transport standards. Each package type is defined by the maximum activity of its content and it has different safety margins. For LILW, industrial or type A packages may be used and must follow a series of restrictions on mechanical and thermal strength described in[22, 23]. The characteristics of the packages considered in this paper are described in section 3.1.

3. Overall Data Input Description

The CGR is 55 meters high (23°0' S, 44°30' W) on the coast of the State of Rio de Janeiro (Figure 2). The site has a complex topography, hindering the use of Gaussian models, which justifies the two approaches used in this study for
atmospheric dispersion. An evaluation of the NPP meteorological data showed that the preferred wind directions are S, SSW, SSE during daytime and N, NNE, NNW and E at night, with predominantly light winds, strong stability and stagnant air[24]. To simplify the study, two critical points were selected for dose calculations: a point 1000 meters north of the release point, and a closer location at 650 meters northeast because it is downwind to the coast. It may be noted on Figure 2 that these points are on a highway, where an individual could be immersed in the radioactive plume.

Figure 2. CNAAA satellite image (with emphasis on CGR, the closer northeast point and the north point)

3.1. Package Description

Four types of packages were analyzed: 200 liter drum containing resin from the primary circuit immobilized in cement, 200 liter drum containing resin from the primary circuit immobilized in bitumen, 200 liter drum containing compacted waste and liners containing resin from the primary circuit immobilized in cement. Design activities of each radionuclide contained in these packages are shown in Figure 3[25-27].

4. Atmospheric Models

For both models, Gaussian and CFD, an exfiltrated air rate of $5 \times 10^4$ kg/s from the ventilation system was considered. It is assumed that after the accident, 3% of the packaged radioactive material is released and undergoes suspension. Next, the ventilation system operates until all the source term in suspension is flushed out of the building. It is important to note that 3% of the material contained in the package is 20 times greater than the most severe postulated release in[9] for scenarios of free fall of packages containing radioactive material, but it was conservatively used because of a lack of specific information on the packages considered in this paper.

There is a difficulty in calculating the dose due to accidents, since the dose coefficients recommended by regulatory bodies are annual. In this way, a continuous release was assumed, and the plume concentration (kg/m$^3$) was evaluated. For converting it to Bq/m$^3$, it is assumed that all radioactive material is released in a period of one year with a concentration equal to $A_0/m$, in Bq/kg, $(A_0$ is the initial activity released and $m$ is the contaminated air mass released over a period of one year).

4.1. Gaussian Model

The concentration of the radioactive plume, in kg/m$^3$, due to a stationary source term $Q_m$, in kg/s, at a height $H_c$ above ground level, in $m$, with wind direction $x$ and constant wind speed $u$ in m/s, is given by[11]:

$$
(C)(x,y,z)=\frac{Q_m}{2\pi\sigma_y\sigma_zu}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \times
\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H_c}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z-H_c}{\sigma_z}\right)^2\right]\right\}
$$

where $\sigma_y$ and $\sigma_z$ are the Pasquill-Gifford dispersion coefficients for open field, which depend on the dispersion direction $x$. These coefficients are usually valid for distances in the range $10^2$-$10^4$ m from the source.

Class E stability and a wind velocity equal to 1,3 m/s were assumed for NE and N wind directions because they are the most frequent site stability class and wind speed[24]. According to[7], as the closer point is above the release point, the concentration was calculated on ground level from a release height of 15 meters (building height). For the north point, the concentration was calculated at the plume center (higher concentration) from a release height equal to 65 meters.

4.2. CFD Model

The numerical simulation was performed using the CFX 14.0 code, which uses Reynolds averaged Navier-Stokes (RANS) equations and is based on the finite volume method. Figure 4 displays the code flow diagram.

The first step is to determine the problem geometry. Two geometries were considered for the calculation of the dispersion with wind directions NE and N. For the first direction, the following path is followed: the Monitoring Building is 55 meters above sea level and at a horizontal distance of 200 meters from the sea. It is assumed that the building is located on a flat region of 100 m. The building is 15 m high and has a release area of $10 \times 10$ m$^2$. Then, there is an elevation increase of 100 m at a distance of 250 m. Next,
there is a flat region of another 100 m long down to a descent of 250 m in the horizontal direction and 50 m vertically up the road. For the second geometry for an N direction wind, the plume passes through a valley, where Angra 1 and 2 plants are located until the highway is reached. There is a flat region of 100 m where the building is located. Then there is a decline of 50 meters at a distance of 200 northward. The valley is another 700 m long until the ascent to the highway. These domains are shown in Figure 5.

Figure 4. Flow diagram for the used Computational Fluid Dynamics model

The second step is to determine the mesh (Figs. 6 and 7) by ANSYS ICEM CFD 14.0. Data for meshing are shown in Table 1.

Table 1. Mesh data input

<table>
<thead>
<tr>
<th>Inputs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Size (m)</td>
<td>0.5</td>
</tr>
<tr>
<td>Maximum Face Size (m)</td>
<td>20.0</td>
</tr>
<tr>
<td>Maximum Size (m)</td>
<td>50.0</td>
</tr>
<tr>
<td>Growth Rate</td>
<td>1.2</td>
</tr>
<tr>
<td>Minimum Edge Length (m)</td>
<td>15</td>
</tr>
<tr>
<td>Refinement*</td>
<td>3</td>
</tr>
<tr>
<td>Statistics</td>
<td></td>
</tr>
<tr>
<td>Nodes (geometry #1)</td>
<td>11,732</td>
</tr>
<tr>
<td>Elements (geometry #1)</td>
<td>58,370</td>
</tr>
<tr>
<td>Nodes (geometry #2)</td>
<td>10,671</td>
</tr>
<tr>
<td>Elements (geometry #2)</td>
<td>52,841</td>
</tr>
</tbody>
</table>

*On building walls

The data model is introduced in CFX-Pre. For both geometries key data are shown in Table 2. The standard k-epsilon turbulence model was chosen because it does not need the equations for the walls and the kinematic diffusivity was constant and isotropic and equal to $10^{-5}$ m$^2$/s.

Table 2. CFX input

<table>
<thead>
<tr>
<th>Domain</th>
<th>Fluid</th>
<th>Air at 25ºC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Transfer</td>
<td>Isothermal at 25ºC</td>
<td></td>
</tr>
<tr>
<td>Turbulence</td>
<td>k-Epsilon</td>
<td></td>
</tr>
<tr>
<td>Additional Variable</td>
<td>Transport Equation</td>
<td></td>
</tr>
<tr>
<td>Kinematic diffusivity</td>
<td>$10^{-5}$ m$^2$/s</td>
<td></td>
</tr>
<tr>
<td>Boundary Wind</td>
<td>Normal Speed</td>
<td>1.0 m/s</td>
</tr>
<tr>
<td></td>
<td>Turbulence</td>
<td>Medium (5%)</td>
</tr>
<tr>
<td>Boundary Release</td>
<td>Release rate</td>
<td>$5 \times 10^{-4}$ kg/s</td>
</tr>
<tr>
<td></td>
<td>Turbulence</td>
<td>Medium (5%)</td>
</tr>
<tr>
<td>Boundary atmosphere</td>
<td>Type</td>
<td>Opening</td>
</tr>
<tr>
<td></td>
<td>Relative Pressure</td>
<td>0 Pa</td>
</tr>
<tr>
<td>Solver Control</td>
<td>Turbulence Numeric's</td>
<td>First Order</td>
</tr>
<tr>
<td></td>
<td>RMS</td>
<td>$10^{-4}$</td>
</tr>
</tbody>
</table>
5. Dose

The dose in this accident is due to inhalation of contaminated air and immersion in the radioactive plume (Eq. 2), by adding the contribution of each radionuclide[2].

\[ E = E_{\text{inh}} + E_{\text{im}} \]

\[ E_{\text{inh}} = C_A R_{\text{inh}} D_{F\text{inh}} \]

\[ E_{\text{im}} = C_A D_{F\text{im}} O_f \]

\( E_{\text{inh}}, \) dose due to air inhalation[Sv],
\( C_A, \) radionuclide concentration in air[Bq/m\(^3\)],
\( R_{\text{inh}}, \) inhalation rate[m\(^3\)/yr],
\( D_{F\text{inh}}, \) dose coefficient per inhalation[Sv/Bq].

\( E_{\text{im}}, \) dose due to radioactive plume immersion[Sv],
\( C_A, \) radionuclide concentration in air[Bq/m\(^3\)],
\( D_{F\text{im}}, \) dose coefficient due to immersion[Sv/yr per Bq/m\(^3\)],
\( O_f, \) year fraction for which the critical group is exposed to radiation (equal to one for the model proposed for this work).

The inhalation rates considered are shown in Table 3. The dose coefficients are divided into six age groups according to[3].

Table 3. Inhalation rates

<table>
<thead>
<tr>
<th>Age range (yr)</th>
<th>Inhalation rate (m(^3)/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;1</td>
<td>1400</td>
</tr>
<tr>
<td>1 to 2</td>
<td>1400</td>
</tr>
<tr>
<td>2 to 7</td>
<td>3700</td>
</tr>
<tr>
<td>7 to 12</td>
<td>8000</td>
</tr>
<tr>
<td>12 to 17</td>
<td>8400</td>
</tr>
<tr>
<td>&gt;17</td>
<td>8400</td>
</tr>
</tbody>
</table>

6. Results

The concentrations at the plume center (y = 0) for the two cases analyzed in this work can be seen in Figures 8-11. Figures 8-9 display the distance from the monitoring building to the nearest point on the highway. Figures 10-11 display the distance from the monitoring building to the north point. The Gaussian model was calculated using the Mathematica 7.0[28] software.

For both cases, the Gaussian plume reaches a concentration 10\(^5\) times greater than that calculated by CFD, thus being more conservative. After evaluating the radioactive plume concentration in kg/m\(^3\), the activity due to the fall of each type of package is calculated, assuming that the radionuclides were uniformly dispersed in the plume. The activity per unit volume of each radionuclide i, \(\chi[x, y, z, i]\), is found from Equation (5).

\[ \chi[x, y, z, i] = \frac{C[x, y, z] \times l \times A_0[i]}{m} \]

where \(C[x, y, z]\), the plume concentration[kg/m\(^3\)]
\(l, \) the released fraction due to the package fall (3%)
\(A_0, \) is the initial activity for each radionuclide i (Figure 3)
m, is the mass of contaminated air.

Figure 9. Plume concentration for NE wind direction. The plume originates at the CGR Monitoring Building and reaches the highway nearest point (Gaussian model). Shown are the isopleths for the concentration displayed.

Figure 10. Plume concentration (kg/m\(^3\)) and velocity profile for the N direction wind. The plume originates at the CGR Monitoring Building and reaches the highway point to the north of the building.
CFD allows for assessing the velocity profile around a building, such as can be seen in Figure 12, for the NE wind direction. This tool is very useful when one wants to calculate the concentration near the release point, where the Gaussian model is not valid.

![Figure 12. Velocity profile near the Monitoring Building](image)

The dose values found for six age groups are shown in Tables 4-7 for each package. For the NE wind direction, the maximum doses at the highway point closest to the release are shown in Tables 4 and 5 for Gaussian and CFD models, respectively. For the North wind, the maximum doses at the highway are displayed in Tables 6 and 7 for the Gaussian and CFD models, respectively.

The nonlinear parameters used in this work are in the models for calculating plume dispersion. After evaluating the plume concentration, dose values vary linearly with the conversion coefficients used, fraction of each radionuclide and inhalation rates of each age group. The combination of these factors provided the highest dose for the 7-12 year old group due to the fall of a drum containing resin from the primary circuit of Angra 1, equal to $7.32 \times 10^{5}$ Sv at the highway closest point. The highest dose for the N wind direction is less than half of the one for NE wind direction, as can be seen from Table 6.

### Table 4. Dose (in Sv) from Gaussian model (for NE wind direction). Highest dose is shown in bold

<table>
<thead>
<tr>
<th>Package</th>
<th>Age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RP1</td>
<td>&lt;1 3.44E-05 3.18E-05 5.28E-05 7.32E-05 5.95E-05 5.49E-05</td>
</tr>
<tr>
<td>RP2</td>
<td>&lt;1 5.89E-06 5.56E-06 9.71E-06 1.42E-05 1.24E-05 1.20E-05</td>
</tr>
<tr>
<td>RC2</td>
<td>&lt;1 1.66E-11 1.53E-11 2.73E-11 3.99E-11 3.42E-11 3.27E-11</td>
</tr>
<tr>
<td>Liner</td>
<td>&lt;1 1.98E-11 1.83E-11 3.04E-11 4.22E-11 3.43E-11 3.17E-11</td>
</tr>
</tbody>
</table>

*PR1 = Angra 1 primary circuit resin drum; PR2 = Angra 2 primary circuit resin drum; RC2 = Compact waste drum of Angra 2; Liner = primary circuit resin liner

### Table 5. Dose (in Sv) from CFD model (for NE wind direction). Highest dose is shown in bold

<table>
<thead>
<tr>
<th>Package</th>
<th>Age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RP1</td>
<td>&lt;1 3.57E-09 3.30E-09 5.48E-09 7.6E-09 6.18E-09 5.71E-09</td>
</tr>
<tr>
<td>RP2</td>
<td>&lt;1 6.12E-10 5.56E-10 1.01E-10 1.49E-10 1.29E-10 1.25E-10</td>
</tr>
<tr>
<td>RC2</td>
<td>&lt;1 1.66E-11 1.53E-11 2.73E-11 3.99E-11 3.42E-11 3.27E-11</td>
</tr>
<tr>
<td>Liner</td>
<td>&lt;1 1.98E-11 1.83E-11 3.04E-11 4.22E-11 3.43E-11 3.17E-11</td>
</tr>
</tbody>
</table>

### Table 6. Dose (in Sv) from Gaussian model (for N wind direction). Highest dose is shown in bold

<table>
<thead>
<tr>
<th>Package</th>
<th>Age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RP1</td>
<td>&lt;1 1.34E-05 1.24E-05 2.05E-05 2.85E-05 2.32E-05 2.14E-05</td>
</tr>
<tr>
<td>RP2</td>
<td>&lt;1 2.29E-06 2.08E-06 3.78E-06 5.58E-06 4.84E-06 4.69E-06</td>
</tr>
<tr>
<td>RC2</td>
<td>&lt;1 6.22E-08 5.73E-08 1.02E-07 1.50E-07 1.28E-07 1.23E-07</td>
</tr>
<tr>
<td>Liner</td>
<td>&lt;1 7.44E-08 6.88E-08 1.14E-07 1.58E-07 1.29E-07 1.19E-07</td>
</tr>
</tbody>
</table>

### Table 7. Dose (in Sv) from CFD model (for N wind direction). Highest dose is shown in bold

<table>
<thead>
<tr>
<th>Package</th>
<th>Age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RP1</td>
<td>&lt;1 3.01E-09 2.87E-09 4.76E-09 6.60E-09 5.37E-09 4.95E-09</td>
</tr>
<tr>
<td>RP2</td>
<td>&lt;1 5.34E-10 4.82E-10 8.76E-10 1.29E-10 1.12E-09 1.09E-09</td>
</tr>
<tr>
<td>RC2</td>
<td>&lt;1 1.44E-11 1.33E-11 2.37E-11 3.46E-11 2.97E-11 2.84E-11</td>
</tr>
<tr>
<td>Liner</td>
<td>&lt;1 1.72E-11 1.59E-11 2.64E-11 3.66E-11 2.98E-11 2.75E-11</td>
</tr>
</tbody>
</table>

### 7. Conclusions

This paper presented the atmospheric dispersion and dose evaluation due to the fall of a radioactive package at a LILW facility by means of the Gaussian dispersion model and also by means of computational fluid dynamics.

After calculating the concentrations by the two dispersion models, the activity from each radionuclide due to the release of 3% of the initial activity in four different kinds of packages was estimated and the dose for six age groups was calculated. The highest dose (7.32 $\times 10^{5}$ Sv) was found for 7 to 12 year old children due to the fall of a drum containing resin from the primary circuit of Angra 1, representing only 3.0% of the annual limit stipulated for normal operation of CNAAA nuclear power plants[29] and 0.03% of the one stipulated for the exclusion area due to an accident[30].

The use of computational fluid dynamics for atmospheric
dispersion calculations enables a more realistic simulation of
ground conditions and velocity profile as compared to the
Gaussian model. The simple modeling performed in this
work using the ANSYS CFX 14.0 software, showed the
ability of this tool to model such dispersion problems. The
comparison with the Gaussian model in this work is very
important, since the latter is the most adopted model in the
licensing of nuclear facilities. However, the Gaussian model
is very conservative and leads to excessive and exaggerated
preventive measures.

Many other variables can also be considered in both
models to make them closer to the real problem, as velocity
and temperature gradients, boundary layer height, deposition
mechanisms, time-dependent release, soil roughness and
other turbulence conditions. However, the Gaussian model
is limited in its applicability range and does not predict good
results near the release source. Furthermore, it depends on
the dispersion coefficients, which were experimentally
obtained for well-defined conditions and many times are not
applicable to real conditions. CFD, on the other hand, allows
for a wide variety of considerations and modeling
capabilities, and thus has been widely used for pollutant
dispersion evaluations.

The use of both Gaussian and CFD modeling for plume
dispersion showed the importance of performing CFD
modeling for plume dispersion evaluating in order to get less
conservative results in comparison with the Gaussian
approach. The consideration of the aforementioned variables
would make the results of both models more closer. As to
wind velocities if we had considered a higher wind velocity
the estimated concentration would be lower so that lower
dose estimations would be obtained, too. However the wind
field data used were obtained from site weather stations.
Moreover even considering new variables the Gaussian
model would still be limited due to the analyzed terrain
complexities and also due to the lack of site specific
dispersion coefficient data, thus leading to conservative dose
estimates.

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