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Computational modeling of atmospheric dispersion applied to a small modular reactor

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***Abstract*— *This study describes the computational modeling of the atmospheric dispersion resulting from a postulated radiological accident in a small modular reactor (SMR), with a power of 16 MWe (50 MWt), and containing three fuel enrichment regions, at 4%, 5 % and 20%. Among the hypothetical inventory radionuclides, derived from nuclear reactions during fuel burnup after 2 years of operation, the contribution of Cs-137 was considered for simulation, using the HotSpot code, of the concentration and total effective doses (TEDE) received, both depending on the distance from the event. A locality in the interior of Brazil was chosen to install the SMR, where information on meteorological conditions was collected to identify the predominant atmospheric stability class. The results suggest that the maximum calculated TEDE was 3.6 Sv, 34 m from the reactor, decreasing with time and distance, and following the Gaussian dispersion model, and that the contamination plume is dependent on the Pasquill-Gifford criteria and Cs-137 activity. For doses between 1 mSv and 10 mSv and between 10 mSv and 50 mSv, it is suggested that the population be housed in existing buildings in the locality, and for values above 50 mSv, shelter in these conditions or the evacuation of people close to the reactor in movement contrary to the spread of the plume. The relevance of this investigation shows the importance of emergency response planning and the influence of meteorological conditions, considering the data assumed in the simulation.*

***Keywords* — SMR, Modeling, Dispersion, HotSpot.**

I. INTRODUCTION

The study presents a computational modeling of the atmospheric dispersion resulting from a hypothetical radiological accident, in a small modular reactor (SMR), whose power is 16 MWe (50 MWt). SMRs are defined as small nuclear power reactors, capable of generating up to 300 MWe of electrical power [1]. Because it is manufactured in modules, its versatility allows transportation and installation in places less likely to build a conventional nuclear reactor (PWR), which can be a solution for places where energy supply or access is necessary, such as in Northern Brazil [2].

By hypothesis, and within in this context, a situation analysis for study, by computational modeling, becomes relevant, seeking to evaluate the implementation of protection measures in emergency situations, proposals to avoid or reduce the population's exposure to radiation, in the case of an accident with a reactor of this size, installed in a distant area. This analysis would allow to verify with more detail the appropriate selection of the site for the execution of nuclear activities and practices with this type of modular reactor [1,3].

The objective of the research is to perform a computational simulation of the atmospheric dispersion of radionuclides, using the HotSpot Health Physics code (version 3.1.2) [4], released during a hypothetical accident in the SMR, and to analyze the data obtained, in order to verify the adoption the immediate protective measures in the initial phase of this postulated radiological event, as well as the influence of weather conditions on the contamination plume.

II. MATERIALS AND METHODS

2.1 Description of the SMR reactor

For this study, it is assumed that the SMR, whose power is 16 MWe (50 MWt), has been operating continuously for 2 years (720 days), at maximum power [5], and that the atmospheric dispersion of radionuclides was generated by the burning of fuel from this reactor.

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The core of this SMR has three fuel enrichment regions, 4%, 5% and 20%, as shown in Fig. 1.

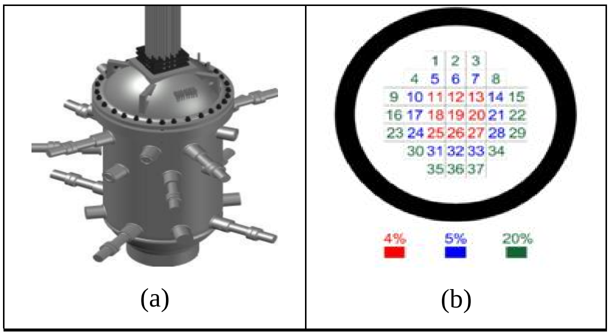

Fig. 1: Nuclear installation illustration: a) on the left, the SMR pressure vessel; b) on the right, the top view of the core.

Source: AUTOCAD,2019.

In this context, for the analysis of the average activities of the radionuclides resulting from the nuclear reactions occurred during the burning, Table 1 presents a hypothetical inventory, containing possible radionuclides accumulated in the reactor, after 2 years of uninterrupted operation, with their respective masses, average activity and fraction of release to the atmosphere, considering the fuel enrichment adopted for the SMR of this study [6,7].

Among the radionuclides from the SMR inventory, the atmospheric dispersion modeling and the doses calculation were conducted based on the contribution of Cs-137.

This isotope is important in the analysis of the consequences of radiological accidents, as it is extremely toxic and has a long half-life (30 years) [3]. Several records in the literature indicate the main risks of exposure, internal and external, to this radioisotope, which can be seen, for example, in the reports of the accident in Goiania, in 1987 [8].

In addition, the choice for Cs-137 can also be justified by the innovative character of this proposal, in allowing an analysis by computational simulation of possible situations of radiological accident involving atmospheric dispersion, favoring the adoption of immediate protective measures in its initial phase. Such situations could not be analyzed using experimental methods, due to the high risk associated with exposure to ionizing radiation. Thus, the option for a radionuclide of relevance in the area of radiological protection [3], for application in this study, gives support to the use of the same methodology for more general situations as in the case of the reactor inventory in question, in its entirety, for example.

Table 1: Hypothetical inventory of radionuclides in the SMR after 2 years of operation [6].

Radionuclide	**Mass (*g*)**	**Activity (Bq) in the core**	**Release fraction**	**Activity (Bq) released into the atmosphere**
Ba-140	3,409E+01	9,228E+16	0,02	1,846E+15
Cs-137	1,337E+03	4,295E+15	0,30	1,289E+15
I-131	1,032E+01	4,746E+16	0,40	1,898E+16
Kr-85	4,252E+01	6,153E+14	1,00	6,153E+14
Kr-85m	5,700E-02	1,735E+16	1,00	1,735E+16
Rn-220	6,839E-13	2,334E+07	1,00	2,334E+07
Sr-89	5,757E+01	6,185E+16	0,02	1,237E+15
Sr-90	7,325E+02	3,739E+15	0,02	7,479E+13
Te-132	6,049E+00	6,911E+16	0,05	3,455E+15
Xe-133	1,443E+01	1,000E+17	1,00	1,000E+17

Source: Research Data

2.2 Modeling of radiological accident simulation

For the occurrence of radiological accident in the SMR, the following premises were considered: a) the reactor was operating at maximum power for 2 uninterrupted years; b) the cladding, based on Zircaloy-4, reached temperature values beyond its design specifications; c) the limit of 340ºC [9] led to the creation of cavities. This rise in temperature was motivated by an supposed failure of the control bar locks (cadmium-based neutron absorbers) and the delay in the insertion of borated

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water, which caused, not only the insertion of positive reactivity in the core, i.e, the reactor in the supercritical condition, but also a substantial loss of fluid, characterizing the *Loss of Cooling Accident* (LOCA) [10].

With this cladding failure scenario, it was assumed that the gaseous fission products were released into the water in the reactor pressure vessel and collected at its top, continuing to operate without any replacement of the elements in a failure condition. Consequently, the radionuclides in question were dispersed, instantly, into the atmosphere, for a period of 10 min, in a single release. This release occurred through the venting system in the reactor building, located 10 m above the ground, as described in Fig. 2.

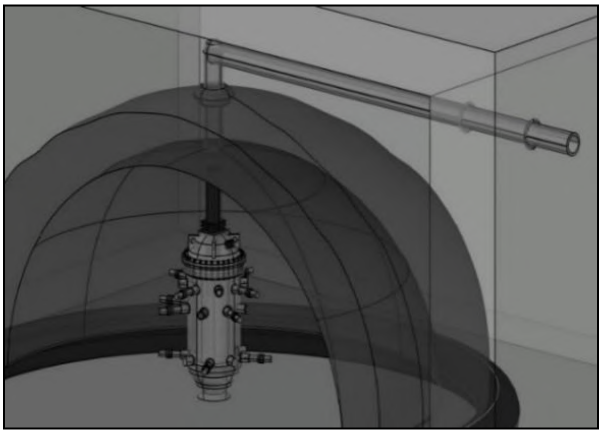

Fig. 2: Simplified illustration (out of scale) of the vent pipe system of the nuclear installation.

Source: AUTOCAD, 2019

2.3 Modeling of radiological accident simulation

The Atmospheric dispersion was calculated using the Gaussian plume dispersion model, using the HotSpot code, a Health Physics code from Lawrence Livermore National Laboratory used as a computational tool to perform the atmospheric transport modeling [4]. This software takes into account the wind speed for calculating the transport of the radioactive material released into the environment and the local atmospheric stability, named A (extremely unstable) to F (moderately stable), according to the Pasquill-Gifford stability classes [4].

The HotSpot allows to determine the atmospheric concentration of the radiological agents dispersed in any point of space, where the origin of the coordinate system is located at ground level (x = 0, y = 0, z = 0), with the release coordinates of the radionuclides in (x = H, y = 0, z = 0), using the following equation [4]:

$$C(x,y,z,H)=\frac{Q}{2\pi U\sigma_y\sigma_z}\exp\left(\frac{-y^2}{2\sigma_y^2}\right)\left\{\exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right]+\exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right]\right\}e^{\left(\frac{-\lambda x}{u}\right)}DF(x) \qquad (1)$$

where *C(x,y,z,H)*, consists of the atmospheric concentration (*Bq.s/m³*); *Q*, the source activity (Bq); σ_y, the standard deviation of the concentration distribution in the direction perpendicular to the wind (m); σ_z, the standard deviation of the concentration distribution in the vertical direction (*m*); y, the distance perpendicular to the wind direction (*m*); z, the distance from the vertical axis (*m*); *H*, the effective[1] release height (*m*); *λ*, the radioactive decay constant (s^{-1}); *x*, *u*, the average wind speed at the effective release height of the material (*m/s*); *DF(x)*, in the plume depletion factor, calculated by the following equation [4]:

$$DF(x)=\left\{\exp\int_0^x \frac{1}{\sigma_z \exp\left[\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right]}\right\}^{-\frac{v}{u}\sqrt{\frac{2}{\pi}}} \qquad (2)$$

where *v* is the deposition speed (*m/s*) of the radioactive material, and the other variables are in accordance with equation (1). Fig. 3 schematically illustrates the radionuclide dispersion process based on the Gaussian model.

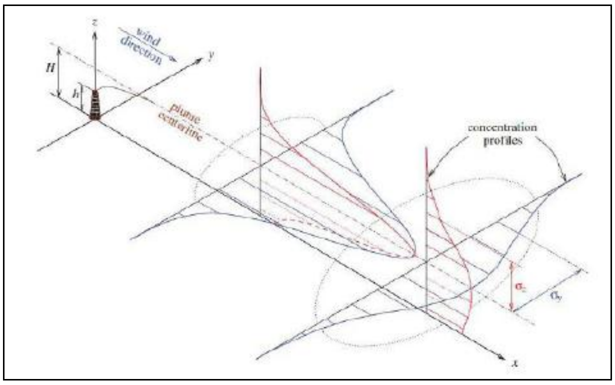

Fig. 3: Representation of the radiological plume dispersion, from a continuous point source, with the wind direction aligned with the x axis [12].

Source: Adapted from STOKIE, 2011

[1]For this work, it was assumed, by hypothesis, that the effective release height is the physical height of the release of the radioactive material into the atmosphere (in this case, the height of the venting system, located at 10 *m* in relation to the ground).

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For the simulation of the total effective dose (TEDE[2]), The HotSpot code uses the radiation dosimetry methodologies recommended by the International Commission on Radiological Protection (ICRP), to convert the concentration provided by equation (1) into the dose to which individuals who remain in the same location and in the direction of the wind will be exposed. For this case, the code uses the values of dose coefficients from the documents Federal Guidance Report (FGR) 11, 12 and 13, which provide the factors of dose conversion by inhalation, submersion and ingestion [3,4].

The chosen area for the simulations is located in the interior of the State of Amazonas, in Brazil, 700 km from Manaus-AM and 200 km from Porto-Velho-RO, with geographical coordinates 7º 32 '60"(S) and 63º 04' 48" (O). The justification for this location is due to the fact that this region has been identified as one of the places in the country where many Brazilians live without access to the electricity service [13]. This location also presents peculiarities because it has a flat surface in most areas, including the critical direction to be studied (the atmospheric dispersion models fit well in this type of terrain), it has rural and urban areas, lakes and rivers, highways, in addition to being close to public establishments, like the Brazilian Army and the Highway Police, which may favor the physical security aspect of the nuclear installation of this study. This entire region and geographical characteristics can be seen in Fig. 4.

According to Fig. 4, the reactor is located at an approximate distance of: 250 m from the Highway Police Station; 1 km from the Federal Institute of Education, Science and Technology; 1.2 km from the Brazilian Army Unit; 1.5 km from the Regional Airport of the locality under study; 1.4 km from the set of residences shown in that figure. Such information aims to subsidize the analysis of atmospheric dispersion in the initial phase of response to the postulated radiological event, in which immediate protective actions, such as shelter and evacuation, in addition to the application of its generic levels of intervention, will be considered [14].

For the simulation, information about meteorological conditions was collected in order to identify the possible classes of atmospheric stability existing in the region under study.

[2]TEDE (Total Effective Dose Equivalent) is the sum between the effective dose for external exposures (submersion, resuspension and deposition) and the compromised absorbed dose for internal exposures (inhalation) [11].

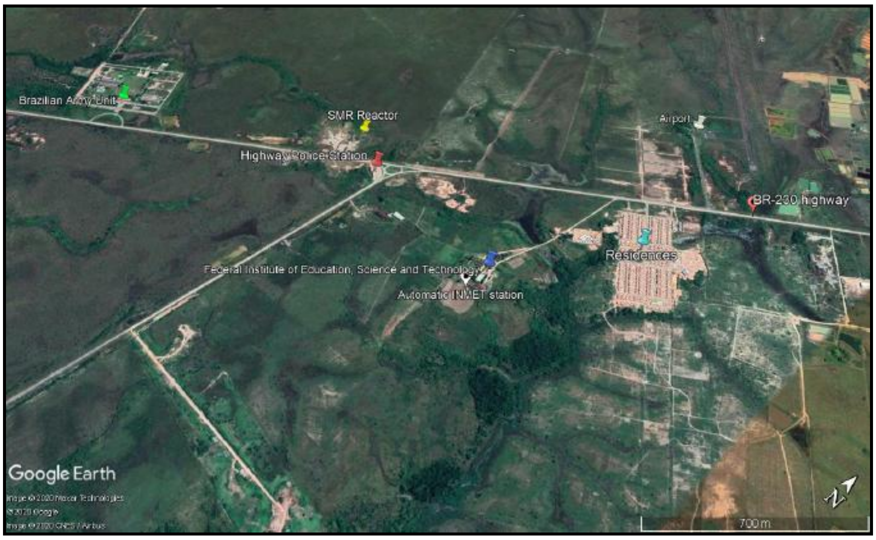

Fig. 4: Visualization of the SMR installation location, showing adjacent areas.

Source: Google Earth, 2020

The data were obtained from the database of the National Institute of Meteorology (INMET), the National Institute for Space Research (INPE) and the literature, considering an observation period for the last 5 years.

Based on meteorological information, the direction and speed of the wind in this locality were defined, throughout the year. It was found that the wind speed in the region oscillates in the range of 0 and 4 *m/s*, with the highest recorded speed being 6 *m/s.* The period of day when this maximum speed can occur is between 12 noon to 6 pm. The preferred wind direction is most frequent between 0 to 90º, although other directions may occur throughout the year. In addition, the average obtained for the intensity of solar radiation, with the data for the period considered, was greater than 700 W/m^2 [15-17].

Based on the meteorological data of that place and assuming a plausible scenario, it was assumed that, at the moment of the postulated accident, the wind speed was 3 *m/s*, the release of radionuclides into the atmosphere occurred during the day, there were no precipitations and the solar radiation was 700 W/m^2, which allows to classify atmospheric stability, for the present study, in Pasquill-Gifford's Class A (extremely unstable) [4]. In addition, considering the areas adjacent to the SMR operation site, the analysis of the atmospheric dispersion of the Cs-137 was carried out based on the wind direction coming from the West (270º), a situation in which the greatest negative effects will be caused, due to the existence of relevant points (university center, Highlight Police Station and residences) in the region of incidence and displacement of the winds, according to the legend in Fig. 4, justifying its use in this study.

Thus, considering the dispersion model, the type of terrain, the characteristics of the reactor of this study and the meteorological information, these data were analyzed and entered as input parameters in the HotSpot software. All calculations were performed considering the Pasquill-Gifford stability class A. Table 1 presents these parameters for the simulation of the radiological accident caused by an assumed failure in the SMR cladding.

Table 2: Parameters for HotSpot simulation.

Parameters	**Input**
Radioactive material	Cs-137
Activity	4,295E+15 *Bq*
Wind speed	3,0 *m/s*
Wind direction	270º West
Distance coordinates	Distance from plume centerline
Stability class (standard terrain)	A (extremely unstable)
Receptor height	1,5 *m*
Sampling time	10 *min*
Factors of dose conversion	FGR nº11 [18]
Exposure time	24h
Effective release height	10 *m*

Source: Research Data

Under the boundary conditions defined in Table 1, the study zones were delimited in isodoses curves, according to the TEDE values received, depending on the distance to the origin of the dispersion. These curves are organized as internal, intermediate and external, assuming the limits of 50 mSv, 10 mSv and 1 mSv, respectively. The first two values refer to the dose avoided by the evacuation (50 mSv) and shelter (10 mSv) actions [14] and the third (1 mSv), only as a reference for the third curve, in reference to the annual limit of dose for an individual of the public (1 *mSv/year*), expected for a normal exposure situation, before the accident [19].

The results obtained, in terms of the TEDE received and the concentration of Cs-137, at different distances downwind, due to atmospheric dispersion, were analyzed and compared with the normative thresholds stipulated by the regulatory authorities for radioprotection, in order to verify the influence of weather conditions on the contamination plume, the population potentially affected during this radiological event and also the protective measures to be taken in the initial phase of the accident described in this study.

III. RESULTS AND DISCUSSION

After the data in Tables 1 and 2 (referring to Cs-137) are entered in the HotSpot code, the TEDE values and the concentration profile are shown in Table 3, considering a maximum distance of 100 km from the origin of the dispersion. The data refer to the period of one day (24 hours) of exposure.

Table 4 presents other important information for the analysis of atmospheric dispersion, considering the assumptions adopted in the simulation.

In this way, Fig. 5 and 6 show the isodoses curves, representing the TEDE of 50 mSv, 10 mSv and 1 mSv, respectively, generated over the terrain, showing the affected area, in which the extremely unstable stability class (Class A) was considered acting in the SMR's operating region.

The calculation of the atmospheric transport of the Cs-137 was also carried out for comparison with other stability classes, in the hypothesis that there are different atmospheric classes operating in the region where the reactor is operating, relating the dose values received at different distances from the origin of the dispersion, as well as the maximum TEDE value achieved, in the different stability classes, as described in Fig. 7 and presented in Table 5.

Table 3: Dispersion data of the Cs-137 from the SMR accident.

Distance (km)	TEDE (Sv)	Air concentration [(Bq.s)/m³]	arrival time of plume (hora:min)
0,03	3,50E+00	1,80E+11	<00:01
0,1	9,90E-01	5,50E+10	<00:01
0,5	4,00E-02	2,50E+09	00:02
1	9,70E-03	6,40E+08	00:05
2	2,40E-03	1,70E+08	00:11
3	1,10E-03	7,70E+07	00:16
4	6,10E-04	4,50E+07	00:22
5	3,90E-04	3,00E+07	00:27
10	1,10E-04	8,60E+06	00:55
15	5,10E-05	4,30E+06	01:23
20	3,10E-05	2,60E+06	01:51
30	1,50E-05	1,30E+06	02:46
40	9,50E-06	8,50E+05	03:42
50	6,60E-06	5,90E+05	04:37
60	4,90E-06	4,40E+05	05:33
70	3,80E-06	3,50E+05	06:28

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80	3,10E-06	2,80E+05	07:24
90	2,60E-06	2,40E+05	08:20
100	2,20E-06	2,00E+05	09:15

Source: Research Data

Table 4: Data obtained from computational simulation in HotSpot code regarding the dispersion of Cs-137.

Information	Observation
Maximum TEDE Value	3,6 Sv
SMR distance the TEDE is maximum	0,034 *km*
Distance from the SMR at which the TEDE exceeds the internal isodose	0,45 *km*
Distance from the SMR at which the TEDE exceeds the intermediate isodose	0,98 *km*
Distance from the SMR at which the TEDE exceeds the external isodose	3,1 *km*

Source: Research Data

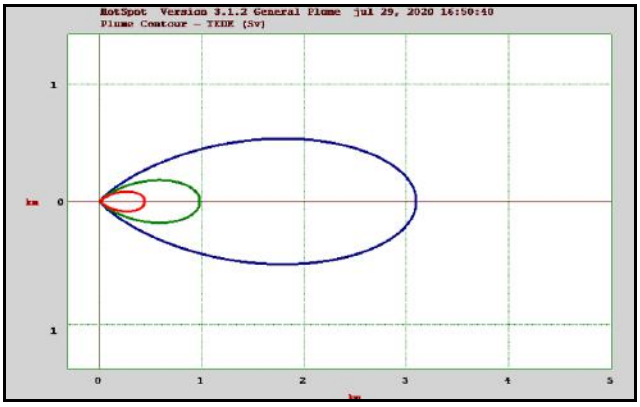

Fig. 5: Isodose curves due to Cs-137, obtained from HotSpot code, considering stability class A. Internal isodose (red color): 50 mSv (0.055 km²); Intermediate isodose (green color): 10 mSv (0.26 km²); External isodose (blue color): 1 mSv (2.4 km²).

Source: HOMANN, 2019

Fig. 6: Contour limit of the isodoses referring to the contamination plume with Cs-137.

Source: Google Earth, 2020

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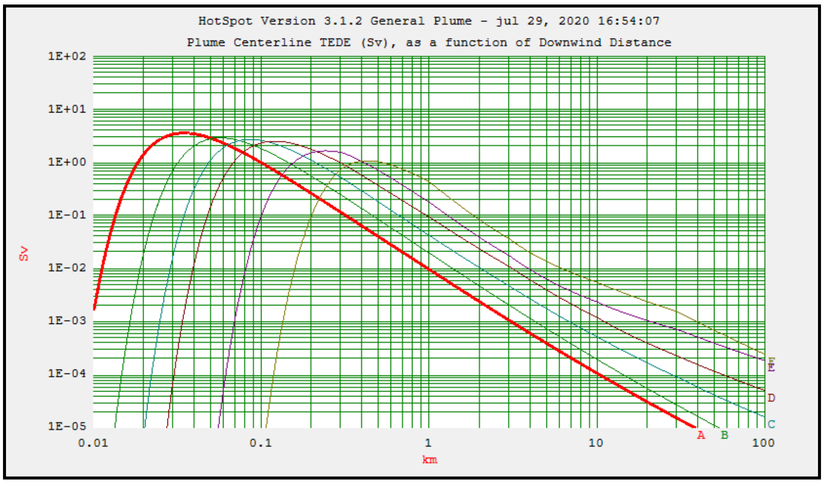

Fig. 7: TEDE values received at different distances downwind, considering all stability classes. Source: HOMANN, 2019

Table 5: Maximum values of TEDE for different stability classes.

Atmospheric stability class	**Dispersion data for Cs-137**		
	Description	**Maximum TEDE (Sv)**	**Distance (km) from SMR**
A	Extremely unstable	3,6	0,034
B	Moderately unstable	2,9	0,057
C	Slightly unstable	2,8	0,085
D	Neutral conditions	2,5	0,120
E	Slightly stable	1,7	0,240
F	Moderately stable	1,1	0,430

Source: Research Data

From the origin of the dispersion, the calculated values showed that the maximum TEDE, due to Cs-137, is obtained at 34 m, with a value of 3.6 Sv, decreasing with time and distance. These results are obtained at different times, as this radioactive material reaches designated receiving points in downwind locations [3], as shown in Table 3. Such behavior is shown to be acceptable from the theoretical point of view, since the release of this radionuclide into the atmosphere follows the Gaussian model of dispersion, shown in Fig. 3 [4,12].

Fig. 5 and 6 show that the highest dose values, above 50 mSv, are found in the area between zero point and 0.45 km, followed by the intermediate dose value, greater than 10 mSv and smaller than 50 mSv, within the distance of 0.45 km to 0.98 km, and the last curve in the distance from 0.98 km to 3.1 km, representing values above 1 mSv and less than 10 mSv. The curves cover an area of 0.055 km², 0.26 km² and 2.4 km², respectively.

Regarding the influence of weather conditions on atmospheric dispersion, the results showed that the more unstable these conditions prevail in the location, the greater the TEDE values at a shorter distance from the origin of the Cs-137 dispersion, as shown in Table 5. This can also be seen in Fig. 7, which shows the decrease in maximum TEDE values when atmospheric stability conditions become more stable. In addition, due to the curves presented in this same figure, there is also an increase in TEDE value for greater distances when considering the most stable classes. These observations suggest that situations of high turbulence in the atmosphere favor the mixture of pollutants, increasing the rate of deposition of radioactive material in the soil and decreasing the transport of this radionuclide over greater distances, i.e, generating lower dose values from submersion to the cloud of Cs-137. In addition, the results also denote the dependence of the plume on radioactive contamination with the criteria of atmospheric stability, proposed by Pasquill-Gifford [3,4].

Furthermore, according to the calculated data, for doses above 50 mSv, the intervention may occur in the direction of evacuation of people from the vicinity of the reactor, in a movement contrary to the propagation of the plume. According to the geographical characteristics presented in Fig. 4, and according to the assumed atmospheric dispersion scenario (daytime, main wind direction coming from the West and without rain at the moment of the postulated accident), there are locations in this region, such as the Airport and also the Brazilian Army unit, which besides being close to the reactor site, are not being influenced by the preferential displacement of the plume, which would allow the execution of this protective action. In addition, the existence of the BR-230 highway would facilitate the transportation and removal of the population to the designated locations, provided that this measure occurs for a period of up to 1 (one) week, as recommended by regulatory agencies [14].

For doses in the range between 10 mSv and below 50 mSv, the results suggest the adoption of shelter as a protective measure. As seen in the isodoses curves in Fig. 6, the Highway Police Station, the Federal Institute of Education, Science and Technology and the set of existing residences are receiving exposures below 10 mSv. The same procedure can also be adopted for the population that is submitted to doses ranging from 1 mSv to 10 mSv, since in emergency situations, the pre-established levels of intervention can be reassessed, when implemented, in depending on the conditions existing at the time of the accident, as long as the dose levels are not exceeded (foreseen, in this case, for the shelter, in 10 mSv) [14]. This measure would considerably reduce the doses due to irradiation from the cloud, irradiation from contaminated soil and inhalation of Cs-137, due to the reduction factor inherent in these constructions.

However, even in the case where the doses are above 50 mSv, the shelter, under the conditions mentioned above, can be applied, as long as the dose limits imposed for this action (10 mSv) are respected. The ideal time to implement the evacuation would be before the passage of the plume, which may not be possible given the results achieved in this study, since the radioactive cloud reaches the points closest to the reactor in less than 5 min. If the evacuation was performed during the passage of the plume, it would be possible that higher doses would be received by the evacuees than by those who remained sheltered. In addition, depending on weather conditions, the number of people to be evacuated and the means of transport available, evacuation could take a long time, corroborating the option for shelters, so as not to put the population potentially involved in the accident at risk. It should be noted that the shelter period should not exceed two days of exposure [14], when evacuation, in a later stage, i.e, after the passage of the plume, could be more effective.

From the distance of 3.1 km from the origin of the accident in the SMR, the TEDE values, at different points, are below 1 mSv. The results suggest that Cs-137 can be transported over long distances, however, the dose values due to the contribution of this radionuclide, in the amount in which it was released into the atmosphere (Table 1), will be below the intervention levels proposed for the shelter and evacuation, therefore, it is not necessary to adopt these protective measures, under simulated conditions [3]. These values, in fact, are in the same order of magnitude as those allowed for normal operation situations, before the accident moment, in which the dose limit is 1 *mSv/year* for the individual of the public [19].

IV. CONCLUSION

The objective of the research was achieved through simulation by computational modeling of atmospheric dispersion resulting from a hypothetical radiological accident in a small modular reactor (50 MWt), in a region where electricity is scarce, to analyze the adoption of immediate protective measures in the initial phase of the postulated radiological event, as well as the influence of weather conditions on the contamination plume.

The main results of this research showed that, for stability class A, assumed at the time of the hypothetical accident, a maximum TEDE value of 3.6 Sv was obtained, at a distance of 34 m from the origin of the dispersion, as a contribution of a radionuclide with significant importance in radiological protection, the Cs-137, which was obtained from of a hypothetical SMR inventory, considering the condition of total burnup of this reactor. From this result achieved, the present study allowed to verify that the other calculated concentration and dose values decrease with time and distance, following the Gaussian dispersion model [4,9].

The research also allowed to verify the influence of the meteorological conditions in the atmospheric dispersion, showing the dependence of the plume of radioactive contamination with the criteria proposed by Pasquill-Gifford. The results showed that the more unstable these conditions prevail in the place, the greater the TEDE value at a shorter distance from the origin of the Cs-137 dispersion, and that an increase in doses occurs, for greater distances, when considering the classes more stable atmospheric stability.

Another relevant finding from this study, is that, for doses above 50 mSv, the intervention may occur in the sense of evacuating of population from the vicinity of the reactor, in a period of less than a week, both for the region's Airport, as well as for the Brazilian Army Unit, featuring a movement contrary to the preferential direction of the plume. For doses in the range between 10 mSv and below 50 mSv and between 1 mSv and 10 mSv, the results suggest the adoption of the shelter as a protective measure, considering that in the reactor location there are the Highway Police Station, the Federal Institute of Education, Science and Technology and residences, which are receiving exposure below 10 mSv. In addition, for all these cases, depending on the time of arrival of the plume, the climatic conditions, the amount of people to be removed and the existing means of transport, the option for shelters may be the most relevant, as long as it does not exceed two days of exposure, when evacuation is the most effective option.

Therefore, the research shows that, for studies of atmospheric dispersion, with a well-defined characterization of the source of ionizing radiation, the methodology applied in the computational modeling resulting from a radiological accident in an SMR allows to verify the compliance with the standards regarding the planning of emergency responses and the influence of weather conditions.

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