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Consequence Analysis of a Station Blackout in Brazilian Nuclear Power Plant Angra 2

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ABSTRACT

The article consists, through a Severe Accident, evaluating the impact of radionuclides released into the atmosphere in the vicinity at Nuclear Power Plant. The source term used in present work is obtained by means of proportionality between Angra 1 and Angra 2. That is, the source term of Angra 2 is calculated based on its activity estimated from numbers of fuel pellets of both power plants and the already known activity of Angra 1. This calculation resulted in total activity of Angra 2 equivalent to 146.18% of activity of Angra 1. The results indicate that for severe accident scenarios, the protective measures to be adopted will be general emergency; and the impact area, which currently has a distance of 5 km, would become greater than this value.

Keywords: **CALPUFF, Atmospheric Dispersion, Severe Accident.**

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1. INTRODUCTION

Since the three major nuclear accidents had occurred in different parts of the world [1, 2, 3], the Nuclear Regulatory Commissions of all the countries producing nuclear energy were requested by the International Atomic Energy Agency (IAEA) to carry out computational simulations of some conceivable severe accidents in their facilities. The purpose of these simulations was verifying the integrity of each facility under the assumption that the same is subjected to such events. Nevertheless, the necessity of studying the beyond-the-design-basis-accidents (BDBA) was already perceived after the well-known core-melt accident of the Three Mile Island – 2 (TMI-2) on March 28, 1979 [4].

Although very unlikely, if a severe accident should take place, and be followed by successive failures of the physical barriers and problems with the control and protection systems in a nuclear facility, the resulting release of radioactive material into the atmosphere would be significant. Consequently, these catastrophic events could entail an increase of radioactive level in the vicinity, and this in turn, would pose a threat to the life of the population.

2. MATERIALS AND METHODS

There are diverse scenarios of severe accident in a nuclear power plant, and by definition, every one of these involves partial or total meltdown of the reactor core. Thus in this context, the present work aims to deterministically analyze the consequences of the scenario of Station Blackout (SBO) in the Angra – 2 nuclear power plant (NPP).

2.1. Description of the accident scenario

Naturally, proper operation of systems, devices and equipment in a nuclear power plant requires a stable electric power supply. In normal condition it puts into operation the refrigeration systems, monitoring and control systems, lighting and other routine services; whereas in emergency conditions, it activates safety systems and several devices which are called CLASSE IE to ensure a safe and successful shutdown of the reactor if necessary.

If or when a reactor is shutdown, the residual heat generated from the decay of the fission products must be removed from the core to prevent the melting of fuel rod claddings, which in turn, ultimately avoids the release of radioactive materials into the atmosphere. However, when SBO takes place, the reactor coolant pumps (RCPs) are shutdown as a result, and that makes the core temperature rise, which leads to a severe accident in the reactor. Table 1 shows the sequence of successive failures leading to the accident of that scale. These sequences are based on the FSAR document [5].

Table 1: Sequence of successive failures. [5]

Failure	**Description**
Loss of External Power Supply	Failures in power transmission lines of 500 kV and 138 kV.
Internal Power Supply failure	Although subdivided into four redundant, partial and independent buses, loss of 50% of its supply capacity is considered as a system failure.
Reactor Coolant System failure	Without residual heat removal (RHR) the fuel rod temperature increases abruptly causing the core melting.
Chimney Cooling System failure	The spray system for the heat removal from inside the containment failures leading to the containment pressure increase.

Also, once the fuel elements begin to melt, hydrogen is produced by the chemical reaction of steam with Zircaloy, which is the material the fuel rod cladding is made of. Hydrogen gas so generated would become ignited if allowed to increase to flammable concentration and thus causing serious damage to the containment structures and equipment. To avoid such occurrence, devices such as Passive Autocatalytic Recombiner (PAR) are placed inside the containment to lower the concentration of hydrogen, due to the fact that PARs combine it with oxygen turning them into water. In Angra 2 there are 60 PARs distributed all over the containment for such purpose.

Furthermore, the chimney venting system may possibly release radioactive material to the atmosphere out of control, becoming dependent only on the butterfly type isolation valves of the containment purge system, which open by pressure difference between the valves after reaching a containment pressure of 6.2 bar. It is assumed that the time needed to release all radioactive material from inside the containment is 72 hours and the valves open hourly. Another assumption is that the radionuclides pass through a filtration system before they are released to the atmosphere. The filters used for Iodine and particulates such as Cesium are made of activated carbon and high-efficiency particulate absorber (HEPA), respectively, and the design retention factor of both filter is 99.99% for the respective type of radionuclides. All the noble gases may escape the containment since both filters are unable to retain them.

2.2. Source Term

Source term stands for the radioactive inventory located in a system, equipment or component and it serves as a reference for the safety aspects assessment under different operation conditions of the reactor under discussion. It also represents one of the most important design bases for analysis of the performance of the facility, distribution of fission products in reactor systems and, in case of accidents, in the environment.

The source term used in present work is obtained by means of proportionality between Angra 1 and Angra 2. That is, the source term of Angra 2 is calculated based on its activity estimated from numbers of fuel pellets of both power plants and the already known activity of Angra 1 [6]. This calculation resulted in total activity of Angra 2 equivalent to 146.18% of activity of Angra 1. Table 2 shows the radionuclides in Angra 2 and the respective activities which exceeds those of Angra 1 by 46.18%.

Table 2: Source term[1] and the radionuclides. [6]

Radionuclides	Activity per pellet (Bq)
I-131	1.09E+18
CS-137	1.43E+17
Kr-85m	8.64E+17
Xe-131m	7.47E+15
Xe-133m	1.31E+17

2.3. Meteorological Aspects of the Region

Meteorological conditions of the region under discussion are quite complicate, mainly due to the peculiar geomorphological features which result in climatological diversity across the entire region. Analyses of the main factors affecting the local meteorological conditions (e.g., the prevailing wind directions, atmospheric intensities and stability, etc.) are fundamental for the definition of scenarios for the application of specific models, especially with regard to the pollutants dispersion.

Moreover, Oliveira Júnior [7] points out there are clear indications of the sea breeze interacting with the local mountain range so that it recirculates inside the region. In addition, other factors such as the region's nearness to the ocean, topographical features and intense insolation render the local wind framework weaker and more unstable. Figure 1 shows the intensity and direction of the local wind field obtained from the data gathered by four meteorological towers in the region. The wind intensity varies from 0.5 m/s to 8.8 m/s.

[1] Assuming that reactor have been operating at full power since the beginning of the fuel cycle for six effective days of fuel burnup.

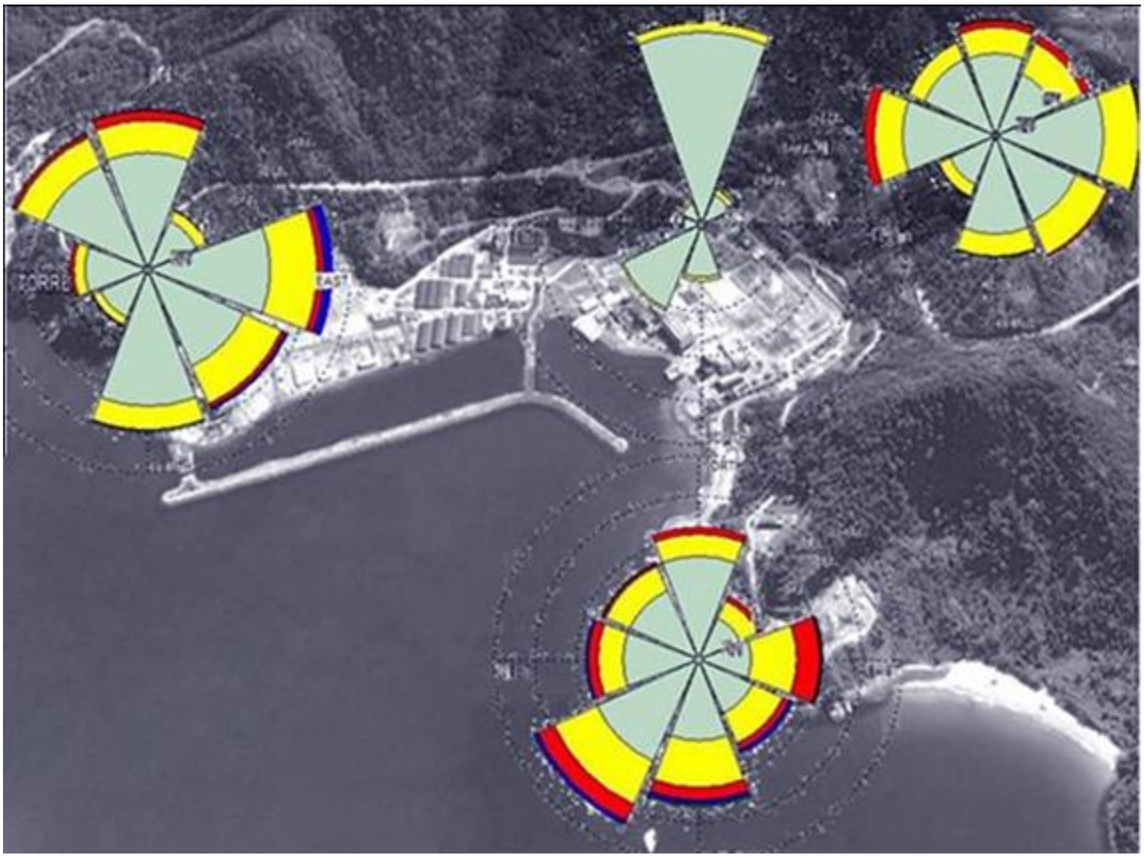

Figure 1: Intensity and direction of the wind field in Angra dos Reis region

The simulation of the wind field in Angra dos Reis region during the entire month of January 2009 is available at the following link: https://www.youtube.com/watch?v=lLgcjxWT41U.

2.4. Atmospheric Model – WRF/CALMET

Weather Research and Forecasting, WRF, is a numerical modelling system designed for weather forecasting and the atmospheric phenomena study on a micro and meso scale. This system is developed as a result of collaboration of research centers and U.S. government agencies: National Center for Atmospheric Research (NCAR), National Centers for Environmental Prediction (NCEP), National Oceanic and Atmospheric Administration (NOAA), US Department of Defense, Oklahoma University and Federal Aviation Administration (FAA).

Moreover, California Meteorological Model, CALMET, is a three-dimensional meteorological model integrated with an air quality dispersion model (CALPUFF) and a postprocessing package (CALPOST) which allows the calculation of the time-average concentrations and deposition fluxes predicted by other models [8]. CALMET is a diagnostic model which incorporates meteorological observations and/or outputs of some forecast models in order to yield variables needed for simulation on the dispersion model above, such as velocity fields and temperature, using techniques of objective analysis. In general, meteorological and geophysical data are previously processed by means of some preprocessors to render them compatible with the model.

2.5. Dispersion Model – CALPUFF

The modelling of atmospheric dispersion allows estimating the concentration of pollutants in a given set of points using influencing variables. It is useful not only for identification of emission sources, but also for management of gaseous effluents and air quality in so much that many regulatory entities utilize it as an important tool for assessing air quality for environmental legislation.

California Puff [8], CALPUFF, is a non-steady-state puff model developed to simulate the dispersion of pollutants and widely employed in study of air quality modelling. The model has been adopted by the U.S. Environmental Protection Agency (EPA) as the regulatory model for environmental impact analysis across the region covering from 50 to 300 km with complex topography and meteorological systems. The CALPUFF software is entirely open for public use and can be utilized to simulate the release of pollutants into the atmosphere so as to forecast the effects of accidents in a facility, which in turn allows planning effective emergency managements.

2.6. Coupling - WRF/CALMET

The configuration of the WRF model, as well as its domains, spatial resolution and grid nesting are set so as to obtain meteorological data required for the CALMET model INPUT file. The initial and boundary conditions for WRF are derived from Global Forecasting System Model (GFS) of the National Centers of Environmental Prediction (NCEP) whose spatial and temporal resolutions are 0.5º (i.e., about 55 km) and 3 hours, respectively. Also, both the horizontal and vertical definitions of the domain in GFS are made up using a model of data interpolation along with estimates provided by satellites. A detailed explanation about this model is provided by Kalnay et al. [9] and the GFS data is freely available at the following link: https://www.ncdc.noaa.gov/data-access/model-data/model-datasets.

It is worth noting that the data used for WTF simulation are those of January, 2009 because they are the last data obtained by four meteorological towers of Electronuclear. In addition, the domain of the grid used in CALMET has a range of 80 km with its center in CNAAA and 229 x 229 cells. Specifically, within the influence area of CNAAA with a radius of 5 km, the data related to wind field provided by those four towers are used for CALMET calculation.

2.7. Whole Body Dose Calculation

Whole body dose is the sum of the contribution of both the internal dose (by inhalation or ingestion) and external dose (plume immersion) [10]. The basis for the calculation of the exposure pathways, as well as respiration rate, is extracted from IAEA-TecDoc-1162 document [11]. Dose coefficient of each radionuclide for adult individuals is obtained based on the Regulatory Position (Posição Regulatória) which is recommended in CNEN 3.01/011:2011 Standard [12].

3. RESULTS AND DISCUSSION

3.1. CALPUFF Transport Model

The simulations on CALPUFF code were carried out assuming an emission point source representing the chimney of the Angra 2 NPP, which in turn, was considered to be 155m tall. The emission rate is a function of the radionuclides' total activity, see Table 2, and its total release time, 72 hours, i.e., 259200 seconds. Table 3 enumerates the release rate of each radionuclide taking into account the presence of the containment filtering system in the plant.

Table 3: Release rates of the radionuclides to the atmosphere

Radionuclides	Release rate (Bq/s)
I-131	2.18E+12
CS-137	2.85E+11
Kr-85m	1.73E+16
Xe-131m	1.49E+14
Xe-133m	2.63E+15

The simulation was initiated on 5 January 2009, at 6:00 AM and it was conducted during 72 hours. For this, it was assumed that the movement of all the radionuclides in Table 3, once in the atmosphere, is strictly in accordance with the wind field of the region of analysis during the whole simulation time. Concentrations of the radionuclides at 1 and 72 hours from the moment of the release were taken into account. Figure 2 shows both the wind field of the region and the radionuclides transport.

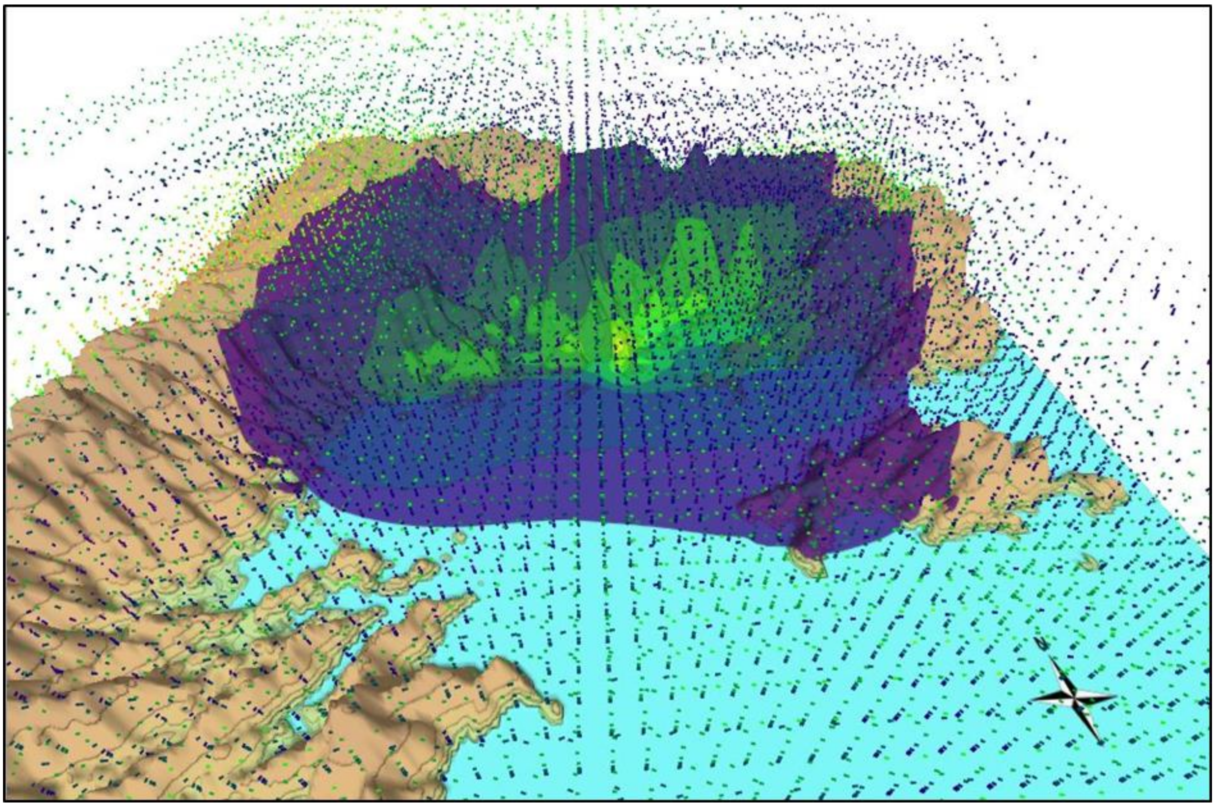

Figure 2: Concentration of the radionuclides and the wind field around Angra 2 NPP

An illustration of the simulated plume dispersion in the atmosphere of Angra dos Reis is available at the following link: https://www.youtube.com/watch?v=uws8etaIcE8.

The analysis of radionuclide concentration is made at specific areas carefully selected regarding the respective population. The selected areas and their distances to the Angra 2 NPP are listed in Table 4.

Table 4: Relevant areas for the radionuclides concentration and dose analyses

Area	Distance to Angra 2
The Eletronuclear Plant Property	1 km
Praia Brava	2 km
Região do Frade	5 km
Mambucaba	8 km
Angra dos Reis (downtown)	15 km
Ilha Grande	25 km
Paraty	35 km

The concentrations of the radionuclides in each area in the table above are shown in Table 5. These concentrations were used as the basis for whole body dose calculation at 1 and 72 hours from the moment of release in the respective areas. In these calculations the plume exposure was considered to be 100%, namely, the public individuals were assumed not to be provided with any mean of radiation protection.

Table 5: Whole body doses calculated on the basis of the radionuclides concentrations in the analyzed areas at 1h and 72h

AREA	Time (h)	RADIONUCLIDES CONCENTRATION (Bq/m^3) I-131	CS-137	Kr-85m	Xe-131m	Xe-133m	WHOLE BODY DOSE(mSv)
Eletronuclear Plant Property	1	1.66E+05	2.17E+04	1.61E+09	1.39E+07	2.45E+08	4.30E+01
	72	8.11E+03	1.06E+03	9.85E+07	8.48E+05	1.50E+07	1.87E+02
Praia Brava	1	8.82E+05	1.15E+05	7.61E+09	6.55E+07	1.16E+09	2.04E+02
	72	2.58E+04	3.38E+03	2.61E+08	2.24E+06	3.96E+07	1.87E+02
Região do Frade	1	6.18E+04	8.08E+03	7.81E+08	6.72E+06	1.19E+08	2.06E+01
	72	2.85E+03	3.73E+02	4.23E+07	3.65E+05	6.44E+06	7.99E+01
Mambucaba	1	1.24E+05	1.62E+04	1.20E+09	1.03E+07	1.82E+08	3.19E+01
	72	1.20E+04	1.57E+03	1.49E+08	1.29E+06	2.27E+07	2.83E+02
Angra dos Reis (downtown)	1	5.78E+04	7.55E+03	7.68E+08	6.62E+06	1.17E+08	2.02E+01
	72	2.33E+03	3.05E+02	3.66E+07	3.16E+05	5.57E+06	6.91E+01
Ilha Grande	1	8.38E+04	1.10E+04	8.04E+08	6.92E+06	1.22E+08	2.14E+01
	72	3.17E+03	4.15E+02	3.60E+07	3.10E+05	5.47E+06	6.86E+01
Paraty	1	8.85E+03	1.16E+03	8.95E+07	7.71E+05	1.36E+07	2.38E+00
	72	9.42E+02	1.23E+02	1.66E+07	1.43E+05	2.52E+06	3.11E+01

On the other hand, according to the External Emergency Plan of the State of Rio de Janeiro (PEE/RJ) [13], the preventive evacuation of the population establishes an effective protection measure up to the range of 5 km from the plant. From this distance on, no additional benefit is expected from the evacuation. Thus, the Emergency Planning Zones (EPZs) are ranked as follows:

- Preventive Action Zone:

EPZ-3: A restricted area around the site 3 km in radius with its origin at the NPP of CNAAA excepting the Electronuclear plant property.

EPZ-5: Also defined as impact area, it is a ring-shaped area with the same origin as EPZ-3 and its inner and outer radii are 3 and 5 km respectively.

- Environmental Control Zone:

The following two zones are also ring-shaped area with origin at the NPP of CNAAA as the preventive action zones above and range in radius:

EPZ-10: from 5 to 10 km

EPZ-15: from 10 to 15 km.

According to the study conducted at CNEN [14], the protective measures for CNAAA can be divided as follows:

- Local Area Emergency: The public in EPZ-3 and EPZ-5 are notified of event and instructed to remain at home or work awaiting further instructions, while the population in EPZ-10 and EPZ-15 are asked only to remain alert and continue their normal activities.

- General Emergency: The public is evacuated in EPZ-3, sheltered in EPZ-5, while in EPZ-10 and EPZ-15 it is instructed only to remain at home or work awaiting further instructions.

The Regulatory Position CNEN 3.01/006:2011 [15] establishes dose levels for the public sheltering and for its evacuation as 10 mSv and 50 mSv respectively, according to which the proper protective measures must be determined for each area listed above in Table 4. The recommended measures thus determined are shown in Table 6, from which it can be inferred that evacuation is the measure that best meets to the dose levels established by the Regulatory Position.

Additionally, since the scenario the present work deals with is one of severe accidents, which are classified as General Emergency, the proper measure the local authorities must take is the public evacuation in every area in Table 4 except the region of Paraty, where the population could be only sheltered, at least during the first few hours.

Table 6: The recommended protective measures for the relevant areas

AREA	Exposure time 1h	Exposure time 72h
Eletronuclear Plant Property	evacuation	evacuation
Praia Brava	evacuation	evacuation
Região do Frade	evacuation	evacuation
Mambucaba	evacuation	evacuation
Angra dos Reis (downtown)	evacuation	evacuation
Ilha Grande	evacuation	evacuation
Paraty	sheltering	evacuation

4. CONCLUSION

Based on the results obtained from the simulation, it can be asserted that: (1) For the chosen period of time, a great displacement of wind field toward the West is observed, so that the most affected areas are Praia Brava and Mambucaba; (2) In fact, occurrence of a severe accident means a general emergency taking place; (3) Unlike the External Emergency Plan of the NPP, the radius of the impact area (i.e., EPZ-5) presented in this study surpasses 5 km; (4) The most proper protective measure in severe accident scenarios for the relevant areas is the public evacuation, except only the region of Paraty, where the population sheltering could be taken as an alternative measure during the first few hours; and (5) The faster the mitigation of the accident, the lesser are its radiological consequences and hence the lighter protective measures will be needed.

Furthermore, with respect to the impact area, the former three severe accidents in history show that it has been much wider than that which is currently adopted by the local authority for CNAAA. Actually, the evacuations ordered by each government due to the severe accidents in Chernobyl, Three Mile Island and Fukushima were to the publics within the range of 10 km, 16 km and 30 km respectively. The authority of the former U.S.S.R, specifically, has gone as far as to extend the initial range after a while, form 10 km to 30 km. On the basis of these facts, therefore, a claim may be made against the current impact area for CNAAA which had been established contemplating only design-basis-accidents. The reason is that the prospective studies considering the beyond-the-design-basis-accidents, which deserve to be taken seriously, are very likely to draw a conclusion which would lead to an adjustment of the definition of impact area.

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