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Research article

Assessment of environmental radioactive surface contamination from a hypothetical nuclear research reactor accident

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ABSTRACT

The environmental surface contamination by radioactive elements following a nuclear research reactor hypothetical accident is evaluated employing the hotspot code, IAEA safety guide, and NRC guidelines. Gaussian plume depositions of radioactive contaminants are calculated under very conservative assumptions for a worst-case accident scenario, and site most probable wind speed and metrological conditions. Results reveal that the contamination strongly decreases with distance, dropping seven orders of magnitude from 2.2E+09 kBq/m^2 at the reactor site to 9.5E+2 kBq/m^2 60 km from the reactor at the plume centerline. In rainy weather, the wet deposition is depleted to 6.0E+2 kBq/m^2 after 50 km, limiting the spread of contaminants to a much smaller area. Although the results of this work tend to overestimate the surface deposition of radionuclides, they present a clear insight into the radiological consequences of nuclear accident worst-case scenario. Thus, it assists with the development of a comprehensive emergency preparedness program by identifying all areas with potential risk to contamination.

1. Introduction

The uncontrolled release of radioactivity to the environment following a nuclear accident can lead to widespread radiological contamination through the depositing of radioactive substances on the ground and other surfaces. The contamination from the Fukushima accident reached the northern hemisphere, depositing about 20 Bq/m^2 in Europe [1]. In the case of Chernobyl, accident contaminants were deposited across the world, including Europe, Asia, America, and the Middle East [2]. The radiation hazard to public health and the environment from such deposits can last for many years, specifically from long-lived contaminants such as ^{137}Cs and ^{90}Sr, with half-lives of 30.17 and 28.8 years, respectively.

In nuclear incidents and accidents, swift decisions must be taken to protect potentially affected populations and the environment. Thus it is imperative to assess areas with the highest risk to contamination adequately and to develop in advance an emergency preparedness program that provides emergency management and decision-makers with comprehensive information and clear protective actions to mitigate the risk.

Although most research reactors have a smaller potential for hazard to the public compared with power reactors, the international atomic energy agency (IAEA) safety guide [3] calls for the analysis of the radiological consequences of accidents in a research reactor. To be adequately conservative, one approach usually used in the safety analyses of research reactors is to assume a hypothetical accident that results in most severe consequences, by presuming that 100% of the core melts [3].

2. Methodology

2.1. Site

The JRTR research reactor is a 5 MW open-tank-in-pool type reactor, fueled with 19.75% enriched uranium silicide (U_3Si_2). It is water cooled and moderated, with beryllium and Heavy water reflectors [4, 5, 6]. It is located in Jordan University of science and technology campus, home to more than 20,000 students [4], in Irbid governorate. It is surrounded by farmland used to grow vegetables and rain-fed annual cropland used for cultivating wheat, barley, lentils, and chickpeas, in addition to thousands of olive, grape, almond, and pomegranate trees. The Land use map is shown in Figure 1 [7], with two major population centers; the city of Ramtha, which is approximately 7 km away, has a population of 200,000

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Table 1. Pasquill stability class selection criteria used in HotSpot, and the site wind relative frequency at each group.

Ground wind speed (m/s)	Relative frequency at the site	Sun high in sky	Sun low in sky or cloudy	Night time
<2.0	20.9%	A	B	F
2 .0–3.0	38.6%	A	C	E
3.0–4.0	20.2%	B	C	D
4.0–6.0	17.0%	C	D	D
>6.0	3.3%	C	D	D

Table 2. Ground surface deposition (kBq/m^2) of radioisotopes for each chemical group and its relative contribution to the total (%).

	Alkali Metal	Alkaline Earths	Cerium Group	Halogen	Lanthanides	Tellurium Group	Noble Metal
Deposition (kBq/m2)	4.08E+09	4.60E+08	8.86E+06	5.58E+09	7.58E+06	7.58E+06	4.85E+07
%	40.05%	4.51%	0.09%	54.73%	0.07%	0.07%	0.48%

people, and the city of Irbid, which has nearly 750,000 people, located about 15 km from the site.

2.2. Postulated accident

To demonstrate the reactor safety, a hypothetical severe accident scenario that results in the maximum environmental release of radioactive contaminants is selected. The scenario is that an airplane or missile hit the reactor, destroying its building, the reactor pool, and the core. Furthermore, assuming that 100% of the core melts [3], it is uncovered, and its radionuclide inventory escapes to the atmosphere; thus, no water retention is assumed in this scenario.

2.3. Release fraction

Although gases will readily transfer to the atmosphere, only a fraction of the other radionuclides will be carried out by the air depending on its physical and chemical properties. The United States nuclear regulatory commission (NRC) classified the radionuclides into eight groups [8] and recommended a release fraction for each group for both pressurized water reactors (PWR) and boiling water reactors (BWR). The NRC regulatory guide 1.183 [8] is used to classify the core inventory of radionuclides and calculate their release using the fraction for PWR.

2.4. Meteorological scenarios

The site has a Mediterranean climate with four seasons. The summer average temperatures range from 27 °C–33 °C and drops to an average of 10 °C in the winter. The average annual rainfall for the last 30 years is 225.7 mm [9], spread over 57 rainy days.

Local hourly wind observation data from Irbid meteorological station located near the reactor site, for the last five years (2015–2019) [10], is used to calculate the wind speed and direction in our scenario. Data set consisting of 4384 measurements that passed all quality control checks was constructed and is published [11] with this article; the data contains the direction angle from which the wind is blowing, wind type, and the speed rate (m/s). The hourly wind direction varies throughout the year, prevalently blowing from SSW direction, as shown in the wind rose Figure 2. Data analysis show that the most frequent directional angel is 260°, wind observation at this angle were recorded 447 times with an average speed of 2.8 m/s and a median of 2.6 m/s, the most frequent wind speed at this angle is 2.1 m/s observed 30% of the time. The recorded wind type is normal throughout the data.

Atmospheric stability is categorized using several meteorological measurements such as weather conditions, solar insolation, humidity, and wind speed. The five categories according to Pasquill stability classes are; A (very unstable), B (moderately unstable), C (slightly unstable), D (neutral), E (slightly stable), and F (moderately stable) [12]. The criteria for selecting the stability category in HotSpot are tabulated in Table 1. Based on the selected wind speed of 2.1 m/s, it can be seen that the stability class will be A, C, or E, depending on if its day or night, and on the sun fluctuating position in the sky between summer and winter. The relative frequency distribution of the data shows that the most probable (38.6%) daytime stability classes at the site are A or C, as shown in Table 1, with class C being the more conservative choice than class A.

Calculations are performed for dry and wet deposition using primarily slightly unstable atmospheric conditions (Pasquill class C), with the wind blowing at an average speed of 2.1 m/s from the SSW (260°) direction

Table 3. Ground deposition source term.

Nuclide	Core inventory (TBq)	Release Fraction (NRC)	Activity released (TBq)	Nuclide	Core inventory (TBq)	Release Fraction (NRC)	Activity released (TBq)
Cs-134	2.62E+02	0.30	7.87E+01	Ba-142	8.72E+03	0.02	1.74E+02
Cs-134m	1.01E+02	0.30	3.03E+01	Sr-89	6.13E+03	0.02	1.23E+02
Cs-136	1.23E+02	0.30	3.68E+01	Sr-90	2.69E+02	0.02	5.39E+00
Cs-137	2.88E+02	0.30	8.64E+01	Sr-91	8.47E+03	0.02	1.69E+02
Cs-138	1.03E+04	0.30	3.09E+03	Sr-92	8.68E+03	0.02	1.74E+02
Cs-139	9.71E+03	0.30	2.91E+03	Sr-93	9.21E+03	0.02	1.84E+02
Cs-140	8.64E+03	0.30	2.59E+03	Sr-94	8.96E+03	0.02	1.79E+02
Rb-86	5.08E+00	0.30	1.52E+00	I-130	3.57E+01	0.40	1.43E+01
Rb-88	5.11E+03	0.30	1.53E+03	I-131	4.64E+03	0.40	1.86E+03
Rb-89	6.76E+03	0.30	2.03E+03	I-132	6.93E+03	0.40	2.77E+03
Rb-90	6.32E+03	0.30	1.90E+03	I-133	1.05E+04	0.40	4.18E+03
Rb-90m	1.89E+03	0.30	5.66E+02	I-134	1.21E+04	0.40	4.84E+03
Ba-139	9.84E+03	0.02	1.97E+02	I-134m	6.88E+02	0.40	2.75E+02
Ba-140	9.40E+03	0.02	1.88E+02	I-135	9.83E+03	0.40	3.93E+03
Ba-141	8.92E+03	0.02	1.78E+02	Total		3.43E+04	

Table 4. The core inventory and released activity of several research reactors compared to this work.

Reactor	Power (MW)	Inventory (Bq)	No. of Isotopes	Released (Bq)
This work JRTR	5	1.73E+17	29	3.43E+16
PARR-1 [22]	5	2.75E+17	30	—
TRR [24]	5	3.75E+16	32	1.71E+16
IAEA [25]	10	2.95E+17	30	—
SAFARI [3]	20	1.68E+18	66	—
Nur [23]	1	2.80E+16	30	1.53E+16

constantly throughout the release, the result will be compared with other stability classes.

This is a very conservative assumption, since the release may last for days or weeks, during which atmospheric conditions, wind direction, and speed, or the other parameters would probably change. A change in these parameters would lead to a significant difference in the expected maximum doses [3].

2.5. Hotspot

The HotSpot [12] code provides a conservative estimation of the downwind radiological effects of atmospheric dispersion calculations of radioactive material using the Gaussian plume model (GPM). This model's adequacy for making initial dispersion estimates or worst-case safety analyses has been tested and verified for many years [13]. The radioactive plume is depleted with downwind distance by multiplying the source term with depletion factor DF(x) [14].

HotSpot uses a dual-deposition velocity methodology based on particle aerodynamic diameter being smaller or larger than 10 microns. The deposition velocity values selected based on empirical comparisons with the national atmospheric release advisory center (NARAC) deposition data are 0.3 cm/s for small particles and 8 cm/s for large particles [12].

The radiation dosimetry methodologies in Federal Guidance Reports (FGR) are applied in HotSpot; the FGR-13 [15] gives dose coefficients using the new International Commission on Radiological Protection (ICRP), ICRP-66 lung model and ICRP series 60/70 methodologies [12].

The source term radionuclides are selected from the FGR-13 library, where a one-micron (1 μm) activity median aerodynamic diameter (AMAD) is assumed [12, 15]. The radionuclide particulates absorption-type are selected according to the ICRP recommendations of three absorption types; F, M, and S referring to fast, moderate, and slow, respectively, based on their rate of absorption into the blood from the respiratory tract [12, 16, 17].

2.6. Model input

The release height is at ground level (0 m). Wind speed 2.1 m/s referenced at the height of 10 m. Atmospheric stability class stable (C). The holdup time is 0 s. Receptor height is at ground level (0 m). The sample time is 10 min. Standard terrain is selected as it will usually produce the most conservative estimates. The rainout coefficient is 0.0002 s^{-1}. The release location, according to the World Geodetic System (WGS), is 32.46287N 035.97267E degree. The model input and output calculations are published [18] with this article.

3. Results and discussions

3.1. Released activity

The released activity of the core inventory consisting of 200 radionuclides was calculated for each of eight chemical groups, using the release fraction of each group [8]. The core inventory is obtained from

Table 5. Plume movement and deposition of radioactive contaminants on the ground surface (kBq/m^2) with time and distance from the reactor source at the plume centerline. Including the contamination levels (CL); extremely contaminated (EC), heavily contaminated (HC), slightly contaminated (SC), and non-contaminated (NC).

Distance (km)	Arrival time (hour:min)	Dry Ground Surface Deposition (kBq/m^2)	Dry Ground Shine (Sv/hr)	CL	Wet Ground Surface Deposition (kBq/m^2)	Wet Ground Shine (Sv/hr)	CL
0.03	<00:01	2.20E+09	1.20E+01	EC	2.70E+09	1.50E+01	EC
0.10	<00:01	1.90E+08	1.00E+00	EC	3.10E+08	1.70E+00	EC
0.20	0:01	4.50E+07	2.40E-01	EC	1.00E+08	5.50E-01	EC
0.40	0:03	1.10E+07	5.80E-02	EC	3.60E+07	2.00E-01	EC
0.60	0:05	4.60E+06	2.50E-02	EC	2.10E+07	1.10E-01	EC
0.80	0:07	2.50E+06	1.40E-02	EC	1.40E+07	7.40E-02	EC
1.00	0:09	1.60E+06	8.60E-03	EC	1.00E+07	5.50E-02	EC
2.00	0:18	3.90E+05	2.10E-03	EC	3.80E+06	2.00E-02	EC
4.00	0:37	9.90E+04	5.10E-04	EC	1.30E+06	6.80E-03	EC
6.00	0:55	4.60E+04	2.20E-04	EC	6.50E+05	3.20E-03	EC
8.00	1:14	2.70E+04	1.30E-04	EC	3.80E+05	1.70E-03	EC
10.00	1:33	1.80E+04	8.00E-05	EC	2.30E+05	1.00E-03	EC
15.00	2:19	8.90E+03	3.60E-05	HC	8.50E+04	3.40E-04	EC
20.00	3:06	5.50E+03	2.00E-05	HC	3.60E+04	1.30E-04	EC
30.00	4:39	2.80E+03	9.50E-06	HC	7.60E+03	2.50E-05	HC
40.00	6:12	1.80E+03	5.60E-06	HC	1.80E+03	5.70E-06	HC
50.00	7:46	1.30E+03	3.70E-06	HC	4.80E+02	1.40E-06	C
60.00	9:19	9.50E+02	2.60E-06	C	1.30E+02	3.60E-07	C
80.00	12:25	6.00E+02	1.50E-06	C	1.00E+01	2.60E-08	SC
100.00	15:32	4.20E+02	1.00E-06	C	8.50E-01	2.00E-09	NC
120.00	18:38	3.10E+02	7.00E-07	C	7.40E-02	1.70E-10	NC
155.00	24:00	2.00E+02	4.20E-07	C	1.10E-03	2.30E-12	NC

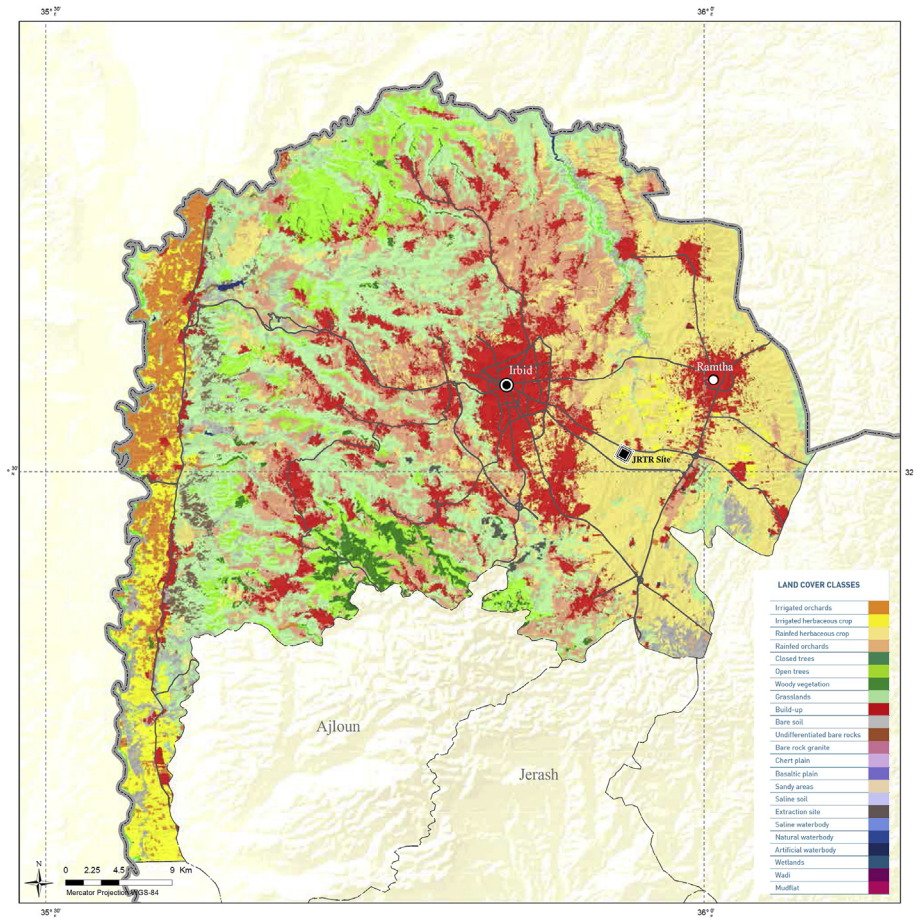

Figure 1. Land cover/use map of Irbid, Jordan, showing the reactor site [11].

reference [6, 19], where it has been calculated via the Scale/Triton depletion sequence using the Origen-S generation and depletion code. In order to evaluate the importance of each chemical group on the risk of environmental contamination, the ground deposition of radionuclides is calculated for each group separately.

The obtained results for dry deposition (kBq/m^2) are tabulated in Table 2 for each chemical group. Noble gases are inert and will not have a contribution to ground deposition; thus, this group is not shown in Table 2. The Cerium Group, Lanthanides, Tellurium, and Noble metal groups' relative contributions are 0.09%, 0.07%, 0.07%, and 0.48%, respectively; consequently, these four groups have an insignificant impact on the ground deposition source term, since they account for less than 1% of the total deposition.

The halogen group consisting of 20 radioisotopes of bromine (Br) and iodine (I) are released into the environment [19]. Bromine has seven short-lived isotopes, two of which (^{84}Br and ^{85}Br) are included in the Hotspot library and were found not to affect the ground deposition source term. Iodine release comprises 13 isotopes; six have a very short half-life (seconds) and are not part of the Hotspot library; thus, only seven of iodine radioisotopes are included in the source term as shown in Table 2.

The Alkali metal group release consists of 21 radioisotopes of rubidium (Rb) and cesium (Cs), nine of them have a short half-life (seconds) and are not part of the Hotspot library as shown in Appendix 2 [19]. Cesium seven radioisotopes are beta emitters and decay to their corresponding barium isotopes. ^{137}Cs have the highest half-life (30.2y), which along with its physical properties, reactivity, and high-energy beta emission, makes it the most significant and the hazardous isotope connected with major reactor accidents such as Fukushima and Chernobyl.

The remaining five rubidium isotopes (^{86}Rb, ^{88}Rb ^{89}Rb ^{90}Rb ^{90m}Rb) are beta emitters and decay to strontium (^{86}Sr, ^{88}Sr ^{89}Sr ^{90}Sr), the long-lived strontium-90 has a half-life of 28.9 years decaying to yttrium (^{90}Y) by emitting a high-energy beta. It is a hazardous environmental contaminant that finds its way to humans through the food chain, acting like calcium, strontium-90 becomes part of the teeth and bones [20, 21].

The Alkali earth group release comprises 18 radioisotopes of barium (Ba) and strontium (Sr), eight of them have a very short half-life (seconds) and are not part of the Hotspot library as shown in Appendix 2 [19]. The remaining four barium isotopes ($^{139\text{-}142}$Ba) and six strontium isotopes ($^{89\text{-}94}$Sr) are all beta emitters and contribute about 4.5% of the total ground deposition of radioisotopes, as shown in Table 2.

The source term for ground deposition comprises of 29 radioisotopes selected from three groups, as shown in Table 3, along with the reactor core inventory, release fraction, and activity released.

The results obtained for the released activity and core inventory are compared with other published results for several reactors worldwide [3, 22, 23, 24, 25], as shown in Table 4. The results are in agreement and within the same range of other work considering the differences in fuel type and burnup, reactor power, and the isotopes found in each case.

3.2. Plume deposition

The release plume deposition of radioactive contaminants on the ground surface was modeled in the HotSpot code, using the derived source term and stated input parameters. The calculation results for dry deposition are presented in Table 5; the results reveal that the radioactive plume would travel 120 km from the reactor in approximately 18 h, spreading radioactive contaminants in a narrow corridor along its centerline.

Although the dry deposition at the plume centerline starts with the maximum value of 2.2E+9 kBq/m^2 within 30 m from the reactor core, this value drops three orders of magnitude in 5 min, reaching 4.6E+6

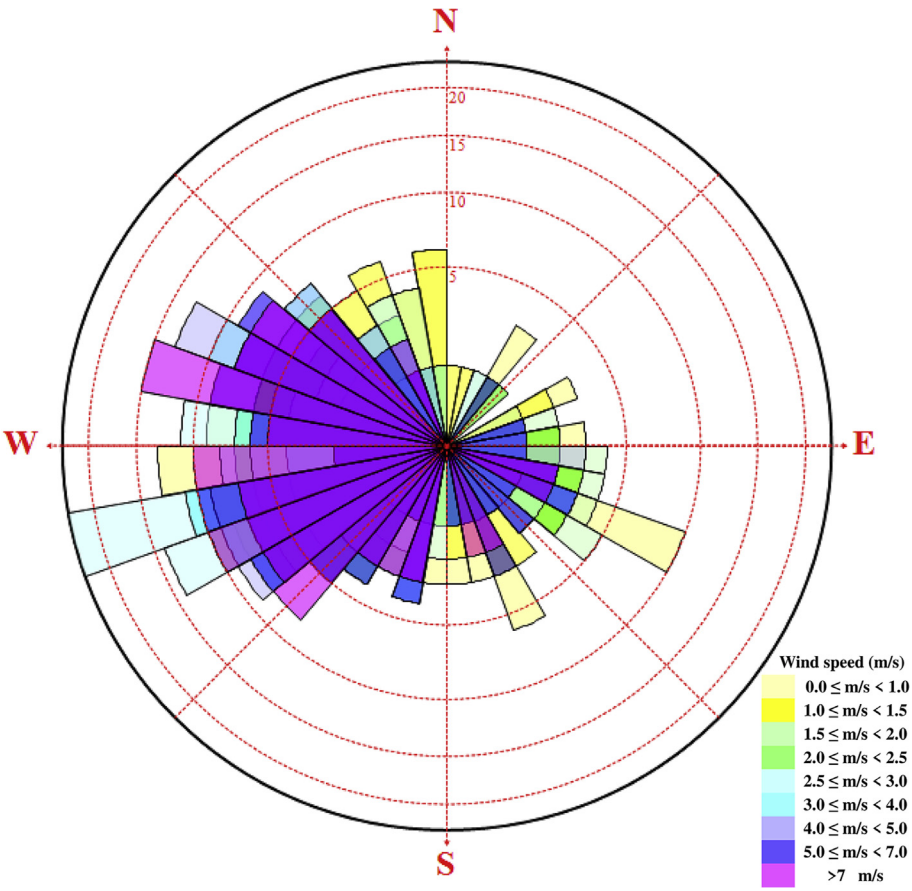

Figure 2. Wind rose in ramtha, Jordan, 2015–2019.

kBq/m^2 600 m from the source. The plume deposition continues to drop with downwind distance from the reactor, as shown in Figure 3a, falling an additional three orders of magnitude to 8.90E+03 kBq/m^2 in approximately 2 h, traveling 15 km from the reactor. After 24 h, the plume would travel 155 km, depositing 200 kBq/m^2. Areas along the plume centerline receiving more than 1E+4 kBq/m^2 are classified as extremely contaminated areas, based on the Nordic [26] guidelines for protective measures in early and intermediate phases of a nuclear or radiological emergency. The radiological contamination of strong gamma and beta emitters is classified into five levels starting from slightly contaminated for areas with less than 100 kBq/m^2 to extremely contaminated for regions with more than 1E+4 kBq/m^2 [26]. These levels signify the severity of radiation exposure and offer a practical guide to consider the need for protective measures and decontamination.

In rainy weather, the wet ground deposition rate is higher than that of dry one for the first 30 km from the reactor. Starting with the maximum value of 2.7E+9 kBq/m^2, it takes the plume 16 min to drop to 4.6E+6 kBq/m^2, 1.76 km from the reactor, comparing to 5 min, 600 m in the dry deposition case. This means that the plume will continue to deposit more radioactive contaminants due to rain, leading to a significant increase in ground contamination in areas closer to the reactor site. As shown in Figure 3b, the plume deposition falls sharply after 10 km, decreasing from 2.30E+05 kBq/m^2 to only ten kBq/m^2, 80 km from the reactor, limiting the spread of contaminants to a smaller area, as shown in Table 5. This is mainly due to washout, where the water droplets carry the plume radionuclides, moving them directly to the ground. Which is in agreement with what was observed following the Fukushima accident where rainfall washed out the plume into the soil, leading to a significant increase in the ambient dose rate, in areas to the south of the plant [27].

When comparing the most probable stability class (C) selected in our scenario with other stability classes, it can be seen from Figure 3 that for dry deposition, all stability classes decrease linearly with distance having a higher magnitude with each class level from A to F, respectively. Class F drops sharply after 15 km falling below class E. In rainy weather the deposition magnitude increase with each class level from A to F for the first two km from the reactor. After that, class F falls sharply, moving from the highest magnitude of all classes to the lowest one. Classes E and D deposition magnitude start falling after 30 km, placing class (C) on top with the highest value of all.

The external dose rates from the ground surface contaminated with radionuclides were evaluated; results of the ground shine (Sv/hr) versus distance from the reactor at the plume centerline are tabulated in Table 5. The dose rate within the reactor site is in the range of Sv/hr; this is exceedingly more than the annual effective dose limit of 20 mSv recommended by the international commission on radiological protection (ICRP) [28] for radiation workers, which translate to approximately 10 μSv/hr. As shown in Table 5, external exposure from the surface contamination at the plume centerline decreases with distance from the reactor, decreasing from 8.6 mSv/hr at 1 km to 9.5 μSv/hr at 30 km, and finally falling to 1 μSv/hr at 100 km from the reactor. For the rainy case, the external exposure at the plume centerline is higher than that of the dry case for the first 40 km from the reactor; the same increase in the ambient dose rate was observed in areas with rainfall located less than 50 km from Fukushima accident [27]. Starting at a maximum value of 15 Sv/hr at the source, it decreases to 6.8 mSv/hr 4 km from the reactor and finally falling to 0.92 μSv/hr at 53 km from the reactor. Considering the high exposure levels, protective measures should be identified and described as part of the emergency preparedness plan, including evacuation and monitoring of radionuclide contents in foodstuffs.

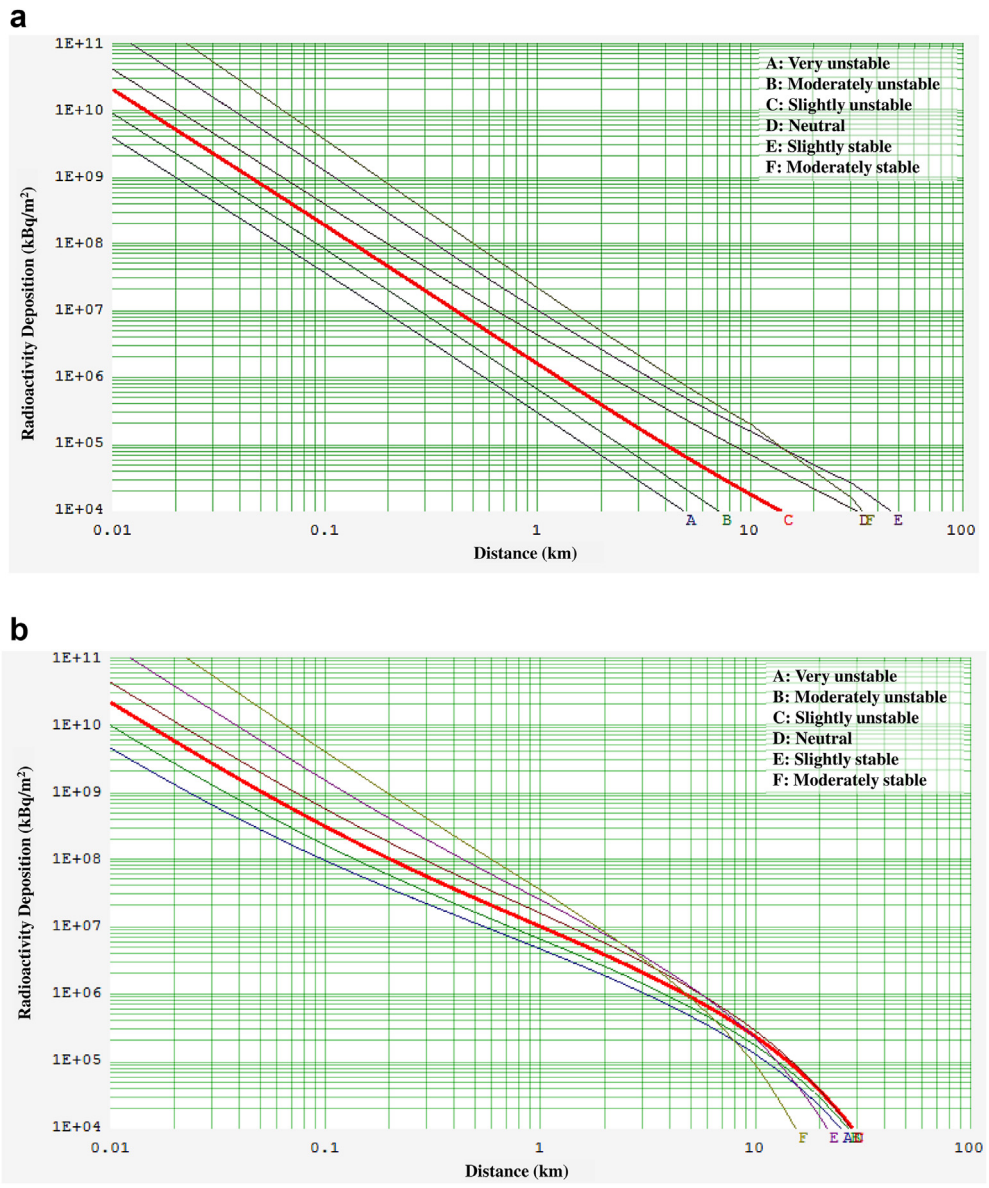

Figure 3. Radioactivity ground deposition (kBq/m^2) at plume centerline as a function of distance (km), for all atmospheric conditions based on Pasquill stability classes, (a) dry deposition (b) rain deposition.

3.3. Surface contamination

Environmental contamination in the form of the spread of radionuclides on the ground surface is shown in Figure 4, a complete clear picture can be accessed via our interactive map included in Appendix A of the supplementary data as dry deposition of radionuclides map. Calculations of dry plume deposition show that a total area of 214 km^2 will be exposed to the contamination level of more than 1E+3 kBq/m^2, extending more than 50 km from the reactor as displayed in Figure 4(a). A small area of 2 km^2 would be extremely contaminated with more than 1E+5 kBq/m^2; this area is next to the reactor building, however, extending 2 km from the source means that it will surpass the reactor site boundaries.

The second zone of 18 km^2 and extending approximately 14 km from the reactor would be covered by contamination level between 1E+4 and 1E+5 kBq/m^2. Al Buwayda, a small town of 11,000 residents, would be at risk of receiving this extreme contamination level.

The third contaminated zone receiving between 1E+3 and 1E+4 kBq/m^2 has an area of 194 km^2; extending 50 km, it crosses the Jordanian boundary to Syria. Several small localities located within this zone; Sama-Alsarhan, a small Bedouin village of 7000 residents, Maghir-Alsarhan a Bedouin village of 11000 residents, Smad, a small Syrian village of 5000 residents. Consequently, these and other small farms and dwellings in the plume path would be at risk of being contaminated with levels higher than 1000 kBq/m^2. Calculations of dry plume contamination assume that the radionuclides did not migrate into the soil or other material and are still on the surfaces of ground, buildings, trees, and plants.

Calculations results of wet plume contamination is shown on our interactive map included in Appendix A of the supplementary data as wet deposition of radionuclides map. Results show that a total area of 234 km^2 will be exposed to more than 1E+3 kBq/m^2 and extending approximately 40 km from the reactor, as displayed in Figure 4(b). Although the surface area covered by radioactivity is more significant than that of the dry case, the contaminants spread is broader and does not extend as far. The area covered by contamination level of more than 1E+5 kBq/m^2 is one order of magnitude larger than that of the dry case,

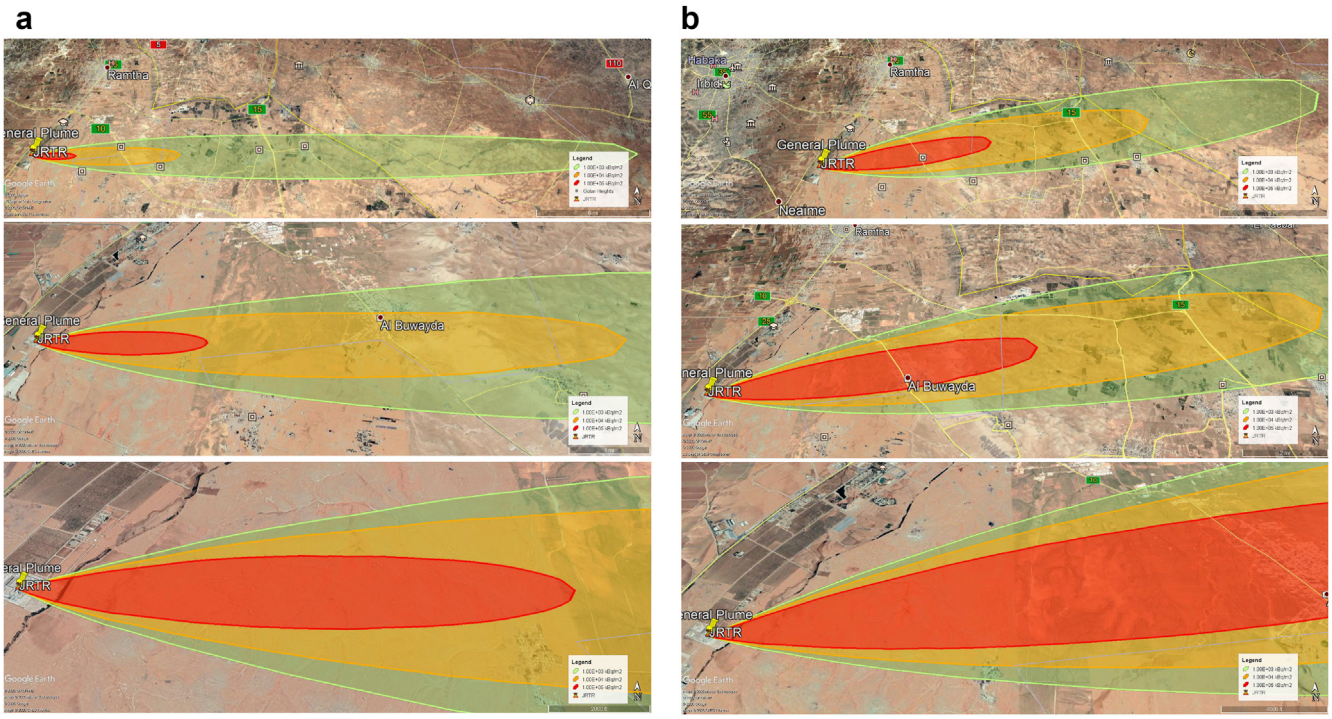

Figure 4. Deposition of radionuclides on the ground surface following a hypothetical nuclear accident, (a) dry weather release (b) wet weather release.

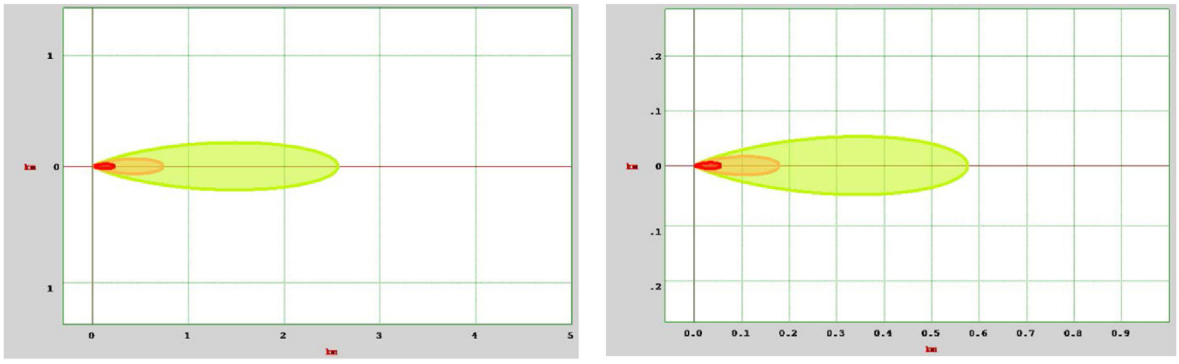

Figure 5. Plume contour of ground surface deposition vs. distance from the reactor, (a) ^{137}Cs (b) ^{90}Sr. Showing contamination levels of; inner 1E+5 kBq/m^2 (red), middle 1E+4 kBq/m^2 (orange), outer 1E+3 kBq/m^2 (green).

covering 22 km^2 and extending approximately 14 km from the reactor, exposing Al-Buwayda town to the risk of extreme contamination level.

The second zone exposed to contamination levels between 1E+4 and 1E+5 kBq/m^2 is increased from 18 km^2 to 69 km^2, impacting new areas such as Swailmeh with a population of 2000, Jabber-AlSarhan with a community of 2500, and the Jordanian-Syrian joint industrial free zone. The third contaminated zone receiving between 1E+3 and 1E+4 kBq/m^2 has an area of 141 km^2; localities at risk located on the plume path within a distance of 40 km from the reactor.

The impact of rain in washing the radionuclides can be seen by considering the total area exposed to a radiation level of more than 1E+2 kBq/m^2, which is reduced from 2000 km^2 in the dry deposition case to 457 km^2 in the wet deposition case.

3.4. Cesium and strontium

Although numerous radionuclides may be released in a nuclear accident, the importance of cesium (^{137}Cs) and strontium (^{90}Sr) stems from their high long term risk to people. The substantial release of these two isotopes combined with their long half-life of 30 and 28.8 years, respectively, making them the longest-lasting contaminants. In fact, more than 30 years after Chernobyl, ^{137}Cs, and ^{90}Sr remain the most significant radionuclides contaminating the exclusion zone around the nuclear plant.

The ground surface contamination was calculated along the plume centerline for both radioisotopes, as depicted in Figure 5. ^{137}Cs contamination of more than 1E+5 kBq/m^2 is limited to the reactor site, extending 200 m from the release point and covering a small area of 0.007 km^2, as shown in Figure 5(a) the second contamination level between 1E+4 kBq/m^2 and E+5 kBq/m^2 covers an area of 0.065 km^2. The third zone has an area of 0.745 km^2 that is contaminated with radiation between 1E+3 and 1E+4 kBq/m^2. High contamination of more than 1000 kBq/m^2 of ^{137}Cs is limited to a small area of 0.81 km^2; it extends 2.5 km from the reactor. Lower contamination levels between 100-1000 kBq/m^2 travel 11 km from the reactor contaminating 10.2 km^2.

The ground surface contamination of ^{90}Sr is constricted compared to that of ^{137}Cs. The radiation level of more than 1E+5 kBq/m^2 is limited to the reactor building extending 30 m from the release point and covering a

tiny area of 0.0004 km^2, as shown in Figure 5(b) the second contamination level between 1E+4 kBq/m^2 and E+5 kBq/m^2 covers an area of 0.0036 km^2, the third zone with radiation level between 1E+3 and 1E+4 kBq/m^2 has an area of 0.041 km^2. High contamination of more than 1000 kBq/m^2 of ^{90}Sr is limited to a minimal area of 0.045 km^2 and extends only 0.5 km from the reactor; this is approximately 20 times smaller than the size contaminated with ^{137}Cs. Lower contamination levels between 100-1000 kBq/m^2 travel less than 2 km from the reactor contaminating 0.45 km^2.

4. Conclusions

Results show that radioactivity contamination following a nuclear accident in research reactors could pose a high risk to the people and the environment. Radionuclides can spread to areas located tens of kilometers from the reactor, contingent upon the source term and metrological conditions.

Although, the conservative assumptions made in our calculations tend to overestimate the surface deposition of radionuclides, both in magnitude and in areas it covers. It presents a worst-case scenario that highlights the potential risk of research reactors, critical in updating emergency preparedness program to include all areas with potential risk to contamination.

Results show that the total area exposed to radiation levels higher than 100 kBq/m^2 is 2000 km^2 and extends more than 200 km from the reactor in the dry deposition case. The wet deposition case's area is only 457 km^2 and extends approximately 60 km from the reactor.

Rain washes the radioactive elements from the plume, depositing radionuclides faster and closer to the source, thus reducing the total contaminated area. Results show that the wet ground deposition rate is higher than that of dry one for the first 30 km from the reactor.

Rainfall causes fallout/washout/rainout of radionuclides leading to a significant increase in dose rates. The external exposure dose rate at the plume centerline during rainfall is higher than that of dry weather for all areas located less than 40 km from the reactor, a significant increase of ten times the dose is observed in some areas.

The ground surface contamination of ^{90}Sr is constricted comparing to that of ^{137}Cs. High contamination of more than 1000 kBq/m^2 for ^{90}Sr is limited to a minimal area of 0.045 km^2 and extends only 0.5 km from the reactor, comparing to 0.81 km^2 and extends 2.5 km from the reactor for ^{137}Cs.

Declarations

Author contribution statement

Ned Xoubi: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Additional information

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