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Systematic model for estimation of future inadvertent human intrusion into deep rad-waste repository by domestic groundwater well drilling

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A B S T R A C T

Future human intrusion into a geological repository for spent nuclear fuels and radioactive waste is a safety case that inherently involves a high uncertainty, especially in areas with a high population density. The uncertainty associated with inadvertent human intrusion needs to account for the complexity of various conceivable circumstances with the long-term evolution of society or technology. In this study, a new dynamic Monte Carlo model is developed to properly incorporate the potential future human intrusion frequency, which has never been performed in past studies. The developed model for inadvertent deep groundwater well drilling into a repository focuses on the assessment of the quantitative effects of factors mitigating or enhancing future human intrusion risk. Assuming the current groundwater well depth distribution in the Gyeongsangnam-do region of the Republic of Korea, the future human intrusion frequency is estimated to be 5.89×10^{-4} 1/yr for a repository with a depth of 500 m and a hypothetical area of 5.27×10^{-1} km^2. The model predicts that the frequency may reach up to 2.18×10^{-3} 1/yr as the depth of a groundwater well increases in the future, as expected from the data trending performed in this study. A sensitivity analysis shows that a proper design can suppress the frequency, which increases positively with the repository area and negatively with the depth of the repository. However, mitigation by a repository design tends to be weakened as the well depth distribution increases. Since the average well depth increases with time, the mitigation effects achieved by reducing the area or increasing the depth of a repository may not be effective against the current expectation. In this case, the most reliable approach for minimizing future human intrusion risk will be a reduction in the radiotoxicity concentration of the waste.

1. Introduction

As spent nuclear fuel (SNF) accumulates, the development of solid repository systems for the isolation of radioactive waste (rad-waste) from the human environment has become an urgent issue. In case of SNF or high-level waste (HLW) disposal, owing to the long-lived radionuclides in the waste, long-term safety over one million years should be assured by a performance assessment (IAEA, 2012; ICRP, 2000). There are two pathways for radionuclide release from a repository: migration by groundwater under anticipated conditions and release by human intrusion (IAEA, 2012).

For the migration pathway, various physical barriers are designed in compliance with a defense-in-depth approach. The performance of barriers to migration has been assured by numerous studies (Arnold et al., 2003; De Marsily et al., 1977; De Windt et al., 2004; Higgo, 1987; Hwang and Kang, 2010; Jedináková-Křižová, 1998; JNC, 2000; Keith-Roach, 2008; Kersting et al., 1999; Krishnamoorthy et al., 1992; Lee and Hwang, 2009; Lee et al., 2007b; Missana et al., 2003; Neall et al., 2007; Neretnieks, 1980; Robinson et al., 2003; Smith et al., 2001; Viswanathan et al., 1998). On the other hand, the only barrier providing effective protection for long-term human intrusion is the depth of a repository. Despite the deficiencies of multiple barriers to human intrusion, a repository with a sufficient depth will assure long-term safety according to evaluations in past studies (DOE, 2014; Gierszewski et al., 2004; JNC, 2000; Neall et al., 2007; Yoon and Ahn, 2010). A sufficient depth means a reduction in the probability of a human intrusion event. Currently, a depth of a few hundred meters is generally applied in SNF or HLW repository design (Bailey and Littleboy, 2000; DOE, 2014; Gierszewski et al., 2004; Hellä et al., 2008; JNC, 2000; Lee et al., 2007a; Neall et al., 2007; Posiva Oy, 2012; Yoon and Ahn, 2010).

The approaches for estimating the probability of human intrusion in past studies assumed that the level of future underground activity would be similar to that today. However, improved drilling technology has been driving increased underground activity and making deep underground development easier. Specifically, deep drilling for oil/gas exploration near the Waste Isolation Pilot Plant (WIPP) in the U.S. has been steadily increasing since its first performance assessment in 1996 (DOE, 2007). Accordingly, it became necessary to reassess the WIPP

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recently (Tracy et al., 2016). In general, the need for deep groundwater is also increasing owing to the depletion of groundwater resources, implying an increase in the development of deep wells in the future (WWAP, 2016). Although not currently observed, the increasing need for other underground resources such as rare-earth materials or geothermal energy (Alonso et al., 2012; DOE, 2012; GEA, 2016; Whiteman et al., 2016) will also drive increased deep exploration. Therefore, past studies have underestimated the probability of human intrusion. Considering the severe radiological consequences of a human intrusion scenario (Greneche et al., 2008; Smith et al., 2013), the risk of human intrusion is highly sensitive to its probability. Accordingly, more thoughtful consideration for the estimation of this probability is required.

In this study, a new systematic model is developed to estimate future human intrusion probability for a deep geological repository using a system dynamics approach. The new model attempts to consider various factors driving the increased or decreased probability of human intrusion. For model parametrization and validation, a domestic deep groundwater well development database in South Korea is used.

The rest of this manuscript is organized as follows. Section 2 systematically analyzes the human intrusion problem for geological repository systems and explains the limitations of past modeling approaches. Section 3 explains the modeling approach and the details of the new model. The probability estimation results are presented in Section 4. In Section 5, the results, a sensitivity analysis of the model parameters, and the human intrusion risk are discussed.

2. What is human intrusion?

2.1. Definition of and safety criteria for human intrusion

Human intrusion indicates a human action resulting in a direct disturbance of a repository, causing the immediate release of radioactivity (IAEA, 2012). Since numerous possible human intrusion scenarios can exist, some representative cases called stylized scenarios (OECD NEA, 1995) have been developed with simplified and conservative assumptions. The most probable scenario for a geological repository is deep drilling for resource exploration or exploitation, resulting in radiological exposure to workers or residents (Black et al., 2001; Kelly and Jackson, 2007; Smith et al., 2013). In some studies, radiological exposure by drinking contaminated groundwater though a deep well near a repository was also considered, although this scenario does not comply with the definition of human intrusion (Hellä et al., 2008; Keith Reid et al., 1989; Lee and Jeong, 2010; Nordman and Vieno, 1989). The radiological dose estimated by the stylized human intrusion scenario was expected to be greater than a few sieverts for HLW (Gierszewski et al., 2004; Greneche et al., 2008; JNC, 2000; Smith et al., 2013). This radiological consequence is very high compared with the IAEA's dose limit for the normal case (IAEA, 2011).

Complying with IAEA safety standards, the probability or consequence of human intrusion should be reduced when the expected annual dose is greater than 1 mSv (IAEA, 2011). Thus, for an HLW or SNF repository, optimization of the design is required to reduce the risk of human intrusion, i.e., the probability, as low as reasonably achievable. Accordingly, most countries set a risk constraint of an order of 10^{-6} per year for the regulatory criteria of human intrusion assessment (AECB, 1987; NIEA, 2009; NSSC, 2012).

2.2. Systematic approach for human intrusion

2.2.1. Factors mitigating future human intrusion

To comply with the regulatory risk criteria, various countermeasures mitigating human intrusion can be applied. Table 1 summarizes the factors affecting the future human intrusion probability.

Table 1
Factors affecting the future human intrusion probability.

Factors reducing human intrusion	Factors enhancing human intrusion
Repository depth	Underground resources
Institutional control	Underground development
Knowledge of repository	Technology improvement
Site surveying	

The primary countermeasure reducing the future human intrusion probability is securing a sufficient depth for a repository. The Japan Nuclear Cycle Development Institute (JNC) in Japan and Nirex in the U.K. analyzed the domestic underground development history and showed that the probability is reduced as the depth of a repository increases (Bailey and Littleboy, 2000; JNC, 2000).

Although the repository depth reduces the risk of human intrusion in the long term, institutional control and information related to the repository location provide a protection system during the early period of post-closure. Several studies expected that these two factors would be effective for a few hundred years after the closure of a repository (Bailey and Littleboy, 2000; EPA, 1985; Gierszewski et al., 2004; IAEA, 2011; JNC, 2000; NIEA, 2009; OECD NEA, 1995). Exceptionally, Woo suggested the reactivation of a protection system in the future due to the significant radiological exposure by a human intrusion event. In this case, the protection system will mitigate human intrusion in the long term (Woo, 1989, 1993).

Another remedy is the selection of a proper location for a repository by site surveying. From the viewpoint of human intrusion, the main purpose of site surveying is to reduce the motivation for deep drilling near the repository. This can be achieved by avoiding a location with abundant resources, a high population density, or easily drillable bedrock (JNC, 2000).

2.2.2. Factors enhancing future human intrusion

The most critical motivation driving future human intrusion into a geological repository will be underground resources. Fossil fuels are representative resources that have driven deep drilling today. The exploration and exploitation history of fossil fuels (Attanasi et al., 2007; OPEC, 2017) demonstrates that the high demand for underground resources arouses deeper and more extensive drilling activity. Similarly, the increasing demand for deep groundwater or critical technology material will drive vigorous drilling activity in near future. Therefore, the assessment of the human intrusion risk should account for the demand for underground resources over time.

Improvements in technology will also be attributed to increased deep underground activity. There have been many advances in drilling equipment, widening the explorable lithosphere that was hardly investigated in the past. The development of horizontal drilling and hydraulic fracturing techniques has facilitated wider production areas of resources using one drill. Moreover, improvements in drilling systems has facilitated faster and easier deep drilling. Considering this, it would be reasonable to assume no technological limitations on future drilling activities into the depth of a repository if the demand for deep drilling exists.

2.3. Limitations of past studies

The estimation of the probability of future human intrusion inevitably relies on the historical observation of regional drilling activities because the future circumstances near a repository are unpredictable. For this reason, a fully verifiable probability estimation model cannot exist. Instead, the acceptability of the model is critical for human intrusion assessment (OECD NEA, 1995). Therefore, reasonable assumptions should be derived on the basis of historical experience to improve the acceptability of model.

Numerous studies on human intrusion have considered the drilling frequency as a time-independent variable. For example, Nirex in the