Assessment of Lifetime Excess Cancer Risk in the Emergency Planning Zone of Koeberg Nuclear Power Station Following a Hypothetical Nuclear Accident

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1. Introduction

Koeberg Nuclear Power Station (KNPS) is made up of two pressurized water reactors (PWRs), referred to as Units 1 and 2. These reactors have been in operation since 1984 and 1985, respectively. The site is located in the Western Cape in South Africa, specifically in the City of Cape Town metropolitan municipality. It is positioned around 25 km north of Cape Town and bordered on the west by the Atlantic Ocean [1]. The priority when creating a nuclear facility is to safeguard both individuals and the environment against the detrimental impacts of ionizing radiation [2]. One of the fundamental safety principles underpinning this aim involves establishing proper measures and readiness for emergencies to guarantee a competent and efficient response in the event of a nuclear incident. Roughly, 140,000 individuals live within the immediate 16 km radius of the KNPS, which is referred to as the Urgent Protective Action Planning Zone (UPZ), however, Koeberg's Emergency Planning Zone (EPZ) also includes a radius from 16 km to 80 km from the reactors, known as the Long-term protective action Planning Zone (LPZ). Significant plans and resources have been dedicated by organizations like ESKOM and the City of Cape Town Disaster Risk Management Centre (CoCT DRMC) to prepare themselves for a potential widespread emergency situation. These preparations include the creation of evacuation simulations, coordinated disaster management strategies among local government bodies and emergency services, as well as safety and readiness guidelines for the public. These guidelines aim to educate and equip the public to minimize their vulnerability to potential radiation-related risk [3]. A study was conducted to evaluate the use of risk insights in developing emergency plans for the Koeberg nuclear plant. Reference accidents and their potential offsite consequences were assessed, focusing on public doses and ground contamination. The study used meteorological data to analyze wind patterns, indicating that prevailing winds mostly move towards the sea and away from major population areas. The study employed two computer codes (PC COSYMA and HOTSPOT) to assess offsite consequences, with results falling within expected ranges. Overall, the study concludes that the existing offsite emergency plans for Koeberg were suitable based on the analysis of worst-case credible accidents [3]. The purpose of this study is to simulate a nuclear accident in the form of a long-term station blackout at the Koeberg Nuclear Plant, using the RASCAL code, and to estimate the potential total effective dose equivalent (TEDE) for populations at varying distances from the plant, under different seasonal conditions. This TEDE data will be further used to estimate the lifetime excess cancer risk to the public, employing the Radiation Risk Assessment Tools (RadRAT). This study aims to enhance our understanding of the risk posed by nuclear accidents under different meteorological conditions and to inform emergency preparedness efforts. The findings can help to ensure that the response to any such incident effectively protects public health.

2. Materials and Methods

The study was carried out using the RASCAL 4.3.3 (Radiological Assessment System for Consequence Analysis) code, developed by the US Nuclear Regulatory Commission (NRC). RASCAL is designed to provide rapid assessments of radiological releases and their consequences during nuclear incidents [4]. The model incorporated a scenario of a Long-term Station Blackout (LTSBO) at the Koeberg Nuclear Plant. Two scenarios, simulating two seasons (autumn and winter), were developed to assess the impact of varying meteorological conditions on radiation dispersion. The TEDE values, converted to milligray (mGy) units, served as the Radiation Risk Assessment Tools (RadRAT) input to estimate the lifetime excess cancer risk. RadRAT, developed by the U.S. Environmental Protection Agency (EPA), employs dose-response relationships derived from the BEIR VII report, adjusted for age and gender to estimate cancer risk [5].

2.1 Rascal Input

In this scenario, it was assumed that unit 1 of KNPS experienced a total power outage, losing its internal and external power sources, culminating in an LTSBO. The core's cooling system malfunctioned, and the Emergency Core Cooling System was not available. To understand the potential differences in radiological outcomes, this event was modeled for two distinct seasons: autumn and winter. Equation 1 is a basic version of the puff model in RASCAL.

$$\frac{X(x,y,z)}{Q} = \frac{1}{(2\pi)^{\frac{3}{2}}\sigma_x\sigma_y\sigma_z} exp\left[-\frac{1}{2}\left(\frac{x-x_0}{\sigma_x}\right)^2\right] \times exp\left[-\frac{1}{2}\left(\frac{y-y_0}{\sigma_y}\right)^2\right] \times exp\left[-\frac{1}{2}\left(\frac{z-z_0}{\sigma_z}\right)^2\right] \quad (1)$$

Where χ is the concentration (Bq/m3 or g/m3), *Q* is the amount of material unconfined (Bq or g) and σ is the dispersion parameter (*m*) which is a function of distance from the release point. When joint with a transport mechanism to passage the center of the puff (*xo, yo, zo).* The STDose module was selected for this scenario to produce source terms that varied over time and to supply the data essential for the atmospheric transport and dispersion model. The module requires input such as event location, type of event, release path, source term, and meteorological data as shown in Table 1.

Table 1. KNPS parameters of RASCAL.

Location Koeberg- Unit 1 Melkbosstrand, Western Cape, South Africa Lat/Long: 33,6768, 18,4315	Reactor Power: 2775 MW_t Average burnup: 46000 MWd/MTU Containment volume $56.6m^3$ Design Pressure 400 kPa Design leak rate 0.17 %/d Fuel Assemblies: 217 Coolant mass: 2.0E+5 kg SG water mass: 42184 kg Release height: 50 m

2.2 Meteorological Data

The meteorological data was sourced from the Meteoblue website, encompassing key parameters like wind speed and direction, stability class, and precipitation levels. The data was collected for the period of 5 years from 2018 to 2022. The week that represents typical weather conditions for each season was selected for each season, i.e., dry season for autumn and wet season for winter.

2.3 Lifetime Excess Cancer Risk Estimation

In the estimation of Lifetime Excess Cancer Risk for all organs using the RadRat tool, three demographic groups were taken into account: Infants (0-5 years), Children (6–15 years), and Adults (16-70 years). Both genders, male and female, were represented within each of these three age brackets. A sample size of 100,000 people was considered in this study. The tool employs the equation below in assessing the Lifetime Attributable Risk.

$$LAR(D,e,s) = \int_{e+L}^{a_{max}} M(D,e,a,s) \frac{S_{aj}(a,g)}{S_{aj}(a,g)} da \quad (2)$$

where, *M (D, e, a, s)* is the risk model, *Saj(a, g)* is the probability of surviving cancer-free to age *(a)* for the unexposed population, L is the minimum latency period, and the ratio *Saj(a, g)/Saj(e, g)* is the conditional probability of an individual alive and cancer-free at age-at exposure (e) to reach at least an attained age *(a)*

In this study, the type of cancer that was assessed for was the lung cancer due to its prevalence in the South African population. The assessment covered an area of up to 80 km from the reactors, the total EPZ of KNPS.

3. Results and Discussion

The simulation was conducted for the period between the 21st and the 25th of March 2020 for the autumn, and for the period between the 25th and the 28th of July 2018 for the winter. The two weeks were selected based on the meteorological data that mostly represent each season as shown in Table 2.

Table 2. Estimated TEDE with Distance for Autumn & Winter

Distance (km)	TEDE (mSv) for Autumn	TEDE (mSv) for Winter
2.41	4.80	6.40
3.22	3.40	3.80
4.83	1.90	1.90
8.05	1.10	1.10
11.27	0.82	0.82
16.09	0.61	0.59
24.1	0.23	0.39
32.2	0.14	0.24
48.3	0.11	0.11
64.4	0.07	0.09
80.5	0.05	0.07

The analyses were done from the distance of 2.41 km up to 80 km because the shorter distances fall within the KNPS Exclusion Area Boundary (EAB). Even though doses looked higher for winter in shorter distances from the source, radiological dispersion was relatively minimal for both seasons. The comparison on risk of excess lung cancer for all ages and genders considered in this study showed that population group that is in the highest risk is the female infant group and the group with the least risk is the adult male, for both seasons as shown in Figure 1 and Figure 2.

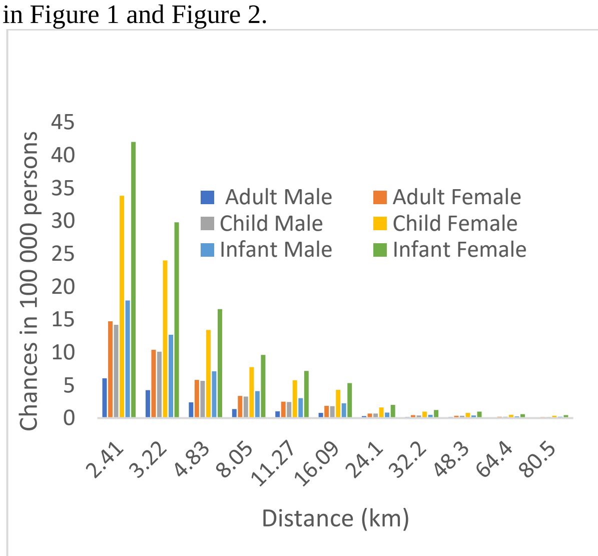

Figure 1. Excess Lifetime Risk of Lung Cancer (Autumn) with Distance

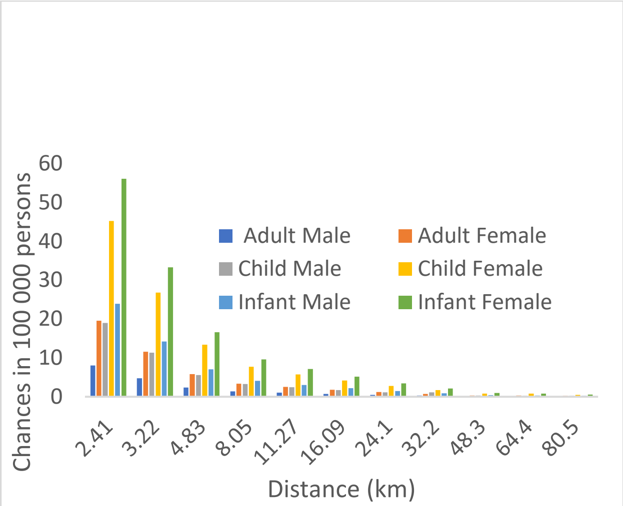

Figure 2. Excess Lifetime Risk of Lung Cancer (Winter) with Distance

4. Conclusion

The study's simulation of a prolonged station blackout at KNPS, utilizing the RASCAL software, along with the assessment of the excess lifetime risk for lung cancer, has shed insight on the potential radiation-related hazards for the nearby population. The results align with prior research, indicating that the excess lifetime risk of cancer attributed to a nuclear accident is relatively low. In line with other investigations, this study also reveals that infants face higher risks than adults, and females are more susceptible than males. One constraint of this research was the reliance on the RASCAL software's design leak rate, owing to the absence of actual containment leak rate data. Nonetheless, as anticipated, the radiation dose values diminished with increasing distance, and the cancer risk patterns remained typical.

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