Nuclear Engineering and Technology 53 (2021) 1652–1657

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Material attractiveness of unirradiated depleted, natural and low-enriched uranium for use in radiological dispersal device

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ARTICLE INFO

Article history:
Received 16 September 2020
Received in revised form
29 October 2020
Accepted 4 November 2020
Available online 9 November 2020

Keywords:
Nuclear safeguards
Nuclear material attractiveness
Radiological dispersal device

ABSTRACT

Nuclear materials can be utilized not only for peaceful uses, but also for military purposes; hence, the international community has devoted itself to the control, management and safeguarding of nuclear materials. Nuclear materials are of varying degrees of usability for development of nuclear weapons. Thus, several methods for assessing the attractiveness of nuclear materials for nuclear weapons purposes have been proposed. When these methods are applied to unirradiated depleted, natural, and low-enriched uranium (DU, NU, and LEU), they are certainly classified as non-attractive nuclear materials. However, when nuclear material attractiveness is to be evaluated for potential radiological dispersal device (RDD) uses, it is required to develop a different method for the different aspects and factors. In the present study, we derived a novel method for evaluating nuclear material attractiveness for use in RDD development. To this end, the specific activity and dose coefficient were identified as the two sub-factors, and, in consideration of those, the mass causing detrimental health effects was determined to be the main factor impacting on nuclear materials attractiveness. Based on this factor, the attractiveness of unirradiated DU, NU, and LEU for RDD use was qualitatively compared with that of ^{137}Cs.

1. Introduction

Nuclear materials need to be secured, controlled, and managed properly to prevent their use in nuclear weapons. Thus, every relevant country has endeavored to meet the international community's regulatory requirements based on the Safeguards Agreement with the International Atomic Energy Agency (IAEA) [1] as well as the bilateral nuclear cooperation agreement between the two countries (i.e., supplier and customer) [2]. To comply with these international norms, each country establishes laws and regulations respecting nuclear materials. For example, in South Korea, various types of nuclear material are designated as internationally controlled materials under the Nuclear Safety Act [3], and nuclear material accountancy and reporting are mandatory by law. In addition, a national management system for nuclear materials and facilities is established through the Act on Physical Protection and Radiological Emergency [4].

Because nuclear safety and security have recently drawn greater attention nationally and internationally, demands on the enhanced regulatory measures in a wider field of applications are increasing. On the other hand, there are limitations to the realistically available regulatory resources; hence, effective and efficient methods need to be developed and applied. For instance, it is reasonable to develop a graded approach for managing nuclear materials considering the degrees of risk of building and using nuclear weapons. To this end, nuclear material attractiveness has been defined as a factor that assesses how likely a nuclear material is to be sought after and diverted or stolen for nuclear weapons fabrication. In the relevant previous studies [5–10], methods for quantitatively assessing material attractiveness have been proposed; however, these studies were limited to the assessment of the attractiveness of nuclear materials for use only in nuclear weapons *per se*.

Indeed, the purposes, means, and targets of recent terrorism have become more diverse and unpredictable. For example, an alternative tool of terrorism, namely a radiological dispersal device (RDD), could be designed to disperse radioactive materials with conventional explosives [11]. Although the explosive power of RDDs is of course very low compared with actual nuclear weapons, their nuclear materials, which are not weapons-grade uranium or plutonium, are relatively easy to obtain by terrorists because they are widely used in many and various applications (e.g., shielding

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https://doi.org/10.1016/j.net.2020.11.005

materials [12], standard materials in non-destructive and destructive analysis [13,14], and various R&D purposes [15–18]). Although unirradiated depleted, natural, and low-enriched uranium (DU, NU, and LEU) are quite useless in terms of nuclear weapons, they could be highly attractive for malicious RDD purposes.

To our best knowledge, no study has yet analyzed the attractiveness of nuclear material for RDD use. Note that the concept of a dangerous source based on the *D* value, quantity of radioactive material in TBq, has been introduced by the IAEA for security of radioactive sources [19–21]. The *D* value for each radioisotope was calculated considering various exposure scenarios (i.e., pocket, room, inhalation, ingestion, contamination, and immersion scenarios). One could consider that the material with the lower *D* value may have the higher attractiveness. However, in the case of DU and NU, the calculated *D* values are 'unlimited'. In the case of LEU, the *D* value is presented based on the criticality limit rather than health effect; hence, it is not proper to be used directly for evaluating the material attractiveness. Developing a method to evaluate the attractiveness of non-weapons-grade nuclear materials for RDD use could make possible an additional, effective and efficient management strategy for enhanced international nuclear security. Thus, in the present study, based on a review of the existing methods for evaluating the nuclear material attractiveness for building of nuclear weapons, we derived a novel method incorporating novel factors for evaluating the attractiveness of unirradiated DU, NU, and LEU for RDD use. Then, the attractiveness of those nuclear materials for RDD use was qualitatively compared with that of ^{137}Cs, a representative artificial radioisotope. The Cs sources are widely used in irradiators for sterilization and food preservation, brachytherapy, and teletherapy as well as radioisotope gauges for industrial uses. The high-activity Cs source is usually in the form of a crystalline powder which have the chemical formula of CsCl [22]. Because the CsCl powder can be widely dispersed and easily soluble in water, it is of great concern in terms of radiological accident and RDD incident.

2. Review of methods for evaluating nuclear material attractiveness

The methods for evaluating nuclear material attractiveness have been developed as tools to assess how attractive nuclear material is as the main substance for fabrication of nuclear weapons. For example, a previous study [5] conducted by the Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), and Pacific Northwest National Laboratory (PNNL) with the United States Department of Energy (US DOE) assessed the attractiveness of various products from the PUREX [23], UREX+ [24], and COEX [25] processes, which are the reprocessing schemes for used nuclear fuels. For categorization of attractiveness levels, the following figure of merit (FOM) equation was proposed:

$$FOM = 1 - \log_{10}\left[\frac{M}{800} + \frac{M \times h}{4500} + \left(\frac{D}{500}\right)^{\frac{1}{\log_{10}2}}\right] \quad (1)$$

where *M* is the bare critical mass of nuclear material in the metallic form in kg, *h* is the heat content in W/kg, and *D* is the radiation dose rate evaluated 1 m from the surface of nuclear material with a mass of 0.2 × M in rem/h. The exponent in the term of the radiation dose rate (i.e., $1/\log_{10}2$) reduces the FOM by 1 when the dose rate increases from 500 to 1000 rem/h if all other factors (i.e., *M* and *h*) are ignored. Based on the calculated FOM value, the attractiveness levels are categorized from A to E: A for weapons; B for pure products (FOM: > 2); C for high-grade materials (FOM: 1–2); D for low-grade materials (FOM: 0–1); and E for all other materials (FOM: <0). DU, NU, and LEU with ^{235}U enrichment of less than 20% for any form and any quantity have an FOM less than 0, resulting in their categorization to the E level (i.e., very low materials attractiveness for weapons use).

This method is considered to be quite reasonable given that the main factors (i.e., critical mass, heat content, and radiation dose) are considered in the FOM calculation comprehensively, and moreover, it is possible to easily assess the attractiveness depending on whether the calculated FOM is greater than 1. For example, when (1) the critical mass of the nuclear material in a metal form is less than 800 kg, (2) the critical mass multiplied by heat content is less than 4500 W, or (3) the radiation dose rate is less than 500 rem/h (=5 Sv/h), the FOM value is calculated to be greater than 1. The reference values for these factors were determined on the following bases [26]:

- Critical mass (*M*, Size Factor): critical mass of uranium with an enrichment of 20 wt%
- Heat content (*M* × *h*, Stability Factor): heat content of ^{238}Pu (80%) + ^{239}Pu (20%) mixture
- Radiation dose (*D*, Acquisition Factor): standard value for conservative self-protecting radiation dose.

Note that this method is applicable only for nuclear material in a metal form and for weapons utility; hence, it is not appropriate for the oxide form of nuclear material or for evaluating attractiveness for RDD use.

Another previous study [9], conducted by the same research group to expand their research, assessed the attractiveness of products from various reprocessing processes (PUREX, UREX, COEX, THOREX [27], PYROX [28]) and MOX spent nuclear fuel. The extent of the nuclear proliferation threat differs according to whether the entity at issue is a proliferant state or a sub-national group. In the case of a proliferant state, the goal might be to improve the performance of nuclear weapons, whereas in the case of a sub-national group (i.e., a terrorist group), their goal would be achieve regardless of the performance of nuclear weapons. To reflect such differences, the same study [9] introduced another factor to evaluate the attractiveness of nuclear materials for unadvanced proliferant nations. This new factor is related to the isotopic composition of Pu, which reflects the spontaneous-fission neutron production rate. The revised equation for FOM calculation is as follows:

$$FOM = 1 - \log_{10}\left[\frac{M}{800} + \frac{M \times h}{4500} + \frac{M \times S}{6.8 \times 10^6} + \frac{M}{50}\left(\frac{D}{500}\right)^{\frac{1}{\log_{10}2}}\right] \quad (2)$$

where *S* is the spontaneous-fission neutron production rate in neutrons/s·kg. The reference value of 6.8 × 10^6 n/s is a value that corresponds to the neutron production rate of reactor-grade Pu with a ^{240}Pu fraction of ~20%. Another change from the former equation is that the dose factor is multiplied by an additional value of M/50. This reflects the difficulty in handling high-dose substances when the critical mass is very large.

On the other hand, in the case of sub-national groups, it could be assumed that they are highly interested in the explosion itself, regardless of the explosive power. Under this assumption, the attractiveness of nuclear materials can be calculated without the spontaneous fission neutron rate term, as follows:

$$FOM = 1 - \log_{10}\left[\frac{M}{800} + \frac{M \times h}{4500} + \frac{M}{50}\left(\frac{D}{500}\right)^{\frac{1}{\log_{10}2}}\right] \quad (3)$$

In another previous study [10], the attractiveness of nuclear material was qualitatively evaluated against various factors and classified into four levels (i.e., High, Medium, Low, and Very Low). The aim of attractiveness assessment is the same whether or not the nuclear material is attractive for use in an actual nuclear weapon. An interesting aspect of this study is that each attractiveness factor was evaluated qualitatively for each diversion stage. Namely, the overall net weight and radiation dose of nuclear material were selected as the main factors at the acquisition stage, while the time and complexity were the main factors at the material processing stage. Finally, critical mass and heat content were the main factors at the use stage. Attractiveness has been assessed based on those main factors. For example, attractiveness in terms of weight is high when it can be carried by a human, while it is low when it cannot be carried even by trucks. In the case of critical mass, attractiveness differs depending on the uranium enrichment. In the case of heat content, attractiveness varies depending on the composition of plutonium.

The IAEA's Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225/Rev.5) [29] has provided a graded approach based on the characteristics of nuclear material. The IAEA's selected factors for this approach are the type of nuclear material, its isotopic composition, its physical and chemical forms, its degree of dilution, its radiation level, and its quantity. Taking these factors into consideration, the IAEA has recommended that nuclear materials can be categorized into three graded categories. Unirradiated DU, NU, and thorium, which have no categories assigned, are recommended to be managed based simply on prudent management practice.

3. Assessment of nuclear material attractiveness

3.1. Selection of evaluation factors

When the existing attractiveness assessment methods described above are applied, unirradiated DU, NU, and LEU are all evaluated to be non-attractive nuclear materials with the negative FOM values. However, those methods are all related to the use of nuclear weapons, and in fact are inappropriate for application to the issue of potential RDD use. Note that the factors relevant to accessing the attractiveness of nuclear material for use in nuclear weapons are not necessarily relevant to RDD use. In the case of unirradiated DU, NU, and LEU, these materials could be attractive for development of explosive devices known as 'dirty bombs', which are used simply to disperse radioactive material over a wide area, certainly not to produce a nuclear explosion. However, no attractiveness assessment method has yet been developed for this purpose; hence, in the present study, a new method was derived to assess the attractiveness of nuclear materials for RDD use.

In the case of terrorist groups, the explosion power of the RDD could be a major factor relevant to the achievement of their goal; however, producing social chaos rather than actual physical harm or infrastructure destruction might be a more important factor for them when considering that the minimal purpose of terrorists is to just announce their presence and intentions. Because terrorism can cause excessive social unrest and enormous response costs regardless of the actual human risk level, an RDD can have great psychological (and economic and political) effects even with a small explosive power. When assessing the attractiveness of nuclear material for RDD fabrication, it is very difficult to set a clear numerical reference value and derive a FOM formula that everyone agrees with. However, it would nonetheless be meaningful to qualitatively compare attractiveness of nuclear materials specifically for RDD use. In the present study, considering the factors used in the previous studies, the sub-factors in assessing attractiveness for RDD use were selected as (1) specific activity (Bq/g) and (2) dose coefficient (Sv/Bq), while the main factor reflective of both of those was determined to be (3) mass causing detrimental health effects (kg). Then, attractiveness was qualitatively compared for unirradiated DU, NU, and LEU with respect to ^{137}Cs, a representative artificial radioactive material.

The selection criteria of the above factors are described as follows. The RDD was not intended for nuclear explosions caused by a nuclear chain reaction, but for nuclear material dispersion; hence, the critical mass, ^{235}U enrichment or Pu isotopic composition, and type of nuclear material (U or Pu), which were all considered as important factors in nuclear weapons fabrication, are not necessarily important factors in RDD fabrication. As an alternative to these factors, the specific activity (Bq/g) was introduced in this study. Provided that specific activity is high, high radioactivity can be dispersed despite a small amount of nuclear material. Therefore, specific activity was considered to be a factor determinative of attractiveness for RDD use.

In the case of radiation dose, previous studies considered it as a self-protecting factor; that is, attractiveness is lowered when the radiation dose level is high, due to the difficulty of handling such material safely. However, the present study was concerned with the attractiveness of DU, NU, and LEU, and the radiation doses of these materials are inherently low. Therefore, there could be no restrictions on the handling of these materials due to radiation dose. Alternatively, therefore, the dose coefficient (radiation dose per unit radioactivity) was selected in the present study as a factor for assessing attractiveness for RDD use. When the dose coefficient is high, the radiation dose to the public by inhalation of polluted air should be high even with only small amounts of dispersed radioactivity, resulting in higher attractiveness for terrorists. Note that the dose coefficient considered here is related not to external exposure but rather to internal exposure, which is the major route of exposure from DU, NU, and LEU.

As the last but most important factor, we selected mass causing detrimental health effects, which was determined in comprehensive consideration of the above two sub-factors. Although the value varies depending on the air concentration of the radioactive material and the duration of the residence time in the contaminated area, the total amount of nuclear material that can affect human health by internal exposure due to inhalation of contaminated air under certain conditions was selected as the main factor. In this case, attractiveness is reduced with increased total amount, because a larger amount of nuclear materials is needed to be dispersed for causing detrimental health effects.

The heat content, which was identified as an attractiveness factor in previous studies, was not selected as the factor in the present study. In the previous studies, when the heat content was large, a handling limitation was incurred, resulting in low attractiveness. However, it is unlikely that the handling of DU, NU, and LEU will be limited, because their heat contents are inherently low. Therefore, heat content was determined to be less important in attractiveness assessment for RDD use when unirradiated DU, NU, and LEU are considered.

3.2. Assessment of nuclear material attractiveness

3.2.1. Specific activity

The radioactivity (A) and mass (m) of radioisotopes can be calculated by the following formula:

$$A = \lambda N \tag{4}$$

$$\mathrm{m} = \frac{N}{N_A} \times M \tag{5}$$

where A is radioactivity (Bq), λ is the decay constant (/s), and N is the number of radionuclides. In Eq. (5), m is the mass of the radionuclide (g), N_A is the Avogadro's number (6.022×10^{23}/mol), and M is the atomic mass (g/mol). Accordingly, the specific activity can be calculated through the following formula:

$$\text{Specific activity}\left[\frac{\mathrm{Bq}}{\mathrm{g}}\right] = \frac{A}{m} = \frac{\lambda\, \mathrm{N}}{\frac{N}{N_A} M} = \frac{\mathrm{N_A}}{M} \tag{6}$$

The specific activities of ^{234}U, ^{235}U, and ^{238}U were calculated by the above formula as 2.30×10^8, 8.00×10^4, and 1.24×10^4 Bq/g, respectively. The decay constant (λ) and atomic mass were obtained from the National Nuclear Data Center (NNDC) [30] and the National Institute of Standards and Technology (NIST) [31], respectively. The calculated specific activities of the DU, NU, and LEU, including that of ^{137}Cs, are listed in Table 1. The enrichment of ^{235}U for DU, NU, and LEU was assumed to be 0.2, 0.72, and 5.0 wt%, respectively. Note that the content of ^{234}U was very small (i.e., 0.001–0.0445 wt%), but that it contributed greatly to the overall specific activity because of its ~10^4 times higher value compared with ^{235}U and ^{238}U. The specific activities of the DU, NU, and LEU were significantly lower than that of ^{137}Cs.

3.2.2. Dose coefficient

Uranium isotopes (i.e., ^{234}U, ^{235}U, and ^{238}U) produce a variety of daughter nuclei through the radioactive decay chain in releasing alpha, beta, and gamma rays. In this decay process, most of the energy is emitted through alpha decay, and consequently, internal exposure is the major concern when uranium isotopes are released into the environment. Accordingly, the dose coefficient (Sv/Bq), which is the internal dose per unit activity intake, was selected as an attractiveness factor. The dose by unit activity intake is increased with a higher dose coefficient, resulting in the high attractiveness for RDD use, specifically because a lower amount of radioactivity can cause a higher radiation dose. The dose coefficients of the three uranium isotopes and ^{137}Cs, as provided in ICRP 119 [32], are summarized in Table 2. Although the dose coefficients are presented according to age in ICRP 119, we used the values for adults for inhalation of Type M particulate aerosols with an activity median aerodynamic diameter (AMAD) of 1 μm.

The dose coefficients of DU, NU, and LEU were calculated based on the dose coefficients for each of the isotopes and the isotopic compositions listed in Table 1. Due to the concentration of ^{238}U being the majority of DU, NU, and LEU, the calculated dose coefficients for the DU, NU, and LEU were almost the same (i.e., ~2.9×10^{-6} Sv/Bq).

In the case of ^{137}Cs, on the other hand, the dose from internal exposure by intake of radioactive material is extremely small compared with the uranium isotopes, while the external exposure due to gamma rays is the main route of exposure. Therefore, when evaluating the radiation dose due to ^{137}Cs, it was appropriate to evaluate external exposure rather than internal exposure.

Table 2
Dose coefficients of uranium isotopes and ^{137}Cs for inhalation, as provided in ICRP 119 (Sv/Bq).

Radionuclide	Dose Coefficient (Sv/Bq)
^{234}U	3.5×10^{-6}
^{235}U	3.1×10^{-6}
^{238}U	2.9×10^{-6}
^{137}Cs	9.7×10^{-9}

Therefore, the dose conversion coefficient (effective dose per fluence, unit: Sv·cm^2) for ^{137}Cs (0.662 MeV photons) in anteroposterior (AP) geometry, as provided in ICRP Publication 116 [33], was used, because it has the highest value among the geometries (i.e., AP, PA, LLAT, ROT, and ISO). If a ^{137}Cs point source of 1 g (=3.21×10^{12} Bq) was located at a 10 m distance, the dose rate was determined to be 6.88×10^{-7} Sv/s when we used the dose conversion coefficient of 3.17×10^{-12} Sv·cm^2 with the equation

$$\text{Effective dose rate}\left[\frac{\mathrm{Sv}}{\mathrm{s}}\right] = \varphi \times DCC = \frac{S}{4\,\pi\, r^2} \times DCC \tag{7}$$

where φ is the gamma-ray fluence rate in cm^{-2}·s^{-1}, DCC is the dose conversion coefficient in Sv·cm^2, S is the source strength (=activity × gamma-ray yield) in s^{-1}, and r is the source distance in cm.

3.2.3. Mass causing detrimental health effects

In comprehensive consideration of the above two sub-factors (i.e., specific activity and dose coefficient), we introduced mass causing detrimental health effects as a new, main factor. Detrimental health effects consist of (1) a deterministic effect by acute or high-dose exposure and (2) a stochastic effect by chronic or low-dose exposure [34]. In the present study, the upper boundary of the reference level for an emergency exposure situations of 100 mSv, as recommended by ICRP 109 [35], was selected as a reference dose for analysis of nuclear material attractiveness. The effective dose of 100 mSv can be considered to be the radiation dose less than the threshold dose for any severe tissue reaction and 0.5%-increased cancer risk when the nominal cancer risk coefficient of 5%/Sv is applied.

Considering the dose coefficients of the DU, NU, and LEU, the required intake of these nuclear materials caused by a 100 mSv radiation dose was determined to be ~3.45×10^4 Bq, regardless of the nuclear-material type (i.e., DU, NU, or LEU). In order to calculate the required mass of nuclear material that causes the intake of 3.45×10^4 Bq, it was assumed that the material is dispersed homogeneously in a rectangular space of $20 \times 20 \times 20$ m^3 by the RDD. The breathing rate of 1.1 m^3/h for adults [34] and the residence time of 1 min were considered. Then, the required initial dispersal amount of radioactivity was determined to be 1.50×10^{10} Bq from Eq. (8) below. Considering the specific activities of the DU, NU, and LEU, the masses with a radioactivity of 1.50×10^{10} Bq were 1,010, 576, and 128 kg, respectively.

Table 1
Isotopic compositions (wt.%) and calculated specific activities (Bq/g) for depleted, natural, and low-enriched uranium as well as ^{137}Cs.

	Isotope	DU	NU	LEU	^{137}Cs
Isotopic Composition (wt.%)	^{234}U	0.001	0.0057	0.0445	100
	^{235}U	0.2	0.72	5.0	
	^{238}U	99.799	99.2743	94.9555	
Specific Activity (Bq/g)		1.49×10^4	2.61×10^4	1.18×10^5	3.21×10^{12}

Table 3
Mass causing detrimental health effects and evaluated grades of nuclear material attractiveness for DU, NU, LEU, and ^{137}Cs.

Radionuclide	Mass Causing Detrimental Health Effects (kg)	Nuclear Material Attractiveness
DU	1010	Low
NU	576	Medium
LEU	128	Medium
^{137}Cs	2.42	High

$$\frac{x\,Bq}{20 \times 20 \times 20\,m^3} \times 1.1\frac{m^3}{h} \times \frac{1}{60}\,h = 3.45 \times 10^4\,Bq \quad (8)$$

In the case of ^{137}Cs, the dose rate when 1 g of that material was placed 10 m away was about 6.88×10^{-7} Sv/s, as mentioned above. Therefore, the mass required to induce a 100 mSv radiation dose was determined to be 2.42 kg for the residence time of 1 min. Considering the specific activity, 2.42 kg of ^{137}Cs corresponds to ~2.1×10^5 Ci. A gamma-ray source whose radioactivity is more than a few kCi, usually is used as a high-intensity gamma-ray irradiator in sterilization and food preservation applications. Due to the very high radioactivity, these sources are classified as Category 1 (e.g., >2.7 kCi for ^{137}Cs) by the U.S. NRC [36] and IAEA [19], which requires various security measures including personnel access authorization, protection of information, training, and monitoring. Additionally, it could have the self-protecting capability against malicious activities.

Finally, based on the mass causing detrimental health effects, we qualitatively assessed how attractive such nuclear materials might be to terrorist groups for demonstration purposes (Table 3). The evaluated grades were categorized into three levels: High, Medium, and Low. The criteria for classification were determined based on the ease of transport of the RDD. For example, if the mass causing detrimental health effects was small, it could be fabricated as a small-size RDD, resulting in easy transportation and, consequently, classification as a highly attractive material. Therefore, the attractiveness grade was set to High for nuclear material of which the required mass is small enough to be man-portable (less than 0.1 ton). If a typical vehicle would be required to transport the nuclear material (mass range of 0.1–1 ton), the attractiveness grade was set to Medium. Finally, if the required mass was more than 1 ton, which is truck-portable material, the attractiveness grade was set to Low. Based on these criteria, the evaluated attractiveness of the DU, NU, and LEU was determined to be Low, Medium, and Medium, respectively. On the other hand, in the case of ^{137}Cs, the attractiveness was evaluated as High, because the mass causing detrimental health effects was evaluated to be only a few kg.

4. Conclusions

In the present study, we derived a novel method to evaluate the material attractiveness of unirradiated DU, NU, and LEU for RDD use, having considered previous studies' methods and factors for evaluating attractiveness specifically for nuclear weapons use. To that end, three factors, specific activity, dose coefficient (the two sub-factors), and mass causing detrimental health effects (the one main factor based on the two sub-factors) were identified. Finally, material attractiveness was qualitatively evaluated based on the ease of transport of the RDD by terrorists. As a result, the considered nuclear materials were all classified into lower grades than was the ^{137}Cs radioisotope.

The limitation of this study is the difficulty of the selection of proper factors among various physical/chemical characteristics and the specification of reference values with a firm scientific basis. For example, it was difficult to set clear criteria for radiation dose, residence time in contaminated area before escaping, and source distance in the external dose calculation for ^{137}Cs. In spite of this limitation, this study can be considered to be meaningful, in that it is the first to propose, for evaluation of nuclear materials' attractiveness for RDD use, 'mass causing detrimental health effects' as the main attractiveness factor based on 'specific activity' and 'dose coefficient' sub-factors. Further study examining and improving the proposed method by experts in related fields should be carried out in order to establish the requisite regulatory framework in a quantitative and objective manner.

In our study, we tried to select scientific and objective factors that were easy to quantify in evaluating the attractiveness of unirradiated DU, NU, and LEU. However, in the case of terrorism using radioactive materials, psychological resistance and anxiety could be more important factors regardless of the actual health effects, and as such, huge social costs could be incurred in efforts to deal with radiological and nuclear terrorism. Although the results of this study indicated that the attractiveness of DU, NU, and LEU is lower than that of ^{137}Cs, the social ripple or confusion could yet be enormous, given the sinister and fearful symbolism of 'uranium' and 'nuclear material' in the public perception. Therefore, in order to establish a reasonable nuclear-material control system in any nation, it is recommended that less-easily-quantifiable social factors be comprehensively considered in addition to scientifically and objectively derived data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) using financial resources granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (2004024-0120-CG100). This study was also supported by the Korea Institute of Nuclear Nonproliferation And Control (KINAC).

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