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ORIGINAL RESEARCH ARTICLE

A Simulated Accidental Release and Dispersion of Gaseous Fission Products from NIRR-1: Implications for Emergency Response Planning

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ABSTRACT
For over seven decades, research reactors have contributed significantly to the global economy, with uses in various fields such as food production, health and environment, industries, research and development, and education and training. The Nigerian Research Reactor-1 (NIRR-1) is vital in neutron activation analysis (NAA) and radioisotope production for education and training. The current NIRR-1 core uses Low Enriched Uranium (LEU) fuel, converted from Highly Enriched Uranium (HEU) fuel. The LEU core achieved its first criticality in December 2018 and has been safely operating at full and half power. This study uses the Hot Spot computer code to examine the dispersion of radionuclides accidentally released from the NIRR-1 LEU core during the final stage of its lifetime. Site-specific meteorological conditions were used to analyze the behavior and movement of selected gaseous radionuclides in the atmosphere. The total maximum respirable time-integrated concentrations of the released gaseous radionuclides in air were estimated at varying distances from the exposed reactor core, and the values obtained were $6.10E+05\ Bq/L$, $5.32E+04\ Bq/L$, $3.47E+03\ Bq/L$, and $3.31E+03\ Bq/L$ at 10 m, 100 m, 300 m, and 1 km, respectively. These results highlight a possible risk within 300 m perimeter downwind for unclassified personnel, which is therefore crucial in developing comprehensive emergency preparedness and response plans.

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INTRODUCTION

In the mid-20th century, the world witnessed unprecedented attention on nuclear technology following the first nuclear reactor to achieve criticality at the Chicago University, Chicago Pile-1 (WNA, 2024). Since then, research reactors (RRs) have been pivotal in sustainable innovations and productivity, placing nuclear science and technology at the front burner in global economic development (IAEA, 2016). The multidisciplinary applicability of RRs supports developments in nuclear power, radioisotope production and nuclear medicine, neutron beam research and applications, materials characterization and testing, computer code validation, various elemental analyses, and capacity building for nuclear science and technology programs (IAEA, 2016). Based on the International Atomic Energy Agency's (IAEA) research reactor database, there are 843 RRs in 70 countries, out of which 227 are operational in 54 countries and 22 are under construction or planned construction in 16 countries, 77 have been given an extended operation in 29 countries while 519 are under decommissioning or decommissioned in 37 countries (IAEA, 2024). It is obvious that more than half of the world's research reactors are either decommissioned already or are being decommissioned. Therefore, much attention is now shifted toward decommissioning exercises for research reactors, taking note of lessons learned to improve the process and better plans toward decommissioning both those under construction and those under extended operation and those operational.

The Nigeria Research Reactor-1 (NIRR-1) is one of the operational research reactors in the world. NIRR-1 belongs to the category of Miniature Neutron Source Reactors (MNSRs), which are low-power research reactors designed and produced by the China Institute of Atomic Energy (CIAE) in Beijing. MNSRs use highly enriched uranium fuel (HEU) in sealed cores to ensure ample neutron flux for neutron activation analysis, training, and nuclear instrumentation tests (Simon *et al.,* 2023). However, due to proliferation concerns, efforts are being deployed to convert the reactor cores to low-enriched uranium (IAEA, 2018). NIRR-1 has been

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successfully converted to LEU and is operating optimally at full power of 34 kW and half power of 17 kW. The conversion process involved the dismantling, packaging, and repatriating of the sealed HEU core to the country of origin (China). This process allowed Nigeria to gain some experiences in various activities that involved decommissioning small nuclear facilities.

While the experience gained from the decommissioning of the HEU core is invaluable, adequate preparation for the decommissioning of the present LEU core and its associated components is imperative, in view of the fact that the uranium loading in the present LEU core is greater than that of the decommissioned HEU core (FSAR, 2019) and that the LEU core is most likely to be decommissioned with several other auxiliary components of the facility since its lifetime is estimated to be more than 50 years (Simon *et al.*, 2021), and decommissioning is known to involve a chain of several activities which includes dismantling, cutting, discharging, packaging etc. Therefore, to achieve a comprehensive preparation for the decommissioning of the NIRR-1, emergency preparedness is key, and hence, possible scenarios that could lead to an emergency during decommissioning activities need to be studied and the associated radiological impacts assessed. Although Simon et al. (2022) carried out the radiological consequence analysis associated with gaseous radionuclides' release from NIRR-1 with a simulation of various release scenarios, the study was limited to dose calculations from inhalation and external irradiation following resuspension of the released radionuclides. The air quality assessment compared with the Annual Limits on Intake (ALI) of each of the released gaseous radionuclide was not performed and the emergency preparedness needs concerning the concentrations of the fission products in the air were also not highlighted. Against this backdrop, the release of some gaseous fission product of higher radiological concern from the NIRR-1 LEU core was modelled in this work, assuming a hypothetical release scenario at the end of the reactor life.

DESCRIPTION OF NIRR-1.

NIRR-1 is a tank in pool type of light water research reactor situated at the Centre for Energy Research and Training (CERT), Ahmadu Bello University, Zaria, Nigeria. The reactor comprises a compact sealed core with 335 active fuel pins of enrichment of 13%. The fuel pins are distributed in concentric rings, ensuring an approximately uniform radial neutron flux distribution at the irradiation sites. The reactor's clean core cold excess reactivity is $3.94\ mk$ measured during the on-site zero-power and criticality experiment (FSAR, 2019). The reactor core is located $4.7\ m$ underwater, close to the bottom of the light water reactor vessel, whose quantity of water is $1.5\ m^3$ and is, in turn immersed in a water-filled pool with a volume of $30.0\ m^3$. The reactor's core is surrounded by 10 irradiation channels, with 5 inside and 5 outside the annular beryllium reflector, as shown in Figure 1 and Figure 2. The detailed description of NIRR-1 is found elsewhere, (Simon *et al.*, 2021).

MODELLING APPROACH

The inventory of NIRR-1 LEU core has been derived using SCALE 6.2.3 computer code, and the source term was evaluated using the IAEA computed transfer factors for a typical UO2 fuel with Zircaloy cladding (Simon et al., 2022; IAEA, 2018). For conservative analysis, a scenario was developed so that there would be a 100% release of the source term for gaseous fission products into the atmosphere. It was assumed that the reactor had operated continuously at a power of 231.931MWD/MTU for 918 Full Power Effective Days (FPED) and had attained its end-of-life time. During the period between permanent shutdown and onset of decommissioning activities, where more radionuclides are expected to have accumulated in the core due to decay and transmutations, a coordinated terrorist attack on the reactor facility was carried out, leading to the 100% release of the inventory, of the gaseous nuclides. For details of the source term derivation and chain of events that could lead to the credibility of this scenario, the reader is referred to Simon *et al.* (2022). Hot Spot computer code was used to calculate the time-integrated concentrations of the released gaseous radionuclides in air at varying distances from the exposed reactor core. The Hot-Spot Health Physics Code provides a first-order approximation of the radiation effects associated with the atmospheric release of radioactive materials. The program solves the Gaussian dispersion model and was created to equip emergency response personnel and planners with a fast, field-portable set of software tools for evaluating incidents involving radioactive material (Homann, 2013).

The Gaussian dispersion model is one of the models used in several nuclear facilities to assess the radiological risk to workers, the public, and biological populations. The Gaussian plume distribution model used for radiological assessment is given by Equation 1 (Muswema *et al.*, 2015).

$$\frac{\chi(x,y,z,H)}{Q} = \frac{1}{2\pi\sigma_y\sigma_z U}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{Z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{Z+H}{\sigma_z}\right)^2\right]\right\} \quad (1)$$

where: χ is the concentration at location x, y, z $(Bq/m^3\ or\ g/m^3)$; Q is the radionuclide or toxic chemical emission rate (Bq, g); σ_y is the standard deviation of concentration in the horizontal direction (m); σ_z is the standard deviation of concretization in the vertical direction (m); U is the wind speed diluting the plume (m/s); x is the downwind distance in the direction of the mean wind (m) y is the distance in the horizontal plane perpendicular to the x-axis (m); Z is the height of the receptor (m); H is the effective release height of the plume centreline (m); $\chi/Q - value$ is the initial parameter for the estimation of radiological releases.

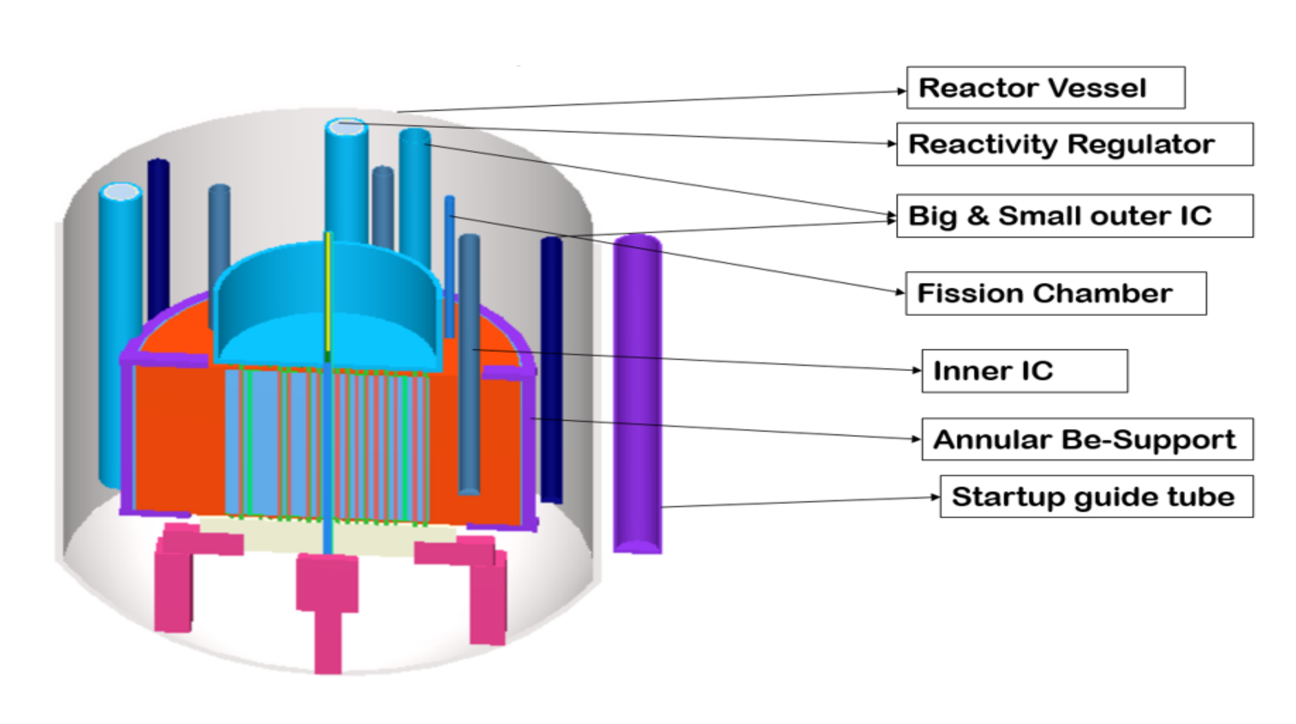

Figure 1: Vertical and Horizontal Cross Sections of 3D SCALE Model of NIRR-1 (Simon *et al.,* 2023).

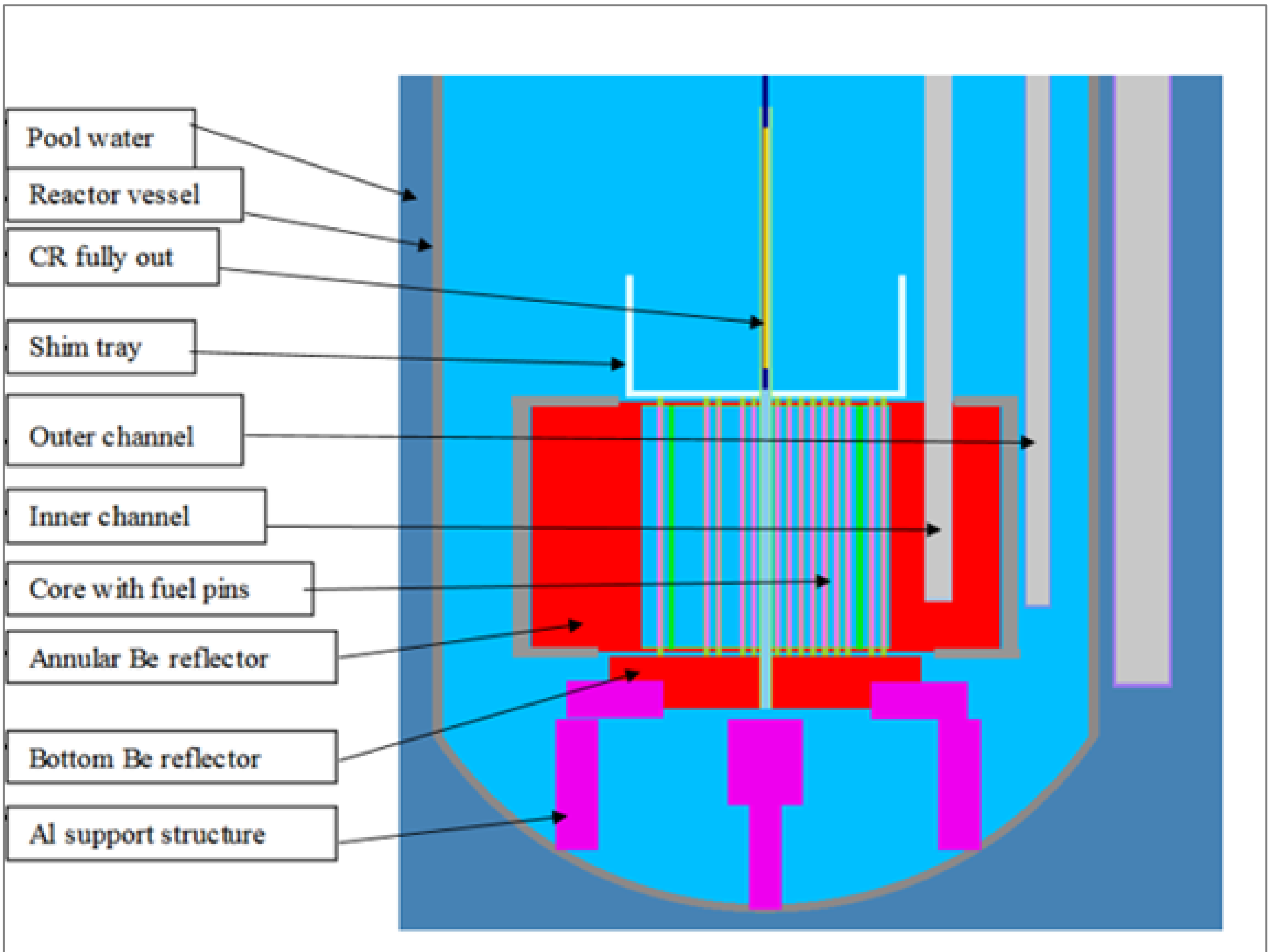

Figure 2: 2D SCALE Model of NIRR-1 (Simon *et al.,* 2023)

The Hot Spot program is designed for short-range (less than 10 km) and short-term (six hours) predictions and performs a conservative estimation of the radiation effects associated with the atmospheric release of radioactive materials (Homann, 2013). The primary user interface screen for Hot-Spot is shown in Figure 3. The input blocks are divided into five, starting with the type of plume model and ending with the input/output setup. At the plume model block, the option of general plume was chosen given the type of scenario used. In defining the source term at the source term input block, the concentration of each of the selected radionuclides was defined accordingly, while other parameters of this block were taken as default. In the Meteorology block, the wind speed and wind direction were defined as obtained from the NIRR-1 facility's meteorological station, and the atmospheric stability class was chosen as class A, which is the very unstable class that suites the assumptions of this study. Values of specified at the receptor block were taken as the default, while at the Setup block, the release time was defined as 60 minutes, and the radiological unit of sievert and dose conversion factors FGR 11 were selected. All other parameters at the setup block were left checked as default.

Hot Spot calculations were performed using the adopted source term and the site-specific meteorological data collected from the meteorological station at CERT. The data for wind speed, wind direction, relative humidity, and average maximum and minimum temperature available for a period of 10 years (2013 to 2023) were specifically collected. The average of the data over the entire period of 10 years was determined for the extreme Pasquill atmospheric stability class A to maintain the conservative nature of this assessment.

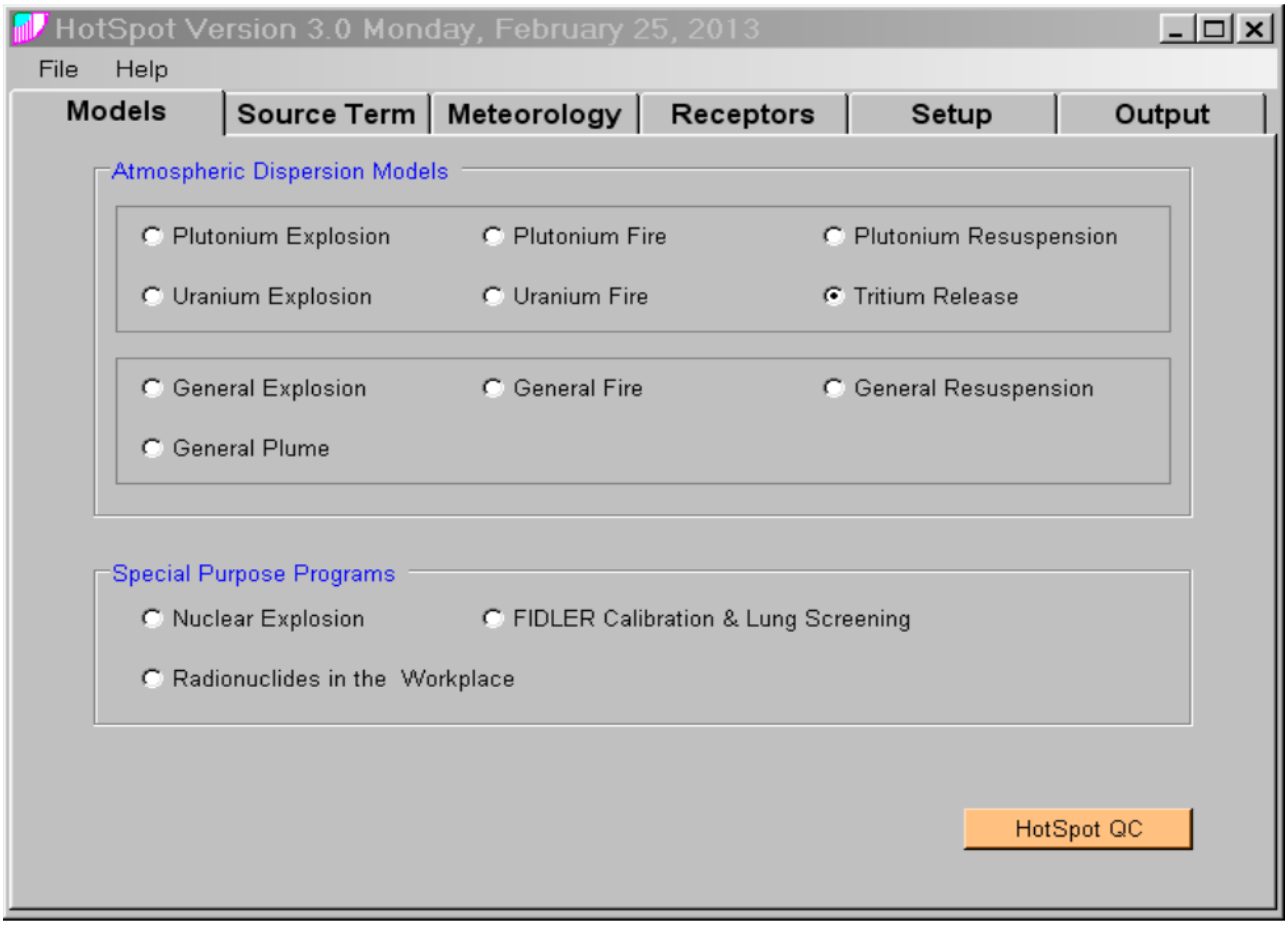

Figure 3: The User Interface for Hot-Spot Health Physics Code (Homann, 2013)

RESULTS AND DISCUSSION

The time-integrated concentrations of the released gaseous radionuclides in the air at varying distances from the exposed reactor core after an exposure period of 1 hour are given in Figures 4, 5, and 6, respectively.

The results presented in Figures 4, 5, and 6, respectively, are the concentrations of each of the selected gaseous fission products as determined by Hot Spot and their corresponding annual limit on intake stipulated by the United States Environmental Protection Agency (USEPA). While their concentrations at a distance less than 100 m from the exposed reactor core are higher than the referenced annual limit on intake, the concentrations begin to drop significantly at 300 m (where the facility muster point is located). At about 1km (where residential buildings are found), the concentrations of these radionuclides further drop to values lower than their annual limits on intake by one order of magnitude. From the results obtained, the total maximum respirable time-integrated concentrations of the released gaseous radionuclides in the air were estimated to be $6.10E+05\ Bq/L$, $5.32E+04\ Bq/L$, $3.47E+03\ Bq/L$, and $3.31E+03\ Bq/L$ at 10 m, 100 m, 300 m, and 1 km, respectively. This shows that minimal or no emergency is envisioned at locations offsite of CERT and a moderate plan onsite for evacuation of unclassified radiation workers within a 300 m perimeter in the event of a severe incident involving the reactor core during the decommissioning activities. The results further underscore the safety of NIRR-1 at its location and confirm that the public remains safe based on this medium of human health risk assessment. These results also support the findings of Simon *et al.* (2022). Moreover, observing that the concentrations of fission products in the air (the fastest contamination pathway) are significantly lower at distances of 1 km and beyond from the reactor core could easily be attributed to the fact that NIRR-1 is a very low-power reactor with a small initial core loading, resulting in a low core inventory and source term. Consequently, the safety of the population in the event of a severe accident at NIRR-1 highlights the significant improvements in the design safety of nuclear facilities, supporting their expanded use in civilian applications.

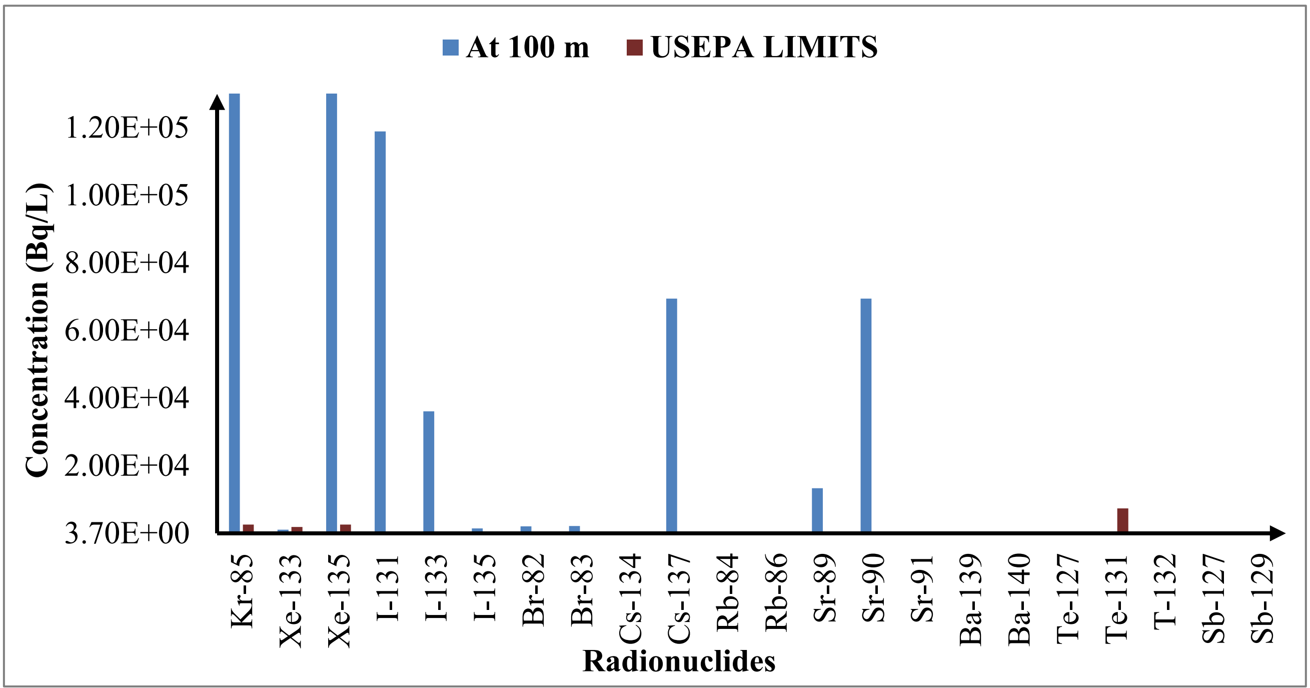

Figure 4: A comparison of Radionuclides' concentrations in Air and US EPA Limits at 100 m

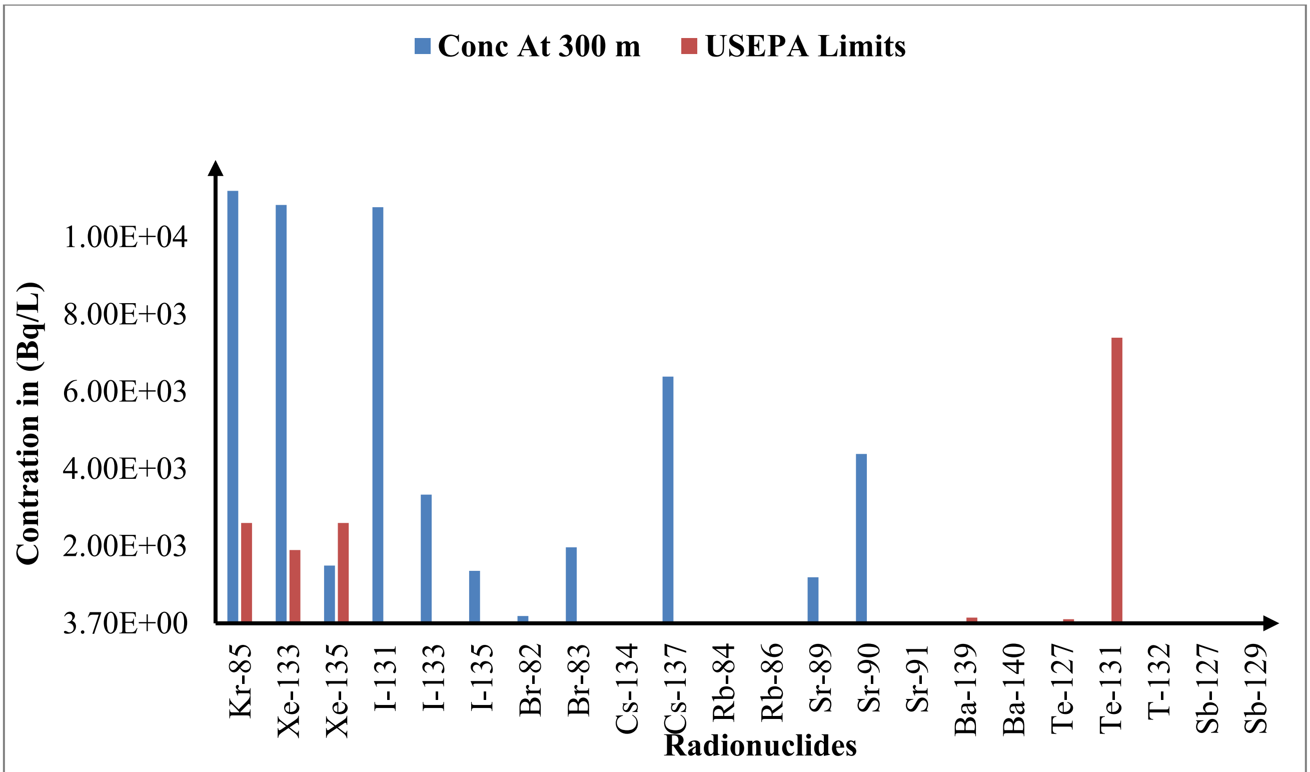

Figure 5: A comparison of Radionuclides' concentrations in Air and US EPA Limits at 300 m

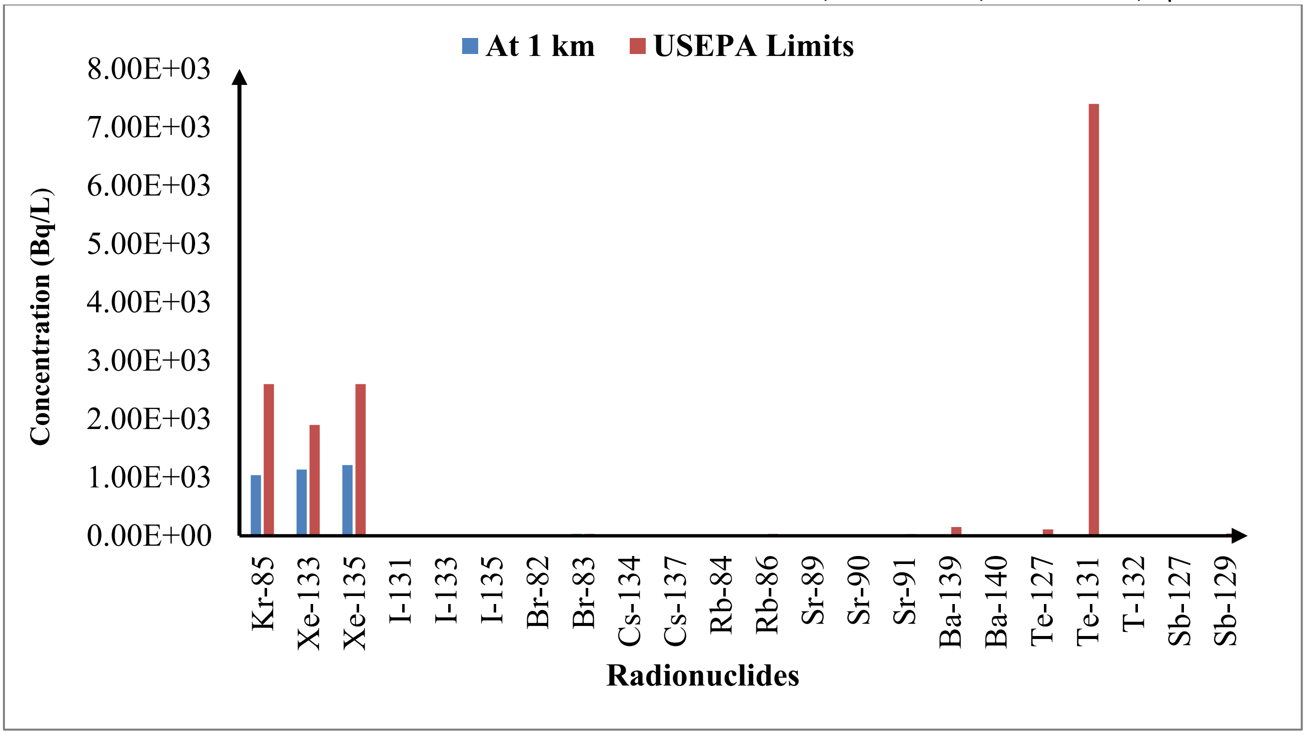

Figure 6: A comparison of Radionuclides' concentrations in Air and US EPA Limits at 1 km

CONCLUSION

The study utilized the Hot-Spot Heath Physics code to model the dispersion of gaseous fission products following a hypothetical accidental release from NIRR-1 during decommissioning activities. The results showed that the concentrations of the released gaseous fission products of concern were higher than their USEPA's annual public intake limits within a perimeter of 300 m from the exposed reactor core and well below the limits at distances of around 1km. This indicates a level of air contamination within the nuclear facility and highlights a necessity for emergency response planning to include evacuation of unclassified workers at CERT to a perimeter beyond 300 m from the reactor core during such incidents. Albeit, no offsite location requires any emergency evacuation even in a worst-case scenario of fission product release and underscores the safety of members of the public from the harmful effect of ionizing radiation emanating from NIRR-1.

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