Chapter

Calculation of the Dose for Public Individuals Due to a Severe Accident at the Angra 2 Nuclear Plant, Brazil

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Abstract

Through a severe accident at nuclear power plant Angra 2, the whole body dose effective of the individuals members of the public located in the Emergency Planning Zones (EPZs) will be calculated, and later, the protective actions in these EPZs will be analyzed. Two different scenarios of radionuclide release into the atmosphere will be considered. In the first scenario, 2 h of the release of Xe, Cs, Ba, and Te, and the second scenario, 168 h of release.

Keywords: MELCOR, CALPUFF, atmospheric dispersion, nuclear power plant, public individuals dose

1. Introduction

From the nuclear accidents that occurred in the world [1–3], the International Atomic Energy Agency (IAEA), together with the licensing bodies of countries that use nuclear energy, requested that they carry out computer simulations of some accidents that are considered credible for their facilities, in order to verify their integrity when subjected to such events.

These accidents are known as the design basis, in other words, accidents of loss of primary coolant by large or small ruptures at points in the primary circuit, whose probability of occurrence is critical to the system. It was after the accident at Unit 2 of the Three Mile Island Nuclear Plant (TMI) in 1979 that it was necessary to study the more severe accidents.

These severe accidents are those in which substantial damage is expected in the reactor core [4]. The knowledge of accidents with core meltdown is based on the simulations with computer programs of the type MARCH [5], APRIL [6], MELCOR [7–9], SCADAP/RELAP5 [10–11], and MAAP4 [12]. Among these programs, MELCOR, SCDAP/RELAP5, and MAAP4 are widely used for the integral analysis of the melted material in the core and the consequences in the lower part of the pressure vessel [13].

In the event of a severe accident, followed by successive failures of physical barriers and problems in the control and protection systems of the reactor, the release of radioactive material into the atmosphere may become significant. The problems generated by these catastrophic events can lead to an increase in levels of radioactivity in the vicinity of the plant, representing a threat to the society and local life.

Therefore, the dispersion study can generate results with impacts on the occupation and dimensioning of the site. Also in this context, it is important to remember that the severity of a possible accident associated with nuclear facilities in general is strongly linked to population density of the regions around the facility, as well as, evacuation policy, medical treatment, and other health measures which should be taken to mitigate its radiological consequences.

2. Description of the accident

A typical PWR modeling was developed by the German company, GRS (Global Research for Safety), and supplied to CNEN, as shown in **Figure 1**. This modeling was chosen, in this study, for the purpose of performing an independent analysis of severe accidents in ANGRA 2 nuclear power plant (NPP). However, although this typical PWR of the GRS is similar to ANGRA 2 NPP, they are not identical, so that an adaptation of the modeling was necessary in order to apply it for analysis of severe accidents in NPP, ANGRA 2. For this reason, a considerable part of this study was dedicated for the adaptation of the modeling.

2.1 Description of the simulated accident scenario

In this study is presented a loss of coolant accident, in other words, Small Break LOCA (SBLOCA), in the hot leg. In this case, it is postulated that the rupture occurs in loop 1. The area of the rupture in the hot leg is 380 cm^2. The total flow area of the piping connected to the pressure vessel is 4418 cm^2, so that the area of the rupture is less than 10% of the piping area; reason why the rupture of 380 cm^2 is considered small.

The SBLOCA alone would not be sufficient to result in a severe accident, as long as the various plant safety systems were available. It was, therefore, necessary to add some aggravating conditions in order to cause the mentioned severe accident.

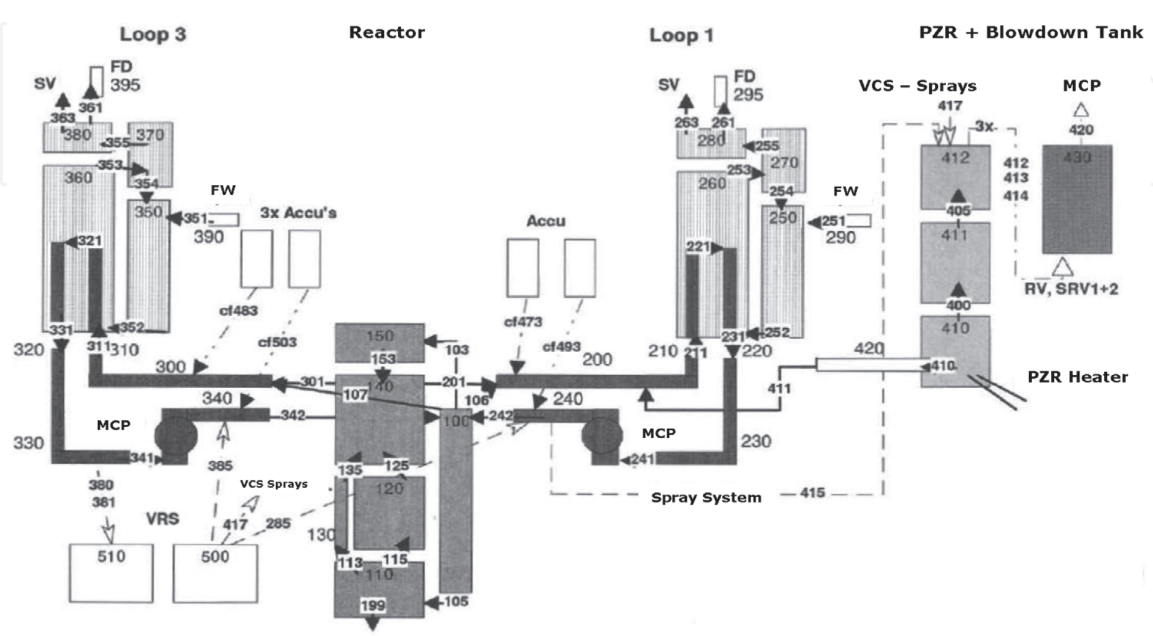

Figure 1.
PWR primary and secondary circuit modeling.

These conditions are conventionally known as boundary conditions. The postulated conditions are as follows:

a. Turbine bypass unavailable;

b. Condenser not available;

c. Loss of suction from sump and residual heat removal – RHR;

d. Injection of the Emergency Core Cooling System – ECCS from Refueling Water Storage Tank – RWST by Safety Injection Pump – SIP e do RHR available; and

e. All accumulators are available.

These boundary conditions, together with the primary circuit breakage, are sufficient to result in total core melting. Two mitigating measures were modeled in this study: Passive Autocatalytic Recombiner – PAR and Filtered Containment

Simulation time	Xe-133 m Bq	Cs-137 Bq	Ba-133 m Bq	Te-127 Bq
C1 – 2 h	2,11E+10	5,28E+01	1,40E+04	3,65E+06
C2 – 168 h	8,17E+19	1,56E+07	7,39E+10	2,00E+12

Table 1.
Source term for scenarios C1 and C2.

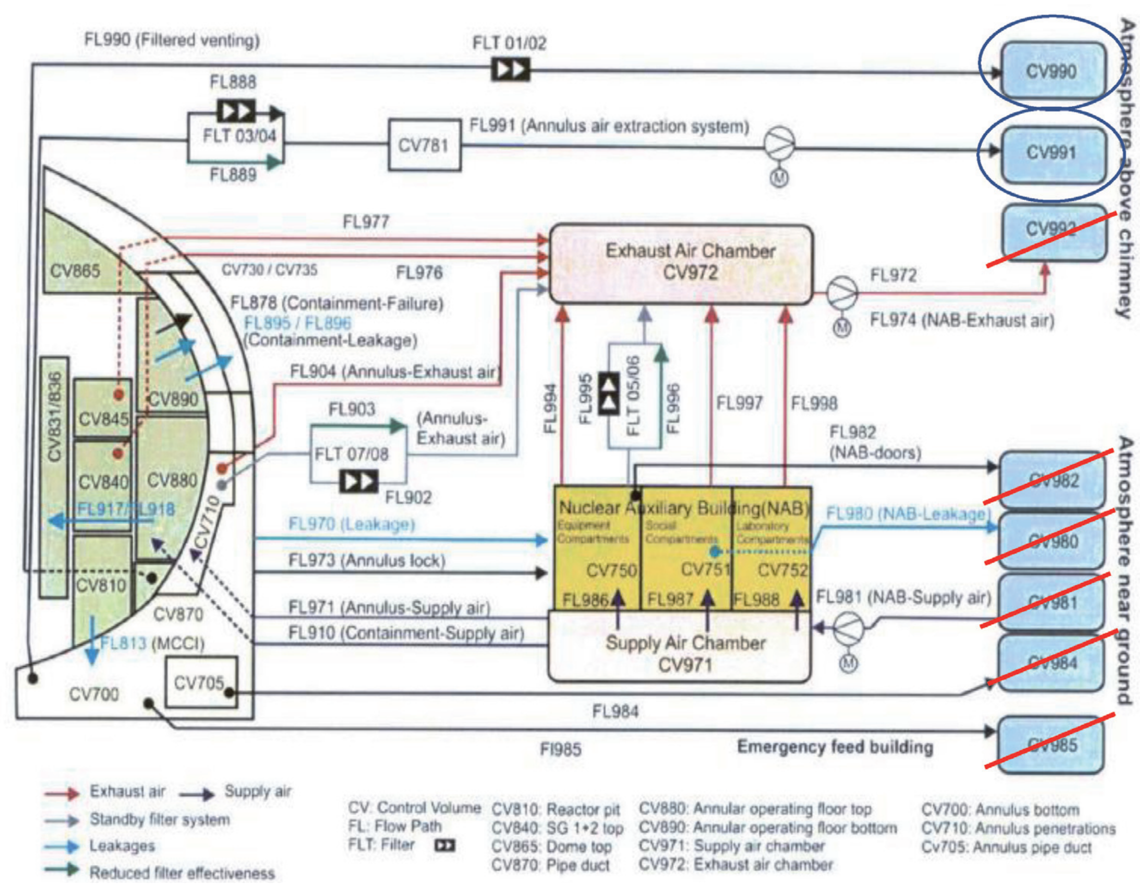

Figure 2.
Flow path (CV990 and CV991) of the radionuclides to the atmosphere.

Venting System – FCVS, with the purpose of evaluating their validity and efficiencies.

The inputs of the simulations performed for this work were elaborated using the input provided by GRS. This original input was modified according to the imposed conditions. It was assumed that the rupture occurs only in the Control Volume (CV) number 200, that is, in CV200 of loop 1, shown in **Figure 1**.

The flow path, given by FL070, has its opening and closing controlled by a CF660 control function. The setpoint for the valve opening is 7.0 bar and occurs after 168 h of simulation, but the setpoint for closing has not been implemented. It should be noted that the opening of the CV990 flow path, see **Figure 2**, occurs only after 168 h of simulation.

The flow path CV990 and CV991, see **Figure 2**, contains filters for aerosols and for fission products vapors so that some fraction of radionuclides are withdrawn through these filters when the vapors and aerosols are transported along of the flow path. A single filter can remove only one type of fission products, whether aerosols or vapors, but not both.

The radionuclide package of the MELCOR code contains a simple filter model which efficiency is defined by the global decontamination factor (DFG) determined by the user. The decontamination value assumed for aerosol filter was 1000, and for vapors of fission products, vapors were 100, which equated to 99.9 and 99.0% filtration, respectively.

2.2 Source term

The source term represents the radioactive inventory located in a system, equipment or component, which serves as a reference to evaluate the safety aspects in different conditions of operation of the reactor. It also represents one of the most important design bases for the study of installation performance, distribution of fission products in reactor systems, and in the environment in case of accidents.

Knowing the source term, there is the possibility of modeling radionuclide dispersion, calculating radiation concentrations and doses, as well as spatializing affected areas and environments. The source term of the present study is based on the radionuclides used in the MELCOR output, being this Xenon-133 m, Césiso-137, Barium-133 m, and Tellurium-127. **Table 1** shows the activities of the radionuclides for the scenarios C1 – simulation time of 2 h and C2 – simulation time of 168 h.

3. Characterization of the study area

The study area is placed in the south coast of Rio de Janeiro State, known region as "Costa Verde," in the city of Angra dos Reis, where the CNAAA is placed zone (23 k), latitude-UTM (7455581.00 m S), and longitude-UTM (555471.00 m E). The region geomorphology is extremely hilly, with quite steep slopes, high or negatives steepness and differences in elevations up to 800 m.

The geomorphology has two units of topography, one formed by ridge and scarps, and the other, by lowlands. The scarps has an average gap of 700 m and are dissected by half parallel valleys, which alternate with stretches of deep cutouts, between the rivers that flow down the mountain. **Figure 3** [14] shows the topography of the region.

DOI: http://dx.doi.org/10.5772/intechopen.92200

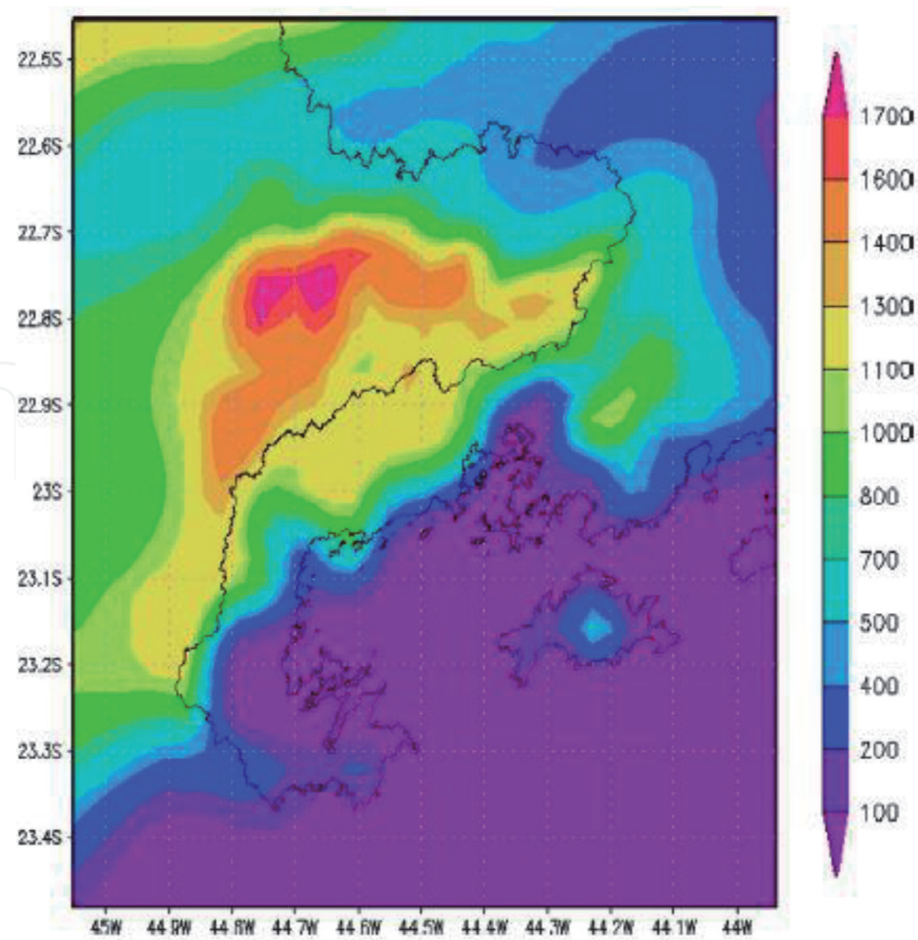

Figure 3.
Topography of the study area.

4. Methodology

The use of mathematical models facilitates the simulation process of transport mechanisms and pollutant deposition. These models provide a conservative theoretical estimate of the concentration levels of pollutants in the air, making it possible to evaluate the spatial and temporal evolution of these pollutants in the atmosphere.

4.1 Atmospheric model: WRF/CALMET

The WRF – Weather Research and Forecasting, is a numerical modeling system, developed for the weather forecasting and study of atmospheric phenomena of micro and mesoscale. Its development is the result of the collaboration between US research and government agencies centers: National Center for Atmospheric Research (NCAR), National Centers for Environmental Prediction (NCEP), National Oceanic and Atmospheric Administration (NOAA), US Departement of Defense, Oklahoma University, and Federal Aviation Administration (FAA).

The CALMET – California Meteorological Model, is a three-dimensional meteorological model that is integrated with the dispersion model – CALPUFF. The CALPOST is a post-processing package that makes possible to calculate the average concentration and deposition fluxes [15].

The CALMET is classified as a diagnostic meteorological model that incorporates meteorological observations and/or outputs of predictive meteorological models to produce, through objective analysis techniques, velocity, temperature, and other variables necessary for simulations with the CALPUFF model.

The CALMET requires that the meteorological and geophysical data are in specific formats before being used. The processing of these data is then performed with the aid of the preprocessors which prepare the data for assimilation in the CALMET processor.

4.2 Dispersion model: CALPUFF

The modeling of the atmospheric dispersion is a technique of simulation of the phenomena that occurs in nature, allowing to estimate the concentration of the pollutants in a set of points, based on a set of variables that influence them. The modeling of atmospheric dispersion is useful not only in the identification of emitting sources but also in the management of gaseous effluents and air quality, constituting one of the techniques of evaluation of air quality indicated by the environmental legislation.

The California Puff Model CALPUFF is a non-stationary puff model for dispersion simulations that can be used for a wide variety of applications in air quality modeling studies. The model was proposed and reviewed by Scire et al. [15] and has been adopted by the United States Environmental Protection Agency – EPA as a regulatory model for environmental impact studies covering distances of 50–300 km and including topography and complex meteorological systems.

The CALPUFF software is entirely public, designed to simulate release into the atmosphere, and is used to predict the effects of an accident, thus enabling effective emergency planning.

4.3 WRF/CALMET coupling

The choice of the WRF model configuration, as well as the domains, spatial resolution, and grid nesting, were made to obtain necessary meteorological data for the INPUT of the CALMET model. The initial and boundary conditions assimilated by the WRF are derived from the GFS (Global Forecasting System Model) of the National Centers for Environment Prediction (NCEP), whose spatial resolution is 0.5° (∼55 km) and a time resolution of 3 h. To compose the GFS domain, both horizontally and vertically, a model for interpolation of the data is used. More details about this model can be found in KALNAY et al. [16]. The GFS data can be obtained for free from the electronic address. Link: https://www.ncdc.noaa.gov/data-access/model-data/model-datasets.

The meteorological data of the January month of 2009 was used for the simulation with the WRF. The January month data was chosen, due to being the most recent data obtained from Electronuclear for the four Angra towers.

The grid used by CALMET has a domain of 80 km and a cell number of 229 × 229. In the region of the NPP, the wind field data of the Electronuclear Towers was used, which radius of influence is 5 km.

4.4 Whole body dose calculation

The whole body dose is the contribution of the internal dose (inhalation or ingestion) added to the external dose (plume immersion) [17]. The calculations of the exposure pathways are in equations (Eqs. (1) and (2)), respectively. For the present study, the whole body dose analysis considered the plume concentration value and exposure time in the Emergency Planning Zones – EPZ, as shown in **Figure 4**.

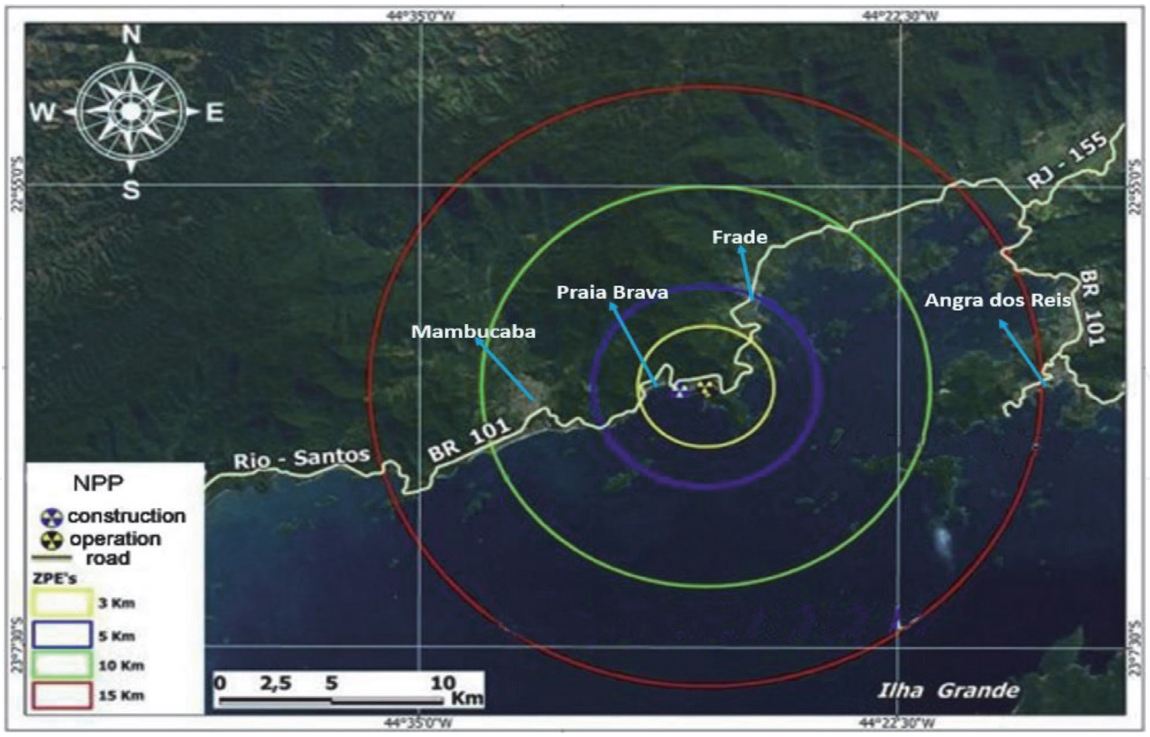

Figure 4.
Regions in EPZ that will be considered the dose calculation and measures protective.

4.4.1 Inhalation dose calculation

The inhalation dose calculation was based on the IAEA-TecDoc-1162 [18] document, as observed in Eq. (1).

$$D_{in} = \sum_i C_i * e(g)_i * B_r * T \qquad (1)$$

Where:

$\boldsymbol{D_{in}}$ = Inhalation dose, Sv;
$\sum_i \boldsymbol{C_i}$ = Concentration of each radionuclide – Bq/m^3;
$\boldsymbol{e(g)_i}$ = Inhalation dose coefficient – Sv/Bq (was used e(g)i for adult e(g) i > 17 years), according to Regulatory Position CNEN 3.01/011:2011 [19];
$\boldsymbol{B_r}$ = Breathing rate, whose value considered 1.5 m^3/h [18]; and
$\boldsymbol{T}$ = Exposure time – h (time the individual of the public will be exposed to the pollutant).

4.4.2 Immersion dose calculation

The immersion dose calculation was based on the IAEA-TecDoc-1162 [18] document, as observed in Eq. (2).

$$D_{im} = \sum_i C_i * e(g)_i * T \qquad (2)$$

Where:

$\boldsymbol{D_{in}}$ = Immersion dose, Sv;
$\sum_i \boldsymbol{C_i}$ = Concentration of each radionuclide – Bq/m^3;
$\boldsymbol{e(g)_i}$ = Immersion dose coefficient – Sv.m^3/Bq.h (was used e(g)i for adult e(g) i > 17 years), according to Regulatory Position CNEN 3.01/011:2011 [19]; and

T = Exposure time – h (time the individual of the public will be exposed to the pollutant).

5. Results

5.1 Pollutant transport model: CALPUFF

The simulations were performed on CALPUFF assuming a point source of emissions related to the chimney of the NPP Angra 2, which height considered was 155 m. The emission rate will follow scenarios C1 and C2, with the constant release rate of the radionuclides released into the atmosphere.

5.1.1 Radionuclides release for scenario C1

The simulation was performed from 05/01/2009 to 08/01/2009 at 06:00 h. It was considered that all the radionuclides of **Table 1**, after release, behave according to the region's wind field during the entire simulation period, 72 h. The respective plume concentration periods that were considered: 1, 3, and 72 h, for each EPZ, see **Tables 2–5**. **Figure 5** shows the wind field and radionuclides transport from **Table 1** for scenario C1.

5.1.2 Radionuclides release for scenario C2

The simulation was performed from 05/01/2009 to 08/01/2009 at 06:00 h. It was considered that all the radionuclides of **Table 1**, after release, behave according

Simulation time	Xe-133 m Bq/m^3	Cs-137 Bq/m^3	Ba-133 m Bq/m^3	Te-127 Bq/m^3
1 h	1,53E+04	3,76E-05	9,97E-03	2,60E+00
3 h	6,04E+03	1,48E-05	3,92E-03	1,02E+00
72 h	5,64E+02	1,21E-06	3,22E-04	8,39E-02

Table 2.
Radionuclides concentration in EPZ-3 km (Praia Brava).

Simulation time	Xe-133 m Bq/m^3	Cs-137 Bq/m^3	Ba-133 m Bq/m^3	Te-127 Bq/m^3
1 h	1,00E+04	2,37E-05	6,29E-03	1,64E+00
3 h	4,30E+03	9,22E-06	2,45E-03	6,37E-01
72 h	1,08E+03	2,15E-06	5,71E-04	1,49E-01

Table 3.
Radionuclides concentration in EPZ-5 km (Frade).

Simulation time	Xe-133 m Bq/m^3	Cs-137 Bq/m^3	Ba-133 m Bq/m^3	Te-127 Bq/m^3
1 h	1,54E+03	3,55E-06	9,41E-04	2,45E-01
3 h	9,34E+02	2,16E-06	5,74E-04	1,50E-01
72 h	1,60E+02	2,92E-07	7,75E-05	2,02E-02

Table 4.
Radionuclides concentration in EPZ-10 km (Mambucaba).

Simulation time	Xe-133 m Bq/m^3	Cs-137 Bq/m^3	Ba-133 m Bq/m^3	Te-127 Bq/m^3
1 h	1,09E+03	1,49E-06	3,96E-04	1,03E-01
3 h	8,29E+02	1,16E-06	3,07E-04	8,01E-02
72 h	2,21E+02	2,83E-07	7,51E-05	1,96E-02

Table 5.
Radionuclides concentration in EPZ-15 km (Angra dos Reis).

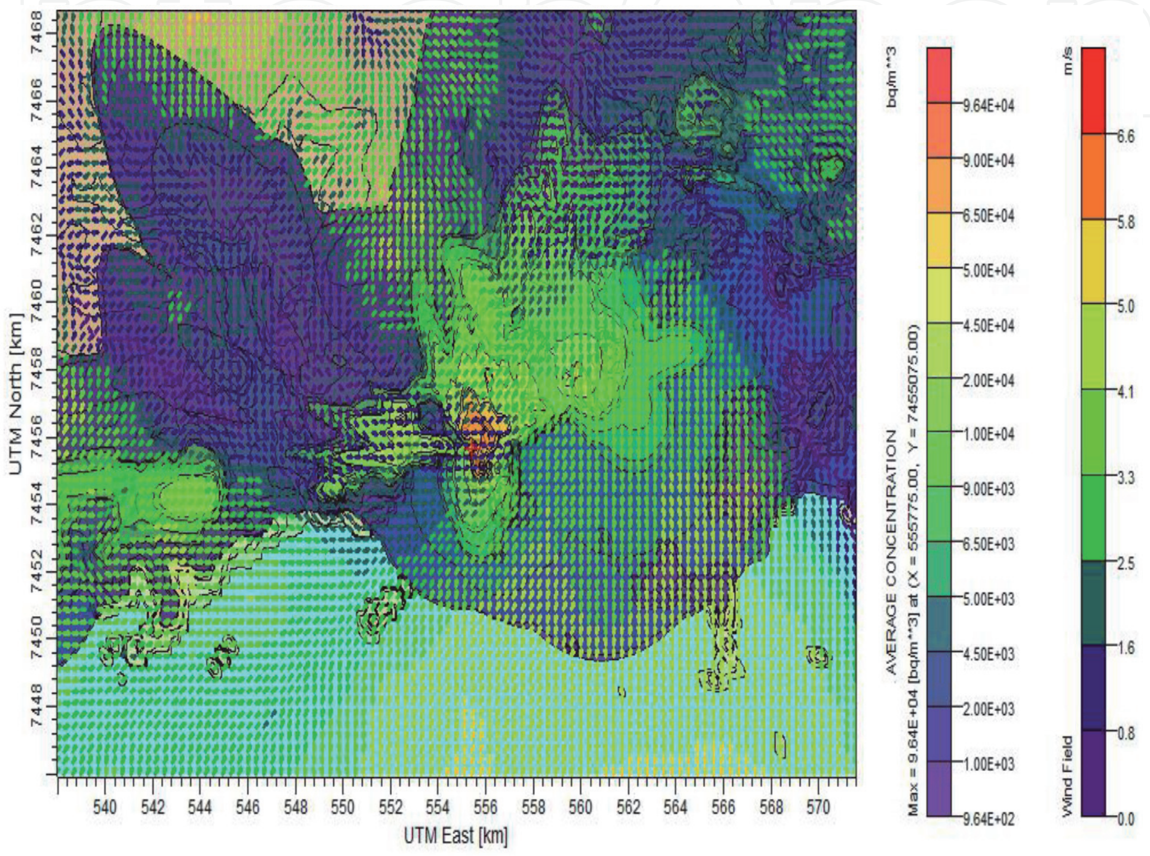

Figure 5.
Concentration and wind field for scenario C1.

Simulation time	Xe-133 m Bq/m^3	Cs-137 Bq/m^3	Ba-133 m Bq/m^3	Te-127 Bq/m^3
1 h	5,92E+13	1,11E+01	5,27E+04	1,43E+06
3 h	2,34E+13	4,37E+00	2,07E+04	5,60E+05
72 h	2,18E+12	3,58E-01	1,70E+03	4,60E+04

Table 6.
Radionuclides concentration in EPZ-3 km (Praia Brava).

to the region's wind field during the entire simulation period, 72 h. The respective plume concentration periods that were considered: 1, 3, and 72 h, for each EPZ, see **Tables 6–9**. **Figure 6** shows the wind field and radionuclides transport from **Table 1** for scenario C2.

5.2 Whole body dose in EPZ

- Whole body dose analysis for Scenario C1

Simulation time	Xe-133 m Bq/m^3	Cs-137 Bq/m^3	Ba-133 m Bq/m^3	Te-127 Bq/m^3
1 h	3,88E+13	7,01E+00	3,32E+04	8,99E+05
3 h	1,66E+13	2,72E+00	1,29E+04	3,49E+05
72 h	4,19E+12	6,36E-01	3,01E+03	8,16E+04

Table 7.
Radionuclides concentration in EPZ-5 km (Frade).

Simulation time	Xe-133 m Bq/m^3	Cs-137 Bq/m^3	Ba-133 m Bq/m^3	Te-127 Bq/m^3
1 h	5,97E+12	1,05E+00	4,97E+03	1,34E+05
3 h	3,62E+12	6,39E-01	3,03E+03	8,20E+04
72 h	6,18E+11	8,64E-02	4,09E+02	1,11E+04

Table 8.
Radionuclides concentration in EPZ-10 km (Mambucaba).

Simulation time	Xe-133 m Bq/m^3	Cs-137 Bq/m^3	Ba-133 m Bq/m^3	Te-127 Bq/m^3
1 h	4,23E+12	4,42E-01	2,09E+03	5,66E+04
3 h	3,21E+12	3,42E-01	1,62E+03	4,39E+04
72 h	8,57E+11	8,37E-02	3,96E+02	1,07E+04

Table 9.
Radionuclides concentration in EPZ-15 km (Angra dos Reis).

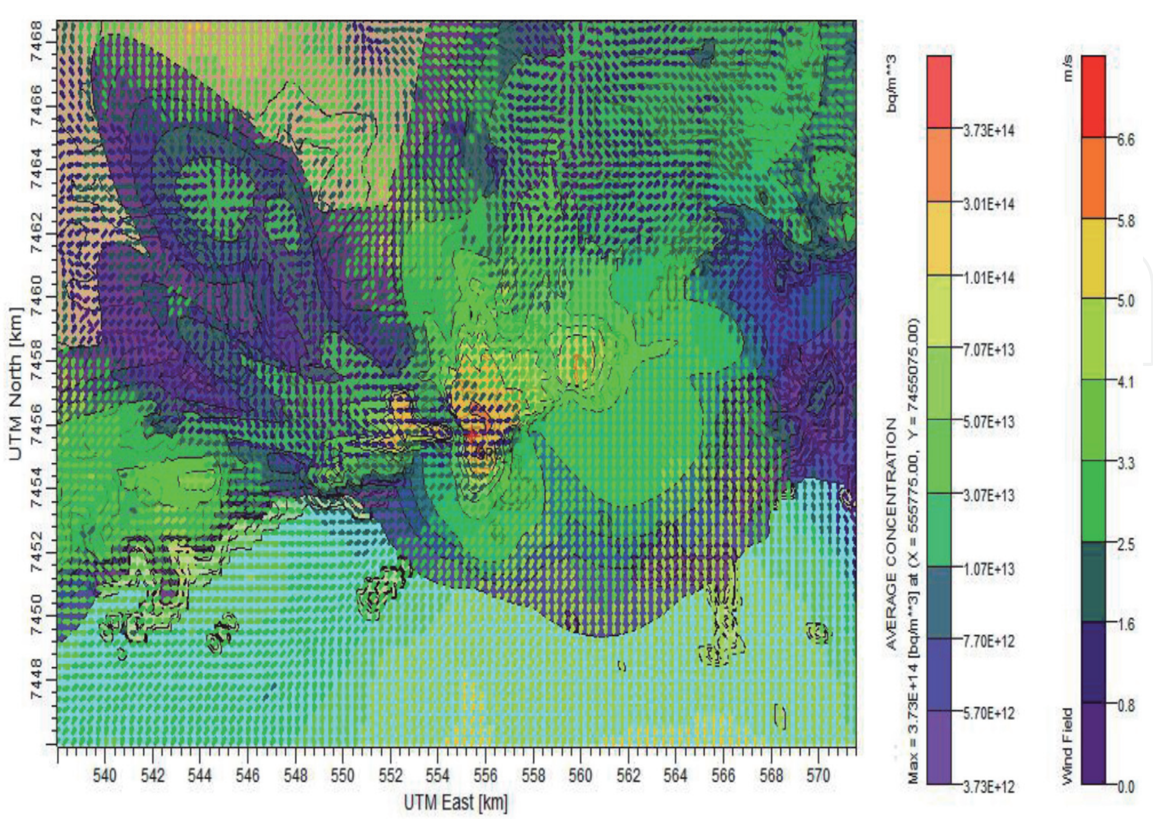

Figure 6.
Concentration and wind field for scenario C2.

C1 exposure time	EPZ 3 km Praia Brava (mSv)	EPZ 5 km Região do Frade (mSv)	EPZ 10 km Mambucaba (mSv)	EPZ 15 km Angra dos Reis (mSv)
1 h	7,06E-05	4,63E-05	7,12E-06	5,04E-06
3 h	8,38E-05	5,96E-05	1,29E-05	1,15E-05
72 h	1,94E-04	3,60E-04	5,31E-05	7,35E-05

Table 10.
Whole body dose in EPZ for scenario C1.

C2 exposure time	EPZ 3 km Praia Brava (mSv)	EPZ 5 km Região do Frade (mSv)	EPZ 10 km Mambucaba (mSv)	EPZ 15 km Angra dos Reis (mSv)
1 h	2,73E+05	1,79E+05	2,75E+04	1,95E+04
3 h	3,24E+05	2,30E+05	5,00E+04	4,44E+04
72 h	7,25E+05	1,39E+06	2,05E+05	2,84E+05

Table 11.
Whole body dose in EPZ for scenario C2.

For the dose calculation, were used the equations (Eqs. (1) and (2)), and the exposure time to individual members of the public was 1, 3, and 72 h. It was considered that these individual members of the public are not under any protection and the plume exposure is 100%. **Table 10** shows the dose values for each exposure time, as well as for each EPZ.

- Whole body dose analysis for Scenario C2

For the dose calculation, were used the equations (Eqs. (1) and (2)), and the exposure time to individual members of the public was 1, 3, and 72 h. It was considered that these individual members of the public are not under any protection and the plume exposure is 100%. **Table 11** shows the dose values for each exposure time, as well as for each EPZ.

6. Conclusions

According to the PEE/RJ [20] – External Emergency Plan of the State of Rio de Janeiro, in order to prioritize the risks and facilitate the planning and implementation of protection measures recommended by CNEN, the concept of EPZ was adopted. The Emergency Planning Zones were subdivided into circular crowns as shown in **Figure 4**.

According to the PEE/RJ, the preventive evacuation of the population constitutes an effective protection measure up to the distance of 5 km around the plant. From this distance, no additional benefit will be obtained with the preventive evacuation. Thus, to the EPZ 10 km and EPZ 15 km, it is preferable to recommend, in the short term, that the population remains sheltered. In this sense, the existing rays are classified as follows:

- Preventive action zones

EPZ 3 km: circumscribed area from 3 km centered on the nuclear unit of CNAAA, so the property area of ELETRONUCLEAR.

EPZ 5 km: circular crown, centered on the nuclear unit of CNAAA, with a 5 km outside radius and inner radius of 3 km. This EPZ 5 km is defined as the impact zone.

- Environmental control zones

EPZ 10 km: circular crown, centered on the nuclear unit of CNAAA with a 10 km outer radius and inner radius of 5 km.

EPZ 15 km: circular crown, centered on the nuclear unit of CNAAA with a 15 km outer radius and inner radius of 10 km.

According to a CNEN study [21], the protection measures for CNAAA can be divided as follows:

a. Area emergency: EPZ 3 km and EPZ 5 km (notification to the population to remain in residences or workplace, awaiting instructions) and EPZ 10 km and EPZ 15 km (notification to the population to keep on the alert for further instructions, keeping their normal activities); and

b. General Emergency: EPZ 3 km (population evacuation), EPZ 5 km (keep population sheltered), EPZ 10 km and EPZ 15 km (notification to the population to remain in the residences or workplace, awaiting instructions).

Based on the dose values for sheltered and evacuation of Regulatory Position CNEN 3.01/006: 2011 [22], whose values are 10 mSv for sheltered and 50 mSv for evacuation, will be recommended the protection measures for each EPZ for scenarios C1 and C2, as shown in **Tables 12** and **13**. The recommendations in **Table 12** were based on the projected doses of **Table 10** and the recommendations in **Table 13** were based on the projected doses of **Table 11**.

It is observed in **Table 12** that for the Preventive Action Zones (EPZ 3 km and EPZ 5 km) and Environmental Control Zones (EPZ 10 km and EPZ 15 km), the recommendations of the protective measures that best meet the dose levels is Sheltered in place. The Scenario C1 is characterized as Area Emergency, having as a measure of the local authorities the notification to the population to remain in their residences or workplace, awaiting future instructions.

C1 exposure time	EPZ 3 km Praia Brava	EPZ 5 km Frade	EPZ 10 km Mambucaba	EPZ 15 km Angra dos Reis
1 h	Sheltered	Sheltered	Sheltered	Sheltered
3 h	Sheltered	Sheltered	Sheltered	Sheltered
72 h	Sheltered	Sheltered	Sheltered	Sheltered

Table 12.
Recommendations for protection measures in EPZ for scenario C1.

C2 exposure time	EPZ 3 km Praia Brava	EPZ 5 km Frade	EPZ 10 km Mambucaba	EPZ 15 km Angra dos Reis
1 h	Evacuation	Evacuation	Evacuation	Evacuation
3 h	Evacuation	Evacuation	Evacuation	Evacuation
72 h	Evacuation	Evacuation	Evacuation	Evacuation

Table 13.
Recommendations for protection measures in EPZ for scenario C2.

It is observed in **Table 13** that for the Preventive Action Zones (EPZ 3 km and EPZ 5 km) and Environmental Control Zones (EPZ 10 km and EPZ 15 km), the recommendations of the protective measures that best meet the dose levels is Evacuation. The Scenario C2 is characterized as a General Emergency, having as a measure of the local authorities the evacuation of the population in EPZ.

In summary, it is possible to conclude that:

- Scenario C1 it is observed the occurrence of an Area Emergency, having as a protective measure in all EPZ, Sheltered in place.
- Scenario C2 it is observed the occurrence of a General Emergency, having as a protective measure in all EPZ, Evacuation;
- The impact zone that is currently 5 km, covering the Preventive Action Zones, for scenario C2, has the extension of this impact zone for distances beyond 5 km; and
- Analyzing the C1 and C2 scenarios, it is inferred that the faster the accident is mitigated, the lower will be the radiological consequences and therefore, the actions to the protective measures will be lighter.

Advance planning is essential to identify potential problems that may occur in an evacuation. The NRC case study cites the following aspects of planning as contributing to efficiency and effectiveness of evacuation [23]:

- High level of cooperation among agencies;
- Use of multiple forms of emergency communications;
- Community familiarity with alerting methods, the nature of the hazard and evacuation procedures;
- Community communication; and
- Well-trained emergency responders.

However, if environmental monitoring confirms that the population's exposure will extend beyond a few days, justifying other protection actions beyond shelter and evacuation, temporary or permanent resettlement should be considered [22].

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