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Radiological impact of ^{137}Cs plume dispersion from a Nuclear Power Plant decommissioning release considering atmospheric stability and surface roughness effects

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1. Introduction

The term "decommissioning" refers to the administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility[1] (except for the part of a disposal facility in which the radioactive waste is emplaced, for which the term "closure" instead of "decommissioning" is used).[2] It is a complex process involving operations such as detailed surveys, decontamination and dismantling of plant, equipment and facilities, demolition of buildings and structures, site remediation, and the management of resulting waste and other materials.[3]

As part of an installation's initial authorization, a decommissioning plan is developed that demonstrates the feasibility of decommissioning, including activities such as planning for decommissioning, physical and radiological characterization, facility and site decontamination, dismantling, and materials management.[4] There may be a period of transition between permanent shutdown[2] and the granting of authorization to begin decommissioning actions.

Within the back-end of the nuclear fuel cycle, radioactive waste storage facilities, treatment and conditioning units, spent fuel pools and nuclear power plants undergoing shutdown present specific challenges due to the high specific activity of the materials handled and the long half-lives of radionuclides such as ^{239}Pu (24,100 years) and ^{137}Cs (30.2 years), activated materials, contaminated structures and large volumes of secondary radioactive waste.[5]

Reactor operation and maintenance generates a range of waste from VLLW to HLW, mostly waste with activation products created by the neutron bombardment of reactor materials (such as ^{60}Co, ^{59}Ni, ^{63}Ni, and others). However, owing to some fuel leakage or owing to fissions occurring outside the fuel, this waste can also contain fission products and alpha emitters. The radioactivity circulates in the primary and secondary cooling systems as well as the spent fuel storage pools, and most of it is captured by the cleanup circuits servicing these systems (such as filters or ion exchange systems).[5]

The IAEA highlights that decommissioning planning shall incorporate the principles of radiation protection, waste minimization, radiological traceability, safe management of contaminated materials and implementation of the ALARA principle (As Low As Reasonably Achievable).

This study aims to evaluate the influence of atmospheric stability conditions and surface roughness on the atmospheric dispersion, ground deposition, and radiological impact of ^{137}Cs released during a hypothetical nuclear power plant decommissioning scenario. The study further seeks to analyze, through the Gaussian mathematical model, how different meteorological conditions affect plume depletion, ground contamination, and the TED (Total Effective Dose) to potentially exposed individuals.

2. Methodology

Scenario: During cutting of primary system piping[7] using oxyacetylene torches or plasma cutting[8,9] in a decommissioning plant, degradation or partial failure of ventilation and exhaust systems with HEPA filters occurs.[7] The negative pressure in the work area is compromised, allowing localized dispersion of particles containing radionuclides such as ^{60}Co (half-life: 5.27 years), ^{55}Fe (half-life: 2.7 years), and ^{63}Ni (half-life: 100 years) and others, which were neutron-activated or deposited on surfaces during plant operation.

The ^{137}Cs was selected as the principal radionuclide for this dispersion analysis due to its high radiological relevance[10,11] in nuclear facilities, relatively long half-life, significant gamma emission, and frequent association with contamination events involving activated systems, spent fuel management, and decommissioning activities. In addition, cesium presents high environmental mobility when dispersed as particulate material, making it a representative radionuclide for evaluating potential radiological impacts associated with accidental aerosol release scenarios during dismantling and cutting operations.[10]

The dispersed activity of ^{137}Cs was discussed and estimated through consultations held in May 2026 with professionals specialized in nuclear decommissioning from IPEN and UFRJ. The assessment was further supported by analyses of IAEA technical reports, published incident reports, and electronic academic literature, including dissertations[6] and theses[12] related to radiological protection, radioactive aerosol dispersion, and nuclear decommissioning activities.

The Gaussian equation was used to calculate the deposition, dose rate and TED throught HotSpot Health Physics Code[13], Where, C is time-integrated atmospheric concentration (Ci sec)/(m3), x is downwind distance (m), y is crosswind distance (m), z is vertical axis distance (m), H is effective release height (m), Q is cource term (Ci), σ_y is standard deviation of the integrated concentration distribution in the crosswind direction (m), σ_z is standard deviation of the integrated concentration distribution in the vertical direction (m), u is average windspeed at the effective release height (H), (m/s), λ is radioactive decay constant (s^{-1}).

$$C(x,y,z,H) = \frac{Q}{2\pi\sigma_Y \sigma_Z u} exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_Y}\right)^2\right]\left\{exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_Z}\right)^2\right] + exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_Z}\right)^2\right]\right\} exp\left[-\frac{\lambda x}{u}\right] \quad (1)$$

3. Results and Discussion

The figures below show the behavior of the radioactive plume, composed of ^{137}Cs, under different atmospheric stability scenarios. Furthermore, they show how wind speed, associated with surface roughness coefficients (Z_0) and different distances, influence the deposition of the radionuclide in the soil, as well as the radiation emitted by ^{137}Cs resulting from the deposition and dispersion of the plume in the air.

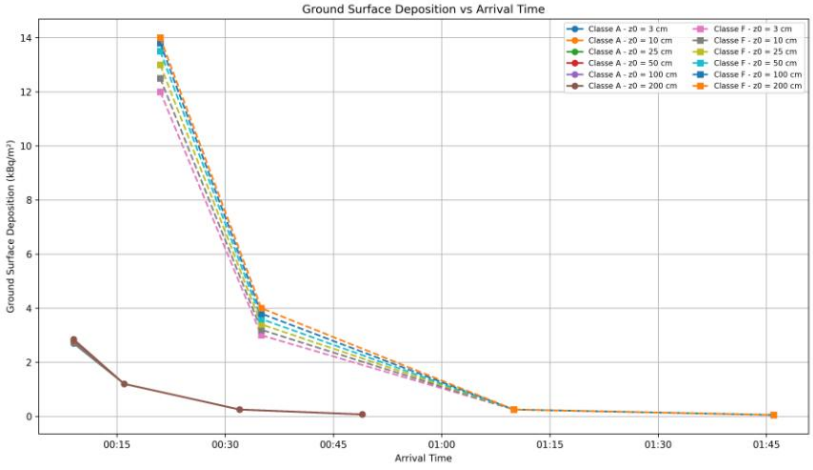


Figure 1: ^{137}Cs Ground surface deposition

Figure 1 shows the influence of Classes A and F on the deposition of ^{137}Cs in the soil. Class A, characterized by atmospheric instability, strong winds, and intense turbulence, is responsible for causing strong vertical dispersion of the plume. As a consequence, a reduction in the concentration of the radionuclide on the soil surface is observed along the plume's movement, making the influence of the soil roughness coefficient less significant and thus justifying the observed exponential trend.

Class F represents a very stable atmosphere, typically associated with low turbulence, weak winds, and a higher concentration of the plume near the ground, resulting in greater deposition of ^{137}Cs compared to Class A. The importance of ground roughness is noted in this scenario, as deposition increases proportionally to Z_0. This occurs because a rougher surface intensifies mechanical turbulence near the ground, facilitating the transfer and deposition of particles.

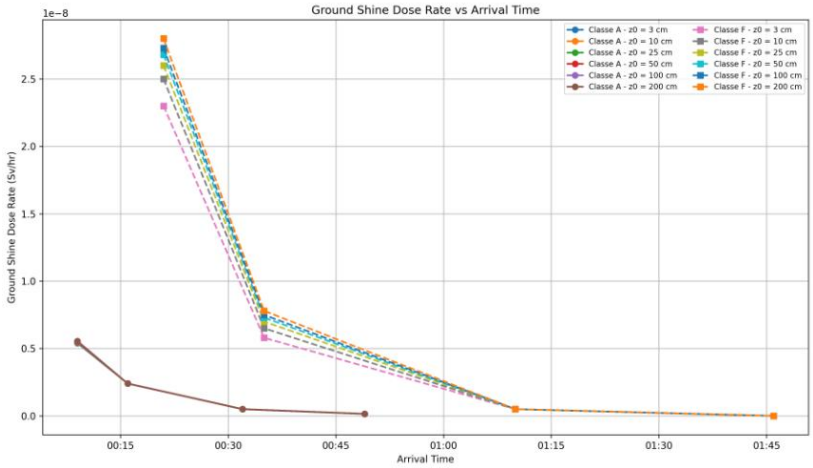


Figure 2: ^{137}Cs Ground shine dose rate

Figure 2 represents the dose rate from the ground after the plume passed. The results show strong temporal decay. The exponential behavior follows the ^{137}Cs deposition observed in figure 1, demonstrating that the dose rate from the ground depends directly on the amount of radioactive material deposited in the soil.

Under stable conditions, the dose rate is observed to be 4 to 5 times higher when compared to Class A. This behavior confirms that stable scenarios favor greater plume depletion, and consequently a higher dose rate originating from the soil.

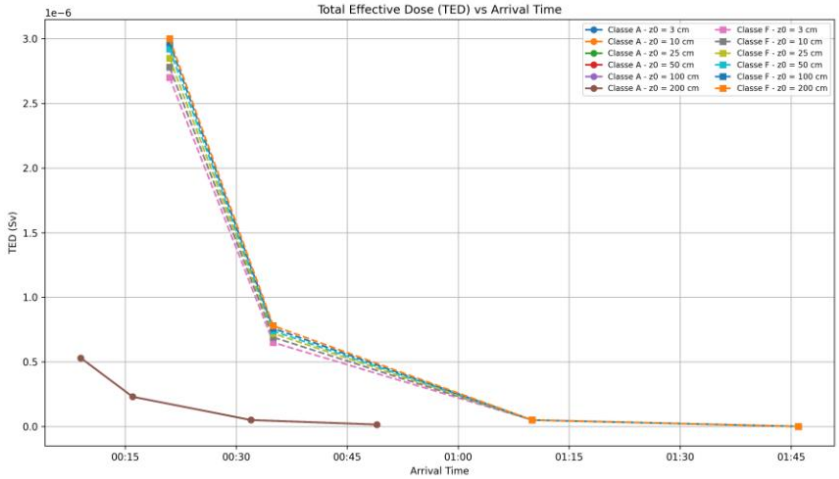


Figure 3: ^{137}Cs Total Effective Dose (TED)

Figure 3 shows the TED characterized by the total effective dose received by the potentially exposed individual, integrating the radiological effects associated with the dispersion of the plume in the air and its interaction with the ground.

In a scenario of atmospheric instability, the calculated TED is relatively low due to the fast dispersion of the plume in the air and, for this reason, a lower concentration of ^{137}Cs was observed in the soil. Conversely, Class F favors the depletion of the plume in the soil and, consequently, higher levels of

radiological exposure from the surface. For this reason, the results are approximately 5 to 6 times higher when compared to Class A.

4. Conclusions

In general, the results demonstrate that atmospheric stability exerts a decisive influence on the dispersion of the radioactive plume, on the deposition of ^{137}Cs in the soil and, consequently, on the levels of radiological exposure. Under conditions of atmospheric instability, intense turbulence and stronger winds promote greater vertical dispersion of the plume, significantly reducing the concentration of the radionuclide near the surface and limiting its deposition in the soil. As a consequence, lower dose rates from the soil and lower TED values are observed.

On the other hand, under very stable atmospheric conditions, characterized by low turbulence and weak winds, the plume remains more concentrated near the ground, favoring the deposition of ^{137}Cs along its path. In this scenario, the Z_0 becomes a relevant parameter, since rougher surfaces intensify mechanical turbulence near the ground and increase the transfer of particles to the surface. This behavior results in higher levels of surface contamination, significantly increasing dose rates from the soil and the TED.

The results obtained also indicate a direct relationship between radionuclide deposition and the observed radiological response, showing that an increase in the concentration of ^{137}Cs deposited in the soil implies higher levels of radiological exposure to the potentially exposed individual. Therefore, it is concluded that stable atmospheric scenarios represent more critical conditions from a radiological point of view, potentially producing dose rates approximately 4 to 6 times higher than those observed in unstable scenarios.

Therefore, the results reinforce the importance of jointly considering meteorological conditions, surface roughness, and atmospheric dispersion dynamics in radiological risk assessment studies, since these parameters directly influence the behavior of the radioactive plume, the deposition of contaminant material, and the associated exposure levels.

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