

Article

Radiological Risk Assessment of Vehicle Transport Accidents Associated with Consumer Products Containing Naturally Occurring Radioactive Materials

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Abstract: Natural and artificial ionizing radiation can be harmful to human health when they come into contact with people and the environment. Transport of naturally occurring radioactive materials (NORMs) and consumer products containing NORM in the public domain is inevitable owing to their potential applications. This study evaluates the dose and risk to the public from transport accidents of NORM and consumer products. Radiological and physical data were obtained from previous literature. The median and maximum values of radioactivity concentration were applied to consumer products and NORM data, which serve as an input. An external dose rate at 1 m from a transported shipment was calculated using MicroShield® Pro version 12.11 code, which serves as input to RADTRAN 6 code. Based on developed transport accident scenarios, a RADTRAN 6 code was used to estimate collective dose and risk. The sensitivity analysis was conducted by considering the variation of release, aerosol, and respirable fractions of radionuclides at 0.1%, 1%, 10%, and 100% from the transported shipment during an accident, respectively. The results of dose and risk to the general public because of the damage of the shipment container following a fire accident are below the annual regulatory limits of 1 man-Sv recommended by IAEA transport regulation of 2018. The sensitivity results of all NORMs and associated consumer products are also below the regulatory limits. Therefore, radiological safety can be ensured in the event of a transport accident involving the transit of NORM and consumer products containing NORM.

Keywords: naturally occurring radioactive material; consumer product; radiation dose; Microshield; RADTRAN

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1. Introduction

Radiation can exist as waves or particles and is classified into ionizing and non-ionizing radiation. Ionizing radiation has sufficient energy to produce ions and exert biological effects when it interacts with matter and biological tissue. The sources of radiation are categorized into natural and artificial. Artificial sources include radiation emitted by nuclear power plants and used in medical sciences and other industries, whereas natural sources include radiation emitted by natural substances in terrestrial soil and rocks, building materials, the human body, cosmic rays, and solar radiation [1,2]. Naturally occurring radioactive materials (NORMs) are natural substances such as rocks and minerals that may contain long-lived radioactive elements, specifically uranium (^{238}U), thorium (^{232}Th), potassium (^{40}K), and their decay series. The activity concentration of NORMs, also known as source materials, significantly varies and is mostly relegated to the natural background level. Therefore, their radiological effect is regarded as insignificant. The activity concentration of radioactive material refers to activity per unit mass or volume of the material in which the radionuclides are essentially uniformly distributed [3]. Therefore, a wide range of activity concentration of NORM in different geological materials has been reported

worldwide, as presented in Table 1 [4,5]. The average yearly radiation dose from naturally occurring radiation sources (NORM), including radon, is 2.4 mSv worldwide. In any big population, around 65% should receive annual doses of 1 to 3 mSv. Yearly doses of less than 1 mSv are expected in about 25% of the population, whereas annual doses of more than 3 mSv are expected in around 10% of the population [6,7]. The greatest known level of background radiation impacting a large population occurs in India's Kerala and Madras states, where over 140,000 people receive gamma radiation doses of over 15 mSv/yr, in addition to radon doses of a comparable magnitude. Brazil and Sudan have also similar levels, with many people exposed to up to 40 mSv/yr on average. Moreover, the greatest level of natural background radiation ever recorded was 800 mSv/yr on a Brazilian beach, but no one lives there. About 200,000 people are also exposed to more than 10 mSv/yr in Ramsar County in Iran [8].

Table 1. Activity concentration of NORM in some geological materials worldwide [4,5].

Country	Geological Material	²³⁸ U (Bq/kg)	²³² Th (Bq/kg)	⁴⁰ K (Bq/kg)	²⁶⁶ Ra (Bq/kg)
USA	Phosphate rock	259–3700	3.7–22.2		1540
	Coal	6.3–7.3	3.7–21.1		8.9–59.2
Brazil	Phosphate rock	114–880	204–753		330–700
	Coal	72	62		72
Egypt	Phosphate rock	1520	26		1370
	Coal	59	8		26
Australia	Phosphate rock	15–900	5–47		28–900
	Coal	8.5–47	11–69	23–140	19–24
Morocco	Phosphate rock	1500–1700	10–200		1500–1700
Austria	Phosphate rock	15–900	5–47		28–90
Chile	Phosphate rock	40	30		40
Tanzania	Phosphate rock	5000			5000
Algeria	Phosphate rock	1295	56		1150
United Kingdom (UK)	Coal	7–19	7–19	55–314	7.8–21.8
Germany	Coal		10–63	10–700	10–145
Italy	Coal	23 ± 3	18 ± 4	218 ± 15	
Jamaica	Bauxite ore	10–9000	35–1000	10–600	

However, human activities such as industrial mining and processing could increase their activity concentrations and impose significant radiation exposures to workers that require regulatory control [9]. Phosphate, zircon and zirconia, oil and gas extraction, extraction of rare-earth elements, tantalum, mining ore other than uranium ore, combustion of coal, mining, and metal production (e.g., iron and steel, aluminum, copper, lead/zinc, ferroniobium, incorporating NORM into building materials, industrial uses of thorium, and water treatment) are industrial sectors associated with NORMs [10]. Technological advancement, market expansion, and free movement of goods have significantly triggered wide applications of source materials (NORM) concurrent with an increase in the number and types of consumer products containing NORM. NORM is used as a raw material or feedstock to produce various products and items. In addition, it is generated as waste material. NORM has also been used in some products for various applications, such as a thoriated gas mantle that emits bright light when heated and the addition of uranium compound to improve the appearance of dentures [11]. Therefore, consumer products are products or items that are actively added with natural or artificial radioactive materials and made available to the public for various consumptions without any regulatory control. Consumer products containing NORMs or source materials include bracelets, necklaces, mattresses, and latex pillows to mention a few [12,13]. Most consumer products are

also exempt from regulatory control worldwide owing to their low-level radioactivity concentration, which results in an exposure dose below the dose limit of 1 mSv of public exposure in a year as recommended by International Atomic Energy Agency (IAEA). Additionally, the level of radioactive material in each consumer product differs [12,13].

NORMs and consumer products incorporating NORMs have been identified as a source of radiation exposure to human health throughout their life cycles. People can also be exposed to radiation through inhalation of aerosolized particles, ingestion of dust particles, direct skin contamination, and external irradiation. For example, Etsuko Furuta in 2013 reported the possibility of the risk of radiation exposure through inhalation of radionuclides in the case of misuse of consumer products containing NORMs in Japan [14]. In Korea, an abnormally high concentration of radon gas obtained from the use of monazite mattresses was reported in 2018, and the radiation dose was above the public exposure limit of 1 mSv/year [15]. In 2020, another study was conducted in Taiwan to investigate or audit other commercial products containing monazites, such as mattresses, masks, quilts, and pillows; a higher exposure dose rate of radon gas above 1 mSv/year of public exposure was also reported [16]. In 2019, Hassan and Chae reported activity concentrations of ^{238}U and ^{232}Th from various industrial NORMs that were higher than the levels recommended by the International Atomic Energy Agency (IAEA) and Korea Act, which are enough to pose a potential radiation hazard. They also stated that radiological NORM information in Korea is still limited [17]. In 2018, radiation exposure doses for workers between 0.003 and 0.364 mSv/yr from external exposure to potassium from the processing potassium industry were also reported in Korea, and it was recommended that this information should be used to better protect personnel handling a NORM [18]. Furthermore, in 2019, high activity concentrations of NORM in hydrocarbon sludge were observed, and high exposure risks necessitated control to an acceptable level in Iran [19]. Therefore, various countries have introduced initiatives to establish guidelines for regulating and controlling these materials and products to protect the people and the environment from the harmful effects of radiation while keeping exposure as low as reasonably achievable. The European Union (EU) regulation on radiation protection assesses the requirements imposed by the competent authorities prior to authorization and licensing arrangements, product testing criteria, classification, and product data requirements, final removal as well as exemptions and exclusions, and collect all available quantitative data for diverse categories of consumer products available in the EU. In case of exposure to natural sources of ionizing radiation, the exemption levels for Uranium and Thorium in secular equilibrium have also been determined and rounded to 0.5 Bq/g, whereas the associated dose criteria for individual and population is 0.3 mSv and 1 person-Sv, respectively [20,21]. The IAEA Safety Standard Series, SSG 36, titled Regulatory Status of Radioactive Consumer Products, provides advice and suggestions on how to satisfy the criteria for justification, optimization, and authorization of consumer product distribution to the general public. It also suggests how the exemption requirements in General Safety Requirements (GSR) Part 3 can be extended to goods containing small quantities of radionuclides, radiation generators, and activation products containing radionuclides. Furthermore, it suggested a radiological safety assessment to be conducted for the transportation of a large number of consumer products to ensure that the radiation exposure dose does not exceed the exemption level. In Case of NORM processing cycle, the IAEA international Basic Safety Standards (IAEA's GSR Part 3, 2014) also established exempt activity concentrations of 1 Bq/g for ^{238}U and ^{232}Th , and 10 Bq/g for ^{40}K in secular equilibrium. The associated dose criteria is 1 mSv and 1 person-Sv for individual and population, respectively. This exemption value is also applicable to IAEA regulation for the Safe Transport of Radioactive Material, 2018 [7,22,23]. The United States National Radiation Commission (US NRC) states that the radiation exposure to workers must be maintained below the annual limits of 50 mSv, and radiation exposure of persons and the general public resulting from use and misuse, delivery, advertising, must be maintained below lower levels [24]. In the same regards, the IAEA Specific Safety Requirements No. SSR-6 (Rev.1), titled "Regulation for the Safe

Transport of Radioactive Material" 2018, also addressed the requirements, including exemption criteria for the transport of NORM that should be followed to ensure the safety of the people and the environment [23]. Furthermore, studies covering different NORM industries on the full impact and technical basis for existing exemption values were recommended to relieve the unnecessary regulatory burden of transporting NORMs with significantly low activities [25].

NORMs and associated consumer products may be a source of radiation exposure during transportation, production, storage, normal use and misuse, accident and after disposal. The gamma radiation from radionuclides of ^{238}U , ^{235}U , and ^{232}Th and decay series, as well as ^{40}K , are the most common external sources of irradiation of the human body. These radionuclides can also be found in the body and can irradiate numerous organs with alpha, beta, and gamma rays [6]. Several studies have also been conducted to evaluate their radiological effects. Studies on the transport of NORMs from various industrial sectors such as oil and gas extraction, phosphate, and uranium ore have been conducted worldwide [25]. For example, in the United Kingdom (UK), several studies on the transport of NORMs from oil and gas industries, ores and mineral sands, coal and coal ash, iron, and steel production, were conducted, and the results showed that the annual doses to transport workers were less than 0.1 mSv, and members of the public were far below 0.001 mSv [26]. Another study on the transportation of tantalum (Ta) and niobium (Nb) containing traces of thorium and uranium was conducted through road, rail, and sea transport modes. The results from the slag containing NORMs showed doses of 0.24, 0.032, 0.0041, 0.019, 0.0038, and 0.00017 mSv for truck drivers, dockworkers, seaman, trainman, public adjacent to the road, and public adjacent to the rail, respectively. These doses are lower than the recommended 1 mSv per year [27]. However, in Korea, studies on radioactive material transport are more concerned with artificial low- and intermediate-level radioactive materials from decommissioned research reactors and various routine operational facilities, and the risk and dose reported during normal (incident free) and transport accidents were below the recommended regulatory limits [28,29]. Therefore, there is a backlog of information on NORM transport and associated consumer products. This information gap must be fulfilled to provide the necessary information in radiological consequences and risk databases that can be used to protect people and the environment. This study evaluates the radiological dose and risk to the public in case of accidents during transport through roads. The availability of the source materials and associated consumer products in most cases involves their transportation from one place or facility to another via one or more transport modes. During transport activities, an accident could occur, exposing the public to the dose and risk. Therefore, radiological risk assessment during transport accidents is crucial for the protection of human health and the environment.

2. Materials and Methods

This study uses radiological data on measured activity concentrations of source materials (NORM) and consumer products from the Nuclear Security Commission (NSSC) of South Korea. Minitab software tool was used to perform statistical analysis of the data of consumer products using normality test, and median values were selected for more statistical significance as presented in Table 2 [30]. The upper limit values were also selected for the data of the source materials (NORM) for this study. However, the mass of ^{238}U , ^{232}Th , and ^{40}K in a consignment of consumer product and NORM was obtained by multiplying the specific radioactivity ratio of each radionuclide or isotope by the mass or capacity of the shipping container, which is 21 tons. Then, the specific radioactivity of each isotope was multiplied by its mass to obtain the radioactivity per shipping container for consumer product and NORM consignment. A similar approach was employed by [31] in the assessment of risk during radioactive material transport, where the radiation source term per cylinder was obtained by multiplying the radioactivity of each isotope in the

feed, tails, and product by the capacities of the cylinder. Therefore, the radioactivity concentration per shipping container was used as an input to the RADTRAN 6 and MicroShield® Pro version 12.11 computer codes for the dose and risk assessment and estimation of external dose rate. However, the external dose rate estimated by Microshield was used as input to the RADTRAN computer code as presented in Table 3. Physical data including distance or length of route segments/links, speed of vehicle, population density, fire accident probability, type of road, and traffic volume were also obtained from the previous literature and online sources [29–32]. Table 3 presents the radiological input data of NORM and consumer products, Tables 4 and 5 present the physical parameters, which serve as input data to the RADTRAN computer code for dose and risk assessment during transport accidents. Table 6 presents radiological and physical input data used in MicroShield computer code for estimating the external dose rate at 1 m.

Table 2. Normality test results for data of consumer products containing NORM using the Minitab statistical tool.

Statistical Parameters	²³⁸ U (Bq/g)	²³² Th (Bq/g)	⁴⁰ K (Bq/g)
Mean	0.7582	4.422	0.23633
Standard deviation	3.3759	18.843	0.42890
Variance	11.3966	355.062	0.18395
<i>p</i> -value	<0.005	<0.005	<0.005

Table 3. Radiological input data used in RADTRAN code for assessment of population/collective dose and risk.

Source Materials (NORM)	Cargo Mass (tons)	²³⁸ U (Bq)	²³² Th (Bq)	⁴⁰ K (Bq)	Total (Bq)	Dose Rate at 1 m (Sv/hr)	Gamma Fraction	Neutron Fraction
Monazite	21	3.41 × 10 ⁷	3.41 × 10 ⁹	3.04 × 10 ⁵	3.44 × 10 ⁹	1.36 × 10 ⁻¹³	1	0
Zircon	21	1.90 × 10 ⁸	6.13 × 10 ⁶	1.44 × 10 ⁵	1.96 × 10 ⁸	6.42 × 10 ⁻¹⁴	1	0
Phosphorus	21	2.32 × 10 ⁷	2.02 × 10 ³	8.16 × 10 ⁴	2.33 × 10 ⁷	3.64 × 10 ⁻¹⁴	1	0
Bauxite	21	3.15 × 10 ⁶	3.37 × 10 ⁶	1.09 × 10 ⁶	7.61 × 10 ⁶	4.86 × 10 ⁻¹³	1	0
Consumer Products	Cargo Mass (tons)	²³⁸ U (Bq)	²³² Th (Bq)	⁴⁰ K (Bq)	Total (Bq)	Dose Rate at 1 m (Sv/hr)	Gamma Fraction	Neutron Fraction
Latex Pillow	21	2.25 × 10 ⁵	3.23 × 10 ⁷	1.76 × 10 ³	3.26 × 10 ⁷	7.85 × 10 ⁻¹⁶	1	0
Mattress	21	1.41 × 10 ⁵	1.87 × 10 ⁷	2.81 × 10 ³	1.89 × 10 ⁷	1.25 × 10 ⁻¹⁵	1	0
Clothing	21	1.73 × 10 ⁵	2.18 × 10 ⁶	1.29 × 10 ⁶	3.65 × 10 ⁶	5.75 × 10 ⁻¹³	1	0
Necklace	21	9.66 × 10 ⁶	7.22 × 10 ⁷	8.50 × 10 ⁵	8.27 × 10 ⁷	3.79 × 10 ⁻¹³	1	0
Bracelets	21	4.29 × 10 ⁶	3.24 × 10 ⁷	4.27 × 10 ⁵	3.71 × 10 ⁷	1.90 × 10 ⁻¹³	1	0
Amnion Patch	21	1.28 × 10 ⁶	6.21 × 10 ⁶	7.21 × 10 ³	7.50 × 10 ⁶	3.22 × 10 ⁻¹⁵	1	0
Cosmetics	21	5.35 × 10 ⁴	3.73 × 10 ⁵	1.84 × 10 ⁵	6.11 × 10 ⁵	8.21 × 10 ⁻¹⁴	1	0
Nippers	21	5.99 × 10 ⁵	3.73 × 10 ⁵	2.65 × 10 ⁴	9.98 × 10 ⁵	1.18 × 10 ⁻¹⁴	1	0
Slippers	21	8.69 × 10 ⁵	4.22 × 10 ⁷	2.10 × 10 ⁵	4.33 × 10 ⁷	9.37 × 10 ⁻¹⁴	1	0
Health supplements	21	2.33 × 10 ⁴	5.75 × 10 ⁶	1.17 × 10 ⁵	5.89 × 10 ⁶	5.22 × 10 ⁻¹⁴	1	0

Table 4. Physical input data used in RADTRAN code for assessment of population/collective dose and risk [29,32,33].

Link Name	Length (km)	Speed (km/hr)	Population Density (Persons/km ²)	Traffic Volume/hr	Accident Rate of Fire (Occurrence/km-car)	Default Fire Conditional Probability	Road Type
Link_1	16.6	110	22,654	9461	6.58 × 10 ⁻¹⁴	6.3 × 10 ⁻³	Highway
Link_2	48.7	110	6906	8827	9.39 × 10 ⁻¹⁴	6.3 × 10 ⁻³	Highway
Link_3	30.9	110	328	5270	2.39 × 10 ⁻¹³	6.3 × 10 ⁻³	Highway

Link_4	46.5	110	4345	8872	2.30×10^{-13}	6.3×10^{-3}	Highway
Link_5	22.9	110	4345	7321	1.12×10^{-13}	6.3×10^{-3}	Highway
Link_6	32.5	110	3024	11,877	4.32×10^{-14}	6.3×10^{-3}	Highway
Link_7	35.7	110	100	4345	6.14×10^{-14}	6.3×10^{-3}	Highway
Link_8	30.3	110	136	4472	5.28×10^{-14}	6.3×10^{-3}	Highway
Link_9	32.4	110	686	15,983	1.10×10^{-13}	6.3×10^{-3}	Highway
Link_10	37.3	110	4813	25,180	7.89×10^{-14}	6.3×10^{-3}	Highway
Link_11	45	110	614	5799	1.00×10^{-13}	6.3×10^{-3}	Highway
Link_12	37	80	204	1423	3.03×10^{-12}	6.3×10^{-3}	Secondary road

Table 5. Physical input data used in RADTRAN code for assessment of population/collective dose and risk.

Critical Dimension	Crew Size	Crew Distance (m)	Width Facing Crew (m)	Crew Shielding Factor	Number of Shipments	Number of Packages	Adjacent Vehicle Occupants	Population Type	Death/Accident
9	2	3	2.4	1 = none	1	1 (bulk)	2	urban	1

Table 6. Radiological and physical input data used in MicroShield computer code for calculation of dose rate from the shipment.

Source Dimensions (m)	Materials Used (g/cm ³)	Source Radioactivity (²³⁸ U, ²³² Th, and ⁴⁰ K) in Bq
Length = 12 Width = 2.4 Height = 2.5 Build up in x direction = 13, while y and z direction = 0	Air Gap = 12.2×10^{-4} Iron = 7.86	Same used in RADTRAN computer code

2.1. Meteorological Condition

Korea Metrological Agency website was used to extract hourly meteorological data including wind speed and direction, sunshine, cloud shine, and precipitation [34]. A wind rose plot online software (WRPLOT view freeware 8.0.2) was employed to analyze the data for a period of 10 years, from 2010 to 2020, as presented in Figures 1 and 2 below. The meteorological information helps to understand the dispersion of released radionuclides to the atmosphere during a transport accident. The most dominant wind direction with an average speed of 2.4 m/s is from the West (W) to East (E) direction and the West North West (WNW) to East South East (ESE) direction.

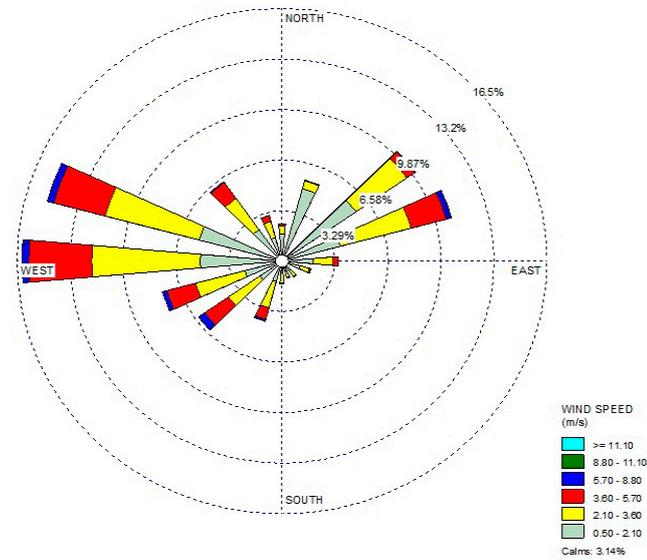


Figure 1. A wind rose diagram showing the pattern of wind speed and direction.

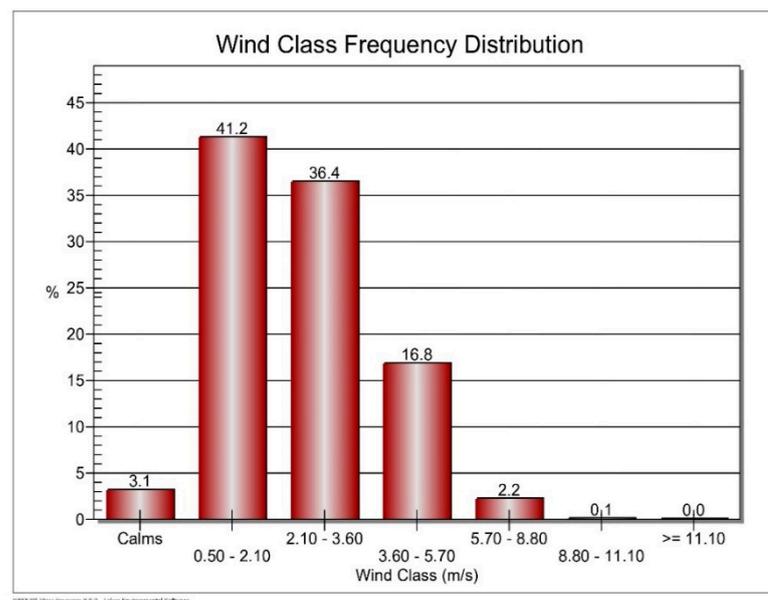


Figure 2. Wind class frequency distribution.

2.2. Transport Accident Scenario

The radiological safety of transporting NORMs and consumer products containing NORMs through an expressway between Seoul and Gyeongju was assessed in this study. This expressway has twelve route segments or links, numbering link 1 to link 12. In another study, the highway was used to transport low-and intermediate-level wastes from decommissioned research reactors and routine operation facilities as indicated in Figure 3. NORMs and associated consumer products were assumed to be transported to the processing industries and for various public consumptions. They were both transported in bulk by a vehicle carrying a shipping container made of carbon steel or iron materials, with the dimensions of $12 \times 2.4 \times 2.5$ m and a maximum loading capacity of 21 tons. The shipping container carrying the source materials (NORM) or consumer products was

damaged due to the occurrence of fire after collision with another transporting vehicle traveling along the same route. The accident was also assumed to occur in every link of the transportation route. The radionuclide contents in the shipment were particulates of ^{238}U , ^{232}Th , and ^{40}K , which were released with a rate of 0.1% of the total transported source materials or NORM–consumer products. The aerosol fraction and respirable fraction of released radionuclides during accident were both set to 1.0 for conservatism. As a representative of aerosolized particles, the ground deposition velocity of the released radionuclide was set to 0.01 m/s. These conservative values of release, aerosol, and respirable fraction were also used by [29]. Furthermore, inhalation, ground shine, cloud shine, ingestion, and resuspension pathways were considered as sources of internal and external exposures to the public during an accident. The simulation was conducted using Pasquill stability class F for the purpose of this study. The collective dose and risk were estimated using the RADTRAN computer code.

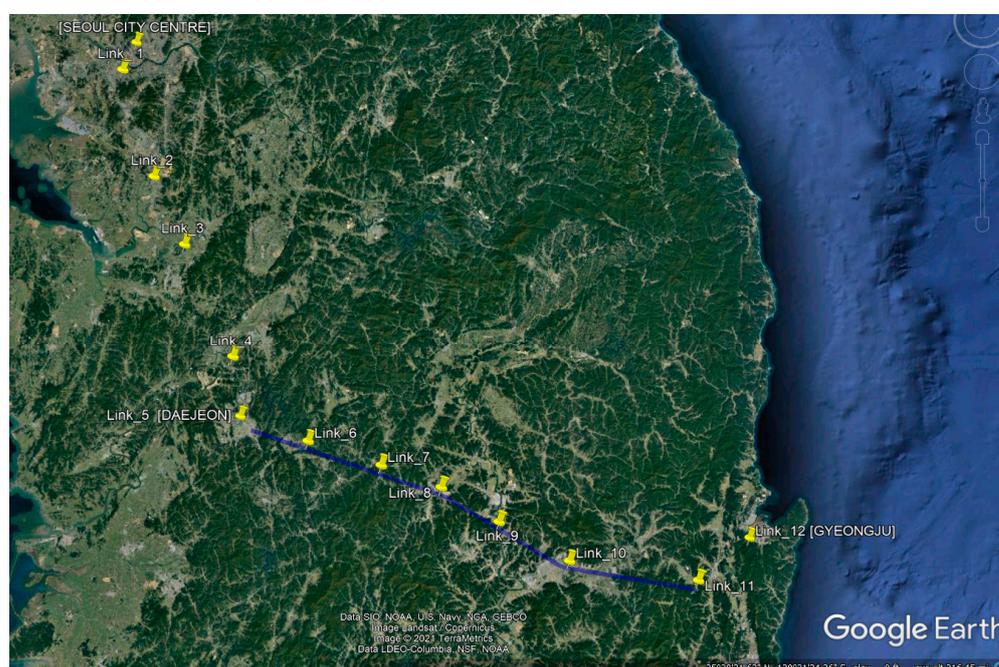


Figure 3. Route segments between Seoul to Gyeongju.

2.3. RADTRAN 6 Code

RADTRAN is an internationally renowned computer algorithm for assessing the risk and effects (consequences) of transporting radioactive materials in both incident-free (normal) and accident situations. It is a transportation risk analysis code in which the analysis is based on transportation scenarios (accident-free and accident situations), the likelihood (probability) of each transport scenario, and the effects or outcomes (dosage) of each scenario. Risk is the product of probability and consequence in a quantitative sense, RADTRAN uses a collection of algorithms that multiply the likelihood and effects of a given situation to calculate risk. The output of both RADTRAN's incident free computations and accident risk calculation are expressed in units of dose and collective dose, but when the probability term is included in accident risk calculations, the collective dose is referred to as "dose risk". RADTRAN can also be used in conjunction with dispersed inputs and a random sampling code to calculate uncertainty and perform probabilistic risk assessments. Highway, rail, and waterways are among the modes of transportation considered in RADTRAN, whereas tractor-trailers and light-duty vehicles for highway, railcars, and barges and other ships for waterway transport are examples of vehicles linked with these modalities.

RADTRAN was developed at Sandia National Laboratory and has since been extended and advanced to improve its analytical capability. The following is the chronological development of the RADTRAN computer code versions, where RADTRAN I, RADTRAN II, RADTRAN III, RADTRAN IV, RADTRAN V, and RADTRAN VI were developed in 1977, 1983, 1986, 1992, 2000, and 2009, respectively. RADTRAN VI is the current version with physical and radiological data in its internal library are used together with analyst input data to assess risk and collective exposure dose. The assessment can be route-specific by assigning values such as vehicle speed, population density, accident rate, and traffic volume. To estimate the risk and exposure dose, the code uses various models, including models for the receptor population, exposure pathways, package behavior in accidents, accident probability, and severity. RADTRAN consists of files for default values for some parameters, including standard meteorological weather, which is the average US weather data, isopleth area, average breathing rate, and residential building factors. There is also a file for dose conversion factors, which are based on ICRP 72 and Federal Guidance reports (FRG) 11 and 12 [35–37]. The ICRP 72 compiles age-dependent committed effective dose coefficients for the members of the public from the intakes of radionuclides by ingestion and inhalation. However, dose estimation using RADTRAN does not consider age-dependent, but rather population or collective dose (Person-Sv or man-Sv). The code also uses the Gaussian dispersion puff model for radionuclide atmospheric dispersion during an accident scenario. Particulate matter concentrations are assumed to change with time in this model [33]. Furthermore, RADTRAN has been used globally to assess the risk and dose for the transportation of artificial radioactive materials with levels ranging from low to intermediate to high, such as spent nuclear fuel, enriched nuclear fuel, and industrial radioisotopes, via land, sea, and air. For example, a collective dose of approximately 5.04×10^{-8} person-mSv was reported during the transport of radioactive materials through the Suez Canal in Egypt using the RADTRAN IV computer code [38]. Chitra et al. (1999) also reported insignificant dose and exposure risk for accident analysis of spent fuel transport by rail in India using the RADTARN IV computer code [39].

2.3.1. Mathematical Equations Describing the Radiation Dose to Receptors from the Shipment during Normal (Incident-Free) Transport

The mathematical equation for calculating single-point receptor's dose at a distance r from the traversing vehicle carrying radioactive consignment or package is as follows:

$$D(x) = Q_1 \frac{2 \times k_0 \times DR}{V} \int_x^\infty \frac{e^{-\mu r} B(r) dr}{r \sqrt{r^2 - x^2}} \quad (1)$$

where $D(x)$ is the dose (Sv) at a distance x from the traversing vehicle, $Q_1 = 1000$ m/km, is the conversion factor needed because V is in km/h and k_0 is in m, k_0 is the package shape factor (m^2), DR is the dose rate at 1 m from the shipping vehicle Sv/h, V is the speed of the shipping vehicle, x is the perpendicular distance of receptor from the shipment path (m), μ is the attenuation coefficient (m^{-1}), which depends on shielding factor and radiation energy, $B(r)$ is the buildup factor expressed as a geometric progression, r is the distance between the receptor and shipment along the traveling route (m).

Additionally, neutrons are rapidly attenuated in air and all gamma treatment provides a slightly conservative estimate of population dose for populations 10 m or more away from the vehicle [32]. Therefore, the maximum value of the product ($e^{-\mu r} B(r) dr$) is 1 for gamma radiation, which is nearly always the main source of radiation from a transport package. This value is mostly used in transportation analysis. Buildup factor ($B(r)$) is also the ratio of the total number of particles at a given point to the number of uncollided particles at that same site, and through a multiplicative change to the uncollided dose, buildup provides for the additional dose contributed by dispersed radiation. The mathematical equation for calculating population or collective dose at a distance r from the traversing vehicle carrying radioactive cargo is as follows:

$$D(p) = Q_2 \frac{2 \times k_0 \times DR \times PD_L \times L}{V} \int_d^\infty \int_d^x \frac{e^{-\mu r} B(r) dx dr}{r \sqrt{r^2 - x^2}} \quad (2)$$

where $D(p)$ is the collective dose of exposed population along the route, L is the distance of the route segment on which the responsible population dwells (km), PD_L is the population density (persons/km²), $Q_2 = (Q_1)^2$ in which Q_1 is a conversion factor equals 1000 m/km.

In general terms, collective effective dose is the sum of all individual effective doses in a group of people over the time period, given X (man-Sv) is as follows:

$$X = \sum_i F_i D_i \quad (3)$$

where F_i is the average effective dose for subgroup i , D_i if the number of individuals in the subgroup i . The basic mathematical equation used to calculate the radiation dose to the population receptors at a distance r from the shipment vehicle at the stop point is as follows:

$$D_{stop} = Q_2 \times DR \times PD_L \times t \times k_0 \times \int_d^r \frac{e^{-\mu r} B(r) dx dr}{r \sqrt{r^2 - x^2}} \quad (4)$$

where D_{stop} is the collective dose of exposed population at a stop point, t is the exposure time (h), d is the minimum distance of the receptor from the source (m).

2.3.2. Mathematical Equations Describing the Radiation Dose to Receptors from the Shipment during Accident Transport.

The following is the mathematical equation for determining the dose during transportation accidents in which no radioactive material is released

$$R(p) = AR \times Q_2 \times DR \times PD_L \times L \times t \times \int_d^r \frac{e^{-\mu r} B(r) dx dr}{r \sqrt{r^2 - x^2}} \quad (5)$$

where $R(p)$ is the collective dose of exposed population, AR is the accident rate of the vehicle (accidents/km), PD_L is the population density (persons/km²) of the given route segment, L is the length (distance) of the route segment.

The Gaussian dispersion puff model is used for accident transport associated with the release of radionuclides in the atmosphere compared to Gaussian plume model, which is appropriate with continuous release from elevated and ground level release, and the release is assumed to be constant with time, whereas in case of a transport accident, the plume is cloud release and should be modelled as puff release. The governing mathematical equation is as follows:

$$\frac{CHI}{Q} = \frac{1}{2\pi\pi u_y \sigma_z} \left[\exp\left\{-\frac{1}{2} \frac{y^2}{\sigma_y^2}\right\} \right] \left[\exp\left\{\frac{-(z-H)^2}{2\sigma_z^2}\right\} + \alpha \exp\left\{\frac{-(z+H)^2}{2\sigma_z^2}\right\} \right] \quad (6)$$

where CHI is the concentration of dispersed substance (Bq/m³), Q is the rate of release of dispersed substance (Bq/s), u is wind speed (m/s), σ_y is the crosswind meteorological constant (m), which represents y -axis Gaussian half-width, σ_z is the vertical meteorological constant (m), which represents z -axis Gaussian half-width, α is the reflection term of dispersed and deposited radionuclides from the release point.

2.4. Microshield® Pro Version 12.11 Code

MicroShield is a computer software code that can be used to analyze shielding and estimate exposure from gamma-ray radiation, design radiological shields and containers, assessing radiation exposure to people and materials, selects temporary shielding for maintenance tasks, minimize exposure to people, infer source strength from radiation measurements for waste disposal, as well teaching principles of radiation and shielding. The computer code has become more important for engineers and health specialists as far

as radiation protection is concerned. In the estimation of gamma-ray shielding, the code uses the point-kernel approach, in which the source region is partitioned into patches of smaller volume where the doses are integrated in terms of space and energy in the analysis [40]. The mathematical equation that governs the estimation of the total dose rate based on the point-kernel isotropic point source is as follows:

$$D = \int dE \times \frac{e^{-\mu r}}{4\pi r^2} \times C(E) \times S(E) \times B(\mu r, E) \quad (7)$$

where D is the total external dose rate, E is the energy of the photons, S is the intensity of the source (specific activity), C is the density of gamma flux, r is the distance between the source and detector, μ is the attenuation coefficient, B is the buildup factor.

3. Results

3.1. Transport Accident Involving Source Materials

Figure 4 presents the collective dose and individual dose due to fire accident that occurred in every route segment during the transport of monazite source material. The individual dose was obtained by dividing the collective dose by the total number of the exposed population in the link as presented in Figure 5. The highest collective dose occurred during the transport of monazite in the route segment or link-4 of all other links. These results are due to higher accident probability rate in link-4 and higher total activity concentration of natural radionuclides of ^{238}U , ^{232}Th , and ^{40}K contained in monazite than that of other source materials (zirconia, phosphorus, and bauxite), as presented in Tables 3 and 4. However, link-3 and 12 have a higher rate of accident probability than link-4 but their population density and number of exposed persons or population are much lower than that of link-4, as a result of lower population or collective dose than link-4. Link-1 also has a higher population density than link-4; however, the rate of accident probability is lower than that of link-4, resulting in lower collective dose than link-4. Moreover, the personal or individual dose in link-12 is the highest of all links due to the highest rate of accident probability and lower population density coupled with lower number of exposed persons. Therefore, the dose and risk during an accident scenario are determined by factors such as accident probability, accident severity, package response, the activity concentration of released radionuclides, and the dispersion environment. The collective dose and individual dose were insignificant compared to 1 man-Sv/yr and 1 mSv/yr for the low-probability scenario (accident) recommended in the IAEA transport regulation (2018).

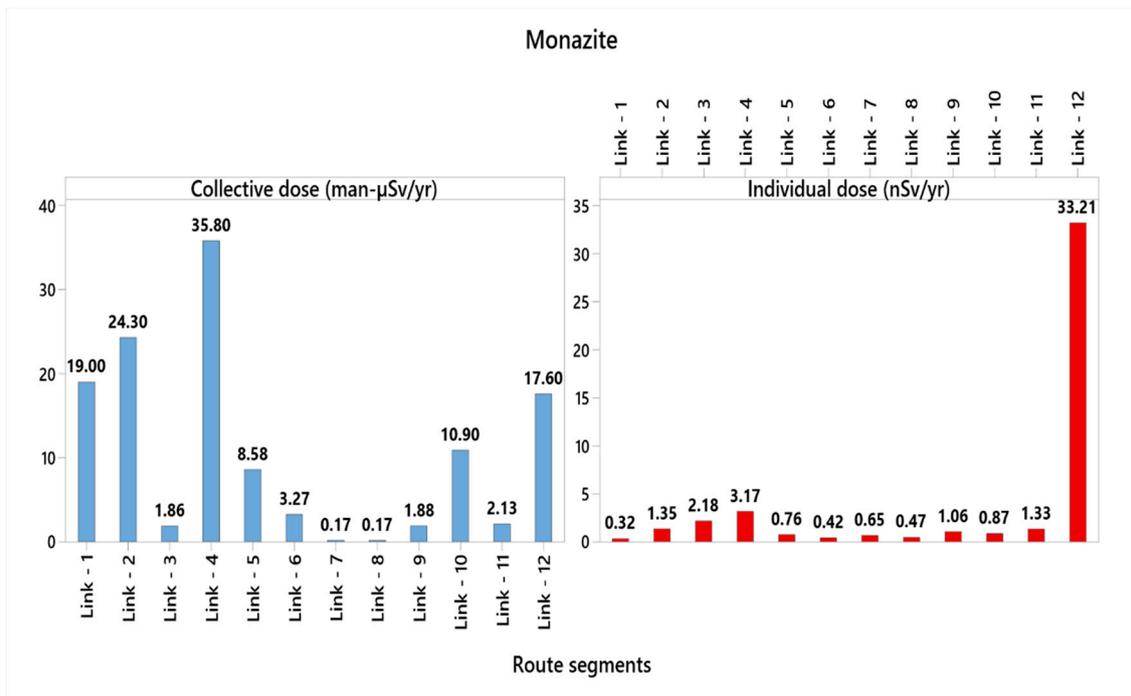


Figure 4. Accident transport result of monazite (NORM).

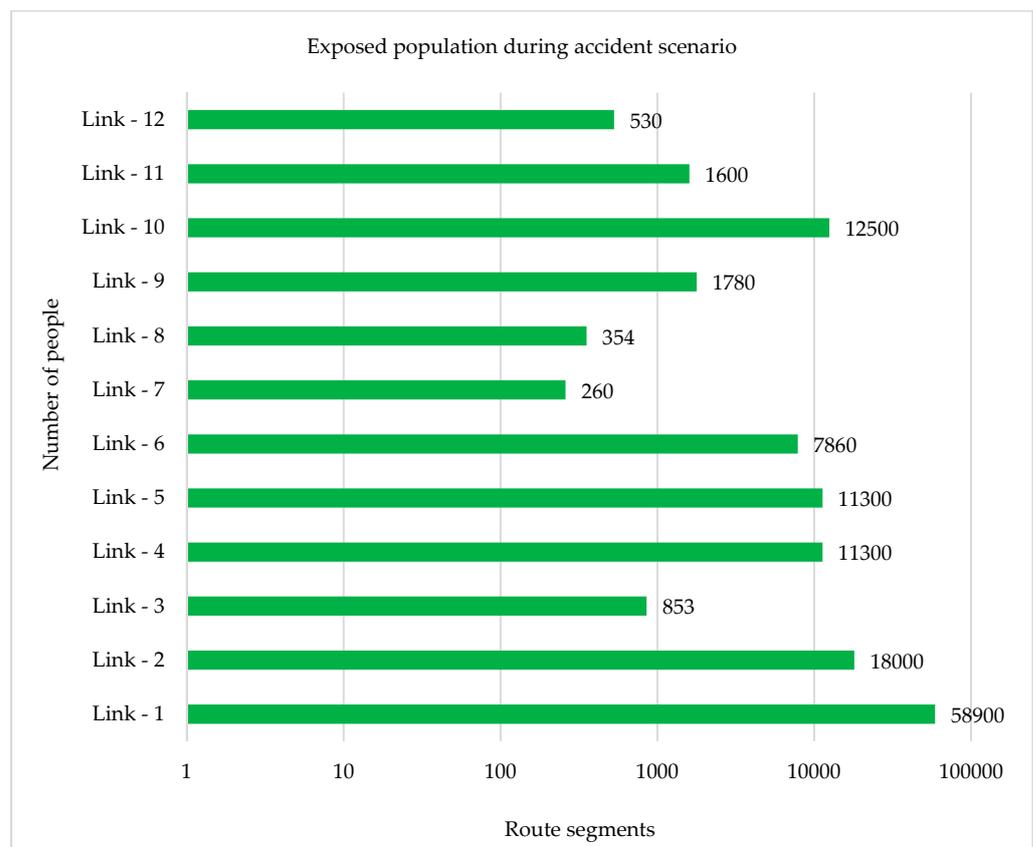


Figure 5. Exposed population in route segments (links) during accidents.

3.2. Transport Accident Involving Consumer Products

Figure 6 also demonstrates that the highest population or collective dose occurred in link_4, and is observed during transport accident involving necklace shipment. The individual dose was obtained by dividing the population dose risk by the total number of the

exposed population as presented in Figure 5. These results are due to a higher rate of accident probability in link-4 and higher total activity concentration contributed by natural radionuclides of ^{238}U , ^{232}Th , and ^{40}K contained in the necklace shipment than the rest of consumer products (latex pillow, mattress, clothing, bracelets, amnion patch, cosmetics, nippers, slippers, and health supplements), as presented in Tables 3 and 4. These factors, along with others, such as accident probability, accident severity, package response, and dispersion environment, affect the public's exposure dose and risk during an accident scenario. The individual dose in link-12 is also the highest of all other links due to the highest rate of accident probability and lower population density coupled with the lower number of exposed persons. However, the exposure dose was below the IAEA annual recommended dose limits of 1 man-Sv and 1 mSv for population and individual dose, respectively.

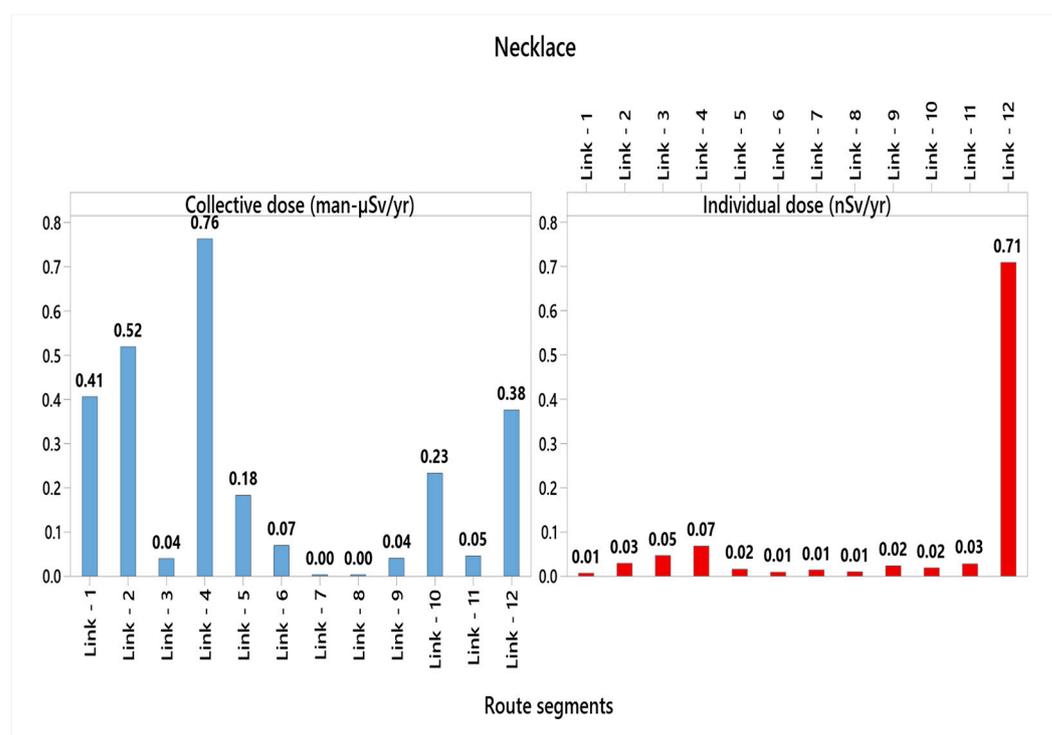


Figure 6. Accident transport result of a necklace (consumer product).

3.3. Sensitivity Analysis Result of Source Materials

Figure 7 presents the results of the sensitivity analysis for the transport of monazite source material. To overcome the estimation performed based on conservative values, the sensitivity was conducted by changing the parameter value for release, aerosol, and respirable fraction by 0.1%, 1%, 10%, and 100%. As indicated by the results, the highest collective dose occurred on route segment or link-4 of all other route segments during accident transport of monazite, with 3.58×10^{-2} man-Sv at 100% release, aerosol, and respirable fraction, respectively. The collective dose risk for monazite was still below and close to the annual regulatory limit of 1 man-Sv, whereas the collective dose for other source materials was also slightly far below the regulatory limits recommended by IAEA. This outcome is contributed by a higher accident rate in route segment or link-4, together with the highest activity concentration in monazite than the rest of source materials (NORM).

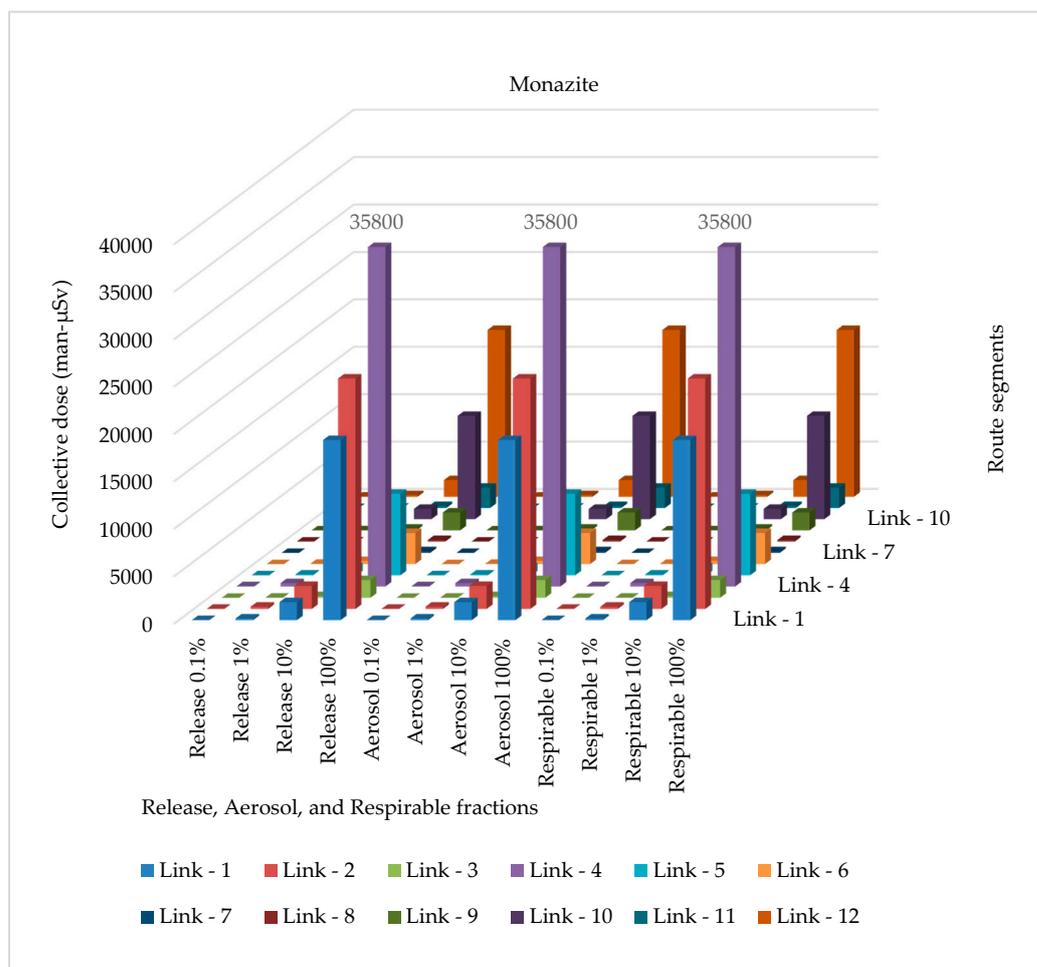


Figure 7. Sensitivity analysis result of monazite (NORM).

3.4. Sensitivity Analysis Result of Consumer Product

Figure 8 presents the results of the sensitivity analysis for the transport of consumer products. To overcome the estimation conducted based on conservative value, the sensitivity was calculated by changing the parameter values for release, aerosol, and respirable fractions by 0.1%, 1%, 10%, and 100%. According to the sensitivity results, the collective dose for all consumer products in all transport route segments is below the annual regulatory limit. However, at 100% release, aerosol, and respirable fractions, the highest collective dose was observed in route segment or link-4 of all other route segments. This was observed for accident transport of necklace shipment with 7.63×10^{-4} man-Sv/year. This result is due to the higher accident rate in route segment or link-4, coupled with a higher activity concentration in necklace than the rest of consumer products containing NORMs.

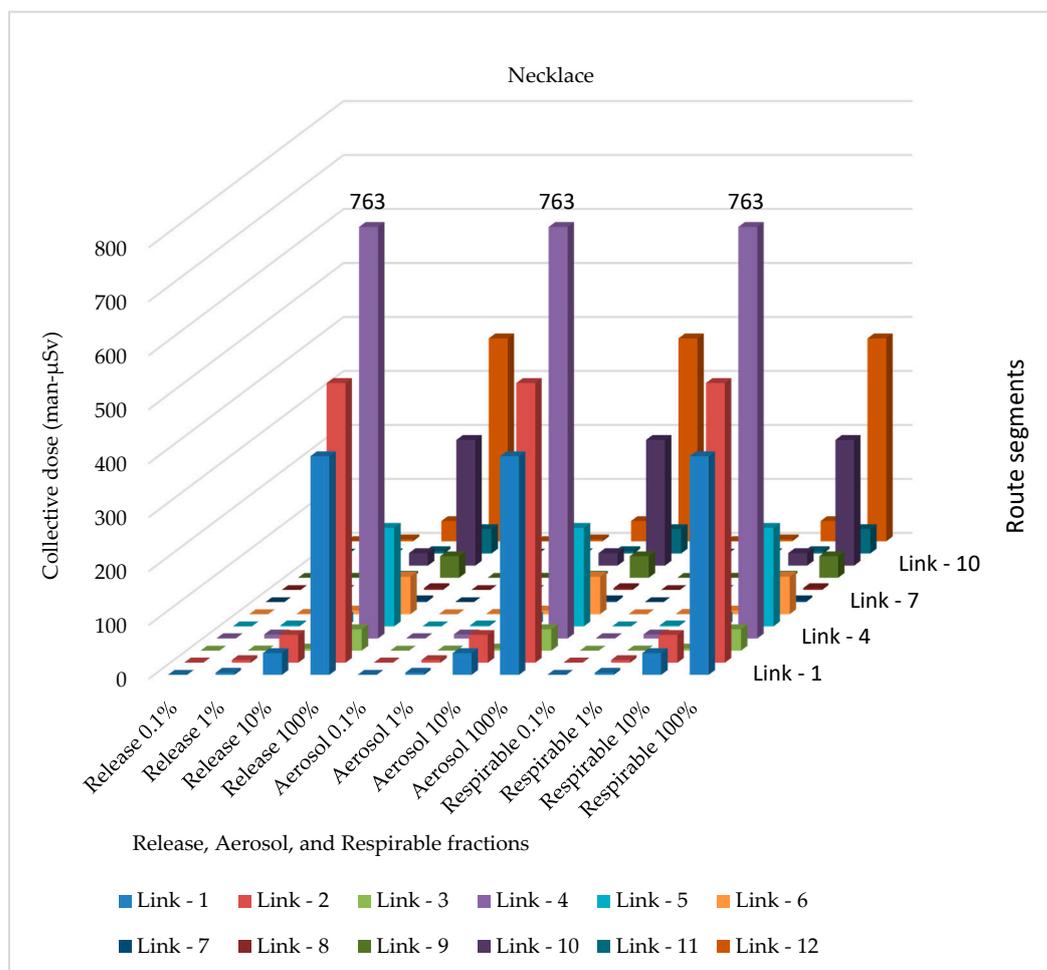


Figure 8. Sensitivity analysis result of necklace (consumer product).

4. Discussion

This study evaluated the dose and risk to the general public for road transport accidents involving NORM and consumer products containing NORM using the median and maximum value of activity concentration for NORM and consumer products, respectively. The accident scenario was simulated under stability class F for all twelve links of transportation route between Seoul and Gyeongju for the purpose of this study. The maximum population or collective dose during accident transport of source materials (NORMs) occurred in route segment or link-4 and was observed during the accident transport involving monazite shipment. This is because of the higher accident probability rate of link-4 and higher total activity concentration of radionuclides in monazite consignment than the rest of NORMs (source materials). The annual population or collective dose observed in link-4 was 3.58×10^{-5} , 1.92×10^{-7} , 1.56×10^{-8} and 3.74×10^{-8} man-Sv, for monazite, zircon, phosphorus, and bauxite, respectively. The highest individual dose was also observed in link-12. This is because of the highest rate of accident probability and lower population density coupled with a lower number of exposed persons. The individual dose observed in link-12 was 3.32×10^{-5} , 1.78×10^{-7} , 1.45×10^{-8} and 3.47×10^{-8} mSv, for monazite, zircon, phosphorus, and bauxite, respectively. The collective doses were also significantly small and below the annual regulatory limit of 1 man-Sv. The individual dose was also far below the annual regulatory limit of 1 mSv recommended by IAEA. Furthermore, the maximum collective dose occurred in link-4 and was observed in necklace shipment for accident transport involving consumer products containing NORMs. This was also due

to the higher accident probability rate in link-4 and higher radionuclide activity concentration in necklace shipment. The annual collective dose was 3.39×10^{-7} , 1.96×10^{-7} , 2.30×10^{-8} , 7.63×10^{-8} , 3.43×10^{-7} , 6.60×10^{-8} , 3.95×10^{-9} , 4.31×10^{-9} , 4.43×10^{-7} , and 6.03×10^{-8} man-Sv, for latex pillow, mattress, clothing, necklaces, bracelets, amnion patch, cosmetics, nippers, slippers, and health supplements, respectively. The individual dose was also highest in link-4 due to the highest rate of accident probability of all links and lower population density coupled with lower number of exposed persons. The individual dose in link-12 was 3.15×10^{-7} , 1.82×10^{-7} , 2.13×10^{-8} , 7.09×10^{-7} , 3.19×10^{-7} , 6.13×10^{-8} , 3.66×10^{-9} , 4.00×10^{-9} , 4.11×10^{-7} , and 5.60×10^{-8} mSv, for latex pillow, mattress, clothing, necklaces, bracelets, amnion patch, cosmetics, nippers, slippers, and health supplements, respectively. The collective dose and individual dose were insignificantly small and far below the annual regulatory limit recommended by IAEA. The results of analysis of wind rose diagram show the pattern of wind speed and direction from 2010 to 2020 with an average wind speed of 2.4 m/s directing from W to E and from WNW to ESE. Therefore, the residents in these wind directions are at a higher risk of exposure to the released radionuclide aerosol during an accident involving transportation of NORM and consumer products. The sensitivity analysis results indicated the maximum collective doses with 3.58×10^{-2} and 7.63×10^{-4} man-Sv at 100% release, aerosol, and respirable fractions for transportation accidents involving monazite (source materials) and necklace (consumer product) shipments, respectively. The highest collective doses occurred in link-4 and were still below the IAEA recommended annual regulatory limit of 1 man-Sv. The collective doses for rest of NORM or source materials and consumer products containing NORM at 0.1%, 1%, 10%, and 100% were also below the regulatory limit. However, collective dose is used to determine the greatest individual dose rate in the future as a result of a continuing practice that exposes a critical group or the entire population to radiation, and to limit current radiation sources of exposure, if it is considered that more sources of radiation exposure in the future may increase the individual dose in a population. In this regard, collective dose was also considered to determine the future individual dose as a result of the frequent transportation of NORM and associated consumer products in our public domain. Moreover, the results population exposure dose or collective dose are higher compared to another study conducted by [29] on fire transport accident involving decommissioning radioactive wastes using the same transportation route segments as presented in Table 7. This higher dose is due to slightly higher activity concentration of NORM from transported shipment compared to decommissioning wastes based on the assumption made by the both studies. This implies that the radiation dose and risk do not rely on the source of radiation, where it is natural or artificial ionizing radiation, but depends on the intensity of activity concentration. The population or collective doses and risks for decommissioning wastes were also further below the annual regulatory limit (1 person-Sv) compared to monazite (NORM) and necklace (Consumer products).

Table 7. Comparison of population dose from fire transport accidents involving NORM and low level.

Route Segments	Monazite (NORM)	Necklace (NORM-Consumer Product)	Decommissioning (Low level) Wastes
Link - 1	1.90×10^{-5}	4.06×10^{-7}	1.25×10^{-14}
Link - 2	2.43×10^{-5}	5.19×10^{-7}	5.50×10^{-15}
Link - 3	1.86×10^{-6}	3.98×10^{-8}	4.22×10^{-16}
Link - 4	3.58×10^{-5}	7.63×10^{-7}	8.10×10^{-15}
Link - 5	8.58×10^{-6}	1.83×10^{-7}	1.94×10^{-15}
Link - 6	3.27×10^{-6}	6.97×10^{-8}	2.15×10^{-15}
Link - 7	1.69×10^{-7}	3.60×10^{-9}	3.82×10^{-17}
Link - 8	1.67×10^{-7}	3.57×10^{-9}	3.79×10^{-17}
Link - 9	1.88×10^{-6}	4.02×10^{-8}	4.26×10^{-16}
Link - 10	1.09×10^{-5}	2.33×10^{-7}	7.17×10^{-15}
Link - 11	2.13×10^{-6}	4.54×10^{-8}	4.81×10^{-16}
Link - 12	1.76×10^{-5}	3.76×10^{-7}	3.98×10^{-15}

5. Conclusions

Transport of NORMs and associated consumer products is inevitable in our public domain owing to their potential applications in our daily life. Artificial and natural ionizing radiation could exert harmful effects on the public and the environment. Therefore, radiological safety assessments must be conducted before the transportation of NORMs and consumer products to ensure that people and the environment are protected from unwarranted radiation exposure. This study estimated the dose and risk to the public involving transport accidents of NORM materials and consumer products containing NORMs. Microshield code was used to estimate the external dose rate, which serves as input for analysis in RADTARN. A RADTRAN code was used to assess the dose and risk during a fire transport accident. The collective dose and risk to the general public were estimated and were found to be far below the annual regulatory limits of 1 man-Sv recommended by the IAEA, and the individual doses were also insignificant. To overcome the conservative estimate, sensitivity analysis was conducted for released, aerosol, and respirable fractions. The sensitivity analysis results have also indicated that radiological safety can be secured regardless of whether all radionuclides (^{238}U , ^{232}Th , and ^{40}K) contained in the transported shipments are released, aerosolized, and respired as well. Therefore, there is a need to conduct radiological safety analysis during accident transport involving NORM and consumer products incorporating NORM. Moreover, a comparison of population collective dose from another study on the transport accident involving low level waste (decommissioning wastes) was made, and the dose and risk were found to be further below the annual regulatory limit recommended by IAEA. Therefore, dose and risk do not rely on whether the source of radiation is artificial or natural, but the intensity of activity concentration. Similar studies are also recommended to estimate the dose and risk involving other transportation modes (rail, sea and air) and NORMs from various geological settings, as well as considering other type of class stability such as stability class A, B, C, D, and E. In accordance with the fundamental principle of radiation protection (GSR-part 3), the person or organization responsible for the facilities and activities that pose a radiation risk bears primary responsibility for safety. As a result, individuals involved in the transportation of NORM and associated consumer products should exercise extreme caution when traveling through areas where accidents are more likely to occur.

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References

1. United Nations Scientific Committee on the Effects of Atomic Radiations (UNSCEAR). Sources and Effects of Ionizing Radiations, 2008 Report to General Assembly, with Scientific Annexes. In *United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) Reports*; United Nations: New York, NY, USA, 2008.
2. Alberto, M.; Leena, K.; Fabriziomaria, G. Solar Radiation Exposure and Outdoor Work: An Underestimated occupational Risk. *Int. J. Environ. Res. Public Health* **2018**, *15*, 2063.
3. International Atomic Energy Agency (IAEA). *Terminology Used in the Nuclear Safety and Radiation Protection, IAEA Safety Glossary 2018 Edition*; IAEA: Vienna, Austria, 2019.
4. International Atomic Energy Agency (IAEA). *Extent of Environmental Contamination by Naturally Occurring Radioactive Material (NORM) and Technological Options for Mitigation Technical Reports Series-419*; IAEA: Vienna, Austria, 2003.
5. World Nuclear Association Home Page. Available online: <https://world-nuclear.org/information-library/safety-and-security/radiation-and-health/naturally-occurring-radioactive-materials-norm.aspx> (accessed on 10 September 2021).
6. UNSCEAR. Exposures from Natural Sources, 2000 Report to General Assembly, Annex B; United Nations: New York, NY, USA, 2000.
7. IAEA. *Radiation Protection and Safety of Radiation Sources: International Basic Safety Standard, IAEA Safety Standards Series No. GSR Part 3*; IAEA: Vienna, Austria, 2014.
8. World Nuclear Association Home Page. Available online: <https://www.world-nuclear.org/information-library/safety-and-security/radiation-and-health/nuclear-radiation-and-health-effects.aspx> (accessed on 10 September 2021).
9. International Atomic Energy Agency (IAEA). Naturally Occurring Radioactive Materials (IV). In Proceedings of the international conference IAEA-TECDOC-1472, Szczyrk, Poland, 17–21 May 2004.
10. IAEA. *Assessing the Needs for Radiation Protection Measures in Work Involving Minerals and Raw Materials, IAEA Safety Report Series No. 49*; IAEA: Vienna, Austria, 2006.
11. United State Nuclear Regulatory Commission. *Systematic Radiological Assessment of Exemptions for Source and Byproduct Materials*; United State Nuclear Regulatory Commission: Washington, DC, USA, 2001; NUREG-1717.
12. Lee, H.C.; Yoo, D.H.; Testa, M.; Shin, W.-G.; Choi, H.J.; Ha, W.-H.; Yoo, J.; Yoon, S.; Min, C.H. Effective dose evaluation of NORM-added consumer products using Monte Carlo simulations and the ICRP computational human phantoms. *Appl. Radiat. Isot.* **2016**, *110*, 230–235, doi:10.1016/j.apradiso.2016.01.002.
13. Furuta, E.; Minowa, H.; Nakahara, H.; Iwaoka, K.; Yonehara, H. Classification of ores used for the radiation source in NORM as consumer products by PGAA. *Proc. Radiochem.* **2011**, *1*, 219–225, doi:10.1524/rcpr.2011.0039.
14. Furuta, E. NORM as consumer products: Issue of their being. *Radiat. Prot. Dosim.* **2011**, *146*, 178–182, doi:10.1093/rpd/ncr142.
15. Kang, J.-K.; Seo, S.; Jin, Y.W. Health Effects of Radon Exposure. *Yonsei Med. J.* **2019**, *60*, 597–603, doi:10.3349/ymj.2019.60.7.597.
16. Lin, M.-H.; Huang, P.-J. Inspection and radiation dose evaluation results for NORM-containing products in Taiwan. *J. Radioanal. Nucl. Chem.* **2020**, *325*, 43–46, doi:10.1007/s10967-020-07196-4.
17. Hassan, N.M.; Chae, J.S. Radioactivity and radiological impact of industrial raw materials in Korea. *Int. J. Environ. Sci. Technol.* **2019**, *16*, 8073–8080, doi:10.1007/s13762-019-02358-8.
18. Jung, H.J.; Seung, W.J.; Jin, H.P.; Ji, Y.S.; Woo, J.K.; Kwang, P.K. Assessment of radiation dose to workers resulting from external exposure to potassium in potassium in NORM industries in KOREA. *J. Korean Phys. Soc.* **2018**, *72*, 1387–1392.
19. Taheri, A.; Taheri, A.; Fathivand, A.A.; Mansouri, N. Risk assessment of naturally occurring radioactive materials (NORM) in the hydrocarbon sludge extracted from the south pars gas field in Iran. *Process. Saf. Environ. Prot.* **2019**, *125*, 102–120, doi:10.1016/j.psep.2019.02.007.
20. Shaw, J.; Dunderdale, J.; Paynter, R.A. *Guidelines for the Regulatory Control of Consumer Product Containing Radioactive Materials in the European Union*; European Commission Radiation Protection: Brussels, Belgium, 2007; Volume 1, pp. 14–16.
21. European Commission. *Practical Use of the Concepts of Clearance and Exemption. Part II. Application of the Concepts of Ex-Emption and Clearance to Natural Radiation Sources. Radiation Protection 122*; European Commission: Geneva, Switzerland, 2001; p. 87.
22. International Atomic Energy Agency. *Radiation Safety for Consumer Products, IAEA Safety Standard Series No: SSG-36*; IAEA: Vienna, Austria, 2016.

23. IAEA. *Regulations for the Safe Transport of Radioactive Materials: IAEA Safety Standards for Protecting People and the Environment, Specific Safety Requirement No SSR-6 (Rev.1)*; IAEA: Vienna, Austria, 2018.
24. United State Nuclear Regulatory Commission. *Radioactivity in Consumer Products, NUREG/CP-0001*; United State Nuclear Regulatory Commission: Washington, DC, USA, 1978.
25. IAEA. *Regulatory Control for the safe transport of Naturally Occurring Radioactive Material (NORM), Report of a Coordinated Research Project 2007–2010*. International Atomic Energy Agency: Vienna, Austria, 2013; TECDOC-1728.
26. Hughes, J.S.; Harvey, M.P. *A study on the Transport of Naturally Occurring Radioactive Material*; PA Radiation Protection Division: April 2008.
27. Tantalum-Niobium International Study Centre (T.I.C). *Radiological Risk Assessment of the Transport of Tantalum Raw Materials*. SENES Consultants Limited: Richmond Hill, ON, Canada, 2007.
28. Seo, M.; Hong, S.-W.; Park, J.B. Radiological Impact Assessment for the Domestic On-road Transportation of Radioactive Isotope Wastes. *J. Nucl. Fuel Cycle Waste Technol.* **2016**, *14*, 279–287, doi:10.7733/jnfcwt.2016.14.3.279.
29. Jeong, J.; Baik, M.H.; Kang, M.J.; Ahn, H.J.; Hwang, D.-S.; Hong, D.S.; Jeong, Y.H.; Kim, K. Radiological safety assessment of transporting radioactive wastes to the Gyeongju disposal facility in Korea. *J. Nucl. Eng. Technol.* **2016**, *48*, 1368–1375.
30. Minitab® 19.1.1 (64-bit) © 2021 Minitab, LLC. Available online: minitab.com/legal/trademarks (accessed on 07 June 2021.).
31. Haley and Aldrich, Inc. *Risk Assessment for the Transport of Radioactive Materials for the Proposed URENCO USA Facility Capacity Expansion Lea County, New Mexico*; Haley and Aldrich, Inc.: Burlington, MA, USA, 2014.
32. Road Traffic Authority (KOROAD). Traffic Accident Analysis System (TAAS). Available online: http://taas.koroad.or.kr/sta/acs/exs/engTypical.do?menuId=WEB_EMP_TAS_SDB_PACR (accessed on 19 May 2021).
33. Ruth, F.; Weiner, K.; Neuhauser, S.; Terence, J.; Brandon, M.H.; O'Donnell, M.; Dennis, L. *RADTRAN 6/Radcat 6 User Guide*; Sandia National Laboratory: Albuquerque, NM, USA, 2014; SAND2014-0780.
34. Available online: <https://data.kma.go.kr/cmmn/main.do> (accessed on 13 June 2021).
35. International Commission on Radiation Protection (ICRP). *Age-Dependent Doses to the Members of the Public from Intake of Radionuclides: Part 5, Compilation of Ingestion and Inhalation Coefficients*, ICRP Publication 72; Elsevier Publishers: Amsterdam, The Netherlands, 1996.
36. Eckerman, K.; Wolbarst, A.; Richardson, A. *Limiting values of radionuclide intake and air concentration and dose conversion factors for inhalation, submersion, and ingestion: Federal guidance report No. 11*; U.S. Department of Energy Office of Scientific and Technical Information: Oak Ridge, TN, USA, 1988; doi:10.2172/6294233.
37. Eckerman, K.F.; Ryman, J.C. External Exposure to Radionuclides in Air, Water, and Soil. In *Federal Guidance Report No. 12, EPA-402-R-93-081*; U.S. Environmental Protection Agency: Washington, DC, USA, 1993.
38. Sabek, M.; El-Shinawy, R.; Gomaa, M. Risk assessment during transport of radioactive materials through the Suez Canal. *Radiat. Phys. Chem.* **1997**, *49*, 331–336, doi:10.1016/s0969-806x(96)00132-6.
39. Chitra, S.; Sharma, V.K.; Mishra, U.C. Accident Risk Assessment of Transport of Spent Fuel by Rail in India. *Int. J. Radioact. Mater. Transp.* **1999**, *10*, 251–264, doi:10.1179/rmt.1999.10.4.251.
40. Grove Software, Inc. *Microshield Pro User's Manual Version 12 (2020)*. Available online: <http://www.radiationsoftware.co> (accessed on 11 June 2021).