Hindawi
Science and Technology of Nuclear Installations
Volume 2020, Article ID 1868965, 9 pages
https://doi.org/10.1155/2020/1868965

Research Article

Source Term Derivation and Radioactive Release Evaluation for JRTR Research Reactor under Severe Accident

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Received 6 February 2020; Accepted 15 June 2020; Published 20 July 2020

Academic Editor: Arkady Serikov

The source term for the JRTR research reactor is derived under an assumed hypothetical severe accident resulting in generation of the most severe consequences. The reactor core is modeled based on the reactor technical design specifications, and the fission products inventory is calculated by using the SCALE/TRITON depletion sequence to perform burnup and decay analyses via coupling the NEWT 2-D transport lattice code to the ORIGEN-S fuel depletion code. Fifty radioisotopes contributed to the evaluation, resulting in a source term of 3.7×10^{14} Bq. Atmospheric dispersion was evaluated using the Gaussian plume model via the HOTSPOT code. The plume centerline total effective dose (TED) was found to exceed the IAEA limits for occupational exposure of 0.02 Sv; the results showed that the maximum dose is 200 Sv within 200 m from the reactor, under all the weather stability classes, after which it starts to decrease with distance, reaching 0.1 Sv at 1 km from the reactor. The radiation dose plume centerlines continue to the exceed international basic safety standards annual limit of 1 mSv for public exposure, up to 80 km from the reactor.

1. Introduction

The utilization of research reactors in a variety of scientific, production, and training applications requires unique design characteristics and operational modes, consequently exerting additional burden on their safety systems and procedures.

Although, in comparison to power reactors, research reactors are small and contain smaller inventory of fuel and radionuclides, they have a higher number of reported accidents. The lack of containment building, proximity to densely populated areas, and high burnup cores, coupled with life extension, have raised worldwide interest for in-depth safety evaluation of these systems.

In 2008, the international atomic energy agency (IAEA) published a research reactor safety report [1]. It aims to provide safety analysts, regulators, and reactor operation staff and management, with the essential calculation methods and techniques for evaluating the source term and analyzing the radiological consequences of accidents in research reactor.

The magnitude, composition, form, and mode of release of radioactive elements released during a reactor accident define the source term. The derivation of the source term is an essential step of the safety analysis [1]. One approach commonly used in research reactors safety analyses is to assume a hypothetical accident that results in generating the most severe consequences [1]; this is the subject of this paper.

Recently, several studies for the evaluation of research reactors source term have been conducted. Foudil et al. have estimated the source term and doses for the NUR research reactor under a hypothetical severe accident [2]. Muswema et al. carried out a study to drive the source term and analyze the radiological safety for the TRICOII research reactor in Kinshasa [3]. Charalampos et al. published a study about source term derivation and radiological consequences for the Greek Research Reactor [4]. Birikorang et al. have estimated the source term and ground deposition of radionuclides following a hypothetical release from Ghana Research Reactor [5]. Sadeghi et al. calculated the source term and dose of a postulated accident release from the

Tehran Research Reactor [6]. Ullah et al. carried out a study to evaluate the source term for the upgraded LEU Pakistan Research Reactor-1 [7].

In this work, the JRTR research and training reactor core inventory is calculated using the SCALE/TRITON [8, 9] depletion sequence to perform burnup and decay analyses via coupling the NEWT 2-D [10] transport lattice code to the ORIGEN-S [11] fuel depletion code.

The corresponding source term and the release of radionuclides during postulated severe accident are estimated in accordance with the IAEA [1] recommendation and the US-NRC regulatory guide 1.183 [12]. The atmospheric dispersion of radionuclide concentrations are simulated based on the Gaussian Plume Model (GPM) using the HOTSPOT code [13].

2. Reactor Description

The JRTR is a multipurpose research reactor optimized for research, training, and isotope production. It is light water moderated and cooled open-tank-in-pool type reactor with nominal power of 5 MW upgradable to 10 MW. The reactor core (shown in Figure 1) consists of 18 MTR plate type fuel assemblies loaded in a 33 squares grid matrix, the remaining 15 grid positions are loaded with beryllium blocks serving as internal reflector, and the grid central position is designated as a flux trap experimental facility. Heavy water reflectors are placed at the four corners of the core. The fuel assemblies and beryllium blocks are interchangeable and can be shuffled to reconfigure the reactor core.

The core is designed to produce the utmost thermal fluxes at the core's internal and external irradiation facilities. The maximum in-core thermal-flux-to-power ratio is $2.9 \times 10^{13}\ \mathrm{cm^{-2}s^{-1}}$ per MW, producing a maximum thermal flux of $1.45 \times 10^{14}\ \mathrm{cm^{-2}s^{-1}}$, at full power. The maximum external thermal flux to power ratio is $1.4 \times 10^{13}\ \mathrm{cm^{-2}s^{-1}}$ per MW producing a maximum thermal flux of $6.78 \times 10^{13}\ \mathrm{cm^{-2}s^{-1}}$ at full power.

Forced convection cooling is used to cool the reactor under normal operating conditions. The coolant flows downward at a rate of 170 kg/s, with an inlet temperature of around 37°C and exits the core with an outlet temperature of 44.2°C. The average heat flux is $17.3\ \mathrm{W/cm^2}$, with a maximum of $51.9\ \mathrm{W/cm^2}$, and the power peaking factor is 2.54 [14–17]. The main design characteristics of the JRTR reactor are listed in Table 1.

2.1. Fuel Assembly. The fuel is MTR plate type, uranium silicide (U_3Si_2) enriched to 19.75% ^{235}U and in aluminum clad. The core loading is 18 standard fuel assemblies containing approximately 7.0 kg of ^{235}U, as shown in Figure 1. Each assembly has 21 plates with a thickness of 1.27 mm and are placed 2.35 mm a part, allowing cooling water to flow between them as shown in Figure 2. The fuel material is 19.75 wt% enriched uranium silicide (U_3Si_2) in aluminum matrix sandwiched between two 0.38 mm thick aluminum plates, 680.0 mm long, and 70.7 mm wide.

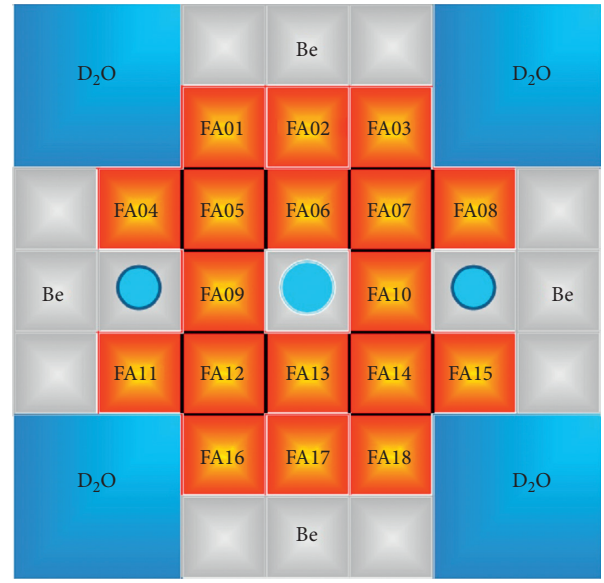

Figure 1: Cross-sectional (*x*-*y*) view of the JRTR reactor core configuration.

The fuel meat covers an area of 640×6.21 mm in each plate with a density of $6.543\ \mathrm{g/cm^3}$. Fuel assembly contains 97.2939 g of uranium in each plate, with uranium density of $4.8\ \mathrm{g/cm^3}$. The fuel technical specifications and material data are listed in Table 2.

2.2. Operating Cycle. The life cycle length of the JRTR is 50 days of full power operation, with an average discharge burnup of 900 effective full power days (EFPD). Fuel reloading consists of adding one new assembly into the F17 position and discharging one assembly from position F09. All of the fuel assemblies are shuffled, such that each assembly is placed in one new position every cycle, covering all 18 positions in the core before being discharged. Thus, at the end of cycle, the core will have assemblies that are burned from one cycle to 18 cycles. Fuel reloading is assumed to take 5 days, during which the reactor is shutdown.

3. Materials and Methods

In this study, the core inventory is calculated using the SCALE/TRITON depletion sequence to perform burnup and decay analyses via coupling the NEWT 2-D transport lattice code to the ORIGEN-S fuel depletion code.

The TRITON depletion sequences use the 2-D arbitrary polygonal mesh discrete ordinates transport code NEWT to calculate the flux distribution in the assembly.

In the T-DEPL calculation sequence, the cross section processing and neutron transport solution of the NEWT sequence is used to create three-group weighted cross sections based on calculated volume averaged fluxes for each material. These newly weighted cross sections are used to update the ORIGEN-S cross section library via the COUPLE code. The NEWT calculated three-group averaged fluxes for each material and they are used for depletion calculations in the ORIGEN-S code [11]. The three-neutron energy groups

Table 1: Design characteristics of the JRTR research and training reactor.

Reactor type	Tank-in-pool
Nominal thermal power (MW)	5
Max thermal flux (n/cm^2 s)	1.7×10^{14}
No. of fuel assemblies	18
Fuel material	U_3Si_2
Uranium enrichment (wt)	19.75%
No. of control elements (box shape)	4
Control plate material	Hafnium
Moderator	Light water
Internal reflector	Beryllium
External reflector	Heavy water
Coolant (flow direction)	Light water (downward)
Coolant inlet temperature (°C)	37.0
Water channel thickness (mm)	2.35
Water channel thickness between two fuel elements (cm)	0.390
Max. heat flux (W/m^2)	1,170,000
Nominal flow rate (m^3/h)	612
Average core flow velocity (m/s)	2.5
Core inlet pressure (MPa)	0.18

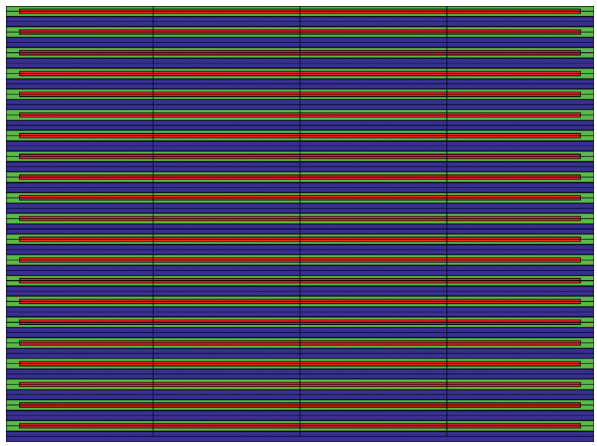

Figure 2: TRITON 2-D model of the JRTR fuel assembly showing the fuel (red), aluminum clad (green), and water coolant (blue).

Table 2: Technical specifications and material data of the fuel element.

Fuel assembly dimensions (mm)	$1015 \times 76.2 \times 8.0$
No. of plates per fuel element	21
Fuel material	U_3Si_2
^{235}U enrichment (wt %)	19.75
Uranium density (g/cm^3)	4.8
Fuel meat density (g/cm^3)	6.543
Fuel plate dimensions (mm)	$680.0 \times 70.7 \times 1.27$
Fuel plate active dimensions (mm)	$640 \times 62.1 \times 0.51$
Cladding material (aluminum alloy)	AG3NE
Cladding density (g/cm^3)	2.700
Cladding thickness (mm)	0.38
Fuel cycle length (EFPD)	50
Discharge EFPD	900

are the thermal group below 0.625 eV, the resonance group 0.625 eV to 1 MeV, and the fast group above 1 MeV [11].

T-DEPL uses a rigorous iterative procedure to update both fluxes and cross sections as a function of burnup. First, transport calculations are performed to estimate fluxes and prepare weighted cross-sections and other lattice physics parameters. Second, depletion calculations are performed using COUPLE and ORIGEN-S codes to update the nuclide concentrations. At each interval, ORIGEN-S updated nuclide concentrations are input into the assembly lattice transport analysis, and the neutron flux spectrum is recalculated. Cross sections are again updated and used by ORIGEN-S for the following computational step [11].

3.1. Assembly Modeling. The TRITON 2-D model was developed for the fuel assembly based on its technical design data provided in Table 2. The geometrical dimensions and material compositions of the fuel, clad, and moderator were explicitly modeled, as illustrated in Figure 2.

Reactor design operational and power data of 50 effective full power days, refueling cycle, and 5 days shutdown established the burnup step in the model. Burnup calculations were performed using burnup steps of 135.95 MW/MTU, with one additional small step at the beginning of the cycle (BOC) to generate cross sections for effectively unirradiated fuel.

The moderator/coolant temperature of 317 K was used as the average water temperature and 325 K as the fuel temperature. The moderator density of water from steam tables at 317 K and 1.4 bars is 0.990 g/cm^3.

3.2. Core Modeling. Aimed at modeling a realistic worst case scenario, the core is modeled at the end of cycle (EOC) for a fully burned up core. As shown in Figure 3, each assembly has been burned for a different number of cycles, and thus it will have a different radionuclide inventory. In each cycle, it is assumed that all assemblies will contribute equally to the reactor power, which results in assembly F09 discharge burnup of 122.36 MWd/kg. The fuel burnup in MWd/kg for each assembly is shown in Figure 3.

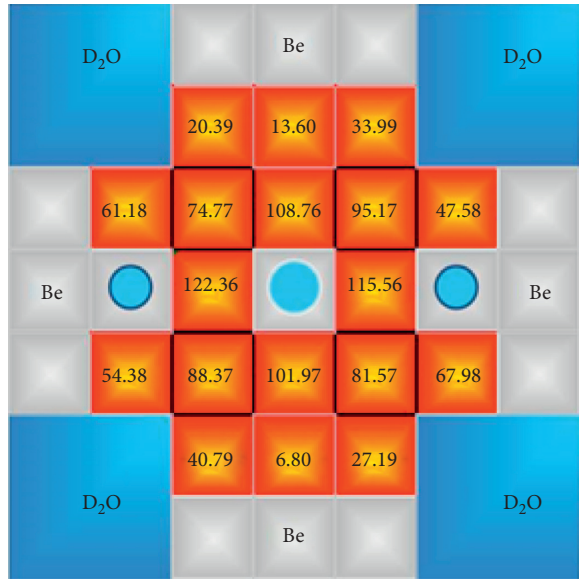

Figure 3: Fuel burnup (MWD/Kg) of each assembly at the end of cycle of a fully burned up core.

3.3. Selected Hypothetical Accident Scenario. The research reactor accident scenario, that is, the accident initiating event and its sequence determine both the magnitude and the nature of radioactive release, and thus the characteristic progressions of different scenarios generally lead to different radioactive release patterns. In this approach, a comprehensive assessment of accident progression for several accident scenarios is performed to calculate several different source terms.

Another approach that is commonly used in performing the safety analyses of research reactors, and adopted in this paper, is to assume a hypothetical severe accident that results in a limiting source term. The accident scenario considered in this study assumes that one or more projectiles target the reactor, leading to the destruction the reactor building and pool, resulting in the uncovering of the core and damaging all of the fuel assemblies.

Not all the fission products that are released from the damaged fuel assemblies transfer to the atmosphere of the reactor building. The atmospheric release fractions assumed in this study are 1.0 for noble gases, 0.4 for halogens, 0.3 for alkali metals, 0.02 for alkaline earths, 0.05 for tellurium, and 0.0025 for noble metals [1].

3.4. Site-Specific Conditions. The JRTR is located in Jordan University of Science and Technology campus, home to more than 20,000 students. The city of Ramtha is approximately 7 km away, with a population of 170,000 people, and approximately two million people reside in Irbid metropolitan located about 15 km from the site.

The site has a Mediterranean climate with four seasons. The summer average temperatures range from 27°C to 33°C and drops to an average of 10°C in the winter. The average annual rainfall is 300 mm, spreading over 77 rainy days.

The prevailing average hourly wind direction in the JRTR site varies throughout the year. However, for about 11 months of the year, it is most often from the west and it switches to the eastern direction from November 12 to December 20. The average hourly wind speed experiences mild seasonal variation over the year, with a speed of more than 3.2 m/s from November 14 to May 2 and 2.8 m/s for the rest of the year [18]. The frequency of wind speed and direction are shown in Figure 4 [19]. The wind rose diagram for Ramtha shows the annual number of hours the wind blows from the indicated direction.

The atmospheric stability classes are estimated using a number of meteorological measurements such as weather condition, solar insulation, humidity, and wind speed and are classified from *A* (very unstable) to *F* (moderately stable) [13].

4. Results and Discussion

4.1. Core Inventory. The core fission product inventory calculations have been performed using the SCALE/TRITON depletion sequence, based on reactor maximum full power operation. The activity of 200 fission products has been tracked, consequently accounting for the maximum possible activity in the core. The reactor core radionuclide inventory available for release to the environment is classified into eight groups, based on the NRC regulatory guide 1.183 [12] and is shown in Figure 5 The complete list of the fission products inventory and the their release fractions is included in Supplementary appendix 1 [20].

4.2. Source Term. Fifty radioisotopes are selected for the source term evaluation, based on their yield, half-life, and radiotoxicity due to both inhalation and ingestion. The activity released in the form of noble gases and other aerosols is presented in Table 3, assuming the core remains exposed and all fission products are released to the atmosphere.

Noble gases which can be considered inert and have very low chemical reactivity are the major contributors to the

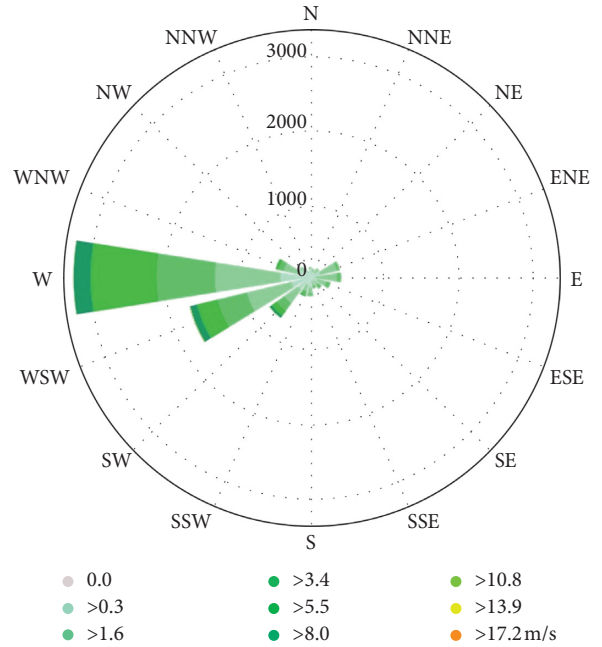

Figure 4: The wind rose for Ramtha showing the annual number of hours the wind blows from each direction [19].

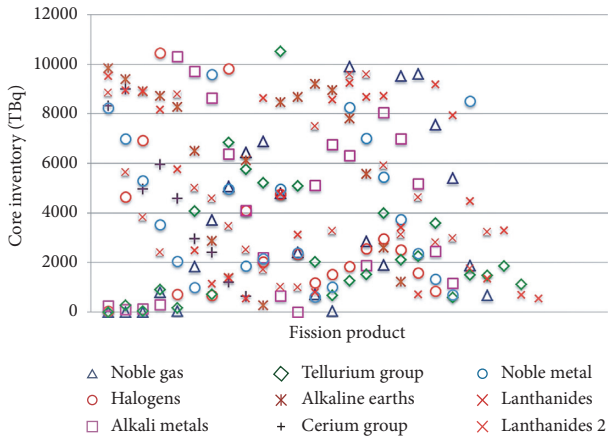

Figure 5: Reactor core radionuclide inventory classified into eight groups.

source term, accounting for 62.7% of the released activity, as illustrated in Figure 6. The highest release of noble gases is ^{133}Xe with an activity of 9.91×10^{15} Becquerel (Bq); this is followed closely by ^{138}Xe and ^{137}Xe with an activity of 9.61×10^{15} and 9.53×10^{15} Bq, followed by the rest of the xenon radioisotopes. Six krypton isotopes contribute 1.79×10^{16} Bq to the noble gas release, with the largest contribution of 6.44×10^{15} Bq from ^{89}Kr.

The second major contributor to the source term is the halogen group consisting of six iodine isotopes in addition to ^{84}Br. The group contributes 22% of the source term released activity, mainly from iodine with 1.76×10^{16} Bq. Indeed, the radioisotopes of krypton, xenon, and iodine contribute a total of 6.94×10^{16} Bq accounting for 84% of the source term.

Cesium and rubidium which comprise the alkali metal group are the next main contributors with a total activity of 9.80×10^{15} Bq accounting for approximately 12% of the source term.

The radioisotopes of the remaining four groups, alkaline earths, tellurium group, noble metals, and cerium group, account for approximately 4% of the released activity, as shown in Figure 6.

5. Atmospheric Dispersion and Dose Calculation

Atmospheric dispersion of 50 selected radionuclides has been evaluated using the Gaussian plume model (GPM) via the HOTSPOT 3.1.0 code [13]. The radiation dose was calculated using FGR 13 library [21] and the ICRP-recommended absorption types [22]. Site-specific

Table 3: Source term selected radionuclide inventory and activity release.

Radionuclide	Group	Half-life ($t_{1/2}$) (ref.)	Core inventory (TBq)	Release fraction	Activity released (TBq)
kr83m	Noble gas	1.83 h	7.97E + 02	1.00	7.97E + 02
kr85	Noble gas	10.756 y	3.49E + 01	1.00	3.49E + 01
kr85m	Noble gas	10.776 y	1.84E + 03	1.00	1.84E + 03
kr87	Noble gas	76.3 m	3.71E + 03	1.00	3.71E + 03
kr88	Noble gas	2.84 h	5.06E + 03	1.00	5.06E + 03
kr89	Noble gas	3.15 m	6.44E + 03	1.00	6.44E + 03
xe131m	Noble gas	11.934 d	5.39E + 01	1.00	5.39E + 01
xe133	Noble gas	5.2475 d	9.91E + 03	1.00	9.91E + 03
xe135	Noble gas	9.14 h	2.86E + 03	1.00	2.86E + 03
Xe135m	Noble gas	15.29 m	1.91E + 03	1.00	1.91E + 03
Xe137	Noble gas	3.818 m	9.53E + 03	1.00	9.53E + 03
Xe138	Noble gas	14.08 m	9.61E + 03	1.00	9.61E + 03
i130	Halogen	12.36 h	3.57E + 01	0.40	1.43E + 01
i131	Halogen	8.02070 d	4.64E + 03	0.40	1.86E + 03
i132	Halogen	2.295 h	6.93E +03	0.40	2.77E + 03
i133	Halogen	20.8 h	1.05E +04	0.40	4.18E + 03
i134	Halogen	52.5 m	1.21E +04	0.40	4.84E + 03
i135	Halogen	6.57 h	9.83E +03	0.40	3.93E + 03
Br84	Halogen	31.80 m	1.53E +03	0.40	6.13E + 02
Cs134	Alkali metal	2.0648 y	2.62E +02	0.30	7.87E + 01
Cs134m	Alkali metal	2.903 h	1.01E +02	0.30	3.03E + 01
Cs136	Alkali metal	13.16 d	1.23E +02	0.30	3.68E + 01
Cs137	Alkali metal	30.07 y	2.88E +02	0.30	8.64E + 01
Cs138	Alkali metal	33.41 m	1.03E +04	0.30	3.09E + 03
Cs139	Alkali metal	9.27 m	9.71E +03	0.30	2.91E + 03
Rb88	Alkali metal	17.78 m	5.11E +03	0.30	1.53E + 03
Rb89	Alkali metal	15.15 m	6.76E +03	0.30	2.03E + 03
Ba139	Alkaline earths	83.06 m	9.84E + 03	0.02	1.97E + 02
Ba140	Alkaline earths	12.752 d	9.40E + 03	0.02	1.88E + 02
Ba141	Alkaline earths	18.27 m	8.92E + 03	0.02	1.78E + 02
sr89	Alkaline earths	50.53 d	6.13E + 03	0.02	1.23E + 02
sr90	Alkaline earths	28.79 y	2.69E + 02	0.02	5.39E + 00
sr91	Alkaline earths	9.63 h	8.47E + 03	0.02	1.69E + 02
sr92	Alkaline earths	2.71 h	8.68E + 03	0.02	1.74E + 02
sb131	Tellurium group	23.03 m	3.99E + 03	0.05	2.00E + 02
te127	Tellurium group	9.35 h	2.85E + 02	0.05	1.42E + 01
te127m	Tellurium group	109 d	4.01E + 01	0.05	2.00E + 00
te129	Tellurium group	69.6 m	9.13E + 02	0.05	4.57E + 01
te129m	Tellurium group	33.6 d	1.63E + 02	0.05	8.16E + 00
te131	Tellurium group	25.0 m	4.08E + 03	0.05	2.04E + 02
te131m	Tellurium group	30 h	7.19E + 02	0.05	3.60E + 01
te132	Tellurium group	3.204 d	6.85E + 03	0.05	3.43E + 02
te133m	Tellurium group	55.4 m	5.21E + 03	0.05	2.61E + 02
te134	Tellurium group	41.8 m	1.05E + 04	0.05	5.26E + 02
Mo99	Noble metal	65.94 h	9.59E + 03	0.0025	2.40E + 01
rh105	Noble metal	35.36 h	2.16E + 03	0.0025	5.39E + 00
ru103	Noble metal	39.26 d	4.97E + 03	0.0025	1.24E + 01
ru105	Noble metal	4.44 h	2.39E + 03	0.0025	5.98E + 00
tc99m	Noble metal	6.01 h	8.51E + 03	0.0025	2.13E + 01
Np239	Cerium group	2.3565 d	2.96E + 04	0.0005	1.48E + 01

meteorological conditions were applied to Pasquill stability classes A through D in this study.

The plume calculations are performed for the 50 radionuclides released into the atmosphere from the reactor at an effective height of 5 m, a receptor height of 1.5 m, a wind speed of 1 m/s, and a sampling time of 10 minutes. Two deposition velocities are used: 0.3 cm/sec for respirable particles and 8 cm/sec for nonrespirable particles.

The results of the total effective dose (TED) as a function of distance from the reactor are illustrated in Figure 7, which shows that the radiation dose may reach people up to 80 km from the reactor, under neutrally stable (D) weather

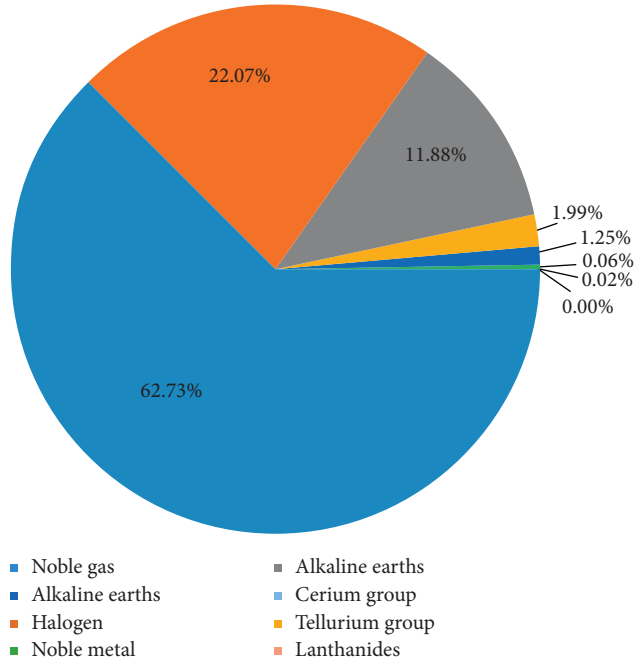

Figure 6: Source term release activity contribution of each of the eight groups.

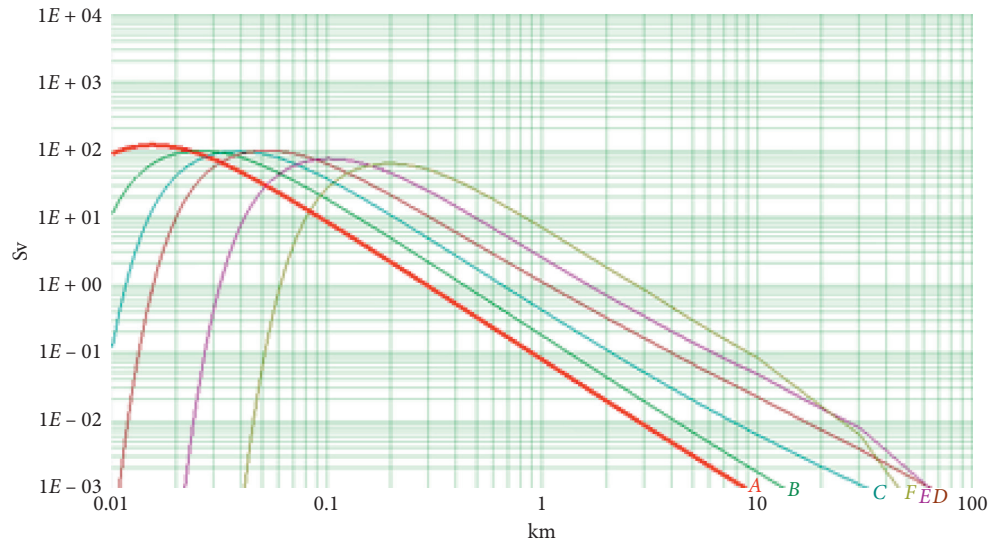

Figure 7: Total effective dose (Sv) as a function of downwind distance (km) from the reactor, for different weather stability classes (*A*–*F*).

conditions. Under very unstable (*A*) weather conditions, the dose will be received by people within 10 km from the reactor.

The maximum dose is about 200 Sv for most weather stability classes (*A*–*D*), and it extends from 15 m to 100 m from the reactor. For people within 300 m of the reactor, the TED dose is above 1 Sv, which is higher than the IAEA limits for occupational exposure of 0.02 Sv per year for radiation workers [23]. Radiation doses exceeding international basic safety standards annual limit of 1 mSv for public exposure [23] extend up to 80 km as shown in Figure 7, depending on the distance from the reactor and the weather stability class.

The results of plume centerline ground deposition are depicted in Figure 8, which shows that the maximum ground deposition is between 9 and $\times 10^8$ kBq/m^2 and falls within 300 meters from the reactor depending on the weather stability class. Contaminant spreads to 100 km depositing more than 1000 kBq/m^2 for all stability classes.

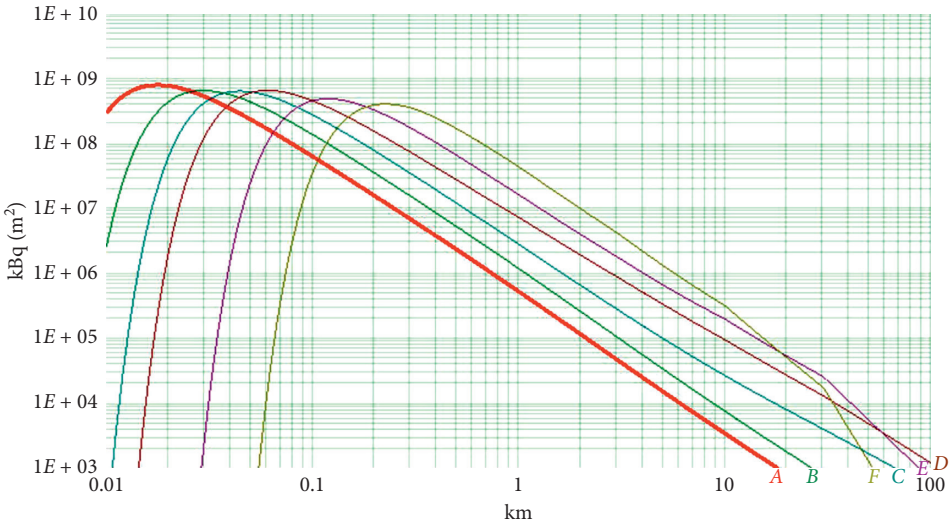

Figure 8: Plume centerline ground deposition (kBq/m^2) as a function of distance (km) from the JRTR reactor for different weather stability classes (A–F).

6. Conclusions

In order to drive the source term, the JRTR reactor was modeled in the SCALE/TRITON code based on its design technical specifications. Burnup and decay analyses for a fully burned-up core using NEWT transport lattice and ORIGEN-S fuel depletion code were performed to calculate the core radionuclides inventory available for release to the environment.

A hypothetical accident scenario assuming that all of the fuel assemblies are damaged and the reactor building is destroyed is selected. The fraction of fission products released to the atmosphere of the reactor building is calculated in accordance with the IAEA recommendation, resulting in the release 191 radioisotopes. Fifty radioisotopes are selected based on their yield, half-life, and radiotoxicity, to evaluate the source term, resulting in an activity of 3.7×10^{14} Bq.

Although the reactor core radionuclide inventory available for release to the environment comprises of 191 radioisotopes, it was found that krypton, xenon, and iodine account for 84% of the source term. Noble gases, halogens, and alkali metal groups consisting of 27 radioisotopes are the vast contributors to the source term, accounting for more than 96% of the released activity.

The Gaussian Plume Model (GPM) via the HOTSPOT code is used to simulate the atmospheric dispersion of radionuclide concentrations. The results show the contaminants spread to 100 km depositing more than 1000 kBq/m^2.

Communities as far as 80 km could be exposed to radiation doses higher than the international basic safety standard annual limit of 1 mSv for public exposure. Radiation workers in the vicinity of the reactor could be exposed to 50 times the recommended IAEA limits for occupational exposure of 0.02 Sv per year.

Data Availability

The data used to support the findings of this study are included within the article. The dataset for the reactor core inventory of 200 radionuclides and their release fraction (Appendix 1) has been deposited in the Mendeley repository (https://doi.org/10.17632/bcy9kg4g7h.1).

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This project was funded by the Deanship of Scientific Research (DSR), at King Abdulaziz University, Jeddah, under grant no. DF-106-135-1441. The author, therefore, acknowledges with thanks the DSR for the technical and financial support.

Supplementary Materials

The complete list of the JRTR reactor core fission product inventory (TBq) and their release fractions. (*Supplementary Materials*)

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