DERIVATION OF A SPECIIC ACTIVITY LIMIT FOR PLUTONIUM FOR NEAR SURFACE DISPOSAL
A Case Study at a Potential Site in Northwest China

by

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Based on the safety assessment framework and site-specific characteristic investigations in northwest China, an approach to deriving the specific activity limit of ^{239}Pu is applied to establish a proposed value. Our analyses, in conjunction with the results of other previous studies, allow for the following conclusions: (1) As an intrusion scenario with a feature of minimal site-dependence and pervasive applicability, the drilling scenario can be used as the limiting scenario for the post-closure period; (2) Given a dose limit of 5 mSv per year, a derived specific activity of 287 Bqg^{-1} (at a disposal depth shallower than 5 m) for ^{239}Pu is obtained through the formulation of models and subsequent calculations. It is suggested that both our approaches to deriving the limit and the results can be effectively applied to establish acceptance criteria of long-lived transuranic nuclides, for the particular disposal facility; and (3) From the standpoint of exploring the approach for limit derivation, the intrusion scenario and the corresponding exposure evaluation can be the focus of concern in the study area. It is implied that, in arid regions, a leaching scenario may lead to a more complex evaluation, with unnecessary effort, and can be virtually excluded.

Key words: near surface disposal, safety assessment, plutonium, derivation of limit

INTRODUCTION

For decades, there has been a widespread adoption of the near surface concept for the disposal of low-level radioactive waste (LLW), including long-lived radionuclides, resulting from nuclear activities, such as the decommissioning of nuclear facilities, environmental regulation and the use of nuclear technology, in many countries throughout the world [1-4]. In the context of LLW subsurface disposal, it is usually accepted that the safety isolation period of the disposal system is several hundreds of years [5]. After this period, the activity content of short-lived radionuclides, *e. g.*, ^{90}Sr and ^{137}Cs, would be very low, as a result of radioactive decay; that is, their levels of radiation could be negligible. Nevertheless, the content of long-lived transuranic nuclides, *e. g.*, ^{239}Pu, remains nearly unchanged over this period. Following the closure of a disposal facility, gradual processes, *e. g.*, natural degradation of engineered barriers or disruptive events, including human intrusion, may increase the risk of radiological impacts from plutonium and may lead to radiation exposure of the public. Thus, it is essential to investigate the activity limit of plutonium and specify the acceptance criteria for near surface disposal facilities, which also relates to an important issue in the formulation of a waste-disposal strategy.

Since the 1980s, much attention has already been paid to studies on the safe disposal of waste and the limits of transuranic elements worldwide. Such studies have provided valuable references for the derivation of transuranic nuclide limits [6-8]. In particular, the United States Nuclear Regulatory Commission (NRC) released the 10 CFR 61 series reports in the 1980s; these reports specified regulations for safety analyses to examine the limit contents of transuranic nuclides and the methodology for an environmental impact assessment (EIA) of a specific site [6, 8, 9]. In addition, the NRC developed several EIA-based software packages, such as INTRUDE (intruder dose calculation), GRWATER (calculation of effects of different distances from the site), and INVERSE (reverse calculation, calculated by the dose limit and nuclide

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concentration limit) [8-10]. In Europe, a report, regarding the reference levels for the acceptance of long-lived radionuclides, was released by the Nuclear Energy Agency (NEA) of Economic Co-operation and Development (OECD). In that report, the NEA expert group reached conclusions regarding the limits for transuranic nuclides, based on intrusion scenario analyses under various conditions (including a minimum-engineered facility in temperate area, a fully engineered facility in a temperate area and a minimum-engineered facility in an arid area) [7].

More importantly, the International Atomic Energy Agency (IAEA) published a report establishing radioactivity limits for radioactive waste in near surface disposal facilities in 2003, which virtually was an application of the ISAM (Improvement of Safety Assessment Methodologies for Near Surface Disposal Facilities) project to derive radioactivity limits for radioactive waste [11]. To date, issues concerning with the plutonium isotopes accumulation in near surface environment, *e. g*., its long-term storage and disposal, have been discussed and analyzed extensively. These include reviews of the environmental transport of plutonium [12, 13], evaluations of global fallout from atmospheric nuclear weapons tests of the 1950s and 1960s [14-16], analyses of plutonium isotopes in the air [17, 18], and experimental and modelling studies of transport mechanisms [19-22]. Nevertheless, reports on approaches to establishing activity limits for transuranic nuclides, *i. e*., ^{239}Pu, as well as their illustrations, are lacking, particularly in China, where limited general research on the concept of intermediate depth disposal for radioactive waste is available [23].

In summary, from the view of the practice of near surface disposal and the determination of LLW acceptance requirements; it is encouraged to calculate the activity limit of radionuclides, *e. g*., ^{239}Pu, by using the safety assessment (SA) methodology for near surface facilities [3, 5, 11]. However, for a specific disposal system, an understanding of the derivation of the proposed limits remains challenging, because of the complexity of identifying critical site-specific characteristics and the systematic development of scenarios and conceptual models.

The objectives of this study are to:

(1) Examine the IAEA approach of deriving a limit for the transuranic nuclide, ^{239}Pu, based on the characteristics of the specific-site environment and near surface disposal system in northwest China.
(2) Identify a critical scenario and an appropriate conceptual model using the SA framework.
(3) Present a proposed value for the site-based radioactivity limit of ^{239}Pu for reference purposes.

This research improves the understanding of establishing waste acceptance criteria at the preliminary planning stage of disposal site development.

APPROACH FOR DERIVING SPECIFIC ACTIVITY LIMITS FOR TRANSURANIC NUCLIDES

As an essential strategy to address the waste acceptance requirement in the context of an environmental safety case, the SA-based methodology has been extensively implemented to determine the limits of radionuclides in a specific waste disposal site [3, 24, 25]. In fact, a synthetic procedure that uses the SA framework to derive quantitative radioactivity limits has been recommended. This procedure includes several main steps (fig. 1): describing the assessment context and disposal system, developing scenarios, formulating models, and calculating the activity limits, *etc*. Details can be found in IAEA reports [11, 26, 27]. Here, we sketch the key information for the purposes of this research.

For a given assessment context and disposal system, it is fundamental to choose reasonable scenarios and a conceptual model, that directly affects the subsequent analysis assessing the radiological consequences. Generally, the methods of developing scenarios include expert judgment, which has been extensively used, and event tree analysis. Depending on the conceptual model for the corresponding scenario and the understanding of the relevant processes, mathematical models, as sets of algebraic and differential equations, can be formulated to calculate the resulting doses/risks for the limiting scenario of the critical radionuclides.

Assuming a linear relationship between the activity and the dose/risk, an activity limit, that meets the appropriate radiological protection criteria, can then be calculated for the radionuclide of concern. For the limiting scenario, the specific activity limit of radionuclides in the waste is xpressed as follows [11]

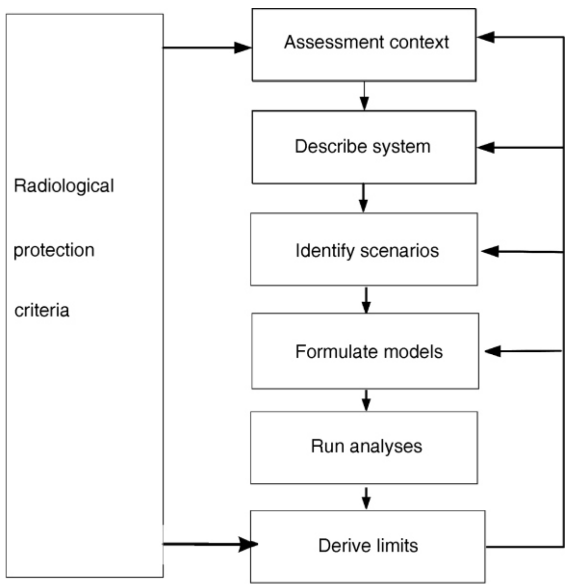

Figure 1. Simplified representation of the approach to the derivation of the activity limit [11]

$$Conc_{\mathrm{lim}} \quad \frac{Dose_{\mathrm{lim}} C_i}{Dose_i} \tag{1}$$

where $Conc_{\mathrm{lim}}$ is the specific activity limit of the radionuclide i in the waste [Bqkg^{-1}], $Dose_{\mathrm{lim}}$ – the dose limit [Sv per year], C_i – the initial specific activity of the radionuclide i in the waste [Bq], and $Dose_i$ – the dose resulting from the initial activity of the radionuclide i in the waste [Sv per year].

APPLICATION CASE

Assessment background

Aim

The aim is to apply the SA-based framework to derive the activity limit of ^{239}Pu, following the closure of a near surface disposal facility that is being designed for a potential site in northwest China. The proposed limit can be used as a reference benchmark in the waste acceptance criteria for long-lived radionuclides that are disposed in this site-specific system to protect both human health and the environment.

Radiation protection criteria

For a disposal facility of radioactive waste, it is widely accepted that SA techniques should be adopted to assess its performance, as well as impact on human health and the environment. The established regulatory criteria should be satisfied for purposes of reaching an acceptable safety level of disposal activities [26]. In order to achieve the related safety objective, doses and/or risks (to members of the public and workers in the long term) are required to be constrained to reasonable limits and established as radiation protection criteria [5]. In effect, dose limits and SA techniques for various exposure scenarios have been extensively discussed and well established in relevant international standards [5, 25-28]. Details with respect to those limits and techniques are beyond the scope of our study, which can be subjects of other documents.

In this study, it is appropriate to specify the limits in accordance to existing references toward comparative analyses of the results. Hence, during the post-closure period of the disposal facility, the dose limits are set as follows [5, 11, 28]: for the relevant critical groups of the public, the average effective dose satisfies a dose constraint of not more than 0.3 mSv per year; for situations of human intrusion (*e. g.*, *on-site* residence, over the long term), the average annual effective dose equivalent shall not exceed 1 mSv per year; and for situations of human intrusion (*e. g.*, construction over the short term), the limit shall not exceed 5 mSv per year in a single acute exposure.

Assessment principle and time scales

According to the actual site and disposal system and to the appropriately conservative principles, parameters and conditions for the evaluation are established to achieve relative conservativeness and significance for reference. Assuming an operation period of 50 years, the control period following the closure of the disposal facility shall be 300 years. During this period, site management and control shall be conducted to prevent human intrusion.

Disposal system description

In the preliminary siting stage, based on the current investigation data and the conceptual design, both information relevant to the background conditions of the waste and the site characteristics are provided as a basis for deriving the limit. In the future, the quality of the information will be improved with further investigations. Nevertheless, some exact information regarding the site is not listed here for confidentiality reasons, as observed for other details.

Waste characteristics

LILW is a form of polluted sand that tends to suspend and spread within the atmosphere due to wind-force action. The radionuclides in the contaminated sands are mostly found in sparingly soluble glassy waste forms, in which ^{239}Pu, as the critical radionuclide of major radioactive contamination, has a distinctly higher specific activity. The preliminary investigation indicates that the resuspension coefficient of the small granular sandy soils increases by orders of magnitude when it is disturbed in a strong wind field.

Environmental setting

The pre-selected site is located in a remote area in northwest China, that includes relatively flat terrain without destructive geological phenomena, *e. g.*, landslides and collapse. The area is of a typical continental arid climatic zone, *i. e.*, hot and dry with intense evaporation. The average annual precipitation is 25 mm, and the average evapotranspiration rate is 3000 mm. Under these extreme climatic conditions, a diversity of vegetation is absent and plant cover is sparse. Mineral resources are not found in the region of the site. The locations of historic heritage sites and local settlements are far from this area. Presumably, the surrounding area will be less affected by human activities in the future.

There is no perennial river in the region, although there are floods of short duration during the rainy season. In terms of environmental hydrogeology, the vadose zone, at a depth of more than 20 m, and the saturated zone below the disposal system consist of sandstone layers, where groundwater is composed of bedrock fissure water in structural zones. Regionally, the site lies in the groundwater system of a runoff area, where the groundwater chemistry types are largely $Cl{\cdot}SO_4$-Na type.

Disposal scheme and engineering barriers

For a specific near surface disposal facility, the concept of multiple barriers, *i. e*., a suitable combination of engineered barrier (*e. g*. waste packages or containers, backfill layers, the facility structure including the overlying cap) and natural barrier (the geological media around the facility), is commonly deployed to realize the requisite levels of safety and to implement the multiple safety functions of the overall system [3, 5, 25].

Currently, a rudimentary concept for near surface disposal is considered for the LLW in this study. Table 1 briefly lists the conceptual design of the disposal facility. It is noted that the issue concerning waste packages remains an open question, because costs of different waste packages vary considerably. Thus, from the perspective of reducing the fees of disposal, an option of unpackaged wastes is suggested with a preliminary cost-benefit analysis.

Scenario analysis and development

Operational period

Although radiation exposures/risks could result from the normal/abnormal operations, for instance, radiation exposure during the transportation process, physical damage to waste packages, leakage, and fire, such exposures/risks are normally considered to be controllable through several measures, *e. g*., limiting the exposure time and accessible distance and developing scientific and rational procedures. Most importantly, such external exposures during the operational period do not apply to plutonium, whose risks/impacts are recognized from inner exposures and include ingestion and inhalation [29]. Thus, the various scenarios during the operational period are not used as the constraint conditions of the limit calculation for plutonium.

However, emphasis should be given to the fact that scenarios for operational period, including gas release, explosion, flooding, criticality incident, and direct irradiation, *etc*., may need to be developed and screened as the constraints of the limit calculation for all relevant radionuclides [11]. As clearly stated above, those scenarios for operational period, as well as associated doses/risks to worker and public, are excluded from this study, which can be explained and justified for other radionuclides in future articles.

Post-closure period

In view of the environmental characteristics, waste characteristics and radionuclides of concern, along with the experience of transuranic nuclide limits in other countries, potential post-closure scenarios are preliminarily listed (tab. 2), upon which the limiting scenario will be screened.

Because of the adverse ecological environment and the harsh climatic conditions in this area, even if inadvertent or intentional human intrusion occurs during the post-closure period, it can be inferred that on-site house construction, residence and agricultural scenarios would be unlikely, which means that internal exposures under these scenarios would be less likely to occur. In the case of a leaching scenario, as the covering layers of approximately 3 m covered the upper surface of the wastes and the disposal units equipped with a waterproof layer, impermeable layer and retardation layer, even if precipitation infiltrates into the disposal units, the water is commonly considered to not be of a gravity moisture amount that is capable of freely flowing as undergoing complex distribution of moistures. Then, while the limited water is in contact with the wastes, the radionuclides within the wastes

Table 1. Conceptual design of the disposal facility for LLW

Type of waste	LLW including the long-lived radionuclide, *i. e.* ^{239}Pu	Explanation
Disposal structure	Unpackaged wastes are emplaced in concrete units upon which several overlying layers are designed. The disposal units (concrete units) consist of side walls, drains, top and bottom plates.	As the integrated barrier, providing containment and isolation of the radionuclides associated with the waste.
Overlying cap or layers	Seven layers as a cap from the top down: 20 cm of a pebble layer for anti-wind erosion, 50 cm of a primary soil layer, 50 cm of gravel as a drainage layer, 80 cm of clay as an impermeable liner, 20 cm of quartz sand for water flow, 50 cm of clay as a block layer, and 40 cm of waterproof-reinforced concrete as a top plate.	As measures to enhance mechanical stability, to prevent the infiltration of water into wastes and to minimize the possibility of exposure of wastes with erosion. In short, to block the release of radionuclides to the biosphere through potential paths.
Intrusion prevention	20 cm of a pebble layer; wooden fences and permanent warning signs are placed around the disposal facility.	As the arrangement to discourage or prevent inadvertent and/or intentional human intrusion.
Drainage design	A collection tank, pump and drainage network with 1% slope are established nearby the final cap.	As the step maintaining the low permeability barrier and encouraging run-off events to restrict infiltration ones.

Table 2. Potential exposure scenarios and radiation exposure pathways during the post-closure period

Scenarios	Radionuclides releases and transfers	Exposure pathways
Drilling	The perturbation of contaminated sands and the atmospheric transfer of resuspended dusts and/or aerosols particles resulting from drilling into the disposal facility with the occurrence of human intrusion.	Internal exposure by inhalation of resuspended particles and ingestion of contaminated soils.
Excavation	The release, transfer and exposure pathway remained nearly the same as under the drilling scenario. However, exceptions may occur in the existence of a cover of less than 5 m.	
Post-drilling	Wastes can be brought to the surface and spread in on-site areas. Atmospheric transfer and resuspension of aerosols particles may occur herein.	Internal exposure by inhalation of aerosol particles.
Post-excavation	Except for the greater amount of wastes brought to the ground and the cover of less than 5 m in this case, the transfer and exposure pathways are similar to those under the post-drilling scenario.	
Construction	On-site house or road construction with inadvertent intrusion. The potential excavation of wastes and the transfer of dust and particles.	Internal exposure by inhalation of radionuclides.
Agriculture	The site is assumed to be used for irrigated agriculture, where crop roots are assumed to penetrate the cover. The transfer of radionuclides may occur through the food chain.	Internal exposure by ingestion of contaminated foods and inhalation of resuspended particles.
Residence	The intruders lived in on-site houses and consumed foods and/or meat yielded from the contaminated soils.	Internal exposure by ingestion of contaminated foods and/or meat and inhalation of resuspended particles.
Leaching	Infiltration of rainfall through the cover or lateral migration into the disposal units can lead to leaching and movement of radionuclides from the waste. Radionuclides may migrate through the vadose zone and enter the groundwater and the biosphere.	Internal exposure by ingestion, *e. g.*, drinking contaminated groundwater.

would rarely be leached and dissolved into the waters, because they are mostly in insoluble glass. Thus, it is believed that the radionuclides would be less likely to travel through the vadose zone and enter the groundwater and biosphere. That is, internal exposures, *e. g.*, human drinking contaminated groundwater would be unlikely over a long period of time under the leaching scenario. Therefore, several scenarios, *i. e.*, the construction, residence, agriculture, and leaching scenarios, can be ignored when evaluating the limit level.

More importantly, many scholars from the NRC, OECD/NEA, have previously assumed a variety of human intrusion scenarios and evaluated the relevant risks. It is proposed that an approach based on human intrusion analysis has the most potential for deriving the activity limits of radionuclides; it is also implied that a groundwater migration scenario, based on the total inventory of radioactivity at a given disposal site, is normally adapted to obtain the limits on the total activity rather than the specific activity [3, 30-34]. Although a specific activity limit can be derived by dividing the inventory through groundwater exposure by the waste volume in the disposal facility, the derived limit could be 2 to 3 orders of magnitude greater than that obtained for human intrusion exposure pathways [31]. Basically, Pu moves slowly downwards in the soil, into the groundwater due to its strong affinities for solids and limited mobility under natural conditions, regardless of the mechanisms of its transport, *e. g.*, colloid forms, microbial activity and desorption, which may enhance or inhibit the mobility of Pu in the subsurface depending on its complex speciation and additional hydrogeological characteristics [19, 21, 29, 35-38]. That is, compared to groundwater migration and well-water drinking, human intrusion cases, which are minimally site-dependent and of general use, may present a restricted condition in the derivation of limits of radionuclides.

According to the aforementioned analysis, the drilling case, which is one of the more likely human intrusion scenarios herein, is used as the constraining or limiting scenario to obtain the activity limit of ^{239}Pu, and it is assumed that the intruders can drill to penetrate through the waste cover layers and into the disposal units. Here, an excavation case is included in the mentioned drilling case because they are both assumed quite similar in terms of radionuclide releases and exposure pathways. For the excluded post-drilling and post-excavation cases, it is more easily inferred that, as an extension of the processes of drilling and excavation, there are fewer resuspended particles and less risk/dose with less perturbation of the wastes. Thus, a conceptual model, illustrating a source term release and exposure scene against the drilling scenario, can be developed (fig. 2).

Model formulation

Based on the previous conceptual model to illustrate source term release and the exposure process for the post-closure drilling scenario, the following models can be used to derive a quantitative limit for ^{239}Pu in the near surface facility.

Source term model

Because of the perturbation of drilling, the concentration of radionuclide in the surrounding air, C_{Air} [Bqm^{-3}], is given by

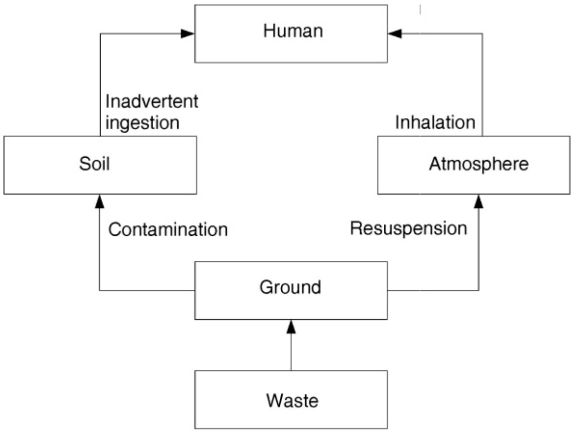

Figure 2. The conceptual model for the post-closure drilling scenario

$$C_{\mathrm{Air}} \quad C_{\mathrm{Soil}} C_{\mathrm{Dust}} \tag{2}$$

where C_{Soil} is the specific activity of the radionuclides in the soil [Bqkg^{-1}], and C_{Dust} – the concentration of re-suspended dusts or aerosols in the surrounding air [kgm^{-3}].

Exposure model

The dose due to the intruder drilling can be expressed as

$$D_{\mathrm{Total}} \quad D_{\mathrm{Inh}} \quad D_{\mathrm{Ing}} \tag{3}$$

where D_{Total} is the total dose resulting from the exposure in the drilling scenario [Sv per year], which is equivalent to $Dose_{\mathrm{i}}$ in eq. (1), D_{Inh} and D_{Ing} are the doses due to the inhalation of dusts or aerosols and the ingestion of contaminated soils [Sv per year], respectively

$$D_{\mathrm{Inh}} \quad C_{\mathrm{Air}} \, O_{\mathrm{Out}} \, Inh_{\mathrm{R}} \, DC_{\mathrm{Inh}} \tag{4}$$

where O_{Out} is the annual duration of the human exposure in the drilling activity (days per year), Inh_{R} – the human respiration rate [m^{-3}d^{-1}], DC_{Inh} – the dose conversion factor for inhalation (SvBq^{-1}).

$$D_{\mathrm{Ing}} \quad C_{\mathrm{soil}} \, U_{\mathrm{Ing}} \, DC_{\mathrm{Ing}} \tag{5}$$

where U_{Ing} is the inadvertent soil ingestion rate (kg per year), DC_{Ing} – the ingestion dose conversion factor [SvBq^{-1}].

Derivation of limit value

Following these model equations, the specific activity limit of ^{239}Pu can be generated based on a drilling scenario with human intrusion. Model parameters are summarized in tab. 3. In an effort to address the uncertainty as much as possible, the significant data, *i. e.*, C_{Dust}, are briefly examined by in situ measurement. However, other parameters have to be defined in an attempt to evaluate the empirical values from publications and the supposed values combined with the site conditions, as only limited investigations can be currently carried out.

Especially, the dose conversion factors (or committed effective dose coefficients), DC_{Inh} and DC_{Ing} herein, depend on many factors, such as the activity median aerodynamic diameter (AMAD), lung absorption types, exposure receptors and chemical forms of the radioactive particles [39-44]. To date, China has issued two valid standards (*i. e.*, GB 18871-2002 and GB/T 16148-2009) on specific topics regarding radiation protection and internal doses [45, 46], both of which explicitly provide recommendations and guidance in terms of the dose conversion factors for ingestion and inhalation of radionuclides. Note that the first standard (GB 18871-2002) was based on the IAEA safety series No. 115, that was published in 1996 and subsequently superseded by the IAEA safety standard

Table 3. Model parameters of the selected drilling scenario

Parameter	Value in calculation	Explanation
C_{Soil}	1 Bqkg^{-1}	As the initial specific activity of the radionuclide in the waste, C_{i}, which has no effect on the calculation result of the limit value herein, C_{soil} is set to a unit activity concentration.
C_{Dust}	6.3 mgm^{-3}	*In situ* measurement under a perturbation condition.
O_{Out}	120 days per year	Assumed the drilling event is seasonal due to the severe cold winter and severe hot summer. Thus, the intruder exposure is limited to a total duration of 120 days during a single year.
Inh_{R}	72 m^{3}d^{-1}	From the ICRP Publication 89 [50], 3.0 m^{3}h^{-1} for adults (male) performing heavy exercise is adopted. This value represents the worst-case scenario.
U_{Ing}	120 g per year	RESRAD uses a daily intake rate of 100 mg for deriving limits for radionuclides in soil [44]. Here, U_{Ing} is assumed to be a conservative value of 1000 mg per day.
DC_{Inh}	3.2 10^{-4} SvBq^{-1}	According to the above-mentioned standards [45-47], the values for workers can be 3.2 10^{-5} (M, 5 μm), 8.3 10^{-6} (S, 5 μm), 4.7 10^{-5} (M, 1 μm) and 1.5 10^{-5} (S, 1 μm) SvBq^{-1} for Pu-239*. Considering the broad range of AMAD in the field, 3.2 10^{-4} SvBq^{-1} is proposed for a conservative case.
DC_{Ing}	2.5 10^{-7} SvBq^{-1}	According to the related standards [45-47], the values of 2.5 10^{-7} (M) and 9.0 10^{-7} (S) SvBq^{-1} for Pu-239 are suggested for workers, among which the greater value is employed conservatively*.

* M (moderate) and S (slow) denote the lung absorption types; 5 μm and 1 μm denote the AMAD. Since the lung absorption type S is listed in the investigated results as the relatively insoluble glass, those values associated with M type are considered to be conservative. More information with regard to absorption types can be found in the above-mentioned literature.

No. GSR Part 3 (2014 edition) [47]; and the second one (GB/T 16148-2009) was mainly revised with reference to the IAEA safety standard No.37 [48], as well as the ICRP Publications [39, 41-43, 49]. In practice, the technical contents of the Chinese standards are equivalent to the ones of the above international-organization standards and provisions, as well as proved to be suitable for China's national conditions [45]. Thus, according to the above-mentioned standards and references, the values of DC_{Inh} and DC_{Ing} in this study can be chosen with available information of site-specific investigation, such as, the AMAD of plutonium aerosols with a range from a couple of tenths of a micron to a dozen, even dozens, of microns depending on the experimental location, and the lung absorption type S (slow) for ^{239}Pu.

RESULTS AND DISCUSSION

In this study, a derived specific activity limit of 287 Bqg^{-1} for ^{239}Pu is obtained using eqs. (1)-(5), where a dose limit of 5 mSv per year is specified for an intrusion scenario.

For transuranic nuclides, *i. e.*, long-lived alpha-emitting radionuclides, limits of 400 Bqg^{-1} on average and up to 4000 Bqg^{-1} for individual packages, for a particular disposal facility, have been adopted in some countries [1, 6]. In addition, based on analyses of intrusion scenarios, under various conditions for long-lived transuranic elements (such as U, Pu, Am, and Np), the OECD/NEA expert group also gave suggestions for the concentration limits. They suggested the range of 10 to 1000 Bqg^{-1} when a disposal depth is less than 5 m, where a maximum upper limit is recommended, and the range of 1000 to10000 Bqg^{-1} when the disposal depth is greater than 5 m and less than 20 m [7]. These imply that our derived activity limit of ^{239}Pu, 287 Bqg^{-1}, is reasonable in the case of the intrusion scenario analysis.

Specifically, for ^{239}Pu, specific activity limits of 370~1100 Bqg^{-1} are proposed in the literature of the NRC, DOE, OECD/NEA, and W. E. Kennedy (tab. 4) [6, 7, 9, 30]. It is generally assumed that the activity limit of each radionuclide is proportional to the dose limit resulting from the corresponding scenario. Then, if the dose limits used for the OECD/NEA and DOE are both 5 mSv per year, with a disposal depth of less than 5 m, we may reasonably reach an activity limit of 500 Bqg^{-1} and 1035 Bqg^{-1}, respectively. Overall, our derived value, based on the conservative case, is roughly approximate to those literature-values. If some conservative parameters, such as Inh_{R} and DC_{Inh}, are set with relatively smaller values and the same dose limit $Dose_{\mathrm{lim}}$ is used, the calculated D_{Total} will decrease correspondingly, and then the derived limit (*i. e.* $Conc_{\mathrm{lim}}$) will increase to the same levels as the literature values above. Again, as the previous discussion implies, the approach for deriving the limit of ^{239}Pu, including limiting scenario development, model formulation, as well as the results, can be effectively applied to identify and evaluate the establishment of limits for long-lived transuranic nuclides for the particular disposal facility in northwest China.

CONCLUSION AND SUGGESTION

Examining the SA-based methodology implemented widely, the establishment of a limit of long-lived transuranic nuclide, ^{239}Pu, for a particular disposal facility in northwest China, is presented. Based on our site-specific analysis, the drilling case, one of the human intrusion scenarios that are minimally site-dependent, is the highest potential prospective for deriving the radionuclide activity limit and is identified to be the limiting scenario for the post-closure period. The analysis, as well as formulation of models with proper parameterization, allow us to conduct the limit calculation. Then, a derived specific activity of 287 Bqg^{-1} (at a disposal depth less than 5 m) for ^{239}Pu is proposed in the case of a dose limit of 5 mSv per year.

As the discussion implies, the approach for deriving the limit of ^{239}Pu is effective and appropriate to

Table 4. Comparative analysis of the derived limits of ^{239}Pu [Bqg^{-1}]

	Depth <5 m*	Depth >5 m*	Comment
NRC	370	3700	Four intrusion scenarios are used, where intruder building and agriculture are the limiting scenarios and inhalation exposure is mainly considered, with a dose limit of 5 mSv per year.
W. E. Kennedy	1100	11000	The scenarios are similar to those of the NRC with the dose limit of 5 mSv per year.
OECD/NEA	100	5000	The dose limits used are 5 mSv per year for building scenario and 1 mSv per year for residence and agriculture scenarios. The main internal exposure of inhalation is identified.
DOE	207	28490	Six intrusion scenarios are considered as follows: Drilling, excavation, post-drilling, post-excavation, farm and residence. The dose limit is 1 mSv per year.
This study	287		The limiting scenario is identified as intruder drilling and the dose limit is 5 mSv per year. The details are as described previously.

* When the depth of waste disposal is less than 5 m which is defined as "Normal Residential Intrusion Zone" by the OECD/NEA expert group, the intrusion scenario that limits the activity content of radionuclides is intruder residence. Then, when the depth is greater than 5 m and less than 20 m, it is just assumed that the wastes remain more stable due to the greater depth and then the limits of radionuclides can be increased by one order of magnitude.

be applied at the site in northwest China. Note that, actually, our derived value of 287 Bqg^{-1} in the conservative condition is broadly consistent with referenced levels (370~1100 Bqg^{-1}) in the literature, when the depth of the waste disposal is less than 5 m, as discussed in last section. Furthermore, with a depth greater than 5 m and less than 20 m, it is implied that the limit can be increased by one order of magnitude.

Essentially, from the perspective of the limit derivation based on the SA processes, the appropriate scenarios and a conceptual model, as the fundamental prerequisite, can strongly affect the subsequent complexity and efforts of modeling and calculating. Much attention has been paid to focus on the intrusion scenario and the corresponding exposure effects rather than the leaching scenario (*i. e*., groundwater pathway migration and internal exposure after nuclide leaching) in arid regions, due to the pervasive applicability of the specific activity derivation, as well as the site-specific characteristics of severer drought and minimal precipitation.

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AUTHORS' CONTRIBUTIONS

D. X. Liu conceived this research, developed the theoretical framework with application to site-specific investigation and evaluated the data. X. W. Xiong projected the main conceptual ideas and contributed to the development of scenarios and models. J. S. Wang, L. T. Hu, and R. Zuo supervised the findings of this project and contributed to state the useful feedback, to shape the research and to check the results of theoretical analysis. All signed authors commented the results and worked on the final manuscript.

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ОДРЕЂИВАЊЕ ГРАНИЦЕ ЗА СПЕЦИФИЧНУ АКТИВНОСТ ПЛУТОНИЈУМА ЗА ОДЛАГАЊЕ ПРИ ПОВРШИНИ ЗЕМЉЕ

Студија случаја на потенцијалној локацији у Северозападној Кини

На основу законских оквира за процену безбедности и испитивања карактеристика локације за одлагање у Северозападној Кини, примењена је метода за одређивање граничне вредности специфичне активности ^{239}Pu. Наше анализе, заједно са другим објављеним студијама, доводе до следећих закључака: (1) Као улазни сценарио са одликама минималне зависности од локације и опште примењљивости, сценарио бушења се може користити као ограничавајући сценарио за период након затварања; (2) С обзиром на граничну вредност дозе од 5 mSv годишње, формулацијом модела и накнадним прорачунима изведена је вредност специфичне активности ^{239}Pu од 287 Bqg^{-1} (при дубинама одлагања плићим од 5 m); препоручено је да се оба наша приступа за одређивање граничне вредности и добијање резултата могу ефикасно применити за одређивање критеријума прихватања дугоживећих трансуранских нуклида одређеног објекта за одлагање; и (3) Са становишта испитивања приступа за одређивање граничних вредности, улазни сценарио и одговарајућа процена излагања могу бити у фокусу разматрања испитиване локације. Подразумева се, у сушним областима, да сценарио цурења може довести до комплекснијих процена, са непотребно уложеним трудом, те се може практично изоставити.

Кључне речи: одлагање при површини земље, процена безбедности, плутонијум, одређивање граничне вредности